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Land management and food/nutrition (in)security in mixed farming systems

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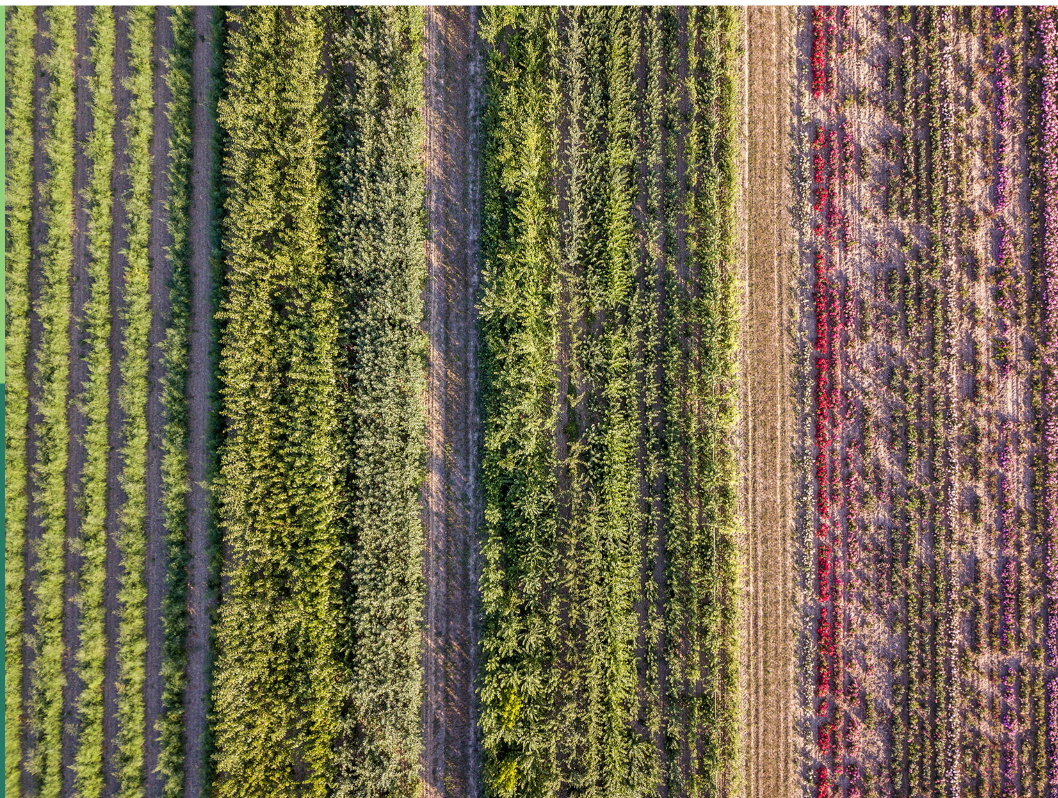
Published in
Frontiers in Sustainable Food Systems



ISSN 1664-8714
ISBN 978-2-8325-6148-5
DOI 10.3389/978-2-8325-6148-5

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Land management and food/nutrition (in)security in mixed farming systems

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Citation
Demessie, E. T., Suryabhagavan, K. V., Kassawmar, T., Tadesse, M., Dakka, A. S., Desta, G., Kaba, M., eds. (2025). *Land management and food/nutrition (in)security in mixed farming systems*. Lausanne: Frontiers Media SA.
doi: 10.3389/978-2-8325-6148-5

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TYPE Editorial
PUBLISHED 07 March 2025
DOI 10.3389/fsufs.2025.1561449

OPEN ACCESS

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RECEIVED 15 January 2025
ACCEPTED 11 February 2025
PUBLISHED 07 March 2025

CITATION
Kassawmar T, Desta G, Tadesse M, Teferi E, Kaba M, Suryabhagavan KV and Shiferaw A (2025) Editorial: Evidences (states and experiences) of land management and food/nutrition (in)security in mixed farming systems: a global perspective. *Front. Sustain. Food Syst.* 9:1561449. doi: 10.3389/fsufs.2025.1561449

Editorial: Evidences (states and experiences) of land management and food/nutrition (in)security in mixed farming systems: a global perspective

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KEYWORDS
rainfed agriculture, mixed farming, land use, land management, sustainability, livelihood, food security, nutrition security

Editorial on the Research Topic
Evidences (states and experiences) of land management and food/nutrition (in)security in mixed farming systems: a global perspective

The world is not on track to meet sustainable development goals for ending hunger, food insecurity, and malnutrition by 2030, with billions still lacking access to nutritious, safe, and sufficient food (Assefa et al., 2017; Iversen et al., 2023). The need to increase agricultural productivity in response to growing population has become a global concern (Wirsenius et al., 2010). As the world faces rapid population growth, climate change, and evolving market dynamics, rainfed farming systems are under increasing pressure to meet the growing demand for food and nutrition while also addressing the urgent need for environmental sustainability (Tully and Ryals, 2017). The challenge is not only to expand cultivated land and enhance agricultural productivity but also to manage land resources in ways that promote long-term ecological health, food security, and resilience to external shocks (Wani et al., 2009). One major sustainability issue is the limited agricultural space, which has become a critical concern as it is increasingly difficult to accommodate the growing of rainfed dependent rural population (Midmore, 2010). Expanding the arable landscape has been a vital strategy, but studies show that horizontal land expansion alone will not sustainably guarantee food security (Pretty, 1999). Ontop of limited agricultural space, mismanagement and progressive degradation of cultivated landscapes have worsened food insecurity, especially for smallholder farmers in developing countries (Zerssa et al., 2021). While conventional ways of enhancing grain productivity requires context-specific, innovative land use and management systems, yet effective solutions remain unclear (Wani et al., 2009). Recent recommendations underline that financing for food security and nutrition, along with effective tracking and innovative financing methods, is crucial for increasing investments needed to eradicate hunger and malnutrition (Iversen et al., 2023; Raj et al., 2022). The objective of the Research Topic were; (1) to explore innovative land use and management solutions to improve rural livelihoods and boost grain production, (2) to document the failures and success stories of land management strategies practiced across diverse regions of the world and finally (3) by highlighting the prevailing challenges in applying effective land use and livelihood systems, like the scalability issue, and indicating the need to co-designing of context and tailored land management solutions and (4) to identify and asses opportunities and challenges of addressing food security issues.

Aiming to understand the challenges and opportunities of sustainable land management on food security, this editorial strive to compile about 23 researches with varied in content, themes and problem addressed. The key issues and findings from these articles are grouped into four sub-themes namely; spatiotemporal dynamics of crop production, sustainable land and green water management, agricultural land management, productivity and Livelihood, and land tenure, gender and governance issues and their implications on food security. The geographic distribution of these research articles is depicted in Figure 1. This editorial systematically synthesizes key findings of research articles published on "*Land Management and Food/Nutrition (In)Security in Mixed Farming Systems*" Research Topic and presents as follows.

Spatiotemporal cropping systems dynamics and intensification strategies

Sustainable global food systems face multiple challenges, grain production declines in various parts of the world both size and productivity, although there is slight cropland area expansion in some regions. In many rainfed-dependent areas, the gap between cropland availability and grain demand remains large (Kassawmar, Tadesse et al.). Studies from Ethiopia and China indicate rainfed supporting landscapes have significant potential to boost grain production. In Ethiopia, about 60% of land is rainfed, providing an opportunity to address food insecurity and landlessness, but only 33% is cultivated due to biophysical, socio-economic, and institutional challenges (Kassawmar, Tadesse et al.).

On the other hand, a study in Ethiopia's Upper Blue Nile Basin found that cropland has increased by 10% since 1985, a small change compared to the population doubling every two decades (Kassawmar, Teferi et al.). However, the impact of increased grain production from efficient cropping systems like residual farming is greater than that of cropland expansion, despite receiving little attention from the government. A study in Northern China analyzed cropland changes over 40 years, revealing about 52 thousand km^2 expansion in grain-producing areas, primarily on black cotton soils, despite significant cropland loss from urban expansion, although struggles with land aggregation and biodiversity loss (He et al.). Such scientific evidences offer opportunities to invent appropriate land management systems. They underpin the importance of policy support for land and water management strategies, especially expansion of croplands in low-elevation areas and multiple cropping systems in black cotton soils and floodplains.

Research findings compiled from 134 countries showed that sustainable intensification requires a combination of strategies tailored to local contexts and environmental conditions, rather than a single practice (Mabhaudhi et al.). In rainfed and mixed farming systems, diversified grain production strategies are essential as they have great potential to cop climate change risks while enhancing multiple ecosystem services. In Ethiopia, intensifying rainfed farming systems through multiple cropping systems can better address landlessness and food security than technological and capital intensive options like irrigation (Kassawmar, Tadesse et al.). Combining intensification strategies like multiple cropping and mixed farming, along with land management practices such as land restoration and utilizing marginal landscapes, can boost agricultural productivity and ecosystem services. However, this requires investment in extension services and farming technologies.

Given the challenges of efficiency, productivity, and political or technological barriers to expanding cropland, the focus should be on implementing multiple-harvest strategies on existing cultivated lands (Kassawmar, Tadesse et al.). A study in northwestern Ethiopia found that since the 1990s, smallholder farmers expanded eucalyptus plantations into croplands, but reverse the trend by 2017/18 due to market changes (Zeleke et al.). An interesting lesson found from this study was, clearing eucalyptus plantations led to higher yields than continuously plowed cereal fields, challenging the belief that eucalyptus harms productivity (Daba, 2016). The study found that converting cropland to eucalyptus led to significant grain losses at various scales, while also raising unexpected and controversial land tenure issues. This indicates that smallholders often prioritize short-term economic factors over long-term ecological and social concerns, highlighting the need for adaptive, context-specific land management strategies (Zeleke et al.).

Sustainable agricultural land and green water management

Managing land and water, key natural capitals in agriculture, is a critical global research focus. A major challenge in sustainable food systems is balancing land use for competing needs like food, feed, timber, and energy. This has led researchers to explore effective strategies for managing agricultural land and green water (Kassawmar, Tadesse et al.). According to Kassawmar, Tadesse et al., unlocking the potential of Ethiopia's rainfed landscapes could enhance food security and support millions more people. A study on land use strategies in Ethiopia's rainfed cropping area found that 60% of the country is rainfed, offering significant potential to combat food insecurity and landlessness. While 33% of this area is used for grain production, supporting 120 million people, the remaining 67% of uncultivated land could benefit millions more smallholders (Kassawmar, Tadesse et al.). The study revealed that 16% of the uncultivated land is suitable for crop production, but requires technological investments and addressing political challenges. The study emphasizes the need for a holistic approach to agricultural development, acknowledging the links between land, water, and food security.

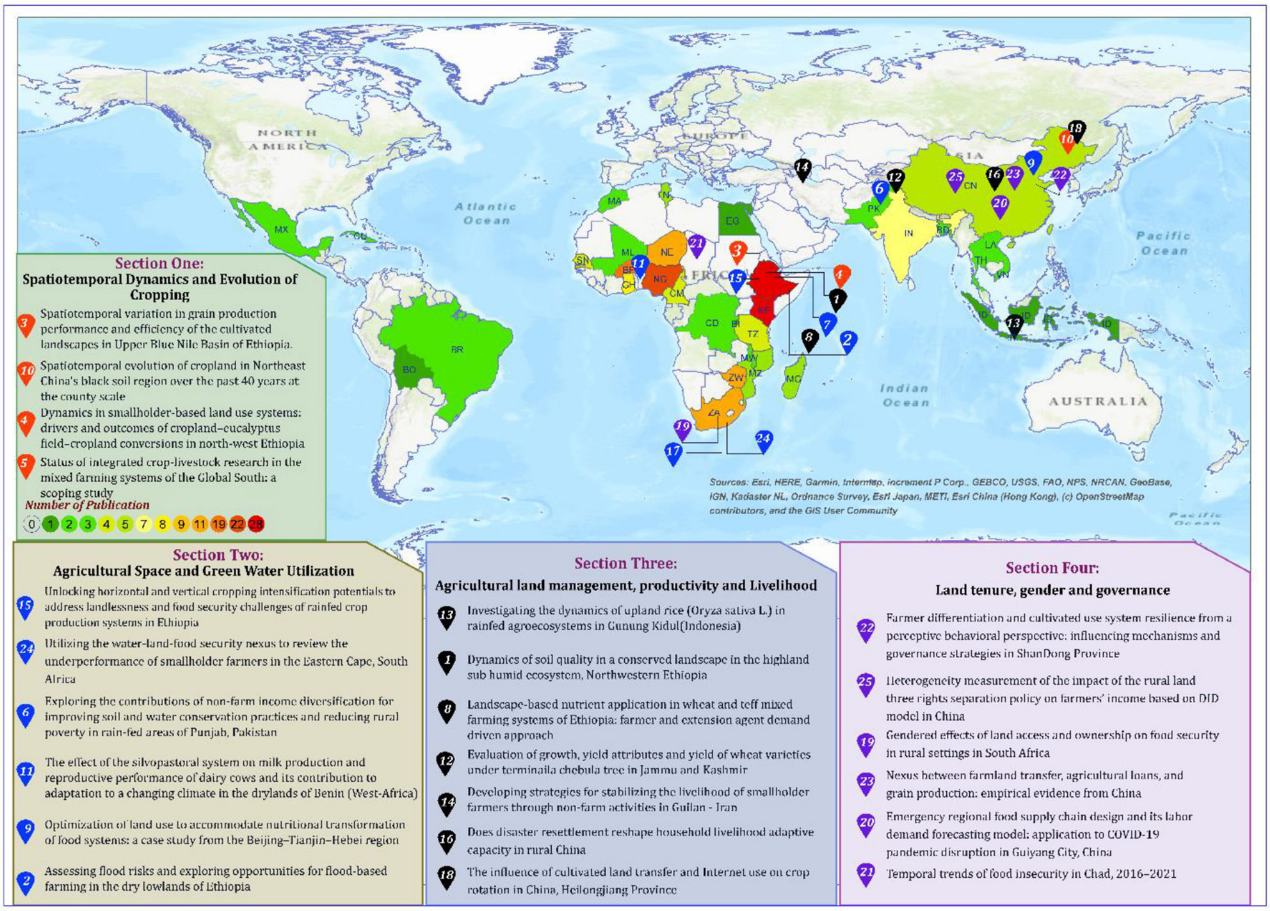

FIGURE 1
Spatial distribution and global representation of the research articles included in this Research Topic.

Another study in Eastern Cape, South Africa, found that inadequate adaptation strategies by smallholder farmers resulted in poor land use performance, limiting resource optimization for food security (Tantoh and McKay). A study from Ethiopia highlights the potential for expanding cropland through efficient systems like residual farming. However, it suggests that producing more grain is more achievable through efficient multiple cropping practices than by simply expanding agricultural land. Smallholders can benefit more by utilizing marginal areas through soil and water conservation measures and adopting multiple cropping systems such as residual moisture farming, flood farming, short rainy season farming, agroforestry, and mixed cropping (Kassawmar, Teferi et al.; Desta, Legesse, Ahmed et al.). Non-crop farming systems, such as livestock farming and eco-tourism, are also have untapped potentials to ensure resilient livelihood systems. A study from Benin, West Africa, found that agroforestry, combining trees with livestock, is an effective strategy for optimizing land and green water (Assani Seidou et al.).

Effective land and water use can be achieved through evidence-based planning aligned with food security and environmental goals. A study in China's Beijing-Tianjin-Hebei region shows that a balanced land allocation strategy, emphasizing crop diversity for better nutrition, reduces land fragmentation and enhances food security (Wang et al.). Another study from Ethiopia show that integrated, data-driven approaches—through landscape segmented flood risk management and flood farming techniques can strengthen smallholder farming systems under drought conditions (Desta, Legesse, Ahmed et al.). These research findings emphasize the importance of smart agriculture and land use planning in optimizing inputs like fertilizers, pesticides, and water, boost productivity while ensuring environmental sustainability. Sustainable agriculture requires balancing economic, social, and environmental goals, focusing on local contexts, and empowering farmers to integrate adaptive farming with food and environmental objectives. This requires huge investment on innovations and strengthening spatial technology applications.

Soil health management and innovations for improved productivity and livelihood: opportunities and challenges

In the pursuit of resilient livelihoods and sustainable farming, studies in India, Ethiopia, China, and Pakistan have highlighted the importance of innovative farming practices. Effective land management, including soil health management, conservation practices, and agroforestry, can enhance soil health and productivity, contributing to sustainable livelihoods. In Pakistan, using biochar, organic fertilizers, and targeted soil amendments on upland rice helped to narrow down yield gaps and boosting production on nutrient-deficient soils (Santosa et al.). A study from Ethiopia shows that, compared to conventional farms, soil and water conservation practices have greatly improved soil quality in degraded landscapes (Tebeje et al.). However, the overall benefits remain limited, mainly due to lack of integration with other technologies. To ensure long-term benefits of soil and water managements, rainfed based mixed farming needs context-specific strategies. In smallholder mixed farming systems, farmers often face losses from blanket applications of costly fertilizers, as they cannot match fertilizer use with crop nutrient needs. Challenges such as extreme soil variability, lack of spatial evidences, and inadequate knowledge and poor government support hinder effective nutrient management. A study from Ethiopia showed that applying landscape-specific fertilizer at different slope positions significantly increased yield, offering higher profits than blanket applications (Desta, Legesse, Agegnehu et al.). Such and similar approaches help reduce yield gaps and improve nutrient use efficiency, with potential for scaling through further innovations. In contrast, studies from Northeast China highlight the negative impacts of cropland aggregation on soil health, emphasizing the need for better management. A study from India's Jammu region stressed that agroforestry systems provide valuable ecosystem services and enhance rural incomes compared to other cropping systems (Kumar et al.). Despite its benefits, agroforestry is underused due to limited awareness and support, with key technical challenges in optimizing crop-tree spatial arrangements and balancing tree canopies with crops.

While land management efforts focus on boosting grain production and resilient food systems, non-farm activities, limited attention and advocacy given to them is very limited while they are crucial for resilient livelihoods (Baghernejad et al.). Land management approaches, such as integrated farming in Benin and land use optimization in China, show that smallholder mixed farming prioritizes productivity resilience over food security and livelihood resilience. Scholars stress that, to effectively enhance livelihood resilience, exploring non-agricultural income diversification and integrating with agricultural sustainability is critical. Given smallholder based agriculture sector has limited employment opportunities, non-farm livelihoods should be considered although a successful livelihood stabilization is not trivial. As there is a risk of shifting entirely from agriculture to non-farm activities like tourism, a study from Benin highlights the need for careful integration of agricultural with non-agricultural systems and prevent sudden decline of grain production.

The application of advanced technologies like mobile apps and remote sensing have become crucial to promote effective land management practices and improve land productivity. In Ethiopia, a mobile app providing landscape-specific fertilizer recommendations helps optimize input use, increase yields, and enhance farmer profitability (Desta, Legesse, Ahmed et al.). Another study from China demonstrated that, digital technologies have become vital in facilitating agricultural supply and boosting sustainable land use (Liang et al.). Although both land transfer and internet use promote crop rotation, the former has stronger effect in specifically benefiting older farmers, the latter benefits more the younger ones. Promoting crop rotation through stable land rights and incentivized land transfer can boost sustainable livelihoods and productivity.

Inclusive land tenure, gender and governance on land investment, food and nutrition security

Global studies emphasize the role of land governance, tenure systems, and gender in improving agricultural productivity. Adaptive land management is crucial for sustainable development, especially in influencing farmers' behaviors. A case study from China evaluated farmers' perception on the resilience of the cultivated land use system (Wang and Wang) and found that farmers' cultivated land use systems exhibit uneven resilience, generally labeled as low production resilience. Poor production efficiency and limited ecological protection indicate weak functioning of the cultivated land use system. Thus highlights strategic needs to improve production resilience, encourage investment in land resources, promote ecological protection, and enhance willingness for land transfer.

The three rights policy in China's land system reform, has positively impacted rural livelihoods and incomes although the effects vary across farmers group (Hu et al.). Since the inception of the reform, farmers who got more training, have larger croplands, and those growing food crops benefit the most by the policy. Although further research is needed to fully understand the direct impacts of the policy, the findings unveiled directly linkage of income with investment, credit access, and non-agricultural employment opportunities. A study using provincial data from China found that farmland transfer and agricultural loans positively correlate with grain production, though agricultural loans have a negative effect (Ding et al.). This suggests that financial access enhance farmland efficiency and grain production, emphasizing the need for government support in land reforms and agricultural finance.

Another study in South Africa, where there is critical gender related land issues, rural women's have limited access to land, hindering their economic opportunities (Masuku et al.). Gender disparities in land access remain a significant challenge in rural South Africa, as customary law challenges women in acquiring equal land ownership. Land reform for equal access is essential for reducing food insecurity and promoting gender equality in agriculture (Ding et al.). Evidences from a case study in China, support the importance of land transfer, which promotes crop rotation and improved land use, while addressing land ownership issues. These findings urge developing countries like South Africa to create land policies that address gender disparities in land access and ownership, as they negatively affect food security. Lessons learned during COVID-19 pandemic highlights that the disruption of global food supply chains during global shocks can only be addressed by building food supply systems proactively (Tian and Mei). A study from Chad showed that while food insecurity had been rising before the pandemic, food security improved after the shock, indicating the impact of increased awareness and knowledge gained from the pandemic's effects (Kang et al.).

In summary, an important concluding remark from the synthesized scientific evidences is that appropriate land use systems and efficient agricultural water management strategies alone cannot enhance incomes and ensure sustainable food system. Rather access to land, markets, financial resources, and extension services are also essential, especially empowering women, are key to sustainability. Besides, to promoting regenerative agriculture and multiple cropping systems authors underline the importance of promoting non-farm activities as they can play crucial role in stabilizing livelihoods and boosting resilience of food systems. Technologies like remote sensing, GIS, and mobile tools can leverage precision farming, and further enhance crop yields and environmental sustainability. Promoting agricultural technology and digital literacy, specifically rural digitalization, help young farmers adopt sustainable practices and further improve productivity and safeguard food supply chains.

We hope this Research Topic of articles on emerging agricultural practices and ways to sustain food production will be useful to scientists, agricultural educators, government regulators, and other relevant stakeholders of food production. We also hope that they will serve as a good course on a global scale to help mitigate improper land use and management, especially on crop production. Authors believed that these published articles are going to impact to a wide range of readers with an insight into practical sustainable agricultural land and water management and technologies among the smallholder farming systems. Authors recommended more in-depth, systematic assessment that spans local, continental, and global scales is crucial because:

1. **Local Scale**: The conditions and challenges at the local level often differ significantly, so it's essential to tailor strategies to local needs. For example, water availability, soil fertility, and access to energy resources vary from region to region and need to be considered in food systems.
2. **Continental Scale**: At the continental level, broader patterns such as climate variability, population growth, and economic trends come into play. Continental policies and infrastructure can also impact resource use and distribution, and solutions need to consider trade, policy coordination, and regional cooperation.
3. **Global Scale**: Global factors such as climate change, international trade agreements, and global supply chains influence resource availability and food security across regions. Policies that consider these interconnected global challenges can help in fostering a more equitable and sustainable food system.

By looking at the land-water-food-energy nexus across all these scales, we can identify trade-offs, synergies, and solutions that balance the demand for food, water, energy, and the health of ecosystems. It requires interdisciplinary efforts combining agricultural, environmental, and socio-economic perspectives, as well as robust data collection, monitoring, and modeling to ensure long-term sustainability.

Author contributions

TK: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. GD: Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. MT: Conceptualization, Investigation, Supervision, Visualization, Writing – original draft, Writing – review & editing. ET: Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. MK: Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. KS: Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. AS: Supervision, Visualization, Writing – original draft, Writing – review & editing.

Acknowledgments

The authors thank the contributors of the Research Topic that pinpoint global evidences highlighting the land management opportunities and constraints for food and nutrition security.

Conflict of interest

The authors declare that this editorial article is developed in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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frontiers | Frontiers in Sustainable Food Systems

TYPE Review
PUBLISHED 12 May 2023
DOI 10.3389/fsufs.2023.1143630

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OPEN ACCESS

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RECEIVED 13 January 2023
ACCEPTED 20 April 2023
PUBLISHED 12 May 2023

CITATION
Tantoh HB and McKay TJM (2023) Utilizing the water-land-food security nexus to review the underperformance of smallholder farmers in the Eastern Cape, South Africa.
Front. Sustain. Food Syst. 7:1143630.
doi: 10.3389/fsufs.2023.1143630

Utilizing the water-land-food security nexus to review the underperformance of smallholder farmers in the Eastern Cape, South Africa

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Supporting agriculture is crucial if food security and poverty alleviation are to be assured. In that regard two crucial aspects - water and land are central to supporting smallholder farmers. This is especially true for the Eastern Cape Province of South Africa with its high rates of poverty and food insecurity. However, attention is seldom given to the fundamental factors of farm production. Access to land for food production in the Eastern Cape is problematic, as is the water situation. It is among the driest provinces in the country, enduring extended drought conditions with resultant water scarcity challenges. This is compounded by poor adaptation strategies deployed by smallholder farmers. This study investigated the relationship between water, land and food security with respect to smallholder farmers in the Eastern Cape. It found that while both food security and incomes could be improved for these smallholder farmers if they had more access to land and water, these two factors alone are insufficient. These farmers also need access to agricultural extension services, markets, cost-effective transport and capital. Although the commercialization of these farmers is a way to improve rural livelihoods, the prevailing conditions in the province significantly inhibit this.

KEYWORDS

water-land-food security, smallholder farmers, climate change, adaptation, Eastern Cape, commercialization

1. Introduction

Promoting small scale localized agricultural production is essential to ensure food security and economic development in the rural regions of the developing world. This is especially true for the rural communities of Sub-Saharan Africa (SSA). However, this requires access to both land and water as they are indispensable factors of food production (Villamor et al., 2018; Rao et al., 2019). But, according to the World Economic Forum [WEF] (2022), the relationship between access to water and land as imperatives for food security for smallholder[1] SSA farmers

1 Smallholder farmers are generally those involved in farming a small piece of land, cultivating food crops, sometimes with small varieties of cash crops. They usually practice mixed crop-livestock farming with some large ruminants around 3–5 managed by family labor primarily for subsistence (Lowder et al., 2016).

is given insufficient attention. For one, emphasis on proper stewardship of the land, water and other natural resources is lacking (Tantoh et al., 2022). Additionally, increased climate variability, temperature instabilities and unreliable rainfall are a serious threat to small scale African farmers (Engelbrecht, 2019). As a result, many rural dwellers have to supplement income with remittances, work in non-farm activities or rely on social support services.

Studies have shown that the historical roots of food insecurity in developing countries are deep (Kalibwani, 2005; Ngumbela, 2021). For example, the era of colonialism saw great emphasis on the production of cash crops, such as cotton, coffee, sugar cane, cocoa, and tobacco. These were usually sold to the 'mother' country, that is the colonial power, with the purpose of sustaining industries in these colonial countries. This was obviously to the detriment of local food production (Kalibwani, 2005). Furthermore, colonial infrastructure was geared toward the transportation and marketing of cash crops and raw materials (timber, minerals). This is one reason why most SSA have no grain silos. This contrasts with South Africa with over 400 grain silos, built to support local maize production, which was primarily for local consumption. Additionally, expats from the various 'mother countries', the United Kingdom, in particular, were encouraged to move to SSA and take up farming. To give these expats a competitive advantage, many small-scale African farmers were systematically undermined, facing many challenges such as being deprived of land, access to water and limitations in terms of bringing their food crops to market. Thus, small-scale SSA farmer contributions to agricultural growth was retarded and even post colonialism struggled to gain ground. As a result, the annual growth of agricultural advancement in the Southern Africa Development Community (SADC) is only 1.5% *per annum*, far too low to keep an ever-expanding population fed (Southern African Development Community [SADC], 2013). This situation is compounded by frequent natural disasters such as floods and droughts, insufficient investment in the sector, lack of political will, political instability and war, as well as value volatility of agricultural goods. Protectionist conduct by European countries regarding their own merchandize and markets further inhibits agricultural exports in the region (Southern African Development Community [SADC], 2013).

In recent years, extreme weather events, ranging from severe droughts (such as that in the Western and Eastern Cape) to major flooding (such as in Mozambique, Durban and Johannesburg) have presented additional challenges to food security, particularly among poor rural households, who often have limited capacity for adaptation (Wheeler and Kay, 2010; Simatele and Simatele, 2015). Many SSA countries are extremely vulnerable to changing climatic conditions due to their geographical location, low incomes, inadequate technological development, fragile institutional capability, prevalence of HIV/AIDS and vector-borne diseases, inadequate government mechanisms, rapid population growth, as well as their reliance on climate-sensitive renewable natural resources such as water, agriculture and energy (Anyadike, 2009; Eboh, 2009). That is, SSA countries are exposed to increasing desertification, deteriorating run-off in river basins and declining soil fertility. These factors compromise economic growth and national development. Each risk factor is elevated in remote rural areas, home to many female subsistence and smallholder farmers (Wheeler and Kay, 2010). As a result, increased food production is hampered, resulting in pervasive poverty, hunger, inequality and social instability (Ahmed and Chamhuri, 2013; Wichelns, 2015). In such circumstances, sustainable livelihoods are but a pipe dream. But improving food production and alleviating poverty require pragmatic reforms within the agriculture sector such as the application of Climate Smart Agricultural[2] (CSA), Integrated Land Use System[3] (ILUS) and farmer empowerment. However, several SSA countries have initiated projects to improve food security and reduce poverty, particularly in rural areas. This has been possible through agricultural policies, stressing on particular aspects and axes. The South African government, for example, has a fundamental role to play in rebuilding the economy by reducing disparities, increasing incomes and employment opportunities for the poor. This has been facilitated by the agricultural policy which is geared toward building an efficient and internationally competitive agricultural sector, supporting the emergence of diverse structures of production by increasing the numbers of profitable smallholder farming establishments and preserving agricultural natural resources for sustainability.[4] Thus, land and agricultural policies through acts [The Animal Diseases Act of 1984 (Act No. 35 of 1984)], The Marketing of Agricultural Products Act, 1996 (Act No. 47 of 1996 etc.) are designed to accommodate diversity of food production and improve food security. These acts and changes in the sector are part of broader processes of rural development, which include land reform, investment in water supply and transport infrastructure, and improved social service delivery. In this regard, access to land and water by smallholder farmers is critical (Ayamga et al., 2022).

Several studies have been conducted on access and stewardship of land and water by smallholder farmers (Villamor et al., 2018; Rao et al., 2019), food insecurity (Kalibwani, 2005; Ngumbela, 2021); poverty, hunger, inequality and social instability (Ahmed and Chamhuri, 2013; Wichelns, 2015) climate variability and food security among smallholder farmers (Ebhuoma et al., 2020; Tantoh et al., 2022), marketing, commercialization and livelihoods of smallholder farmers (Ngumbela, 2021), adaptation to changing climatic conditions by smallholder farmers (Simatele and Simatele, 2015; Kom et al., 2020) among others. However, research on water-land-food security nexus and the underperformance of smallholder farmers is limited. This study, therefore, examines the persistence of poverty among vulnerable rural communities in the Eastern Cape Province of South Africa. Poverty is at extreme levels in the Eastern Cape with 70% living below the poverty line, 10 percent above the national average of 60% (Ngumbela, 2021). As a consequence, most households in the province are food insecure, this includes most smallholder farmers. Thus, one way of alleviating poverty and promoting food security is an increase in the agricultural productivity of these farmers, although this would have to be in conjunction with reducing food losses and waste (Climate Summit, 2014). A central question is how access to land and water by these farmers.

2 Climate-smart agriculture is an approach that helps to guide actions needed to transform and reorient agricultural systems to effectively support development and ensure food security in a changing climate.

3 This refers to combination of different types of land uses and integrates several management goals in the same space for sustainable outcomes.

4 https://www.gov.za/documents/agricultural-policy-south-africa-discussion-document

2. Water-land-food security nexus in a developing world context: a literature review

In recent years, there has been an increasing interest in the notion of the Water-Land-Food Security (WLF) nexus as a possible approach to attain sustainable rural livelihoods. Crucially, the World Economic Forum [WEF] (2022), views unsustainable livelihoods as a significant threat to the global economy. A threat made worse by the COVID-19 pandemic, its associated lockdown and the Russian-Ukrainian war. The WLF nexus is an important aspect of global peace and security nexus, fundamental to social and economic development. The Overseas Development Institute (Overseas Development Institute [ODI] et al., 2012) further acknowledge that challenges associated with the increasing world's population, growing urbanization, changes in consumption, land-use patterns and climate change impact severely in this WLF nexus (Spires et al., 2014; Tantoh et al., 2021). The notion of the nexus, therefore, mirrors the different components of WLF and recognizes the roles of and relationship of these diverse resources for sustainability.

The nexus of WLF has been extensively documented (Rasul and Sharma, 2016; Dombrowsky and Hensengerth, 2018; Villamor et al., 2018; FAO, 2021). Despite this, the applicability and sustainability of and WLF view is yet to be understood and assured (Tantoh et al., 2021). Importantly, many studies and interventions only focus on water or food to the detriment of land, despite it being a crucial factor of production. This is partly because civil unrest is often associated with food and water scarcity, Syria being one recent example. Agriculture also places pressure on freshwater resources, a significant problem for arid and semi-arid countries with expanding populations and competition for scarce water resources (International Fund for Agricultural Development [IFAD], 2012). Within this context, smallholder farmers often lack the financial, social and political capital to secure access to adequate water. However, in rural economies, food security and poverty alleviation also require access to land (Rasul and Sharma, 2016; Villamor et al., 2018; Ayamga et al., 2022). Thus, the Food and Agricultural Organization highlights land as the basis for food security. They are supported in this by the declarations of the 2021 United Nations Food Systems Summit (FAO, 2021). It is, therefore, imperative to acknowledge land, is a vital resource, on which 98% of the world's food is produced. Appropriate stewardship of land, especially soil health is therefore critical to improving food security, improving rural livelihoods and building environmental and community resilience. Effective and efficient land and soil management reinforces nutritious, varied diets and resource-efficient value chains.

2.1. Food security for poverty alleviation among smallholder farmers

The literature on smallholder farmers recognizes the contribution of the farming sector in developing countries to income generation and economic growth. It is also the main driver of rural development in many economies in SSA (Engelbrecht, 2019). Smallholder production, for example, is a key source of rural employment, livelihoods and wellbeing. Smallholder farm also contribute to local and national food security (Nwanze, 2011; Landesa, 2014). Despite this smallholder farms in SSA are generally small, usually under two hectares (Rapsomanikis, 2015; Lowder et al., 2016). These smallholder farmers lead the agricultural sector in Africa, contributing 75% of agricultural, 50% of livestock production, despite these farmers being poor and food insecure themselves (Lowder et al., 2016). However, access to, and proprietorship of land by smallholder farmers is a challenge despite sufficient arable land in Africa (Jayne et al., 2014; Rapsomanikis, 2015). Furthermore, there has been a steady reduction in farm sizes coupled with limited access to markets (Jayne et al., 2014; Rapsomanikis, 2015). Hence, natural resource overexploitation and land degradation prevails, creating a vicious circle of food insecurity and poverty (Khanal et al., 2021).

Rapid urbanization and population growth in SSA have increased food demands (Wichelns, 2015). Thus, accessible, available, affordable, stable and use of food is critical to food security. Importantly, the availability of quality and nutritious food could be limited by production systems, distribution channels, exchange and marketing mechanisms. The ability to get the required amount of food to be used appropriately to meet nutritional needs is, therefore, fundamental to food security. Additionally, food insecurity can be long-term or temporary (Healthypeople.gov, 2021). However, climate crisis places national food security across SSA in jeopardy. Food insecurity is also affected by race/ethnicity, disability, and employment. When there is limited or no money, the risk for food insecurity increases (Healthypeople.gov, 2021). Thus, poor residents of lower-income countries are particularly vulnerable, given their limited ability to modify production and consumption activities (Ebhouma et al., 2019; Kom et al., 2020). But land use intensification has led to the expansion of agriculture into fragile ecosystems systems, degrading natural resources. In view of the multiple demands of land and water resources, it is important to take planning and management decisions to the lowest possible level to empower all the stakeholders (Musavengane et al., 2019). In this regard, strong partnerships between resource users, the private sector and the government are required to achieve more effective and efficient water and land management approaches (Dombrowsky and Hensengerth, 2018). Additionally, integrating natural resource management with climate change adaptation will help reduce risks and increase the resilience of vulnerable households.

2.2. Smallholder farmers in the Eastern Cape-South Africa: opportunities and challenges

The arrival of the Dutch East India Company in 1592 launched a period of conflict, urbanization and colonialism in South Africa. Ultimately people of color ended up with limited access to land, water and agricultural support compared to white farmers (Ngumbela, 2021). This inequality was a major concern of the African National Congress (ANC) government that came to power in 1994. The result was the launch of a land reform program, ostensibly to reverse this injustice. But most land reform projects launched by the ANC have achieved, at best, limited effectiveness with some complete failures. Thus, the needs of smallholder black farmers are still mostly unmet (Altman et al., 2009). While the land tenure and administration situation in the former homelands is precarious, the land tenure system in South Africa is inconsistent (Eastern Cape Socio-Economic

Consultative Council [ECSECC], 2010). Even though individuals are seldom placed under the threat of actual eviction, for example, their tenure can hardly be described as secure. This is because the value of the land rights is low and the extent of the rights is limited, especially as they cannot be traded. Furthermore, the State capacity is inadequate, and the land reform is complex and time-consuming (Cousin, 2005). Despite this, small-scale farmers are not non-productive and can be very profitable if the government lowers transactional costs and reduce the barriers facing smallholder farmers comprising; access to land, credit insurance, information and market (von Loeper et al., 2016).

On the one hand, smallholder farmers in South African are relatively unproductive, producing, at best, just a quarter of commercial farm output (Hendriks, 2014). Similar studies in India revealed that smallholder harmers usually have low incomes mainly due to low harvest prices, high cost of inputs and small operational holding size (Reddy et al., 2019). It is possible that smallholder farmers in the developing world generally face the same challenges as far as productivity is concerned. On the other hand, however, smallholder farmers are a major source of employment and livelihoods, supporting around three million people (Biénabe et al., 2011). Statistics South Africa (2017) noted that in the Eastern Cape 28 percent of households reported being involved in agriculture. While some of these households are associated with commercial farms (mostly white or corporate-owned) the rest (around half a million) are small scale farmers, located mostly in former South African 'homelands' of the Transkei and Ciskei (Aliber and Hall, 2012). In the Eastern Cape, for example, about five million hectares of land are under communal land ownership, cultivated by smallholder farmers on farms often under two hectares in size (Nyondo and Nkwinti, 2003). This region practices two main types of cropping systems: (1) home gardens - fenced plots of land between 0.1–0.5 ha close to the residential site and (2) outfields - situated on the outskirts of the villages and ranging in size from one to five hectares.

Technology use is extremely limited, in part due to inadequate technical know-how (Landesa, 2014). Additionally, around 17 percent of these households consist of unschooled people who have, at best, inadequate farming skills. Furthermore, the region suffers from inadequate agricultural infrastructure, extensive soil degradation and erosion, and poor economic conditions. As a result, production from these farms usually only feeds the household. What limited excess output there is, is primarily sold in local markets (von Loeper et al., 2016). These rural communities have also been badly affected by extreme weather events. Pereira (2017) notes the region has endured the worst drought in a century, making surface water an extremely scarce resource. The drought has aggravated poverty as many smallholder farmers struggle to cope in adverse environmental conditions. They often do not receive vital information timeously, lack insurance to recover from losses and social support networks cannot cope with multiple concurrent demands (Ebhuoma et al., 2020). Long dry spells often result in complete crop failure as most smallholder farmers cannot afford to irrigate or lack access to sufficient water to irrigate (Tantoh et al., 2022). Studies show that farmer distress is a widely recognized problem in the developing world and has multiple causes ranging from climate variability to price volatility and the low risk-bearing ability of farmers (Reddy et al., 2021). Thus, tracking farmers' distress in a localized context is a prerequisite for timely action to provide sustainable livelihood options. Although the challenges are multiple, it has been argued that empowering smallholder farmers and including them in the mainstream agricultural economy will help improve food security. Thus, smallholder agriculture has been identified as a vehicle for rural poverty reduction and development in the Eastern Cape (Department of Agriculture, Forestry and Fisheries [DAFF], 2014; Ngumbela, 2021). Empowerment can be in the form of capacitating them with basic farming skills, marketing of farm produce, facilitating access to credit facilities and ensuring access to appropriate weather information and even processing of farm produce (Ebhuoma et al., 2020).

3. Materials and methodology

3.1. Description of study site

The Eastern Cape province came into being in 1994 by the fusion of the former Bantustans of the Transkei and Ciskei with portions of the Eastern Cape (see Figure 1). It is one of the largest provinces by size and has a population of around 6.5 million. The province comprises mountain ranges (the southern Drakensberg), rippling hills, sandy beaches and patches of temperate forests, creating a varied climate. In the western half, winter is frosty, with occasional snow on the mountains, while summers are relatively dry. In contrast, winters in the eastern part is not as cold with wet, relatively hot, summers. The eastern coastal areas experience a Mediterranean climate with and a sub-tropical one with high rainfall and humidity during summer along its western coastline. The northern part is beyond the escarpment and is semi-arid. Summers are very hot, winters are cold with occasional heavy snowfalls on the mountains. These different climatic conditions strongly affect agricultural production, with water challenges significantly hindering agricultural productivity.

Population wise the province is dominated by Xhosa people who traditionally focused on cattle herding. Commercial farmers, most of whom are white people, focus on wool (mohair, angora) fruit, dairy and grain production. Value add is low, however, with the agricultural sector only contributing 2 % to the economy of the province (Department of Agriculture, Forestry and Fisheries [DAFF], 2014). Thus, the Eastern Cape is predominantly a rural economy with low productivity rates, despite the smallholder farm sector being one of

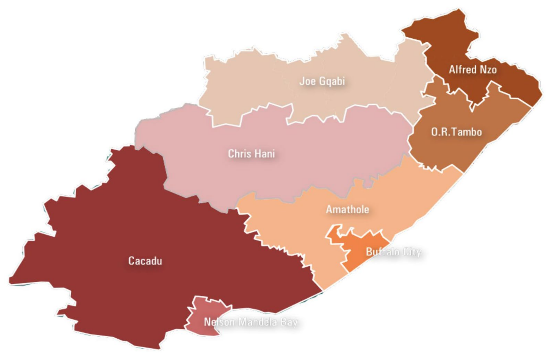

FIGURE 1
The map of the Eastern Cape of South Africa showing some of the district municipalities.

the largest in South Africa (Community Survey, 2016). High poverty rates mean many households rely on social grants, such as the old age grant and child support grant (Chakona and Shackleton, 2019; Statistics South Africa, 2019; Mujuru and Obi, 2020). Although social grants have a positive effect, they need to be combined with access to essential services and the creation of employment opportunities to be effective in the long run.

3.2. Data collection

As food insecurity in rural areas cannot be separated from access to land and water, this systematic review examined academic literature where the nexus of water-land-food security was investigated with respect to smallholder farmers in the Eastern Cape Province. A four-stage process was used to gather appropriate academic literature. Firstly, keywords such as 'water-land-food security', 'smallholder agriculture', 'poverty alleviation', 'commercialization of agricultural products', and 'food value chain' were inserted in the search engine of internet databases of Google Scholar, PubMed, Science Direct, and Scopus (see Figure 2). Literature emanating from South Africa itself was given priority. This phase identified 721 possible articles and working papers. The second stage consisted of scrutinizing the documents to determine if they adhered to the key themes of the study. As a result, 415 articles were rejected. Then the abstracts were further screened, leaving 185 articles. Lastly, scrutiny of the texts found an additional 14 as irrelevant, 15 were duplicates and 18 were without full texts. Thus, these were excluded. In summary, a total of 08 qualitative syntheses, 52 quantitative (meta-analysis), 02 reports from Statistics South Africa, 01 dissertation and 13 reports from ODI, IFAD and FAO were explored. These 74 texts form the basis of this study.

4. Analysis and discussion

4.1. Agricultural overview

The Eastern Cape has a parallel agricultural system: a commercial agricultural system owned mostly by white farmers and corporations and a smallholder household farming sector mostly in Black African hands (Mmbengwa et al., 2015). There are also vast areas of unused land. Despite this, the literature presented empirical evidence that smallholder farmers or household farms have been identified as vehicles of employment opportunities, by the ANC government, in part because smallholder farming is viewed as labor-intensive (Zantsi et al., 2019). That is, although individual smallholder farm requires less labor per farm, as a collective, they have many more employment opportunities than commercial farms (Mmbengwa et al., 2015). Most smallholder farmers in the Eastern Cape focus on the home gardens, which receive more inputs than the outfields. Mandiringana et al. (2005) emphasized that most outfields have been steadily abandoned over the past 60 years. Additionally, the size of farms in the Eastern Cape vary significantly. The size of farms is directly related to the different administrative regimes in the province. One regime is the former Cape Provincial Administration (CPA) while the second pertains to the former homelands (Eastern Cape Socio-Economic Consultative Council [ECSECC], 2010). The CPA farms are medium to large, and mostly owned by private individuals or commercial operators. The former homeland areas fall under a type of communal tenure system. A major challenge of communal tenure is the lack of cadastral clarity. This dualistic nature and division between commercial, large-scale farming and the struggling smallholder sector is a direct result of historical patterns of dispossession (Neves et al., 2009). The communal tenure system lacks economic assets, agricultural support services, market access and appropriate infrastructure. Thus, post 1994 projects initiated to support farmers on communal land to acquire more land have been ineffective (Altman et al., 2009). Thus, there is a lack of agricultural led entrepreneurial activity with the agribusiness sector in the Eastern Cape underdeveloped (Global Entrepreneurship Monitor [GEM], 2011; Kibirige and Obi, 2015).

4.2. The water-land-food security nexus

The review revealed an over-dependence by smallholder farmers on rain-fed agriculture. This is problematic, as the province is plagued by variable and unreliable rainfall, making water shortages both common and acute (Community Survey, 2016). Several studies have documented the susceptibility of the continent in general and South Africa in particular to climate crisis (Rasul and Sharma, 2016; Ebhuoma et al., 2020; Rankoana, 2020; World Economic Forum [WEF], 2022). This strengthens the idea of the Intergovernmental Panel on Climate Change [IPCC] (2019), emphasizing that climate crisis is possible to have wide-ranging effects on the social order, the environment and food security thereof. Extreme weather-related events, for example, have always had adverse effects on both rural and urban productivity although the most affected are the rural poor (Kom et al., 2020; Ngwenya and Simatele, 2020). Furthermore, climate-induced weather events have contributed to increased water and food insecurities in many parts of South Africa (Unganai, 2009). This heavy dependence on climate-sensitive economic sectors such as agriculture makes the component of food security in the Eastern Cape and South Africa more vulnerable to any changes in climate (See Figure 3).

Food insecurity is among the factors hindering developments, particularly in the developing world. It is a fundamental human need, necessary for the wellbeing and welfare of living beings. Hence, accessibility, availability, stability and utilization are critical to food security (see Figure 3). The ability to get regular amounts of nutritious food to be used properly to meet nutritional needs is, therefore, fundamental to food security. At the same time many of these rain-fed crops are at their maximum temperature tolerance (Rankoana, 2020). Thus, climatic risks, especially increased drought conditions, and heat waves, as was the case in the years 2013, 2015, 2016, and 2019, compromise agricultural production (Gandure et al., 2013; Loewe, 2020). This coupled with inadequate access to technology and resources results in low output (Hendriks, 2014; Tantoh et al., 2022). In the same lens, the climate crisis will have severe consequences on the rural poor who are highly dependent on agricultural productivity to improve rural livelihoods in the phase of soaring unemployment and poverty levels (56%) (Singh, 2019). These effects pose a huge threat to food security and rural livelihoods, compromising the wellbeing of smallholder farmers (see Figure 4). Resolving this condition requires considerable policy interventions and private

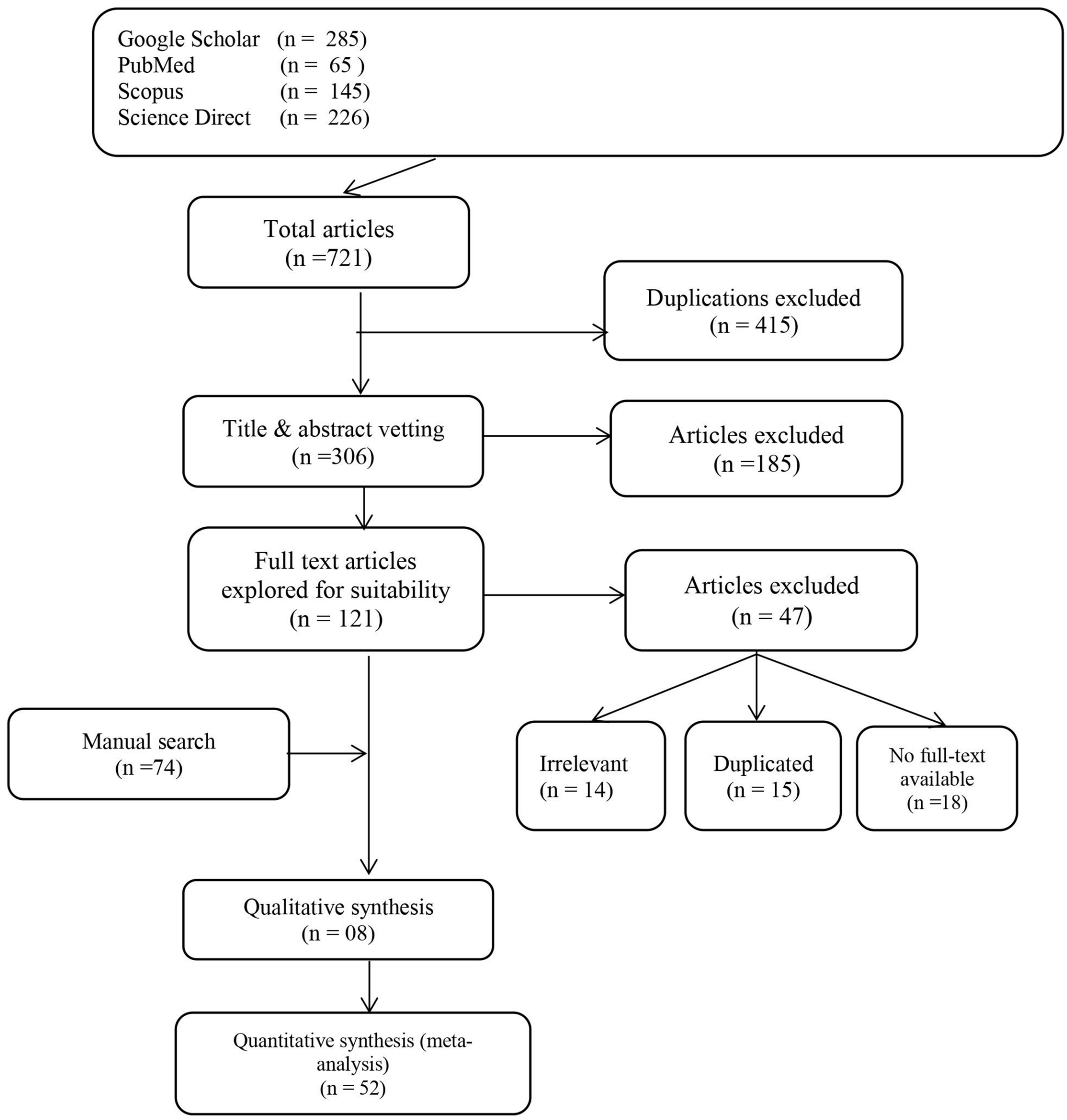

FIGURE 2
Flow diagram illustrating the diverse phases of screening relevant literature for the study (Fieldwork, 2022).

sector investment (Food and Agriculture Organization of The United Nations [FAO], 2015). However, the challenge of agricultural sustainability has become more intense in recent years with climate change, water scarcity, degradation of ecosystem services and biodiversity, the sharp rise in the cost of food, agricultural input and energy as well as financial crisis hitting hard on poor communities.

Noteworthy is also the fact that land is one of the fundamental factors of production and unfortunately, is a bone of contention in South Africa. Thus, a major challenge of the WLF nexus in the context of South Africa is inequalities in the access and possession of the land. The ideal has been to reverse these inequalities through land reforms and support programs for black emerging farmers. However, the government's focus on emerging commercial farmers has given little attention to subsistence farming and smallholder farmers (Altman et al., 2009). Consequently, smallholder farmers still produce a quarter of what commercial farmers produce. It is, however, not logical to resolve food security issues by focusing on improving the output of commercial farmers but by limiting transactional costs, easing access to land and credit insurance among smallholder farmers (von Loeper et al., 2016; Ayamga et al., 2022).

4.3. Policy versus practice

Several studies touted the potential for agriculture to significantly contribute to economic growth in the form of food production, transformation of raw materials, as a market for producers of other goods and services, as a source of foreign exchange and as a producer of savings surplus (Pienaar and Traub, 2015; Ngumbela et al., 2020). For example, Mujuru and Obi (2020) argue that better agricultural

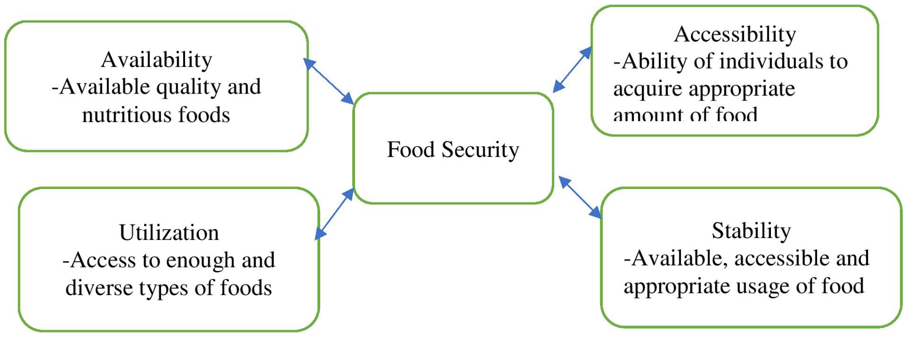

FIGURE 3
Components of food security. Adapted from Healthypeople.gov (2021).

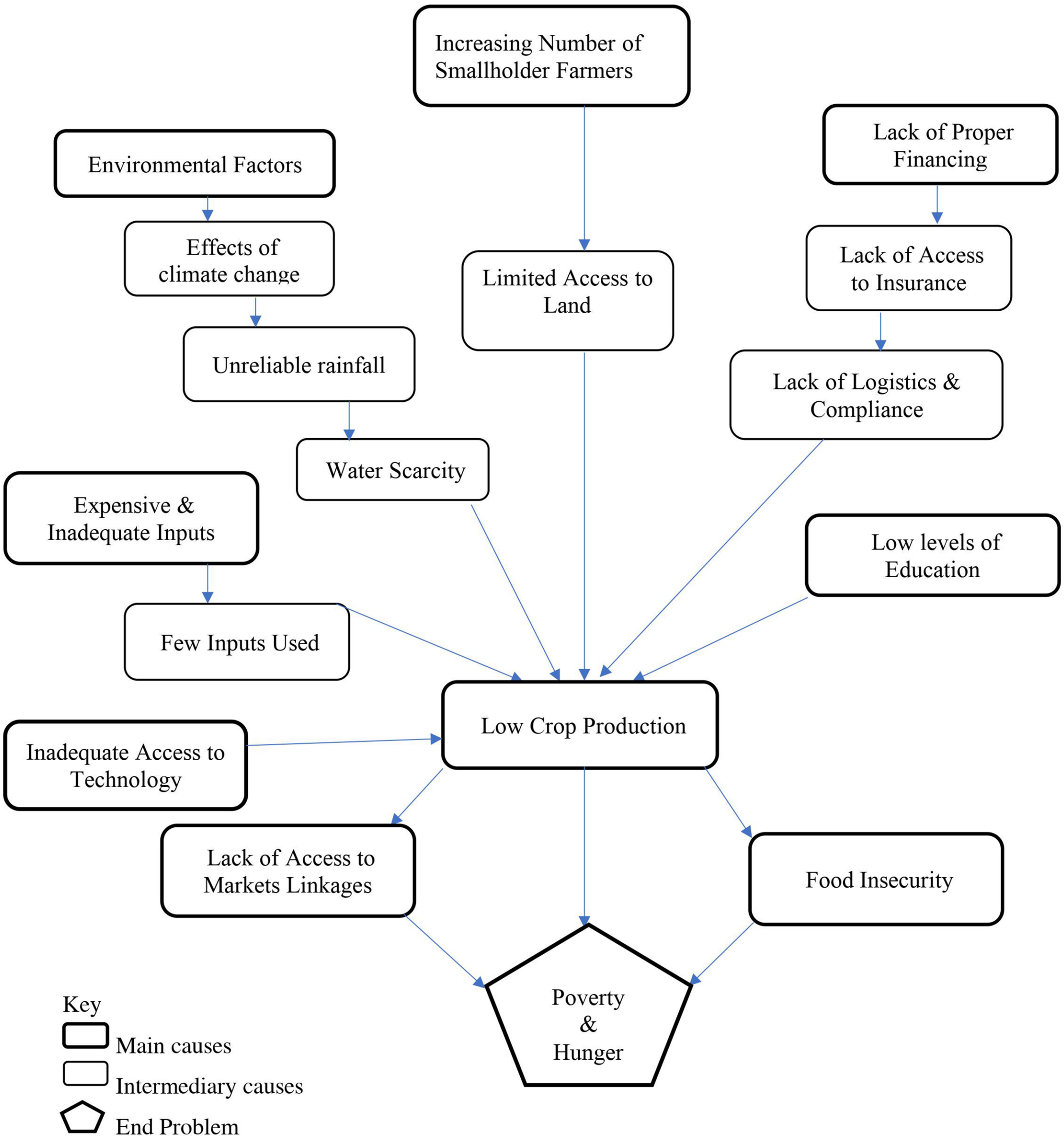

FIGURE 4
Challenging facing smallholder farmers in the Eastern Cape (Authors, 2022).

productivity would decrease unemployment and reduce poverty. That said, improved education opportunities and better healthcare services are a must for this province (Ngumbela, 2021).

Thus, on the one hand, policy makers focus a lot of energy on smallholder farmers. For example, the South African National Development Plan (NDP) lauds smallholder farmers as the champions of rural development, able to improve rural livelihoods and wellbeing, particularly in former Bantustans (NPC, 2011). Furthermore, the South African National Department of Agriculture, Forestry and Fisheries claims to be promoting smallholder farmers in the Eastern Cape through increased budgetary allocations (Department of Agriculture, Forestry and Fisheries [DAFF], 2014). In the same vein, the national treasury has allocated huge financial resources to boost the entrepreneurial activity of smallholder farmers through grants to purchase land under the land reform program, farm input subsidies, small-scale irrigation schemes (GEM, 2011). Scholars such as Rapsomanikis (2015) encourage such a focus, maintaining smallholder farmers are business establishments, balancing risks and profits, striving to raise capital from diverse sources and investing in productive assets. It is also claimed that they are also able farmers, knowing what to plant, what inputs are needed, when and how to cultivate, what and how much to sell and what quantity to store (Ebhouma et al., 2019; Ebhuoma et al., 2020). It is also argued that assisting these farmers to employ the rural poor will also increase rural living standards (Rapsomanikis, 2015; Ngumbela, 2021).

Despite this, there are several constraints to hinder the development of smallholder farmers. Firstly, Pienaar and Traub (2015) maintain that any plan needs to focus on attaining impact and scale. Thus, the success of rural development requires rising smallholder productivity to increase the volume of, and reduce the price of, staple food. Commercialization can increase farm incomes, and through the multiplier effect lead to wider pro-poor growth in the rural economy. However, there are many constraints to commercialization that prevent this process from occurring. In addition, smallholder farmers are caught in subsistence agriculture with limited outputs and disengaged from markets. Consequently, the commercialization of the food supply chain is undertaken by bigger establishments with increasing presence of national supermarket chains which further marginalize smallholder farmers. Rural residents now buy from the supermarkets, not directly from the farmers (Figure 4). Worse is that these supermarkets seldom support farmers by purchasing produce from them (Rapsomanikis, 2015). Although some argued that transport constraints and distance to markets compel most smallholder farmers to sell their produce at the farm gate (Mutero et al., 2016). Furthermore, droughts and floods have been disastrous in both urban and rural communities (Amoah and Simatele, 2021). Such weather incidents have greatly contributed to food and water insecurities in the Eastern Cape (Nwanze, 2011; von Loeper et al., 2016; Ngumbela, 2021). In the same vein, smallholder farmers are relatively uninformed about the weather, and the agricultural market (Mutero et al., 2016). The study by Morton (2007) found that small farm sizes, inadequate technology and finance, lack of information and other non-climate stressors increase the vulnerabilities of smallholder farmers. Similarly, basic farming tools such as hoes, spades, and wheelbarrows are not enough to improve productivity and compete with commercial farmers.

So, while some advances have been made in terms of ratifying treaties and protocols promoting smallholder farmers. These include (1) The African Union Flagship projects and Continental Framework Schemes; (2) The Program for Infrastructure Development in Africa (PIDA); (3) The African Mining Vision (AMV); (4) The Maputo Declaration of 2003 and (5) Agenda 2063 (Abdalla, 2007; Ngumbela, 2021). But it seems that these treaties and protocols alone are ineffective in terms of supporting the smallholder sub-sector. One possible explanation for this is that most smallholder farmers still do not have access to sufficient land, technical know-how and vital information. Additionally, they have low adaptive capacity to extreme weather events (Ebhuoma et al., 2020; Tantoh et al., 2022). Thus, farm yields remain low and transport costs inhibit profits (Mutero et al., 2016).

4.4. Commercialization

The entrepreneurial environment is essential for economic growth and rural development. A potential avenue is commercialization, where smallholder farmers adopt specialized production of products to sell (Aceleanu, 2016). Uhunamure et al. (2021) argue commercialization can improve household food security. For example, the South African government allocated huge financial resources to facilitate the establishment of self-owned or joint ventures businesses to boost entrepreneurial activity, particularly among smallholder farmers (GEM, 2011). Similarly, low incomes, low harvest prices, high cost of inputs and small operational holding size prevent smallholder farmers from breaking the cycle of poverty (Reddy et al., 2019). However, smallholder farmers in some developing countries are provided with small-scale irrigation schemes, farm input subsidies, farm implements, credit facilities and cash grants to even acquire land under land reform programs to encourage and boost their outputs (Ramaila et al., 2011). Other instruments to improve rural food security include expanding possibilities for employment, implementing community and public works plans, improving education and offering vocational training and promoting access to land (Abdalla, 2007; Chikazunga and Paradza, 2013; Pienaar and Traub, 2015; Ebhouma et al., 2019; Amoah and Simatele, 2021; Ngumbela, 2021). In contrast, the low entrepreneurial spirit among smallholder farmers, lagging behind many countries is a major hindrance (GEM, 2011). For example, only 1.7% of businesses started in South Africa do survive after a period beyond three years and six months, and the Total early-stage Entrepreneurial Activity (TEA) rate was reported at 9.1% (GEM, 2011). In addition, even smallholder farmers with surplus production remain trapped in poverty due to a lack of access to markets (Magingxa et al., 2009). More to that, some field extension agents are ill-informed about local markets and do not often provide the necessary training and assistance so that smallholder farmers can gain access to information about markets. This can be averted if the government influence the private sector to ease access to markets using existing value-chain infrastructure. Another possibility for smallholder farmers to access markets is through "quality food" and "high-value food" production (Biénabe et al., 2011). For example, high-value crops and organic crops could preferably be produced by smallholder farmers although certification organizations driven by the dominant retail sector in South Africa are tough and esteem large-scale producers with the capacity to conform to such schemes (Biénabe et al., 2011). Furthermore, public investment in farm infrastructure could be increased, direct benefit transfer schemes for purchase of inputs strengthened, institutional credit delivery mechanisms improved and safety nets in rural areas widened (Reddy et al., 2019).

5. Conclusion

Currently agriculture in the Eastern Cape is characterized by inequality in terms of the distribution of economic assets, support services, market access, infrastructure, and income. This means little has changed since colonial times. Reducing this inequality is necessary if smallholder farmers of the Eastern Cape are to escape the trap of structural poverty. Part of this involves improving rural food security and promoting rural development. This means supporting small scale farmers. This study argued that focusing on the nexus of water-land-food security is an important way to support smallholder farmers of the Eastern Cape. The study found that while these farmers do have access to land, food security and poverty is still prevalent. In terms of land, the challenges are that most farms are too small while community land is under-utilized. Thus, although much attention has been paid in terms of policies regarding land reform in South Africa, serious issues with respect to communal land can no longer be neglected. Another challenge is poor access to adequate volumes of water. Extended drought conditions have also weakened the capacity of smallholder farmers to adapt, which was never a strength to begin with. Relying on rain fed agriculture is not going to improve farming conditions, let alone support commercialization. Thus, water issues need to be addressed with the building of more dams, irrigation schemes and boreholes – although none will help unless the land is better managed to improve infiltration, reduce evapotranspiration and farmers learn how to manage their water demands down. Appropriate, hardy, drought resistant crops and animals are essential. Additionally, the knowledge and skills base of smallholder farmers must be improved and they need can access capital, markets, agricultural extension services and cost-effective transportation.

Author contributions

HT: conceptualization, visualization, design of research instruments, and writing—original draft. TM: writing—review and editing and supervision. All authors have read and agreed to the published version of the manuscript.

Funding

This work is based on the research supported by the National Research Foundation (NRF) of South Africa (Grant Number 138441). The grant holder acknowledges that the opinions, findings,and conclusions or recommendations expressed in any publication generated by the NRF-supported research are those of the author(s) and that the NRF accepts no responsibility whatsoever in this regard.

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frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 01 June 2023
DOI 10.3389/fsufs.2023.1172405

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RECEIVED 23 February 2023
ACCEPTED 15 May 2023
PUBLISHED 01 June 2023

CITATION
Liang C, Du G and Faye B (2023) The influence of cultivated land transfer and Internet use on crop rotation.
Front. Sustain. Food Syst. 7:1172405.
doi: 10.3389/fsufs.2023.1172405

The influence of cultivated land transfer and Internet use on crop rotation

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In the context of China's digital transformation and agricultural modernization, exploring the impact of cultivated land transfer and Internet use on crop rotation holds significant importance for promoting sustainable use of cultivated land and ensuring the supply of agricultural products. This study utilizes an ordered logistic regression model to investigate this issue, based on a social survey of 489 households in Heilongjiang Province. Our findings reveal that (1) cultivated land transfer and Internet use both promote crop rotation, but cultivated land transfer is more efficient than Internet use. In addition, two-years cultivated land transfer are more effective than one-year, (2) The analysis of the mechanism indicates that both have the most significant promotion effect in the maize-soybean transition zone, and the promotion effect of cultivated land transfer is mainly observed in the older age group, while Internet use is mainly observed in the younger age group. As aging farmers become more critical, the role of cultivated land transfer does not change significantly, while the role of Internet use decreases. Furthermore, the interaction effect of cultivated land transfer and Internet use is not conducive to crop rotation in the maize-soybean transition zone, but it can facilitate crop rotation in older age groups.

KEYWORDS

Internet use, digital divide, cultivated land transfer, crop rotation, conservation tillage

1. Introduction

Crop rotation is an inevitable step to implementing ecological civilization policies and protecting cultivated land. Currently, China is facing a serious challenge with food security and a structural problem with agricultural supply (Zhan et al., 2018; Baylis et al., 2019). The issue of food security is mainly reflected in the protection of cultivated land. China's cultivated land area is decreasing year over year, but grain production is increasing. This phenomenon reflects the growth of China's agricultural production technology but also implies that China's cultivated land is being used intensively. This phenomenon is particularly prominent in the black soil region of Northeast China, manifested by the black soil's thinning and hardening (Xingwu et al., 2012; Wang et al., 2022). This situation not only means that the potential for sustainable use of cultivated land in the black soil region has declined, but it has also caused more serious soil erosion problems (Maojuan et al., 2019).

China has recognized this problem and proposed protecting the black soil as protecting a "panda"(http://www.news.cn/politics/2021-10/17/c_1127966614.htm [2022-12-19]), which indicates that the black soil in Northeast China is crucial for crop production and national food security. Then, China's government has focused on supply-side reform in its economic development of the agricultural system, particularly since 2015. The problem on the supply side of China's agricultural products is mainly the high import of soybeans (Wei and Junfeng, 2019).

Combining these two challenges, the Chinese government aimed to protect cultivated land and restructure the supply of agricultural products by strengthening the crop rotation in the black soil region. So, the challenge is how to effectively encourage farmers in Northeast China to carry out crop rotation which is of great significance to the locally cultivated land ecosystem health and the agricultural product supply in the country. In response to this issue, in August 2022, a social survey was conducted by the "Sustainable Utilization of Black Land" team in typical black soil regions, namely Baiquan, Wangkui, and Jixian counties.

Crop rotation emphasizes the cultivation of different crops in different years, which achieves the conservation of land strength and the reduction of production inputs and improves the overall profitability of agricultural production (Munkholm et al., 2013; Bowles et al., 2020; Yu et al., 2022), which is one kind of conservation tillage technique. Whether farmers adopt conservation tillage techniques is affected by many factors. For instance, age, labor force, cognition level, cultivated land area, agricultural machinery supply, and government subsidies (Teklewold et al., 2013; Grabowski and Kerr, 2014; Chalak et al., 2017; Khataza et al., 2018; Yang and Sang, 2020; Guo et al., 2022). Among them, the cognition level represents farmers' willingness, while the cultivated land area is related to the scale economy of agricultural production. In the process of agricultural production patterns, the consolidation of contiguous arable land serves as a crucial prerequisite. Due to the household contract responsibility system, Chinese rural families own almost equal areas of cultivated land (depending on local conditions) and are scattered (Xie and Jiang, 2016). So, the fulfillment of this condition primarily relies on the transfer of cultivated land, referring to the transfer of land use rights for cultivated land. In addition, the farmer's age and low education level in our study area are critical challenges. Most of the respondents' education levels do not exceed the primary school level. In the context of China's digital transformation, previously published papers have focused on the impact of internet use on the cognitive limitations of farmers and have identified the positive effects of internet usage in this regard (Kan, 2020; Zhang et al., 2022; Zhou et al., 2023). However, this situation presents several shortcomings. First, the current studies regard crop rotation as a form of conservation farming and do not fully consider the high stability requirement of crop management rights for crop rotation. This characteristic may determine that short-term crop management rights cannot promote crop rotation (Zhao et al., 2020; Yu et al., 2022). Then, crop rotation requires consideration of the combined benefits of growing different crops. This context involves climatic suitability under different accumulation conditions (Xiaozhong et al., 2017; Haijiang et al., 2019). Accordingly, it's worth noting that the spatial perspective has not been deeply analyzed in previous studies. Second, crop rotation is currently being piloted in the black soil region of Northeast China, and the policy content changes yearly (http://hlj.people.com.cn/n2/2022/0221/c220027-35143454.html [2022-12-18]). Additionally, because local farmers are getting older, accessing current and useful policy information has become problematic. The difference between this and technical awareness issues is that policy information requires accuracy and timeliness. Therefore, different groups of farmers may lead to different outcomes in Internet use (Twumasi et al., 2021; Khan et al., 2022). The effects of this issue are not clearly described in the previous studies; correspondingly, it is considered a shortcoming.

Therefore, based on social surveys and existing scientific research results, this research aims to investigate the effects and mechanisms of cultivated land transfer and Internet use behavior on crop rotation. Then, it discusses whether this effect has different manifestations in different accumulated temperature conditions and age groups. This paper is arranged as follows: part I presents the context, including a background introduction and literature review; part II analyzes the theoretical mechanisms of cultivated land transfer and Internet use affecting farming rotation and proposes research hypotheses; part III introduces the econometric model setting and data sources, and conducts a descriptive statistical analysis of the data; part IV reports and analyzes the estimation results; and part V focuses on the discussion and conclusions.

2. Theoretical analysis and hypothesis

Crop rotation is the practice of growing crops on the same land in a predictable sequence at various periods of the year, forming a rotation within a cycle. At the same time, crop rotation also has specific positive spatial externalities. The research in agronomy has shed light on the fact that maize-soybean intercropping effectively boosts maize yields due to the nitrogen fixation of legumes, the activation of soil phosphorus by root secretions, and the shading effect of maize on soybean yields (Yu et al., 2009; Yamei et al., 2020). This situation implies a "You cannot have your cake and eat it" situation between the finely fragmented plots for maize and soybean. Moreover, the benefits of conservation tillage for agricultural production also concern crop rotation. However, in contrast to straw mulch and deep tillage, which can be applied in the same year and obtain the effect, crop rotation needs to be implemented over several years to get higher returns over a longer period (Munkholm et al., 2013; Shuhao et al., 2014; Bowles et al., 2020). Compared to other conservation tillage techniques, it takes longer to complete a cropping pattern rotation. Therefore, it requires higher stability of farmland management rights and has the disadvantages of time and cost. The cultivated land transfer can mitigate the problem of cultivated land fragmentation (Xiao et al., 2011). Inevitably, short-term contracts for the transfer of cropland will result in a loss of externalities for farmers' crop rotation (Bo and Ruimei, 2021). Long-term, stable cultivated land transfer not only alleviates the problem of fragmentation but also addresses the 'positive time externality' of crop rotation. Therefore, stable cropland management rights are essential for implementing crop rotation, and the transfer of cultivated land for a long period should be an important step toward implementing crop rotation. As a result, a multi-year cultivated land transfer is more effective than a short-term one to carry out crop rotation. The time limit of the cultivated land transfer becomes an important factor for farmers to decide whether to practice crop rotation or not.

Also, crop rotation requires a high level of cognitive ability. Crop rotation is difficult to implement if farmers lack technical and policy knowledge and awareness of crop rotation. For this study, both technical and policy aspects are involved. Regarding technology, the land area under maize cultivation in the black soil region of Northeast China has been expanding due to the significant changes in temperature conditions under climate change (Ray et al., 2015). Due to the influence of international markets, the land area under soybean cultivation in the black soil region has decreased since China joined the World Trade Organization in 2001. Since 2000, under the combined influence of changing climatic conditions and international market shocks, the diversity of crops in the black soil region has significantly reduced, and the cropping pattern of mainly maize continuous crops has gradually structured (Han and He, 2012). Some of the younger groups of farmers have less experience in making practical decisions about cropping behavior and have not been able to appreciate the long-term effects of crop rotation practically. The lack of intuition and perceptual understanding of crop rotation has led to a lack of technical knowledge (Weizhen et al., 2017; Li and Liqi, 2020). This situation is not conducive to them carrying out crop rotation (Weizhen et al., 2017). Regarding policy, to enable operators of crop rotation to be duly compensated, China began exploring a trial crop rotation exercise in 2016, with a policy subsidy of RMB 150 per mu (a unit of area in China, about 666.7 square meters) for farmers who carry out crop rotation. Now there are still many details to be optimized in practice. Firstly, the annually updated pilot implementation program for crop rotation and fallowing has different target requirements for the area to be rotated in different areas. This information often needs to be passed down from the Ministry of Agriculture and Rural Development before it reaches the farmer. This issue runs the risk of delaying the farming process in practice. Secondly, the problem of population migration and farmer aging is critical in black soil regions (Zuopeng et al., 2021). Farmers are often typically a disadvantaged information group. Or, crop rotation truly has a high level of financial subsidies.[1] However, it is often difficult for specific information about the implementation program of the pilot crop rotation fallow to reach the increasingly aging group of farmers in the black soil region in a timely and effective manner (Yusheng et al., 2016; Zuopeng et al., 2021). Farmers' insufficient awareness of crop rotation systems and area standards makes it difficult to be effectively motivated by the policy, which greatly weakens their enthusiasm to carry out crop rotation. During the social survey, farmers affirmed that they could not obtain crop rotation subsidies and were generally unsatisfied with the crop rotation policy.

Both cognitive problems are expected to be alleviated through the Internet (Li and Liqi, 2020; Zheng et al., 2022). The Internet provides farmers with an effective channel to acquire new knowledge and information. Farmers' internet usage behavior implies that they are able to obtain more information about crop rotation technologies and policies. Especially in sparsely populated areas, digital technology can alleviate the characteristics of geographical constraints, allowing information to be communicated effectively and quickly between different groups (Zhuqing et al., 2013). Continuous innovation in communication technology has greatly reduced the cost of Internet communication, while the construction of digital villages has provided rural residents with good Internet infrastructure. The current level of digitization in Chinese society is increasing. Added to this background, the price of friendly mobile devices with adequate information facility coverage has effectively increased the informational level of rural residents. Thus the role of Internet use in various aspects of farmers' behavior is beginning to receive widespread attention (Michels et al., 2019; Liang et al., 2022). Internet use can effectively alleviate the information exclusion suffered by rural residents (Zhang et al., 2022), which is essential for farmers to have timely and accurate access to effective information about crop rotation. Relevant studies related to conservation farming have mainly concluded that Internet use can enhance farmers' cognition and thus promote adoption behavior (Wenhuan and Guixia, 2021; Zhang et al., 2022; Zhou et al., 2023). So, in the contribution of this research, this role may be reflected in the fact that farmers have more accurate and effective access to technical and policy information about crop rotation through Internet use, which helps them carry out crop rotation.

The conclusion that stability of land rights can improve conservation farming should, in our view, be accompanied by additional preconditions, such as consideration of regional heterogeneity or age heterogeneity (Xiaozhong et al., 2017; Haijiang et al., 2019; Chandio et al., 2022). In areas with high cumulative temperature levels, crop rotation subsidies can hardly bridge the yield gap between maize and soybeans and cannot effectively promote crop rotation. In areas with low cumulative temperature levels, the impact of other factors is limited because the yield gap between maize and soybeans is small, and the proportion of basic crop rotation is high. In areas with middle cumulative temperature levels, where suitable for both maize and soybeans, so it also forms a maize-soybean transition zone in the agricultural landscape. In this region, the yield gap between maize and soybean is at an intermediate level and more susceptible to fluctuations due to other factors. Therefore, more significantly affected by land rights stability and Internet use. In addition, rural areas are currently facing a severe aging problem, and Internet use may create an information divide between different groups of farmers, resulting in "elite capture." Younger farmers are more likely to benefit from access to accurate information through Internet use (Zhuqing et al., 2013).

To some extent, the transfer of cultivated land is the tool basis for farmers to carry out crop rotation, and Internet use improves the farmers' cognition level. The transfer of cultivated land is helpful to crop rotation by solving the externalities in space and time. The use of the Internet deepens farmers' cognition of the ecological and production benefits of crop rotation through the acquisition of technical and policy information. Increasing the material base motivates farmers to expand their skills and cognitive capabilities. The improvement in the cognition level encouraged the farmer to expand the production scale. These two factors should therefore be able to facilitate each other's effects. However, other studies have shown that Internet use can promote farmers' non-agricultural employment and expand income sources to some extent (Xiaona and Xuekai, 2020; Fang et al., 2022). This tendency of farmers to go non-agricultural will also reduce their investment in agricultural means of production, and they tend to use machinery to replace labor input (Qing et al., 2013). In this study, cultivated land's *per capita* area is generally higher than in other regions of China. If there is a cultivated land transfer situation, the farmer's cultivated land area will increase to a higher level, which may take a considerable farm income. Therefore, the non-agricultural effect of Internet use behavior may disappear, which means it cannot promote the development of crop rotation. The general aging problem and lagging industrial development in the study area may also make this path only exist in the younger group. In other words, the older group has difficulty expanding off-farm income through the Internet, while the younger group has more opportunities to increase off-farm income.

1 In Heilongjiang Province, the average subsidy for crop rotation is about 150 yuan per mu, which is lower than the soybean producer subsidy (about 250 yuan) and higher than the cultivated land protection subsidy (about 60 yuan).

Based on the above analysis, this research proposes the following research hypothesis:

> *Hypothesis 1*: Cultivated land transfer can promote crop rotation, which is more significant in the transition zone. Moreover, cultivated land transfer with a two-year term can promote crop rotation over 1 year.
>
> *Hypothesis 2*: Internet use promotes crop rotation, particularly in the transition zone and younger age groups.
>
> *Hypothesis 3*: There is an interactive effect between cultivated land transfer and Internet use. There was a negative moderating effect in the younger group and a positive moderating influence in the older group.

3. Materials and methods

3.1. Data description

The data in this research were obtained from a social questionnaire survey of farmers conducted in 18 towns in 3 counties in Heilongjiang Province in August 2022. Based on the characteristics of the accumulation temperature conditions, the three counties are part of the same annual agricultural maturity zone. Baiquan County has the lowest accumulation temperature, with an average daily accumulated temperature suitable for soy farming of 2,300 ~ 2,500°C·d. Wangkui County has a medium value (2,300 ~ 2,700°C·d), is suitable for maize or soybean cultivation, and is a transition zone between maize and soybean cultivation areas. Or Jixian County has the highest average with 2,500 ~ 2,700°C·d, suitable for maize cultivation. The average daily accumulated temperature in Jixian County is 2,500 ~ 2,700°C·d, which is suitable for maize cultivation. The research was conducted through face-to-face interviews between the researcher and the farmers, and the researcher filled out the questionnaires on-site. The interviewees are decision-makers within agricultural households who engage in agricultural production. They determine which crops to plant, the types of seeds and pesticides to use, which agricultural machinery services to employ, and so on. In our investigation, we are solely concerned with whether they are decision-makers, rather than their gender or age.

As shown in Table 1, the collected questionnaires were screened, and 489 valid questionnaires were obtained, including 148, 149, and 192 questionnaires in Baiquan, Jixian, and Wangkui Counties.

3.2. Model setting

In this research, the ordered logistic regression model was used to estimate the impact of cultivated land transfer and Internet use on farmers' crop rotation. The probability function is:

$$p\left(Y_L = j / x_i\right) = \frac{1}{1 + \exp\left(-\left(\alpha + \sum_{i=1}^{n} \beta_i x_i\right)\right)} \quad (1)$$

For instance, let the dependent variable Y_L represent the crop rotation method adopted by the respondents, where $Y_L = 1$ indicates the start of crop rotation, $Y_L = -1$ indicates the cessation of crop rotation, and $Y_L = 0$ represents other cases. Let x_i denote the i-th factor that affects crop rotation. The ordinal logistic regression model can be defined as follows:

$$\log it\left(P_j\right) = \ln\left[\frac{P\left(y \le j / x\right)}{1 - P\left(y \le j / x\right)}\right] = -\alpha_j + \sum_{i=1}^{n} \beta_i x_i \quad (2)$$

Here, P represents the probability of whether the interviewees rotate, and β_i represents the coefficient of the model's influencing factor $x_{i.}$ When the coefficient β of the influencing factor is positive, it indicates that as the value of x increases, the potential variable Y_L will also increase, meaning that the probability of the dependent variable Y_L taking a higher level increases; when β is negative, it is the opposite.

Considering that some control variables may be missing, we add a dummy variable of the towns to which the farming household belongs to Eq. 2 above. The model is as follows:

$$\log it\left(P_j\right) = -\alpha_j + \beta_1 Trans1_i + \beta_2 Trans2_i + \beta_3 P_i + \sum_{i=4}^{n} \beta_i x_i + \gamma_{town}\phi_{town} + \varepsilon_i \quad (3)$$

where Φ_{town} is the towns dummy variable, γ_{town} is the corresponding coefficient. Other symbols have the same meaning as in Eq. 2. The ordinal logistic regression model with the inclusion of the "town" dummy variable fixes the region effect at the township scale.

To examine the interaction effect between cultivated land transfer and Internet use, we tried to build an econometric model based on Eq. 3 by adding the interaction term of cultivated land transfer and Internet use as follows.

$$\log it\left(P_j\right) = -\alpha_j + \beta_1 Trans1_i + \beta_2 Trans2_i + \beta_3 P_i + \beta_4 Trans2_i \times P_i + \sum_{i=5}^{n} \beta_i x_i + \gamma_{town}\phi_{town} + \varepsilon_i \quad (4)$$

where $Trans2 \times P$ is the interaction term with cultivated land transfer and internet use, and β_4 is the corresponding coefficient. Other symbols have the same meaning as in Eq. 2.

As for the regulation effect of age, we explored it in the form of group regression. The aging phenomenon among farmers in the research area is very serious, and it may be difficult to obtain unexpected results using the form of interaction terms. Specifically, we divided the sample into two groups based on the sample mean, the older group of age greater than or equal to 55 years old, and the younger group of age less than 55 years old.

TABLE 1 Description of the social survey information.

Counties	Location	Main crop type	Towns	Number	Date
Baiquan County	Central Songnen Plain	Soybean	Shangsheng, Shizhong, Xinsheng, Xingguo, Xinghua, Xiongnong	148	August 2022
Jixian County	West Sanjiang Plain	Maize	Fengle, Fuli, Jixian, Yong'an	149	August 2022
Wangkui County	Eastern Songnen Plain	Soybean and maize	Dengta, dongjiao, dongjiao, huiqi manchu, huojiang, lingshan manchu, xianfeng	192	August 2022

3.3. Variable selection

The explained variable. Since the Chinese government started the pilot work of crop rotation in 2016, whether farmers started crop rotation after 2016 was taken as the explained variable in this paper. We took the state of the crop rotation before 2016 as the original state and focused mainly on changes in farmers' crop rotation behavior after 2016. There are two types of such changes: those that start the crop rotation, which is the change we most want to see, and those that stop, which is the change we least want to see. The worst case scenario, where the farmers stay in the same original state, is also better than if the farmer has stopped the rotation. If farmers did not crop rotate before 2016 but started it after 2016, the value is 1. A value of −1 is assigned for crop rotation before 2016 but stops after 2016. Otherwise, it's 0. Therefore, the explained variable is an ordered categorical variable. As its value increasing, the farmer's crop rotation behavior is more positive.

Core explanatory variables. The core explanatory variables include two, namely, cultivated land transfer and Internet use. Based on relevant studies, this research selects the period of farmers' transfer into cultivated land (Gao et al., 2019; Zhou et al., 2023) and whether they use WeChat software as the core explanatory variable (Liwei, 2019; Min et al., 2021). WeChat is an instant messaging software developed by Tencent, just like WhatsApp, which also has functions such as payment and video, and has been widely used in rural China and become an important tool for rural information dissemination and community governance (Liwei, 2019; Yilan, 2019). By asking farmers, "If you transfer in someone else's cultivated land, how long is the transfer period?." To obtain information about the cultivated land transfer period, assign values to variables according to the corresponding time. The information about whether farmers use the Internet is obtained by asking them "whether you use WeChat and other software in daily life." If they do, the value is assigned as 1. Otherwise, it's 0.

Control variables. Context-aware by the findings of scientific studies (Zhaoda and Zhigang, 2021), this research selects control variables from three aspects: individual farmer characteristics (Chalak et al., 2017; Khataza et al., 2018; Derrouch et al., 2020), household characteristics (Yonghong and Hongyun, 2012; Teklewold et al., 2013; Yang and Sang, 2020; Guo et al., 2022), and agricultural operation characteristics (Hung et al., 2007; Grabowski and Kerr, 2014; Yang et al., 2022), including factors such as age, position, type of farming household, and area of cultivated land. Some of the missing values were filled in as the mean value for the village. Specific variable assignments and descriptive statistics are shown in Table 2.

3.4. Correlation analysis

Before exploring their causality, we should first confirm that they are directly correlated. And we hope that the proportion of "Stop crop rotation" will decrease, not increase. As shown in the cross table, Table 3, in a sample of "one-year cultivated land transfer period," the rate of "Stop crop rotation" grown from 7.39 to 8.88%, and "Start crop rotation" grown from 15.65 to 26.64%. In the sample of "two-year cultivated land transfer period" and "Internet use," the rate of "Stop crop rotation" all decrease, and "Start crop rotation" increase. This situation indicates a positive correlation between cultivated land transfer, internet usage, and crop rotation, with the two-year cultivated land transfer showing a more pronounced correlation. This statistical correlation suggests that we should pay more attention to its internal causal relationship.

4. Results

4.1. Baseline regression

The baseline regressions (Table 4) were conducted by adding each variable according to model (2): Model1 is the result of adding only the core explanatory variables. Model2, Model3, and Model 4 are the estimated results of adding external factors, individual factors, and business characteristics, respectively. Then, Model5 is the result of adding all control variables. The variance inflation factor value is less than 2 in each model, which strongly excludes the effect of cointegration problems.In Model 1 to Model 5, the two-year cultivated land transfer is all significantly positive at a statistical level of at least 10%, while the internet usage variable is 5%.

Combining the models' estimation results, the variable representing the cultivated land transfer, Transfer2, basically shows a more significantly positive contribution. The coefficient on the Internet use variable was incredibly positive in all models. Although positive, the coefficient on the Transfer1 variable was not significant in all models. This result means that both cultivated land transfers and Internet use contribute to farmers' crop rotation decisions. In this case, hypotheses 1 and 2 are partially confirmed. Comparing the coefficients and significance of the Transfer1 and Transfer2

TABLE 2 Descriptive statistics of main variables.

Statistic	Define	Num	Mean	St. Dev.
CR	Crop rotation behavior after 2016; Start crop rotation =1; Stop crop rotation = −1; Otherwise =0	489	0.13	0.53
Transfer1	One-year cultivated land transfer-in; Yes =1, no =0	489	0.53	0.5
Transfer2	Two-year cultivated land transfer-in; yes =1, no =0	489	0.05	0.22
Internet use	Internet use; Yes =1, no =0	489	0.52	0.5
GDD	Transition zone; Wangkui County =1, other =0	489	0.39	0.49
sex	Sex; male =1, female =0	489	0.88	0.33
age	age	489	54.64	9.8
health	Health status; good =1, generally =2, poor =3, very bad =4	489	1.14	0.42
culture	Education level; very little literacy or literacy =1; primary school =2, middle school =3, technical secondary school or high school =4, junior college, undergraduate degree and above =5	489	2.38	0.72
labor	Number of the labor (person)	489	2.27	1.78
workout	Migrant work experience;In the province =0, outside the province =1	489	0.45	0.5
govjob	Whether to be a village committee cadre; Yes =1, no =0	489	0.08	0.28
rualincomeperc	The proportion of agricultural income in the total household income; 0–20% =1; 20–50% = 2; 50–80% = 3; 80–100% = 4	489	3.42	0.90
partymem	Member of the Communist Party of China; Yes =1, no =0	489	0.05	0.21
farmtype	Types of farmers;Normal farmers = 1， Big farmer = 2(>100 mu)	489	1.46	0.56
ALmaxarea	Maximum cultivated land area (mu)	489	27.88	68.58
Cognition	Crop Rotation can increase the perception of yield; complete disagreement =1, great disagreement =2, uncertainty =3, comparative consent =4, complete consent =5	489	4.52	0.66

variables shows that a two-year cultivated land transfer period is more likely to encourage crop rotation than a one-year cultivated land transfer. Hence, hypothesis 1 is further corroborated. From Model1 to Model5, the model's effect on the variables has grown. Still, the importance and sign of the coefficients of this study's primary explanatory variables have largely remained the same. The basic robustness of the regression results is illustrated from the perspective of model construction.

TABLE 3 The correlation of cultivated land transfer, Internet use and crop rotation.

CR	Transfer1		Transfer2		Internet use	
	0	1	0	1	0	1
Stop crop rotation (−1)	17(7.39%)	23(8.88%)	39(8.42%)	1(3.85%)	23(9.83%)	17(6.67%)
Otherwise (0)	177(76.96%)	167(64.48%)	327(70.63%)	17(65.38%)	174(74.36%)	170(66.67%)
Start crop rotation (1)	36(15.65%)	69(26.64%)	97(20.95%)	8(30.77%)	37(15.81%)	68(26.67%)

TABLE 4 Baseline Regression results.

	Model1	Model2	Model3	Model4	Model5
	Only core explanatory variables	Add individual farmer characteristics	Add household characteristics	Add agricultural operation characteristics	All controls
Transfer1	0.2278 (0.2852)	0.2849 (0.2974)	0.2122 (0.2820)	0.2000 (0.2756)	0.2309 (0.2928)
Transfer2	1.0853** (0.5465)	1.0716* (0.6050)	1.1061** (0.5504)	1.0472** (0.5273)	1.0382* (0.5792)
Internet use	0.4772** (0.1860)	0.5048** (0.1977)	0.4920*** (0.1834)	0.4580** (0.1938)	0.4900** (0.2043)
age		0.0031 (0.0168)			0.0030 (0.0165)
Cognition		−0.3701** (0.1679)			−0.3769** (0.1692)
culture		−0.1817 (0.1876)			−0.1863 (0.1821)
govjob		−0.0345 (0.3408)			−0.0452 (0.3129)
labor			−0.0201 (0.0391)		−0.0258 (0.0395)
coomem			0.1187 (0.3867)		0.0741 (0.3433)
rualincomeperc			0.1432 (0.1395)		0.1217 (0.1441)
farmtype				0.1446 (0.2089)	0.1883 (0.2088)
ALmaxarea				−0.0013 (0.0017)	−0.0011 (0.0018)
Fixed effect	Town	Town	Town	Town	Town
Num. Obs.	489	489	489	489	489

*, **, and *** are significant at the levels of 0.1, 0.05, and 0.01, respectively; Adopt robust standard error, and the standard error is in parentheses.

4.2. Robustness test

To further verify the reliability of the baseline regression results, this research uses the method of replacing the explanatory variables and the core explanatory variables to verify the robustness of the baseline regression results. "Whether you can shop online" was used as a proxy variable for Internet use behavior. The difference between this variable and the original core variable is that the replaced core explanatory variable has stricter requirements for the depth of internet use. The explanatory variable was replaced with "whether to continue crop rotation after 2016," with crop rotation after 2016 being assigned a value of 1. Otherwise, it is 0. The difference between this variable and the original explanatory variable is that the new explanatory variable only emphasizes crop rotation after 2016 and does not focus on whether crop rotation occurred before 2016. The above variables were brought into the model (2) and estimated. The results are presented in Table 5.

Overall, the significant contributions of two-year cropland transfer and Internet use remain. The coefficient on the two-year cropland transfer remains important, at least at the 0.1 level, in all models except model 8. The coefficient on the Internet use variable is not only lightly significant in Model9, at least at the 0.1 level in all other cases.

These results confirm that the results of the baseline regression discussed above are robust and plausible. Overall, the estimates from the robustness tests remain largely consistent with the theoretical analysis and the baseline regression estimates. Parts of Hypothesis 1 and Hypothesis 2 are once again corroborated.

Endogeneity. First of all, our study area is representative of a variety of natural conditions, and the subjects (farmers) were randomly selected within each county. Therefore, the selection bias can be excluded in this study. Secondly, as we introduced in the introduction part, the study area are facing with almost the same problems of aging farmers and low literacy. And as Table 2 shown, the crop rotation has a obvious different statistical distribution than cultivated land transfer and Internet use. In addition, We also control individual farmer characteristics, household characteristics and agricultural operation characteristics in all regressions. The results of the "4.4. Further discussion" part further support our view. So, sample self-selection will not seriously affect this study.

However, to ensure that the baseline regression results are not affected by the sample self-selection problem, we utilize the PSM method for causal inference between variables. Then take "Transfer1," "Transfer2," and "Internet use" as processing variables respectively, and the obtained ATT effect is as follow in Table 6. It can be seen that the impact of the two-year cropland transfer and Internet use is still

TABLE 5 Results of the robust test.

	Model6	Model7	Model8	Model9
	Replace X	Replace X	Replace Y	Replace Y
Transfer1	0.2639 (0.2270)	0.4542** (0.2056)	−0.3711 (0.2793)	−0.1019 (0.1994)
Transfer2	0.9964** (0.4869)	0.7941* (0.4238)	1.0927 (1.1580)	2.7004*** (1.0267)
Internet use	0.6032** (0.2449)	0.5302** (0.2260)	0.5483* (0.2955)	0.3532* (0.2172)
Controls	Yes	No	Yes	No
Fixed effect	Town	Town	Town	Town
Num.Obs.	489	489	489	489

*, **, *** denote significance at the 0.1, 0.05, and 0.01 levels, respectively; robust standard errors clustering to town. The value of p for the coefficient on the Internet use variable in Model9 is 0.1039, considered significant at the 0.1 level.

TABLE 6 Results of the robust test.

	K =1	Caliper (0.05)	Kernel
Transfer1	0.11 (1.50)	0.11 (1.50)	0.06 (1.14)
Transfer2	0.27* (1.84)	0.28** (1.90)	0.18 (1.58)
Internet use	0.20** (2.30)	0.12** (2.31)	0.18*** (2.64)

t-value is in parentheses.

relatively significant. This shows that the above results based on benchmark regression are reliable.

4.3. Mechanism analysis

Taking into account the characteristics of the study area and the analysis results presented above, we considered it necessary to conduct a first-group regression from a regional perspective to observe the impact of the core explanatory variables in different regions. Secondly, agricultural operators in the study area are heavily aged, with an average age of 55 years old. Farmers' recognized level of crop rotation and the digital divide are closely related to their age. It was, therefore, necessary to run regressions by age grouping to see the impact of the core explanatory variables across age groups. The estimated results are shown in Table 7.

Model11 and Model12 show that the impacts of cultivated land transfer and internet use are more pronounced in the transition zone areas, with the variable coefficients exhibiting satisfactory statistical significance.[2] In the same sense, Model13 and Model14 show that a two-year land transfer significantly promotes arable crop rotation for the older group (age > 55). For the younger group (age <= 55), the effect of Internet use is more significant. Possible explanations for this are that in the transition zone areas, where the difference in returns between maize and soybean cultivation is relatively small and the proportion of previous rotations is not high, farmer rotations are relatively more influenced by other factors. In terms of age, older farmers are more aware of crop rotation and tend to undertake it when land rights are relatively more stable. On the other hand, although older farmers can use the mobile Internet, the information literacy gap is challenging to fill. Conversely, younger groups are more able to obtain adequate information and incentives to progress with crop rotation through their Internet use.

We also observe whether the two core explanatory variables have the ability to influence each other and create an interactive effect. We, therefore, test hypothesis 3 by including an interaction term between the cultivated land transfer variable and the Internet use variable. The results of the model estimation are shown in Table 8. Because of the intractable cointegration problem in Model18, we used group regressions to recheck. The results are shown in Table 9.

In Table 8, the interaction term variable only showed statistical significance in the transition zone and the older group. In Table 9, the coefficient on the Transfer2 variable is more significant for the subgroup of the older group that uses the Internet than for the group that does not use it. A possible explanation is that the region of interest in this research has a relatively high share of primary industries and a general lack of non-farm employment among farm households. Internet use can increase farm households' income sources to some extent (Xiaona and Xuekai, 2020; Fang et al., 2022), improving their income structure and raising their household income levels. Farming households with non-farm income no longer rely primarily on farmland output. The significant input–output efficiency difference between the agricultural and non-agricultural sectors means they may not put more effort into farming when transferring farmland to them. They are more inclined to use agricultural machinery for labor substitution (Kung, 2002)through crop-scale cultivation to improve input–output efficiency. They are, therefore, less likely to undertake crop rotation than farm-based farmers. However, this effect does not apply to older groups. Because of their age, it is difficult for them to benefit from using the Internet to take up non-farm jobs and find non-farm sources of income. So the absence of this pathway would result in this group being tied to agricultural production and having the relative energy to undertake crop rotation. Based on these descriptions and results, hypothesis 3 was not entirely substantiated.

Furthermore, we discuss heterogeneity in terms of the presence or absence of the labor force and literacy. The results (not reported) show that the effects of cultivated land transfer and Internet use to promote crop rotation are more prevalent in the group of farmers with labor experience, the group with primary school education or less, and the group with less than 80% of farm income. One possible explanation is that farmers who do not have migrant work experience and have less education are more aware of crop rotation and are more likely to do it because of cultivated land transfers and the Internet. This situation also confirms that farmers are less inclined to rotate their crops when they have non-farm jobs or non-farm sources of income.

5. Discussion

This research explores the specific effects of cultivated land transfer and Internet use on crop rotation and further examines the heterogeneity across regions and farmer groups. Our results show that

2 The t-statistic of the exponent for the internet usage variable is 1.6479, very close to the critical value at the 10% significance level. This study considers this test result to be supportive of the conclusions drawn.

TABLE 7 Regression results by regions and age groups.

	Model10	Model11	Model12	Model13	Model14
	All Samples	No-transition zone	Transition zone	Age>55	Age<=55
Transfer1	0.2309 (0.2928)	−0.1965 (0.3572)	0.9385*** (0.2216)	0.2938 (0.3533)	0.1076 (0.3772)
Transfer2	1.0382* (0.5792)	0.6316 (0.6624)	2.6896*** (0.6976)	2.4430*** (0.6562)	0.1640 (0.7914)
Internet use	0.4900** (0.2043)	0.4245* (0.2457)	0.6010 (0.3657)	0.3281 (0.4545)	0.7877*** (0.2975)
Controls	Yes	Yes	Yes	Yes	Yes
Fixed effect	Town	Town	Town	Town	Town
Num.Obs.	489	297	192	221	268

*, **, and *** are significant at the levels of 0.1, 0.05, and 0.01, respectively; Adopt robust standard error.

TABLE 8 Test of the interaction effect between cultivated land transfer and Internet use.

	Model15	Model16	Model17	Model18	Model19
	All samples	No-transition zone	Transition zone	Age>55	Age<= 55
Transfer1	0.2259 (0.2882)	−0.2049 (0.3591)	0.9179*** (0.1822)	0.3609 (0.3679)	0.1102 (0.3918)
Transfer2	1.4403** (0.5697)	0.9379* (0.4971)	10.0891*** (0.6612)	2.0328*** (0.6567)	−0.0680 (0.4001)
Internet use	0.5221** (0.2285)	0.4581 (0.3032)	0.6165* (0.3643)	0.2619 (0.4694)	0.7770** (0.3032)
Transfer2 × Internet use	−0.8725 (0.8605)	−0.6129 (1.0706)	−8.8936*** (0.6607)	14.8061*** (0.000002)	0.3002 (0.9234)
Controls	Yes	Yes	Yes	Yes	Yes
Fixed effect	Town	Town	Town	Town	Town
Num.Obs.	489	297	192	221	268

*, **, and *** are significant at the levels of 0.1, 0.05, and 0.01, respectively; Adopt robust standard error.

both cultivated land transfer and Internet use promote crop rotation, with the effect of cultivated land transfer being stronger than Internet use behavior. Then, a two-year period of cultivated land transfer significantly facilitates crop rotation, which is more significant than a one-year cultivated land transfer. This result is consistent with the results of related studies (Gao et al., 2019; Bo and Ruimei, 2021). As significant externalities characterize crop rotation in space and time, the stability of farming rights helps increase farmers' willingness to rotate their crops. The empirical results of this research also show that Internet use behavior can significantly promote crop rotation among farmers. The analysis shows that farmers can use the Internet to get more accurate and useful technical and policy information about crop rotation. This situation makes farmers more likely to rotate their crops. This context is consistent with the findings of related studies (Zhou et al., 2023).

It is important to note that some studies have found that the decentralization of cultivated land can contribute to the diversification of agricultural production (Ciaian et al., 2018; Qiu et al., 2020). In contrast, this research concludes that centralized, stable management can contribute to diversification. The former conclusion presupposes that local farmers rely solely on agricultural production to meet their subsistence needs or to develop urban agriculture, both of which are far from the reality of our study area. This context exists because the study area is one of China's major commodity grain bases and is responsible for the bulk of grain production. That is why the above-perceived differences arise.

The research also finds that cultivated land transfer and Internet use have differential impacts across regions and age groups. The impact of crop rotation was more significant in the transition zone regions and less statistically significant in the non-transition zone regions. This discussion is innovative in this research because it incorporates natural conditions into studying crop rotation decision mechanisms. However, studies have focused on the differential effects of cumulative temperature conditions on farmers' willingness to be paid (Xiaozhong et al., 2017; Haijiang et al., 2019). But there is not enough empirical talk looking at mechanisms of action. Our findings also revealed that the role of Internet use behavior was most prevalent among younger groups. Our results also highlighted that the role of Internet use behavior was mainly among the younger groups. These results may be because younger farmers can obtain adequate information from Internet use; they show that the digital divide exists among different age groups in rural areas. The multi-level digital divide between rural and urban areas in the digital economy is a phenomenon that has answered this discussion (Yi and Jie, 2021).

This study also has three major shortcomings. First, this research argues that the temporal–spatial externality of crop rotation can be solved by means of cultivated land transfer. But this problem can also be solved with farmers' cooperation. Some studies have found that farmers' social network relationships also affect the adoption of conservation tillage techniques (Schneider et al., 2012; DeDecker et al., 2022). This issue appears in this study and should be considered in future studies. Second, farmer aging is general in the study area and directly affects agricultural production's labor input. In order to solve this problem, the local government is also actively developing social services for agricultural production. This service is also expected to solve the age factor's restriction on cultivated land use. However,

TABLE 9 Group regression based on age and Internet use behavior.

	Model20	Model21	Model22	Model23
	Internet use=0 and age>55	Internet use=1 and age>55	Internet use=0 and age<=60	Internet use =1 and age<=60
Transfer1	0.6736 (0.4335)	0.0306 (0.7651)	−0.5521 (0.4490)	0.5672 (0.4753)
Transfer2	3.3584*** (0.8850)	28.3671*** (9e-10)	0.8115 (1.1798)	0.2274 (1.0639)
Controls	Yes	Yes	Yes	Yes
Fixed effect	Town	Town	Town	Town
Num.Obs.	155	66	123	189

*, **, and *** are significant at the levels of 0.1, 0.05, and 0.01, respectively; Adopt robust standard error. In order to meet the sample requirements of regression, we adjusted the age in Model22 and Model23 to 60 years old.

we have not obtained sufficient information due to the survey limitations, such as the data collection time. Consequently, it is not convenient to easily achieve the above goals. We believe that future research can be further discussed from the perspective of society, which is a new idea in rural aging. Third, in this study, we consider the use of the internet as an important means to enhance farmers' cognitive level. Therefore, the causal relationship between internet use and crop rotation that we have revealed is an indirect one, and further research can verify it through more direct means. Particularly, with the current intensification of international food trade risks, price signals can be disseminated more rapidly through the internet. Fluctuations in international food prices may trigger changes in farmers' cultivation behaviors.

6. Conclusion

This study finds that cultivated land transfer and Internet use promote crop rotation, mainly in the maize-soybean transition zone. Cultivated land transfer has a more substantial effect than Internet use. A two-year cultivated land transfer enables crop rotation more significantly than a one-year cultivated land transfer. The analysis of the mechanisms shows that the promotion of cultivated land transfer is mainly in the older age groups, while the promotion of Internet use is primarily in the younger age groups. The role of crop rotation does not change with the farmer's age, while the effect of Internet use decreases with it. The combined impact of cultivated land transfer and Internet use is not conducive to crop rotation in the transition zone but can facilitate crop rotation in the older age groups. The main contribution of this study is to reveal that there is not only age group heterogeneity but also region heterogeneity in the effects of land tenure and cognitive level in the farmer's decision-making mechanisms.

The findings of this study have positive policy implications.First, crop rotation in the maize-soybean transition zone has much scope for expansion and is vulnerable to external forces. This context suggests encouraging crop rotation in the maize and soybean transition zones. In this region, the economic yield gap between maize and soybeans are smaller, and the climate suitability is higher, giving farmers economic incentives to carry out crop rotation driven by policies. Second, stable land rights help farmers carry out crop rotations for long periods, and highly constrained cultivated land transfer should be encouraged. Particular attention should also be paid to the concentration of cultivated land transfer to mitigate the loss of spatial externalities from crop rotation. At the same time, the government should strengthen the formalization of the cultivated land transfer contract in rural areas to protect the legitimate rights of farmers on both sides. We should pay special attention to the needs of the older farmers and provide them with more comprehensive intermediary services for cultivated land transfer by utilizing socialized agricultural production and service organizations. Thirdly, the digitalization of rural areas should be strengthened to improve the information literacy of farmers, alleviate the urban–rural digital divide, and provide differentiated information support for different groups of farmers. For young farmers, in particular, digital information is more easily disseminated, which means that digital information support contributes to the intergenerational sustainability of agricultural production. As the world's development becomes increasingly digital, it's necessary to consider rural areas and agricultural production and use digital means to bridge the information gap between urban and rural areas.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

CL: conceptualization, data curation, formal analysis, investigation, ethodology, and writing—original draft. GD: data curation, investigation, funding acquisition and project administration. CL and BF: writing—review & editing. All authors contributed to the article and approved the submitted version.

Funding

This work was supported by the National Social Science Foundation of China, No. 21BJY209.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 26 July 2023
DOI 10.3389/fsufs.2023.1179919

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RECEIVED 05 March 2023
ACCEPTED 21 June 2023
PUBLISHED 26 July 2023

CITATION
Jabbar A, Wei L, Zhang J, Liu J, Wang Y, Wu Q and Peng J (2023) Exploring the contributions of non-farm income diversification for improving soil and water conservation practices and reducing rural poverty in rain-fed areas of Punjab, Pakistan.
Front. Sustain. Food Syst. 7:1179919.
doi: 10.3389/fsufs.2023.1179919

Exploring the contributions of non-farm income diversification for improving soil and water conservation practices and reducing rural poverty in rain-fed areas of Punjab, Pakistan

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Attaining agricultural sustainability and eliminating poverty are the key challenges of rural areas. Non-farm income diversification is a vital livelihood strategy that endorses sustainable agriculture and alleviates poverty. Considering the land degradation and poor economic situation of Pakistan's rain-fed areas, the current research examined the potential effects of non-farm income diversification on household poverty and adopting soil and water conservation (SWC) technologies. A survey of 441 farmers was conducted in rain-fed areas of Punjab, Pakistan, and for econometric analysis, the propensity score matching (PSM) technique was employed to explore the objectives. The results signified that diversified farmers were more likely to adopt SWC practices and were less vulnerable to poverty. The findings suggest that farmer-based organizations and agricultural extension activities must be strengthened as they support non-farm income diversification, thus facilitating investment in soil and water conservation technologies and reducing poverty.

KEYWORDS

non-farm income diversification, soil and water conservation practices, poverty, rain-fed areas, propensity score matching

1. Introduction

The rain-fed farming areas of Pakistan are recorded to have relatively high poverty levels due to overdependence on rain for farming activities and other livelihoods (Rashid and Rasul, 2011; Bakhsh and Kamran, 2019). Moreover, because of poor agricultural production, inefficient land use, and inadequate off-farm options, Punjab's northern regions, such as the Potohar region, confront significant challenges such as food security and poverty (Suleri and Iqbal, 2019).

Addressing pressing challenges, such as poverty and climate vulnerability, for a nation is the biggest obstacle to achieving sustainable development goals (Issahaku and Abdul-Rahaman, 2019). Poverty increases vulnerability, and susceptibility to climate uncertainty further exacerbates poverty (Eriksen and O'brien, 2007). In addition, soil degradation in rain-fed areas is primarily caused by primitive farming practices that physically, chemically, and biologically deteriorate the soil (Ali et al., 2020).

Intensive agriculture systems significantly negatively impact climate change, greenhouse gas emissions, and soil degradation and cause pollution. Adopting sustainable farming practices mitigates these effects and ensures a more sustainable future (Ali et al., 2019). Hence, farmers must replace traditional farming methods with more sustainable conservation practices (Nawab et al., 2021). Soil and water conservation (SWC) includes the set of technologies to cointegrate the management of soil, water, and further environmental resources to fulfill essential human needs by bringing long-term sustainability to biodiversity and livelihoods (Baig et al., 2013). SWC adoption is considered the entry point for increased productivity and income, thus, breaking the vicious circle of poverty (Manda et al., 2016). Despite demonstrating considerable enthusiasm and efforts initially, evidence of adopting SWC practices to achieve optimal results is weak (Qadir and Oster, 2004; Mazhar and Shirazi, 2023). SWC practices are capital-intensive. Therefore, smallholders are often cash-strapped due to crop failures, poor harvests, price instability, and imperfections in financial markets (Abidoye and Odusola, 2015). Hence, smallholders have acknowledged non-farm diversification as a sustainable strategy (Issahaku and Abdul-Rahaman, 2019).

Stifel (2010) described income diversification as increasing sources to stabilize household income. This study applied the concept of income diversification concept where a farmer is engaged in sources other than farming, such as self-employment, trading, paid work, and other occupations or enterprises. The major reasons behind income diversification are to decrease the low-income risk through diversification ex-ante, to achieve food security in the event of diminishing farm yield, and to avoid climate shocks through diversification ex-post due to failure of insurance coverage and lack of credit availability (Ellis, 2010). Additionally, it is a norm among households to diversify their income during the off-farm season to avoid low income (Ellis, 1998).

Existing literature suggests that income diversification provides a parallel source of household income (Pfeiffer et al., 2009; Owusu et al., 2011). Olugbire et al. (2011) suggested that the non-farm sector significantly donates to economic and rural development in a community. Income diversification facilitates on-farm investments and the adoption of the latest agricultural technologies, while on-farm income can be capitalized in commerce-related activities (Anang, 2019). In addition, income diversification is related to superior revenues and ensures consistent access to food (Babatunde and Qaim, 2010). Literature suggests two probable impacts of income diversification (Babatunde, 2015): the income effect, which increases farm-level investment, and the lost labor effect, the labor numbers probably are lowered owing to other occupations from farming operations. Multiple studies (Desbiez et al., 2004; Chang et al., 2008; Stampini and Davis, 2009; Anríquez and Daidone, 2010; Scharf and Rahut, 2014) acknowledged the significant effect of income diversification on farm production, labor hiring, procurement of farm inputs, and households' food security.

In contrast, Pfeiffer et al. (2009) stated an inverse relation between non-farm participation, farm investment, and productivity. Kousar and Abdulai (2015) found an inverse relationship between non-farm income influx and fertilizer application in rural Punjab, Pakistan. Similarly, Huang et al. (2019) reported a negative association between non-farm diversification and adopting SWC practices among the farmers of the loess plateau in China. Non-farm participation restrains labor availability; hence, it does not necessarily support farm-level investment, contrary to the common assumption. The standard hypothesis suggests that the smallholders depending on agriculture are expected to invest the extra income in on-farm ventures. Conflicting empirical evidence makes it essential to investigate this further in the local context. Though some studies have explored income diversification in Pakistan, only scant literature discusses the role of non-farm income in adopting SWC and household poverty. The study thus contributes to Pakistan's empirical study by investigating the impact of non-farm income diversification on household poverty and the adoption of conservation technologies.

1.1. Farmer's decision to participate in non-farm income diversification

The study employed a sustainable livelihood framework (Figure 1) as the base for exploring the income diversification strategies being used by smallholders (Scoones, 1998). The framework comprises five core capitals: human capital, natural capital, financial capital, physical capital, and social capital. Context is the other major component of the framework, consisting of multiple sources of vulnerability, such as climate shocks, seasonality, and price variability of farming inputs and outputs. In this scenario, Solesbury (2003) argues that people have objectives (livelihood outcomes), and to achieve them, they undertake certain activities (adaptation strategies) using resources (livelihood assets) they can access. The marginal farmers depend heavily on crop production and seasonal wages from labor activities, whereas financially well farmers have sound access to productive assets (such as human and land capital) and use their capital base to engage in productive activities with higher returns. Farm households diversify their income portfolio by engaging in off-farm due to low farm income and excess family labor availability. For instance, Olale and Henson (2012) found a reduction of poverty in the fishing community by diversifying the income source and relieving the extra stress on fishing resources. Multiple researchers (Reardon, 1997; Abdulai and Delgado, 1999; Barrett et al., 2001; Woldenhanna and Oskam, 2001) have reported similar results in the past. Farm households diversify their income portfolio by engaging in off-farm due to low farm income and excess family labor availability. Hence, farmers allocate their part-time labor force to numerous non-farm activities such as sole proprietorship, petty trade, or participation in the migratory labor market. Income diversification enables farm households to generate substantial income, building resilience against climate change,

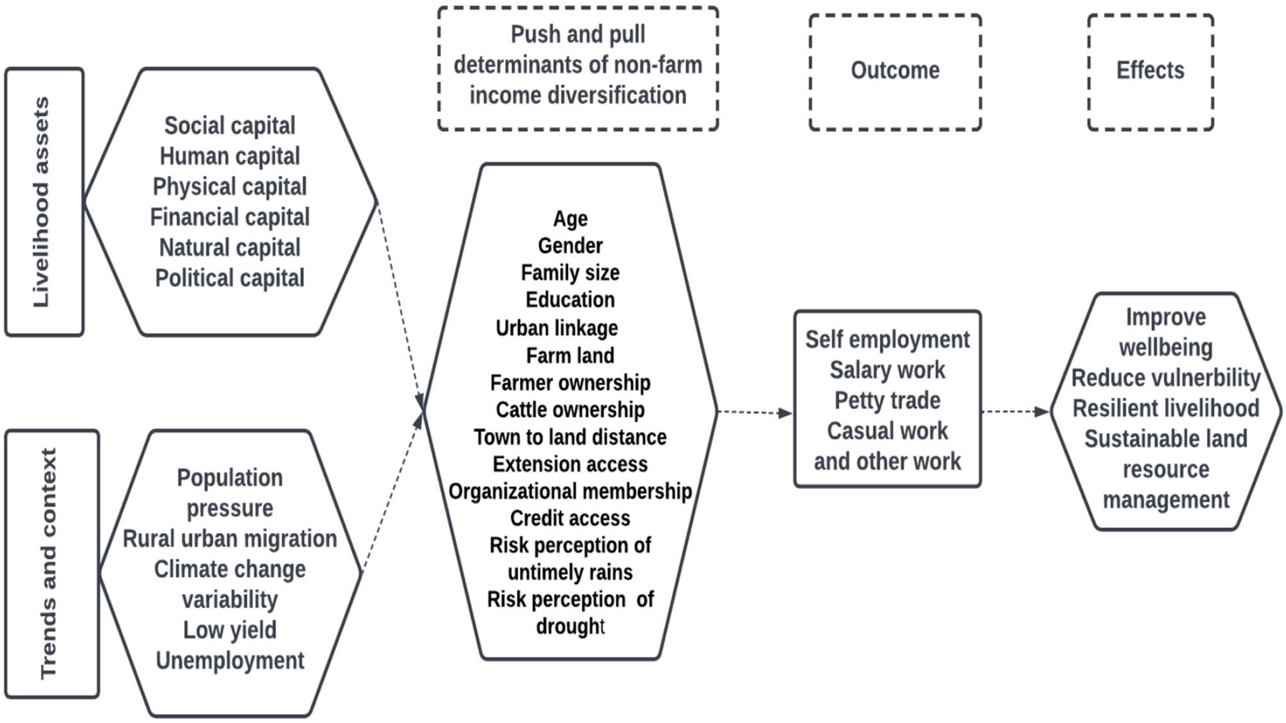

FIGURE 1
Conceptual framework [Source: Adapted from Scoones, 1998].

reducing vulnerability, and escaping poverty. Smallholders from the rain-fed area, often called subsistence farmers, are considered susceptible to climate change and adapt their livelihood systems in the vulnerable context.

The framework offers a theoretical foundation for analyzing and comprehending the determinants that influence the selection of livelihood approaches and their interrelationships. There exists a correlation between the endowment of capital and contextual factors in the decision-making process of households in selecting livelihood activities that either enhance or maintain their means of subsistence. The sustainable dimension pertains to how households can leverage resources to mitigate susceptibility arising from health, climatic, and market-related perturbations.

2. Methodology

2.1. Study area and data collection

The study was conducted in the northern parts of Punjab province, Pakistan, between the Indus and Jhelum Rivers, often called the Potohar plateau shown in Figure 2. The area of the Potohar plateau is 13,000 square kilometers, with elevation from the sea level between 305 and 610 m. The region follows an erratic rain pattern and undulating topography (Amir et al., 2019).

Approximately 994 thousand hectares of the Potohar plateau are under cultivation, with only 4% of the cultivated land irrigated, and approximately 96% of the land depends on rainwater. Rain-fed agriculture has low efficiency because of soil dissolution, unanticipated and inadequate rainfall, relatively low matter substance, and undesirable ecological conditions such as dry air and high temperatures. As a result of these factors, the Potohar plateau is facing severe food shortages and poverty-related issues (Suleri and Iqbal, 2019). The study consists of districts such as Rawalpindi and Chakwal from the Potohar area. This study employs a simple random sampling technique for data collection. A survey was conducted through a well-trained interviewer, and the rural population of these areas was our unit of analysis. Punjab province was selected in the first data collection phase because of its agriculture and economic importance to the country. In the second stage of the study, three districts (Rawalpindi, Chakwal, Jhelum) were selected. Consequently, in the third stage two tehsils were chosen from each of the district. Furthermore, we selected four to five union councils from each of the tehsils, and at the next stage, two to three villages were randomly selected from each union council. Finally, nearly 5 to 7 farmers were randomly chosen from each village, and a combined 441 were chosen.

2.2. Variable specification

This study employed non-farm income diversification as the treatment variable, with 1 signifying participation in non-farm activities and 0 = otherwise. Poverty was measured *via* two indicators: food consumption per capita and vulnerability. Food consumption was the continuous variable suggesting per capita expenditure in rupees. The vulnerability to predicted poverty can be described as the likelihood of household consumption dropping beneath the poverty line. As described by Morduch

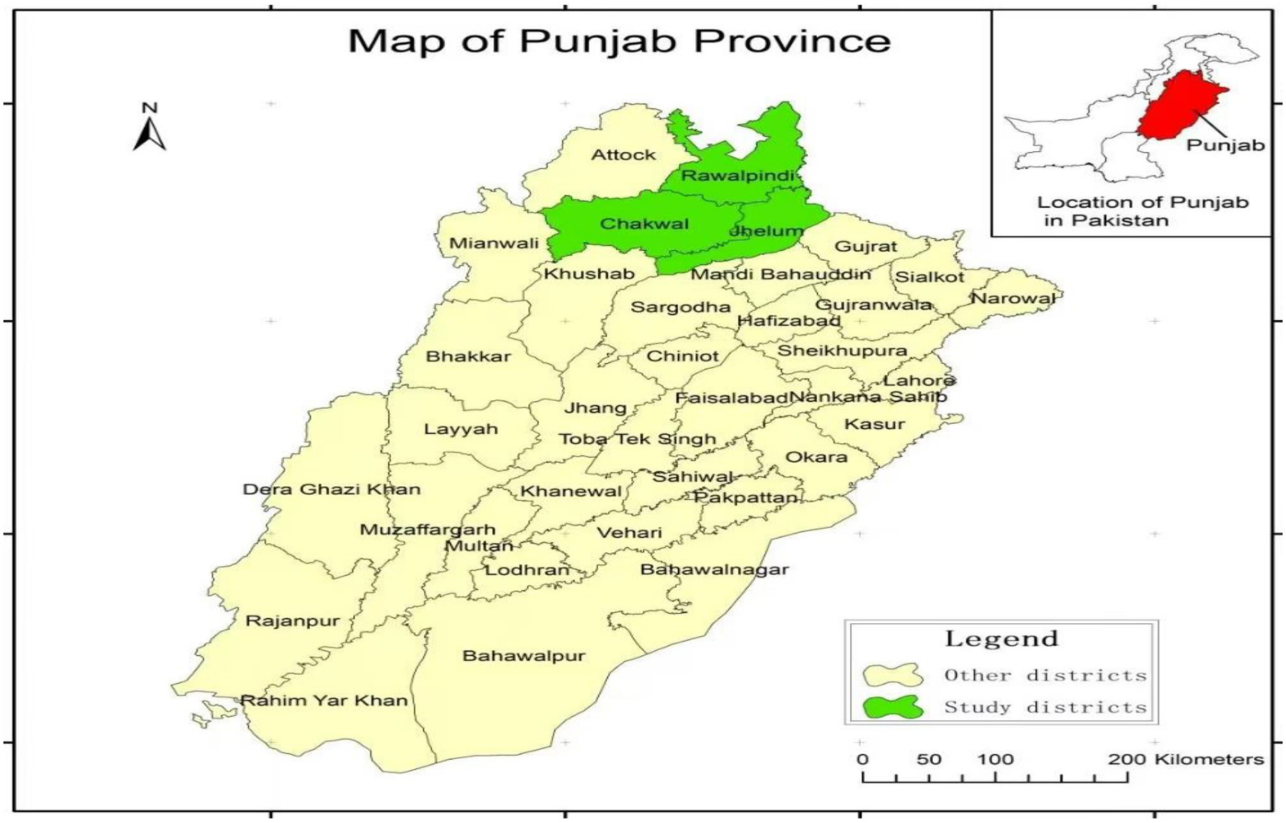

FIGURE 2
Study area.

(1994), stochastic poverty is a significant part of vulnerability and often results when people rely on agriculture that is highly susceptible to weather, has underdeveloped banking systems, and lacks adequate social support. Based on empirical evidence, this study operationalized the dummy variable as 1, signifying a farmer expected to suffer from a poverty incident, and 0 = otherwise. Based on a literature review (Lass et al., 1991; Beyene, 2008; Babatunde, 2015; Iqbal et al., 2015), the determinants of non-farm income diversification were characterized as farmers, farm level, and institutional and environmental characteristics (see Table 1 for definitions). Based on the literature review (Bhutto and Bazmi, 2007; Baig et al., 2013; Usman et al., 2016; Jabbar et al., 2020; Nawab et al., 2021) and local context, we chose three SWC technologies, namely bund making (BM), drip irrigation (DI), and improved varieties, being practiced in the study region. Drip irrigation is an agricultural water technology that uses a systematic network of pipes and tubes to give controlled water flow. It is an effective system supported by government and non-government channels to handle constrained water resources effectively (Usman et al., 2016). DI is taken as a dummy variable with 1 = drip irrigation adoption and 0 = otherwise. Bund making is used to conserve soil moisture and minimize soil erosion. This technique is quite useful in saving water and restoring soil productivity. Contour trenching, terracing, crib structures, stone check dams, etc. are the common forms of bund making (BM) (Pathak et al., 1989). BM is taken as the dummy variable with 1 = if the farmer applies bund making and 0 = otherwise. Improved varieties are considered resistant to heat and droughts and better suited to the warmer and drier climate, with the potential to counterbalance the yield losses linked to climate change (Jabbar et al., 2022).

2.3. PSM for the impact of non-farm income diversification on adopting SWC and poverty

This study employs a random utility framework conferring that farmers would diversify in case of utility gain is positive. Hence, farmers would likely diversify their income portfolio if $U_j^* = U_{DJ} - U_{NDJ} > 0$, whereas U_{DJ} and U_{NDJ} are the utilities for non-farm diversification and non-diversification, correspondingly. Consider y_{i1} is the outcome for the non-farm participants, while y_{i0} is for non-participants. Likewise, Smith and Todd (2001), the effect of non-farm diversification can be expressed as follows:

$$\Delta Y = Y_{i1} - Y_{i0} \tag{1}$$

TABLE 1 Descriptive statistics and definition of the variables.

Variable	Description	Mean	Std. Dev
Outcome variables			
Food consumption	Log food consumption expenditures per capita	9.764	0.270
Vulnerability	Vulnerability to consumption related poverty (1 = yes; 0 = no)	0.539	0.498
Drip irrigation	Household applies drip irrigation (1 = yes; 0 = no)	0.224	0.483
Bund making	Household applies bund making (1 = yes; 0 = no)	0.528	0.447
Improved varieties	Household applies improved variety (1 = yes; 0 = no)	0.511	0.403
Treatment variable			
Non-farm income diversification	Participates in non-farm income diversification activities (1 = yes; 0 = no)	0.412	0.481
Independent variables			
Farmer characteristics			
Age	Age number of years	44.756	13.436
Gender	Household head is male (1 = yes; 0 = no)	0.820	0.384
Family size	Total number of family members	5.790	3.444
Education	Years of education	2.788	1.675
Urban linkage	Household having relatives or friends living in the urban area (1 = yes; 0 = no)	0.548	0.498
Farm characteristics			
Farmland	Land under cultivation, acres	3.216	2.173
Farmer ownership	Household owns the land (1 = yes; 0 = no)	0.753	0.431
Cattle ownership	Household owns cattle (1 = yes; 0 = no)	0.482	0.500
Town-to-land distance	Kilometers from home location to town	3.003	2.183
Institutional factors			
Extension access	Household has access to extension services (1 = yes; 0 = no)	0.460	0.498
Organizational membership	Household has membership in farmer-based organization (1 = yes; 0 = no)	0.195	0.397
Credit access	Household has access to credit (1 = yes; 0 = no)	0.562	0.496
Environmental factors			
Risk perception of untimely rains	Household perceives risk of untimely rains (1 = yes; 0 = no)	0.656	0.475
Risk perception drought	Household perceives risk of droughts (1 = yes; 0 = no)	0.366	0.482

ΔY denotes the impact of non-farm diversification for the sampled farmers. The mean difference in equation 1 is only possible if the farmer simultaneously engages in treatment and control groups. Nonetheless, as the farmer can only be involved in one group, measuring the treatment effect on non-farm participants has severe limitations. This study applied the propensity score matching (PSM) as we are interested in calculating both marginal and average treatment on treated (ATT) effects to provide an accurate understanding. The study operationalized the propensity score matching (PSM) approach to compare the outcomes of non-farm income diversification ("treated") and non-diversification ("controlled") alike in observable characteristics, hence avoiding the bias which may arise when the groups are methodically diverse (Dehejia and Wahba, 2002). It encompasses two stages; in the first stage Eq. (2), we generate the propensity score for participating in non-farm diversification activities. In the second stage, the average treatment on treated is calculated as in Eq. (3).

$$Pr(x_1) = Pr\,(P_1 = 1|Z_1) = E\,(P_1|Z_1)\,, \tag{2}$$

where $P_1 = \{0, 1\}$ is an indicator of choosing to participate in off-farm work (j=1), while Z_1 is the vector of pre-choice characteristics.

$$ATT = E_{p(z_1)|D_1=1}\{E[(Y_1|D_1=1, P\,(Z_1)] - [(Y_0|D_1=1, P\,(Z_1)]\}\,. \tag{3}$$

This study employed kernel-based matching (KBM), nearest-neighbor matching (NNM), and radius-based methods to estimate

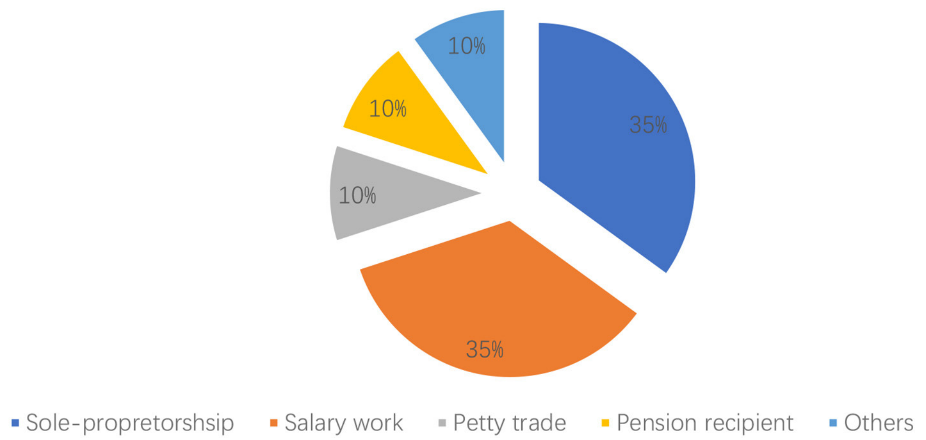

FIGURE 3
Share of different non-farm activities.

the treatment effects on the treated. To further corroborate the findings from the PSM estimations, the study conducts the covariate balancing test. A balancing test is conducted to check whether households with similar propensity scores share parallel characteristics independent of treatment assignment (non-farm diversification).

3. Results

3.1. Descriptive statistics

Table 1 shows the descriptive statistics with food consumption expenditure per capita (ln) was 9.764. Sole proprietorship (Figure 3) was the most employed non-farm activity in the study region, whereas few respondents were engaged in more than one activity. To sum it up, the study found that approximately 42% of households were involved in a non-farming activity.

The average age in this study was 44 years, the average household size was 5.7 people per house, and the average education years was 2.788, indicating that most could read and write. Nearly 32% of the farmers adopted DI and 52% practiced BM. The average farm size was 3.21 acres, and nearly 56% of the farmers had accessed credit in the past 12 months, while 46% received any agricultural advisory during the past year. The average distance from the village to the town was 3 kilometers.

Table 2 highlights a significant difference in means among diversified and non-diversified considering urban linkage, credit access, extension access, organizational membership, and risk perception about drought. The summary statistics suggest that the off-farm participants are younger, affluent, educated, and have better access to social networks than the non-participants.

3.2. Determinants of non-farm income diversification

This study explores the effects of non-farm income diversification on adopting SWC technologies into farming and household poverty. We employed propensity score matching (PSM) to fulfill the research objectives. In the first stage, the PSM model estimates the determinants of non-farm income diversification, and furthermore, the treatment effects determine the impact of non-farm income diversification on poverty. The test statistics in Table 3 show that the LR chi-squared values for non-farm income diversification are positive; moreover, the probability of chi-squared was reported at the 0.000 level. Likewise, the pseudo-R^2 value was also acceptable and showed significant variation. We categorized determinants based on empirical evidence (Lass et al., 1991; Beyene, 2008; Babatunde, 2015; Iqbal et al., 2015), non-farm participation as a farmer, farm, and institutional and environmental characteristics. Since parameter coefficients do not explain regression estimate magnitudes, we used the marginal effect to describe the results. The results suggest that gender and urban linkage positively influence the decision to participate in non-farm activities. The findings revealed that the farmers with some relative or connection outside the district are 12.5% more likely to participate in diversification activities than others with no external link, whereas livestock ownership is inversely related to non-farm income diversification decisions. The coefficient of cattle ownership is negative, showing that farmers with livestock ownership are 2.5% less likely to participate in off-farm activities. Institutional factors such as extension access and organizational membership also significantly and positively determine non-farm income decisions, while climate change risk perception also influences farmers' decisions to engage in non-farm income diversification.

3.3. Impact of non-farm income diversification on SWC adoption and poverty

The mean analysis ignores other factors that may composite the impact of non-farm activities on the outcome. Hence, considering this drawback, we carefully employed comprehensive econometric models to categorize the causal effects of non-farm

TABLE 2 Difference of characteristics for diversified and non-diversified farmers.

	Non–diversified	Diversified	t–test
Outcome variables			
Drip irrigation	0.240	0.491	−5.531***
Bund making	0.280	0.532	−5.531***
Improved varieties	0.443	0.648	−4.313***
Vulnerability	0.599	0.456	2.988**
Log food consumption expenditure (Rs)	9.723	9.824	−3.843***
Independent variables			
Farmer characteristics			
Age	44.61	44.95	−0.261
Gender	0.796	0.836	−1.070
Family size	2.747	2.846	−0.610
Education	5.626	6.021	−1.185
Urban linkage	0.490	0.631	−2.959**
Farm characteristics			
Farmland	3.322	3.065	0.512
Cattle ownership	0.517	0.434	1.725**
Farm ownership	0.754	0.752	0.050
Town-to-land distance	3.063	2.920	0.676
Institutional factors			
Extension access	0.369	0.587	−4.618***
Organizational membership	0.173	0.368	−4.200***
Credit access	0.342	0.401	−1.256
Environmental factors			
Risk perception of untimely rains	0.556	0.571	−0.311
Risk perception of droughts	0.626	0.697	−1.551*

***, **, and * indicate significance at $p \leq 0.005$, $p \leq 0.05$, and $p \leq 0.1$, respectively.

income diversification on SWC adoption and household poverty. Based on propensity score predictions for both diversified and non-diversified groups, the study conducted a diagnostic test to determine the validity of the matching procedure for deciding how income diversification influences the outcome. Figure 4 and Table 4 illustrate the covariate balancing test and the assumption of a common support condition, respectively. The distribution of the propensity scores is depicted in the PSM graph.

The propensity score is well spread, ranging from nearly zero (0.026) to one (0.955), with an overall mean and standard deviation of 0.414 and 0.244, respectively. Figure 4 illustrates that

TABLE 3 Probit model estimates for non-farm income diversification.

	Coefficient	Margins
Age	0.006 (0.008)	0.001
Gender	0.911* (0.495)	0.031
Family size	0.049 (0.067)	0.009
Education	0.035 (0.033)	0.006
Urban linkage	0.687** (0.241)	0.125
Farmland	0.005 (0.022)	0.001
Farm ownership	−0.032 (0.261)	−0.005
Cattle ownership	−0.684** (0.242)	−0.025
Town-to-land distance	−0.080 (0.057)	−0.014
Extension access	1.144*** (0.246)	0.209
Organizational membership	2.428*** (0.326)	0.444
Credit access	−0.003 (0.229)	−0.000
Risk perception of untimely rains	0.371 (0.247)	0.068
Risk perception of drought	0.764*** (0.248)	0.140
Constant	−2.231*** (0.685)	
LR x^2	116.08***	
***Pseudo*−R**^{2}	0.294	
Log-likelihood	−239.811	

***, **, and * indicate significance at $p \leq 0.001$, $p \leq 0.05$, and $p \leq 0.1$, respectively.

the propensity scores for participants and non-participants are identical, indicating that the common support condition is fulfilled. Furthermore, a balance test was also performed in Table 4 to ensure equality across the covariates showing mean factors do not statistically differ; hence, off-farm participants and non-participant farmers share the same characteristics.

Table 5 findings show that after matching, the standardized mean covariate variance dropped from 30.7 to 9.1% leading to a cumulative reduction in the bias of about 70.9%, and the standardized mean is not larger than 5% after matching, as suggested by Rosenbaum and Rubin (1983).

Using three different PSM algorithms, Table 6 displays the impact of non-farm income diversification on poverty and adopting SWC practices. The findings showed that non-farm diversification enhances household consumption per capita by 0.22, 0.19, and 0.18, respectively. Farmers with non-farm involvement were less vulnerable to poverty as the vulnerability was decreased by 13–18% due to non-farm work. Likewise, Martin and Lorenzen (2016) found that non-farm participation in rural areas increases wealth accumulation and improves the financial situation of farmers.

Furthermore, the adoption of SWC practices was positively influenced by non-farm diversification. Accordingly, farmers with non-farm participation were 0.22 to 0.23 more likely to adopt DI, 0.23 to 31 more likely to adopt improved varieties, and 0.22 to 0.23 more likely to adopt BM.

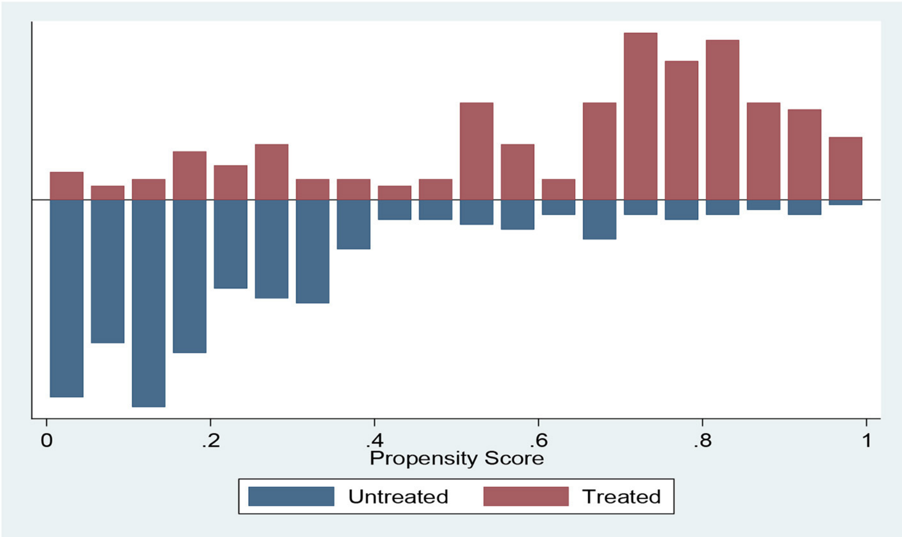

FIGURE 4
Propensity score distribution by non-farm income diversification.

TABLE 4 Test of equality of means of each variable before and after matching.

Variables	Unmatched			Matched		
	Diversified	Non-diversified	*t*-test	Diversified	Non-diversified	*t*–test
Age	44.956	44.615	0.26	44.768	47.659	−2.02*
Gender	0.796	0.836	−1.07	0.801	0.751	1.14
Family size	2.846	2.747	0.61	2.850	2.856	−0.03
Education	6.022	5.626	1.19	6.055	6.234	−0.52
Urban linkage	0.631	0.490	2.96**	0.635	0.646	−0.21
Farm size	3.065	3.323	−0.51	3.071	3.359	−0.50
Farm ownership	0.752	0.754	−0.05	0.751	0.784	−0.75
Cattle ownership	0.434	0.517	−1.73*	0.436	0.441	−0.10
Town–to–land distance	2.920	3.063	−0.68	2.934	2.861	0.35
Extension access	0.587	0.369	4.62***	0.585	0.565	0.38
Organizational membership	0.368	0.073	8.20**	0.364	0.314	1.00
Credit access	0.571	0.556	0.31	0.569	0.505	1.21
Risk perception of untimely rains	0.697	0.626	1.55	0.696	0.735	−0.82
Risk perception of drought	0.401	0.342	1.26**	0.397	0.478	−1.54

***, **, and * indicate significance at $p \leq 0.001$, $p \leq 0.05$, and $p \leq 0.1$, respectively.

4. Discussion

Considering the nation's culture and norms, the gender of the household head is significantly and directly related to participation in non-farm income diversification strategies. The findings seem validated, considering the traditional role of the household head in decision-making in such countries. Likewise, Amare and Belaineh (2013) supported the significant and positive role of gender in determining participation in non-farm income diversification strategies.

Among the farmer's characteristics, the findings revealed that the farmers with some relative or connection outside are more likely to participate in income diversification activities. The network outside the district facilitates their mobility and communication with other groups, enhancing their capacity to trade and employment opportunities better. Multiple studies support the influential role of networks in promoting trade and employment opportunities (Nagoda and Eriksen, 2014). The results are consistent with the study findings by Gautam and Andersen (2016), which also support external linkage's positive and significant role in off-farm decisions.

On the other hand, cattle ownership is negatively related to participation in non-farm income diversification activities. This is because managing livestock requires time and labor, leaving little space to work off-farm. Likewise, Kousar and Abdulai (2015) reported a negative relationship between livestock ownership and non-farm income diversification.

The farmer-based organizational membership (FBOs) significantly determined farmer engagement with non-farm income diversification. Membership in any organization will improve access to social capital and polish entrepreneurship skills. Organizational membership has been observed as an essential means to minimize the financial constraints among rural and urban communities (Yebisi, 2014). The farmer-based organizations provide a social platform where the stakeholders come together to solve their social and economic problems. Through these associations, individuals pool their financial and social resources, thus providing the resources required to fulfill their investment, production, and consumption needs. Likewise, Ritossa and Bulgacov (2009) supported the positive impact of organizational membership on non-farm income diversification decisions. The access to extension services significantly and positively determined the farmer's decision to diversify their income sources. Modern extension services help farmers expand their income sources, specifically in countries like Pakistan, where most farmers depend on the weather for the water demand of crops. Likewise, Danso-Abbeam et al. (2020) also found a significant and positive relationship between extension access and non-farm income diversification decisions.

The results indicate the existence of direct linkages between farmers' risk perception of drought and non-farm participation decisions. The increase in climatic uncertainties remains a significant factor in technology adoption decisions. Our results reflect that extreme climatic events may raise water scarcity and moisture loss issues, ultimately affecting farm output. Hence, non-farm income diversification is a risk mitigation strategy to offset the income losses from climate change. Likewise, Ullah and Shivakoti (2014) highlighted the mitigating risk potential of off-farm diversification against environmental hazards.

The findings highlighted the significance of non-farm income diversification in elevating the adoption of SWC practices. As explained earlier, soil and water conservation practices involve extensive labor and capital. In comparison, non-farm diversification generates an extra income stream that stabilizes the smallholders' economic situation. Hence, in such cases, the additional income can be used to adopt SWC practices or hire additional labor if required. Furthermore, our results indicate that the farmers with off-farm participation are likelier to adopt SWC practices. Likewise, the study by Issahaku and Abdul-Rahaman (2019) showed the positive role of non-farm income in adopting sustainable soil management practices in Ghana.

Smallholders with non-farm participation are food secure and less vulnerable to poverty. Reardon et al. (1992) indicate that the diversification into non-farm activities elevates calorie consumption among the farmers of Burkina Faso. Consequently, Ruben (2001) also reported similar results that showed a strong association between non-farm income and higher food consumption expenditures in Zimbabwe. Furthermore, Scharf and Rahut (2014) suggest that off-farm income effectively improves rural household income. Moreover, Chang et al. (2008) reported that household non-farm income diversification consumes more food than others. Likewise, Issahaku and Abdul-Rahaman (2019) confirmed that households with non-farm work participation are less vulnerable to poverty.

TABLE 5 Overall matching quality indicators pre- and post-matching.

	Unmatched	Matched
Ps R^2	0.196	0.022
LR chi^2	116.93	11.23
p> chi^2	0.000	0.668
Mean Bias	30.7	9.1
Bias reduction		70.9

***, **, and * indicate significance at $p \leq 0.001$, $p \leq 0.05$, and $p \leq 0.1$, respectively.

5. Conclusion

Recent climate uncertainties have endangered the livelihood of the farming community; hence, enhancing income and ensuring the food security of rural communities remain the foremost priority for most developing countries. This study considers the concern by exploring the role of off-farm participation in addressing climate-induced issues and suggests valuable policy insights in the South Asian context. The research employed propensity score matching (PSM) to explore the effects of non-farm

TABLE 6 Effects of non-farm income diversification on SWC adoption and poverty.

Outcome variables	NNM	KM	Radius	
	ATT	ATT	ATT	ATT
Food consumption	0.222 (0.050)**	0.191 (0.037)***	0.186 (0.036)***	0.227 (0.063)**
Vulnerability	−0.138 (0.076)*	−0.181 (0.063)*	−0.180 (0.064)*	−0.122 (0.081)*
Drip irrigation	0.232 (0.071)***	0.223 (0.061)**	0.220 (0.060)**	0.183 (0.084)**
Bund making	0.202 (0.050)***	0.121 (0.040)**	0.111 (0.051)**	0.156 (0.090)**
Improved varieties	0.309 (0.076)***	0.238 (0.064)***	0.231 (0.064)***	0.188 (0.082)**

***, **, and * indicate significance at $p \leq 0.005$, $p \leq 0.05$, and $p \leq 0.1$, respectively.

diversification on SWC adoption and poverty (vulnerability, food consumption). The findings showed that gender, urban linkage, cattle ownership, extension access, organizational membership, and drought risk perception determine farmers' inclination toward non-farm diversification. The results indicate a positive impact of non-farm diversification on SWC adoption. Hence, it can be inferred that non-farm participation generates extra income, which can be used to buy farm inputs and hire labor, thus resolving both cash and labor constraints. These findings imply that farmers with non-farm participation were less vulnerable to poverty and consumed more food. The importance of non-farm participation will likely increase in upcoming years; hence policies and programs (extension access, farmer groups) that aim for environmental restoration must include it. Introducing a well-organized interest-free scheme for sole proprietorship and small-medium enterprise development seems attractive to mobilize and engage human resources. Furthermore, the scheme should prefer women entrepreneurs to eliminate gender biases and patriarchic issues. Female participation may improve the overall rural economy and the welfare of the farming community.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

AJ: conceptualization, data analysis, data description, explanation of results, and writing. LW and JL: data analysis and writing. YW and JP: conceptualization, methodology, explanation of results, reviewing, and editing. JZ and QW: conceptualization, explanation of results, reviewing, and editing. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 27 July 2023
DOI 10.3389/fsufs.2023.1199368

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OPEN ACCESS

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RECEIVED 03 April 2023
ACCEPTED 06 July 2023
PUBLISHED 27 July 2023

CITATION
Baghernejad J, Sabouri MS, Shokati Amghani M and Norozi A (2023) Developing strategies for stabilizing the livelihood of smallholder farmers through non-farm activities: the application of the SWOT-AHP-TOWS analysis.
Front. Sustain. Food Syst. 7:1199368.
10.3389/fsufs.2023.1199368

Developing strategies for stabilizing the livelihood of smallholder farmers through non-farm activities: the application of the SWOT-AHP-TOWS analysis

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Non-farm activities are a means of livelihood stabilization and are regarded as a sustainable approach to bringing balance to the economic, social, cultural, and environmental dimensions of sustainable livelihood. The main purpose of this study was to develop strategies for stabilizing the livelihood of smallholder farmers through non-farm activities using a combined SWOT-AHP-TOWS model. The results of analyzing the strategic space for developing strategies for stabilizing the livelihood of smallholders through non-farm activities revealed that the strengths (0.391) were more than the weaknesses (0.276) in the internal space and that the opportunities (0.195) were more than the threats (0.138) in the external space. Also, it was found that the internal challenges (S + W = 0.667) were more important than the external challenges (O + T = 0.33) in developing livelihood stabilization strategies. Further, the results showed that the beneficial space (O + S = 0.586) dominated the risky space (T + W = 0.414). Eventually, 20 strategies were developed among which the most important ones were "establishing and developing greenhouse cultivation based on the crop patterns considering the relative advantages of the villages" and "establishing microcredit foundations and funds to support the youth in getting involved in rural non-farm businesses." In general, the results can provide new insights into the stabilization of the livelihood of smallholders through non-farm activities.

KEYWORDS

rural livelihood, sustainable livelihood, non-farm activities, SWOT-AHP-TOWS analysis, smallholder agriculture

1. Introduction

Presently, the diminishing power of the agricultural sector and its inability to supply sustainable livelihood is a rural social problem throughout the world because this sector can no longer supply rural livelihood by itself (Bordoloi, 2020; Shabanali Fami et al., 2021). So, to ensure the dynamism of the rural economy, it is unavoidable to provide an alternative to the use of local resources (Shokati Amqani et al., 2016; Black and Cobbinah, 2018). On the other hand, since livelihood in the rural areas of Iran, as with other developing countries, is severely interwoven with the exploitation of environmental resources, we are witnessing a high rate of environmental erosion caused by the excessive burden put on the limited basic production resources and the crisis of the unreasonable agricultural development in some parts (Dehghanipour et al., 2018; Zobeidi et al., 2021). Indeed, data shows that about 70 percent of global freshwater resources are consumed for crop production, although the rate varies in different countries. For example, this rate, whose global average is 71 percent, is as high as about 92 percent in Iran compared to almost 40 percent in the US (Pourkashani, 2022). Similarly, in the economic sense, the share of the agricultural sector in the total global economic loss has reached from 19.2 percent in 2005 to 63.5 percent in 2020 (United Nations Office for Disaster Risk Reduction, 2021). Therefore, an overview of the status of the agricultural sector in recent decades in various dimensions reveals that this sector is growingly struggling with diverse challenges, which are affecting its performance. So, the policymakers of sustainable agricultural and rural development should seek ways to save the agricultural sector from these shocks and challenges (Shokati Amghani et al., 2018; Yazdanpanah et al., 2021). Various research studies have shown that the diversification of rural livelihood with a focus on the development of non-farm activities can be considered by development policymakers and planners as a key solution. Income diversification for rural families is a key approach in that the income of agriculture alone does not suffice for the livelihood of most agricultural families and the income from diverse livelihood sources can be used for the family's welfare and for investment in crop production, which will, in turn, enhance the revenue of the agricultural activities (Bojnec and Knific, 2021; Savari and Moradi, 2022). The social, economic, and environmental developments in recent decades have deeply affected farmers' livelihood strategies, which has, in turn, influenced the agricultural sector profoundly (Savari et al., 2020; Shokati Amghani et al., 2022; Zhu et al., 2022), so farmers obviously have no way but to change to their livelihood strategies (Shivakoti and Schmidt-Vogt, 2008). In the last decades, many farmers in the world have resorted to different income choices to diversify their income sources as a means of avoiding risks, gaining social support, and above all, funding agricultural operations. Indeed, non-farm income generation by farm-holding households has recently turned into a necessary part of their strategies for achieving sustainable livelihood in the turmoil of rapidly evolving demographic and climate changes (Iqbal et al., 2021). Therefore, the agricultural sector is growingly losing its capacity to supply employment and livelihood at the global and regional levels, and the supply of non-farm livelihood must be considered as a supplementary and/or alternative strategy for supplying agricultural livelihood. So, the purpose of this research is developing strategies for stabilizing the livelihood of smallholder farmers through non-farm activities.

2. Literature review

Various studies have addressed the stabilization of smallholders' livelihood through non-farm activities, each covering a part of this phenomenon. This section reviews the research on sustainable livelihood and non-farm activities in Iran and other parts of the world.

Haggblade et al. (2005) argue that the rural non-farm economy plays a fundamental role in structural development processes during which the share of agriculture in national product decreases and the capital and work mobilization acts as an incentive for improving sustainable livelihood. Therefore, we here have a solution by which we can understand many motivational processes of general economic growth and poverty alleviation in least-developed countries.

In their study on livelihood change and sustainable livelihood development in elevated areas of Western Sumatra, Indonesia, Mahdi et al. (2009) sought to analyze livelihood change and endurance of local families in response to changes in natural resources management over the previous decade. The results revealed that low-income people had lower access to capital assets than moderate-income and high-income groups. Nonetheless, access to capital assets had increased over time, and poor families experienced economic improvement and advancement, which reflected the overall increase in economic sustainability. Regarding environmental sustainability, intensive agricultural activities, such as the high rate of pesticide use and intensive tillage in slopped areas, had resulted in soil pollution and erosion.

In a master's thesis at the University of Wageningen, the Netherlands, conducted on farm assets, the features of non-farm activities, and the factors determining Ethiopian smallholders' non-farm activity, Abebe (2012) concluded that the variables of assets, family characteristics, demographic characteristics, time asset and representative cost, cultivation areas, age, gender, and education significantly influenced the participation of the studied communities in three groups of non-farm activities (handicraft, trade, and food/beverage sale) at different significance levels.

Keshavarz and Karami (2012) focused on the stabilization of rural livelihood as a challenge of the agricultural extension system in drought conditions and found that rural families have tried to reduce uncertainty in the agricultural sector by diversifying the household economy, agricultural activities, and social practices, changing living standards, and improving the technical management of agriculture. The regression analysis revealed that the constructs of annual income, governmental facilities received, indemnity received from the crop insurance fund, household head's age, extra-social communications, and the susceptibility of grains were the most important factors accounting for the sustainability of rural livelihood. Therefore, policies in the agricultural sector should allow the optimal use of social functions and human potential in this sector. In this regard, extension institutions and agents can play a key role in achieving these goals by focusing on collective actions and collectivism, empowering, building capacity among rural families, and increasing social participation.

In a study on the diversity of livelihood activities and welfare of rural households in Nigeria, Abimbola and Oluwakemi (2013) proposed the extension and development of non-farm employment as a good supplementary way to increase farmers' incomes, preserve rural balanced growth, and achieve sustainable rural livelihood.

Alavizadeh and Mir Lotfi (2013) investigated the role of the non-farm economy on rural immobility in the rural areas of Semirom County in Fars province, Iran and found that the farmers who were involved in the non-farm sector significantly outperformed the other rural families regarding the studied issues. In other words, these families had higher incomes, more optimal life quality, more satisfaction with life, and a greater tendency to stay in the village.

Sojasi Qeidari et al. (2015) analyzed the entrepreneurial role of non-farm activities in promoting life quality in the rural area of Shandiz District in Beinalud, Iran and reported that the entrepreneurship of non-farm activities had positive and significant effects on the economic, social, and environmental dimensions. The most effective component of the economic dimension was production quality with a beta coefficient of 0.308, the most effective component of the social dimension was access with a beta coefficient of 0.194, and the most effective component of the environmental dimension was the land-use change of fertile lands with a beta coefficient of 0.186. Therefore, the entrepreneurial activities in the region have brought about changes in the life quality of rural people among the studied samples.

In an assessment of the role and place of horticulture-based non-farm activities in diversifying the rural economy in Mahabad County in West Azerbaijan province, Iran, Jami (2016) concluded that the development of these activities had a positive effect on all studied components including employment creation, income diversification, immigration reduction, and the supply of the family's welfare needs. The components of immigration reduction and family welfare had the highest numerical average and the greatest distance from numerical optimality, respectively. Also, the analysis of the correlation between the components of the economic development influenced by the horticulture-based non-farm activities and the welfare of rural families revealed that welfare was most closely correlated with income increase and diversification. In addition, factor analysis revealed that the factor of "job creation and improvement of job opportunities" and the factor of "the improvement of income and investment opportunities" accounted for 31.7 percent of the total variance, reflecting the positive effect of developing horticulture-based non-farm activities on diversifying the rural economy.

Masoumi and Hayati (2016) investigated the orientation of rural development by the entrepreneurial strategy of a non-agricultural economy and concluded that the variables of gender, household's annual farm income, and the number of immigrants from the family had positive and significant effects on the dependent variable and the variable of government facilities received had a negative and significant effect on non-farm activities. The remarkable role of women in non-farm activities reflects the significance of the social and cultural dimensions of these activities. The results revealed that education had no significant effect on the number of non-farm activities. Therefore, it is not necessary to emphasize this variable in efforts to develop non-farm activities.

Asfaw et al. (2017) investigated the factors determining the smallholders' livelihood diversity in Ethiopia and revealed that lack of adequate capital, poor infrastructure, and lack of education were the main limitations hindering farmers from non-farm activities. The regression model showed that several factors dictated the smallholders' willingness to engage in non-farm activities. Families with higher welfare, families with a young and educated head, access to micro-capitals, access to extension services, and social responsibility accounted for the smallholders' participation in non-farm activities. The authors argued that the expansion of agricultural extension services, the supply of micro-capital, the education of entrepreneurship and skills, and the development of infrastructure would increase smallholders' participation in non-farm activities.

In a study on the role of livelihood diversity in the resilience of rural families around Lake Urmia against drought, Heidari-Sareban and Majnouni-Toutakhaneh (2017) reported that the adoption of the livelihood approach has increased the households' resilience to drought around Lake Urmia. Indeed, livelihood was more diverse in villages that were exposed to more severe droughts.

Charaghi et al. (2018) studied the role of non-farm activities in the food security of rural households in the village of Fazl in Neishabur County, Iran and reported that the households' food security increased with increasing non-farm activities. So, diversity in non-farm income sources increases food availability and access and stability in food consumption, which results in food security.

Hajian et al. (2019) addressed the role of diversity in on-farm and non-farm economic activities in the resilience of rural farming families to drought in a case study in Chenaran County and reported that the resilience of the studied households had directly increased by 0.19 through diversity in economic activities and by 0.12 through non-farm diversity. Based on the results, the authors recommended livelihood diversity with an emphasis on the non-farm sector as a strategy for the development of rural areas exposed to drought.

Esmaeili et al. (2019) studied the effectiveness of farm-nonfarm diversity on the life quality of rural people in a case study on the village of Golmakan in Chenaran County and concluded that the diversity of nonfarm economic activities had a significant effect on the variance in the dependent variable (i.e., the life quality of rural people) so that one unit of change in the standard deviation of non-farm activities would cause a 0.6-unit change in the standard deviation of the life quality. The regression model with a standard beta coefficient was as follows: (The diversity in non-farm activities) $(0.6) + (5.795) =$ (the life quality in rural areas). Indeed, there was a linear direct relationship between the diversity in nonfarm economic activities and life quality.

In their study on the role of non-farm employment on the supply of food security among rural families in Colombia, Do et al. (2019) concluded that non-farm employment accounted for about 32 percent of the total annual income of rural households. It was also found that rural families' participation in non-farm activities and non-farm income were significantly influenced by the educational level of the household head, the number of motorcycles and cellphones, the conditions of the rural roads, farm size, the number of income shocks, and the house distance from the closest market.

Rashidin et al. (2020), who investigated the consequences of rural households' non-farm economy for agricultural productivity in Pakistan, conclude that the income source of Pakistani rural households is changing due to the development of modern science and technology and that the nonfarm income is turning into the chief source of sustainable rural livelihood. The results revealed that the availability of banks, communication roads, forests, telecommunication infrastructure, mountainous pastures, and shrub lands influenced nonfarm income. On the other hand, it was found that nonfarm income had a negative effect on *per capita* farm income. But it had a significant positive effect on agricultural productivity.

Han et al. (2021) studied the relationship between the nonfarm rural sector and the income of rural residents in China. According to their results, the nonfarm rural sector had a significant positive effect on the income of rural residents. They proposed that government agencies develop the nonfarm sector based on local conditions. They also asserted that for the long-term rural revival, nonfarm employment should be continuously increased in rural areas in order to improve the income of rural residents.

In a study on the patterns, incentives, and factors influencing nonfarm income diversity among farmer families in Punjab State, Pakistan, Iqbal et al. (2021) concluded that almost 79 percent of the studied farmers participated in nonfarm income-generating activities whereas the income from these sources accounted for almost 15 percent of the total household income. Most respondents were interested in non-farm activities and also investment in self-employment. The main reasons for pursuing non-farm activities included low income of farming, mitigation of agricultural risks, gaining a budget for funding farm operations, and the tendency to increase household income.

Hajian and Ghasemi (2021), who investigated the role of income source diversity on the susceptibility of rural farmer families to drought in a case study in Chenaran County, reported that nonfarm diversity reduced the susceptibility of rural farmer families. The mean susceptibility score of the families with diverse nonfarm income sources was 3.72, whereas it was 3.88 for semi-diverse and 4.18 for non-diverse ones. Also, agricultural diversity had no statistically significant effect on the susceptibility of rural farmer families exposed to drought. Based on the path analysis, nonfarm diversity reduced the susceptibility of the farmer families by −0.23.

Addressing the relationship between the socioeconomic sustainability of rural people and their livelihood diversity, Hosseini et al. (2022) concluded that almost 55 percent of the respondents lacked livelihood diversity and that their socioeconomic sustainability was at a moderate to low and undesirable level. Based on the results of cross-tabulations, there was a positive and significant relationship between their economic sustainability and the likelihood of livelihood diversity among rural people. In addition, the comparison of the mean economic sustainability of those who had livelihood diversity with those who did not show a statistically significant difference at the $p < 0.05$ level. Those who had more diverse jobs and more diverse income sources experienced higher economic sustainability. Finally, the results for the factors underpinning the likelihood of livelihood diversity using the logistic regression test showed that the most important factors included land ownership type, possession of a personal car, and attendance in technical and professional education courses.

In an attempt to design a paradigm for stabilizing the livelihood of orchard owners in the coastal area of Lake Urmia against late spring chilling, Zamzami et al. (2022) found that the causal conditions influencing the paradigm of stabilizing the livelihood of the studied orchard owners against late spring chilling included such categories as management challenges, orchard owners' inability to adapt to climate change, social challenges, lack of participation in decision-making, economic challenges, and lack of infrastructure development. The contextual conditions included categories like equipment and infrastructure factors, specialized human resource, lack of comprehensive and integrated policy-making, lack of coordination in the execution and planning, and economic and cultural factors. Also, production challenges, market management, the need for considering resistant economy programs, the use of regional potential, education-extension factors, and farm smallness constituted the intervening conditions. Eventually, operational and executive, educational and research, economic and livelihood, and managerial strategies were identified to stabilize the livelihood of orchard owners against late spring chilling. In general, stabilizing the livelihood of the orchard owners against late spring chilling would, based on the results, have various ramifications for the target community, including sustainable productivity, the establishment of social justice, livelihood sustainability, sustainable market management, and economic sustainability.

Zhu et al. (2022), who studied agricultural diversity and changes in family livelihood strategies, revealed that farmers who decided not to step away from agricultural livelihood would not make significant changes in their agricultural diversity. Compared to families with an increase in the agricultural diversity index, the families that had a decrease in this index would exhibit more willingness toward livelihood diversity if they were selected for preserving agricultural livelihood in a part-time or full-time manner.

review of the above research shows that each of the researchers has examined different dimensions of sustainable livelihood. Therefore, every researcher has tried to fill the gap in knowledge. The gap in knowledge of rural livelihoods that can be seen here is the discussion of livelihood stabilization, which can be done through different approaches. In this research, one of these approaches is the development of non-farm activities. Based on this, the purpose of this research is to develop strategies for stabilizing the livelihood of smallholder farmers through non-farm activities.

3. Materials and methods

3.1. Study site

The spatial realm of the research includes four provinces in Iran, which have been selected based on the fourfold climatic conditions. Alborz province was selected from the cold climate, Yazd province was selected from the hot and arid climate, Hormozgan province was selected from the hot and humid climate, and Guilan province was selected from the temperate and humid climate.

3.1.1. Guilan province

Guilan is a province in the north of Iran whose capital city is Rasht. This is confined to the Capsian Sea and the Republic of Azerbaijan – with which it has an international borderline in Astara - from the north, Ardabil province from the west, Zanjan and Qazvin provinces from the south, and Mazandaran province from the east. Guilan province has an area of 14,044 km^2 and a population of 2,530,696 people based on the 2016 census. This province is the tenth most crowded province in Iran and the second most crowded province in the north after Mazandaran province. The 2017 and 2020 statistics of rural people's expenses and incomes, the monetary income from non-farm activities in this province increased from 32,043 thousand IRR in 2017 to 46,459 thousand IRR in 2020 (Statistical Centre of Iran, 2022). This shows that the role of non-farm activities in rural income generation has increased in recent years (Figure 1).

3.1.2. Alborz province

Alborz province covers an area of about 5,142 km^2 between the latitudes 35°31′ and 36°21′ N. and the longitudes 50°10′ and 51°30′ E. This province is bordered by Mazandaran province on the north, Tehran province on the east, Markazi province on the southeast, Qazvin province on the west, and Tehran province on the east. Based on the national census of the agricultural sector in 2014, the number of farmers in this province amount to 30,281 who are engaged in

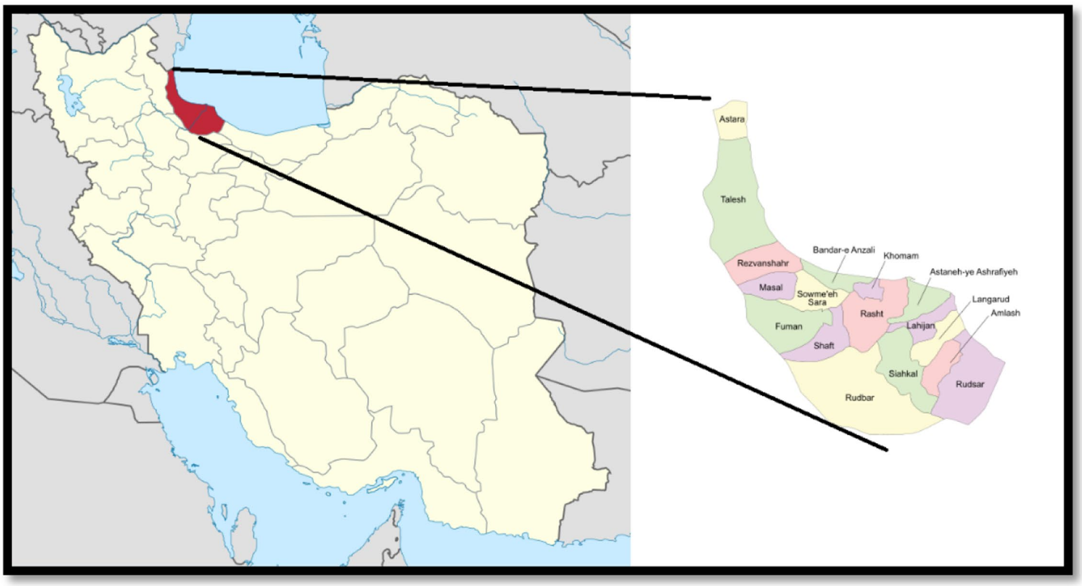

FIGURE 1
The map of Guilan province.

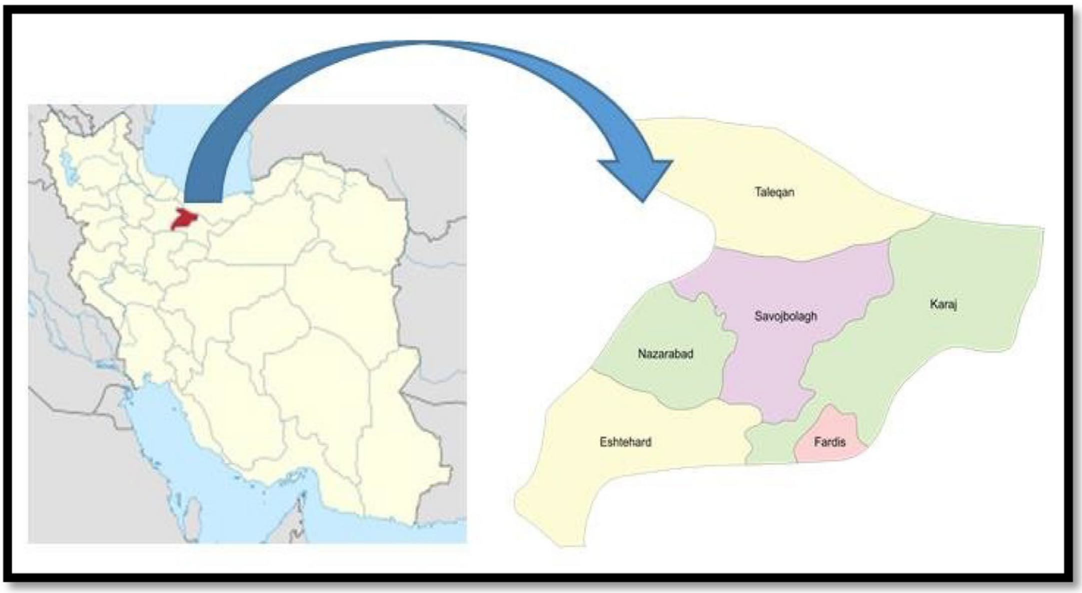

FIGURE 2
The map of Alborz province.

different agricultural sectors. Out of these farmers, 51 percent are residents of the province, whereas 49 percent aren't. Also, 92.4 percent have their own agricultural lands, but 7.6 percent have no land. The statistics of rural families' expenses and incomes in 2017 and 2020 reveal an increase in the monetary income of non-farm activities from 35,234 thousand IRR in 2017 to 95,804 thousand IRR in 2020 (Statistical Center of Iran, 2022), which reflects the promoted role of non-farm activities in rural income generation in recent years (Figure 2).

3.1.3. Yazd province

The capital city of Yazd province is Yazd. The population of this province is 1,138,533 people (340,657 households) based on the 2016 census. Yazd is the water resource-scariest province in Iran due to its arid climate and low precipitation. The main crop production areas are the counties of Khatam and Abarkuh, respectively, where crops like wheat, corn, plum, pomegranate, almond, pistachio, and grapes are produced. They mostly trade their crops with the counties in the north of Fars province. In recent years, many greenhouses have been

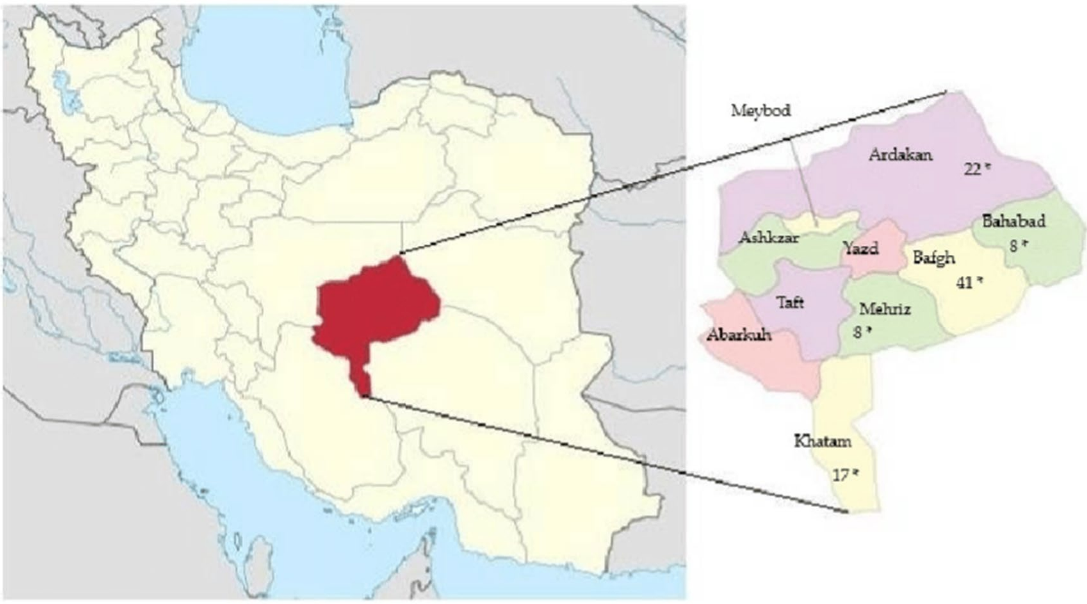

FIGURE 3
The map of Yazd province.

established due to the high return of greenhouse products and the need for managing water scarcity in the Harat region. These greenhouses produce diverse products, e.g., cucumbers, tomatoes, *aloe vera*, and bell peppers. The statistics of rural families' expenses and income in 2017 and 2020 show that the monetary income from non-farm activities has increased from 24,802 thousand IRR in 2017 to 61,351 thousand IRR in 2020 in this province (Statistical Center of Iran, 2022). So, non-farm activities have gained a more significant role in rural income generation in this province in recent years (Figure 3).

3.1.4. Hormozgan province

Hormozgan province is one of the southern provinces in Iran. It is located north of the Strait of Hormuz and is a tourism and economic hub in Iran. Its capital city is Bandar Abbas. Hormozgan province is located between the latitudes 25°24′ and 28°57′ N. and the longitudes 53°41′ and 59°15′ E. The province, which is the 8th largest province of Iran, has an area of about 68,000 km2 (almost as great as Georgia). Hormozgan is bordered by Kerman province on the north and northeast, Fars and Bushehr province on the west and northwest, Sistan and Baluchestan province on the east, and the Persian Gulf and Oman Sea on the south with a coastal line of about 900 km. This province has 13 counties, 39 districts, 88 rural districts, and 50 cities. The statistics of rural families' expenses and income in 2017 and 2020 show that the monetary income from non-farm activities in this province has decreased from 18,378 thousand IRR in 2017 to 12,101 thousand IRR in 2020 (Statistical Center of Iran, 2022). So, non-farm activities have lost their significance in rural income generation in recent years (Figure 4).

3.2. Research design

This research is a quantitative study that is a field study in terms of data collection and a single-sectional study in terms of time horizon. It was conducted in two phases. The strategic status was analyzed in the first phase, and the strategies were developed for stabilizing the livelihood of smallholders through non-farm activities in the second phase. In this phase, multi-criteria decision-making (MCDM) models were used to develop strategies for stabilizing the livelihood of smallholders through non-farm activities. MCDM models are broadly divided into two categories – multi-objective decision-making (MODM) models and multi-attribute decision-making (MADM) models. In general, MODM models are used to design multi-attribute models for the selection of superior alternatives (Opricovic and Tzeng, 2004). The main difference between MODM and MADM models is that the former is defined in a continuous decision-making space while the latter is defined in a discrete decision-making space (Kumar et al., 2017). In this step, the literature was reviewed to identify the internal environment (strengths and weaknesses) and the external environment (opportunities and threats) of the study subject at the study site. Then, the data were analyzed with a combined SWO-AHP-TOWS model. Since informant experts and professionals are usually selected in strategic research studies (Noshad et al., 2018), the statistical population and the research sample were selected out of the relevant experts ($n = 40$) using non-probabilistic purposive sampling (Table 1). They were then interviewed by the SWOT-AHP questionnaire.

3.3. SWOT analysis

The SWOT analysis is an efficient technique to identify internal factors (opportunities and threats) and external factors (opportunities and threats) that influence a subject and analyze the status quo (Gürel and Tat, 2017). The term SWOT stands for four words, i.e., Strengths, Weaknesses, Opportunities, and Threats (Ghazinoory et al., 2011). Weaknesses in the STOW analysis refer to those that stop the performance of an organization at its current level. This part should be improved to sustain competitiveness, but strengths are positive

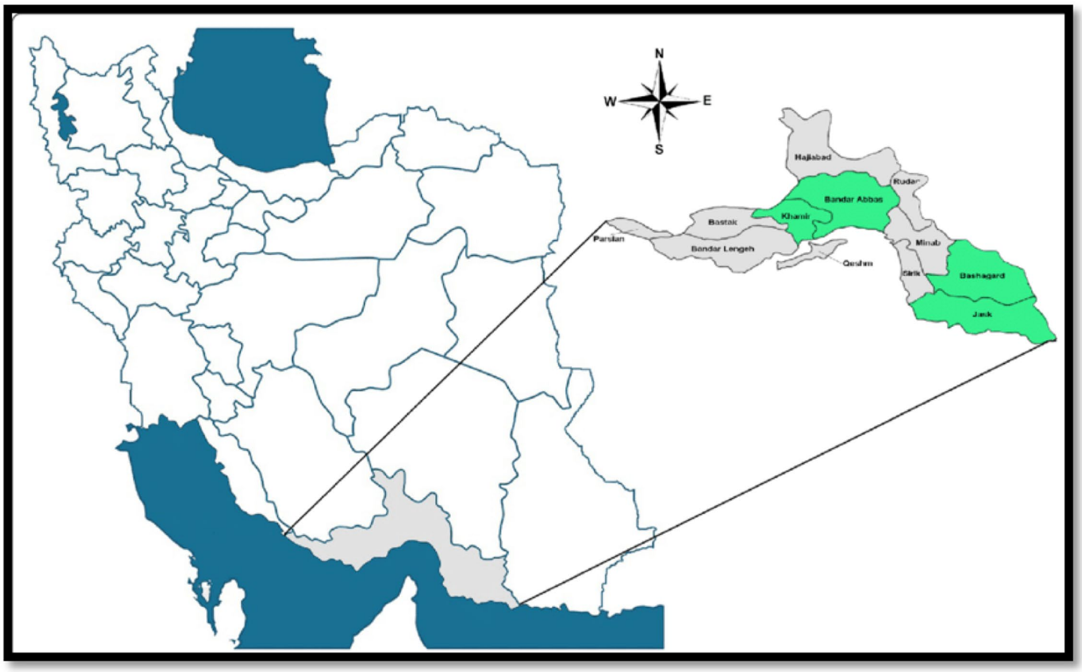

FIGURE 4
The map of Hormozgan province.

TABLE 1 The research samples.

Province	Relevant organization	Frequency	Percentage
Alborz	Agricultural Extension Experts of Agriculture Organization of Alborz Province	5	25
	Experts at the General Office of Cultural Heritage, Tourism, and Handicraft of Alborz Province	5	
Hormozgan	Agricultural Extension Experts of Agriculture Organization of Hormozgan Province	5	25
	Experts at the General Office of Cultural Heritage, Tourism, and Handicraft of Hormozgan Province	5	
Guilan	Agricultural Extension Experts of Agriculture Organization of Guilan Province	5	25
	Experts at the General Office of Cultural Heritage, Tourism, and Handicraft of Guilan Province	5	
Yazd	Agricultural Extension Experts of Agriculture Organization of Yazd Province	5	25
	Experts at the General Office of Cultural Heritage, Tourism, and Handicraft of Yazd Province	5	
Total		40	100

capabilities and features that contribute to the successful achievement of organizational missions (Solangi et al., 2019). Opportunities refer to desirable external factors that can help an organization achieve a competitive advantage, and threats are factors that may be harmful to the organization (Shakerian et al., 2016). In general, the SWOT matrix is a famous instrument to identify the strategic situation and help managers and policymakers in decision-making (Bouraima et al., 2020). Various studies have used this instrument to identify and rank strategies in fields like the formulation of strategies for livelihood stabilization (Gürel and Tat, 2017).

3.4. AHP analysis

In the SWOT model, there is no instrument to determine the importance of the factors or assess the decision-making alternatives in terms of the criteria (Kangas et al., 2003). So, many previous studies have combined SWOT with the Analytic Hierarchy Process (AHP) to tackle this shortage. As shown in Figure 5, the application of this method requires four major actions: (1) Modeling, through which the problem and the purpose of decision-making are derived as a hierarchy of decision elements that are related to each other. Decision elements include "decision indicators" and "decision options." The process of hierarchical analysis requires breaking down a problem with several indicators into a hierarchy of levels. The high level expresses the main goal of the decision-making process. The second level represents the major and basic indicators "which may be broken into sub-criteria and more detailed in the next level). The last level presents the decision options. Figure 5 shows the hierarchy of a decision problem. (2) Making pairwise comparisons between different decision options, based on each criteria and judging the importance of the decision criteria by making pairwise comparisons, after designing the hierarchy of the decision problem, the decision maker should create a set of matrices that are numerically important or to establish the relative preference of the criteria to each other and to measure each decision option according to the criteria compared to other options. This is done by making two-by-two comparisons between the decision elements and by assigning numerical points that indicate the priority or importance between the two decision elements. (3) Determining the weight of "decision elements" relative to each other through a series of numerical calculations. The next step in the process of hierarchical analysis is to perform the necessary calculations to determine the priority of each of the decision elements using the information from the pairwise comparison matrix. (4) Integrating the relative weights in order to rank the decision options, at this stage the relative weight of each element must be multiplied by the weight of the higher elements to obtain its final weight. By performing this step for each option, the final weight value is obtained, and (5) consistency in judgments: approximately all calculations related to the hierarchical analysis process are based on the decision maker's initial judgment, which appears in the form of a pairwise comparison matrix. It takes place and any error and inconsistency in comparing and determining the importance between options and criteria distorts the final result obtained from the calculations. An inconsistency rate is a tool that specifies consistency and shows how much the priorities resulting from the comparisons can be trusted. Experience has shown that if the inconsistency rate is less than 0.10, the consistency of the comparisons is acceptable, and otherwise the comparisons should be revised.

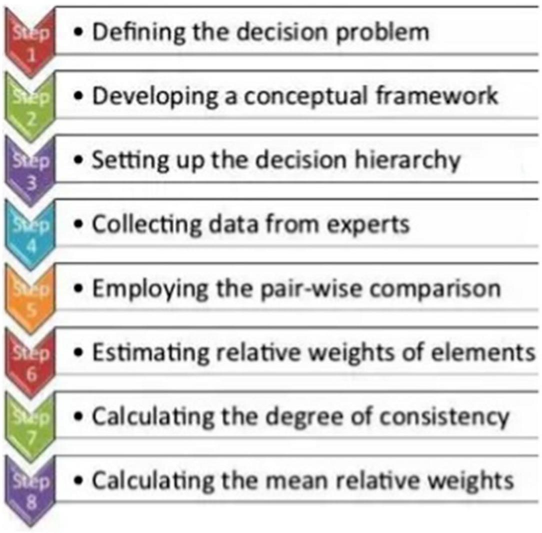

FIGURE 5
AHP Process.

AHP allows pairwise comparison of the factors constituting SWOT and provides a precise estimation of the relative importance of the factors (Kubler et al., 2016). The main instrument in this section was a questionnaire that was designed based on the SWOT-AHP technique. Therefore, AHP was used to assign weights to the SWOT-constituting factors and sub criteria. The hierarchy for this research has been organized into four levels. The primary level, as normal, is the objective to be accomplished by the choice; the following level is constituted by the four bunches of variables as characterized by the SWOT procedure:

Strengths (S), Weaknesses (W), Opportunities (O), and Threats (T); the third level is constituted by the variables included in each one of the four groups of the past level; and at long last, the fourth level is constituted by the strategies that should be evaluated and compared (Haque et al., 2020). A graphical representation of the hierarchy is presented in the Figure 6:

As shown in the Table 2, each of the criteria and sub-criteria was completed through the questionnaire by the studied population, which are Agricultural Extension Experts at the agriculture Organization of Province and Experts at the General Office of Cultural Heritage, Tourism, and Handicraft of Province.

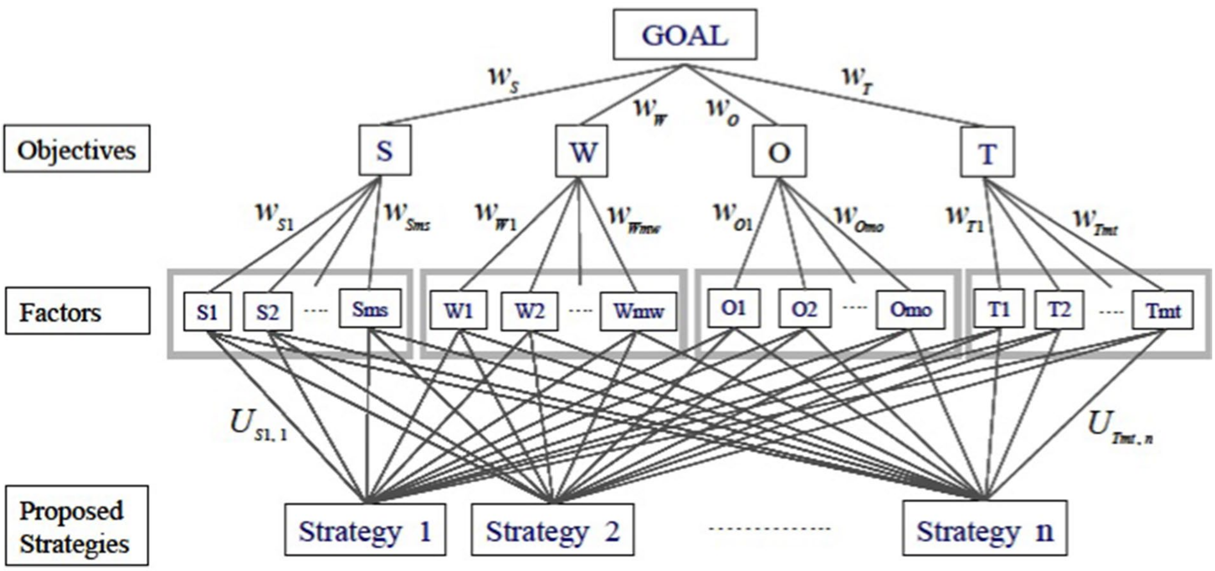

FIGURE 6
The AHP model to select the suitable strategy for stabilizing the livelihood of smallholders through non-farm activities (derived from Osuna and Aranda, 2007).

TABLE 2 AHP Scale.

Raw	Criteria A	Criteria B	Weights (1–9)				
			Equal importance (1)	Moderate importance (3)	Moderate importance (5)	Very strong importance (7)	Very strong importance (9)
1	Strengths	Weaknesses					
2	Strengths	Opportunities					
3	Strengths	Threats					
4	Weaknesses	Opportunities					
5	Weaknesses	Threats					
6	Opportunities	threats					

Data were operationalized in the Expert Choice and Excel software packages. In this step, the weights of the main factors (strengths, weaknesses, opportunities, and threats) were first calculated (RW in Table 3). Then, the weights of the subcriteria were calculated (RP in Table 3). Finally, Eq. (1) was used to rank the subcriteria (TP in Table 3) as follows:

$$\mathrm{TP} = \mathrm{RW} \times \mathrm{RP} \quad (1)$$

In this formula: Relative Weight (RW), Relative Priority (RP) and Total Prioritization (TP).

3.5. TOWS analysis

Although the SWOT analysis provides a clear understanding of the internal and external environment of a phenomenon and specifies the strategic space of the subject, this matrix does not propose a strategy for improving the status quo (Şeker and Özgürler, 2012). The TWOS matrix is an instrument that is usually applied after the SWOT matrix to help propose strategies for improving the present and future status (Gottfried et al., 2018). The TOWS matrix is extensively used to determine strategies for which it relies on strengths, weaknesses, opportunities, and threats (Asadpourian et al., 2020). In the TOWS matrix, the crossing of strengths, weaknesses, opportunities, and threats yields four types of strategies including WT, ST, WO, and SO (Şeker and Özgürler, 2012; Asadpourian et al., 2020).

- SO: All organizations seek ways to maximize their strengths and opportunities simultaneously.
- WO: Adaptive strategies try to take the most advantage of the existing opportunities by reducing the weaknesses.
- ST: These strategies are based on exploiting strengths in coping with threats and aim to maximize strengths and minimize threats.
- WT: These strategies, which can be called “survival” strategies, generally aim to reduce weaknesses in order to reduce or neutralize threats.

Each strategy is usually a mixture of several subcriteria. To calculate the weight of each strategy, the weights of the respective subcriteria should be multiplied. Eq. (2) was considered for calculating the weight of the strategies.

$$\begin{aligned} TWSO2 &= f\left(TPS1,\ S2,\ \ldots\ Sn, / O1,\ O2,\ \ldots,\ On\right) \\ TWSO &= \left(TPS1 \times TPo1\right) + \left(TPS1 \times TPo2\right) + \cdots \\ &\quad + \left(TPS1 \times TPon\right) + \left(TPS2 \times TPo1\right) \\ &\quad + \left(TPS2 \times TPo2\right) + \cdots + \left(TPS2 \times TPon\right) \end{aligned} \quad (2).$$

4. Results

4.1. Identifying the fourfold points of SWOT for the analysis of the status quo

After reviewing the theoretical literature, 16 external points (8 opportunities and 8 threats) and 16 internal points (8 strengths and 8 weaknesses) were identified for formulating strategies for stabilizing the livelihood of smallholders through non-farm activities (Table 4).

4.2. Relative importance of criteria and sub criteria affecting the development of strategies for stabilizing the livelihood of smallholders

To calculate and rank the criteria and sub criteria that affect the development of strategies for stabilizing the livelihood of smallholders, we should first assign weights to the fourfold criteria of SWOT (strengths, weaknesses, opportunities, and threats). Thus, the weights of the SWOT criteria were specified by their pairwise comparison. Based on the results, the strengths and weaknesses whose weights were 0.391 and 0.276, respectively had the greatest impact on the development of strategies for stabilizing the livelihood of smallholders through non-farm activities (Figure 7).

In the next step, the weights of the individual sub criteria in formulating strategies for stabilizing the livelihood of smallholders through non-farm activities were estimated (Table 5). According to the results, the most important factors underpinning the development and formulation of strategies for stabilizing the livelihood of smallholders through non-farm activities included “lower dependence on climate and weather conditions than the agricultural sector” among strengths, “capital-intensiveness of most non-farm businesses” among weaknesses, “the helplessness of the smallholder agriculture sector in supplying rural livelihood” among opportunities, and “lack of expertise of most villagers to get involved in non-farm businesses” among threats.

TABLE 3 The ranking of the sub criteria studied for the development of strategies for stabilizing the livelihood of smallholders.

Criteria	RW	Sub-criteria	RP	TP	IR
Strengths	0.391	S1	0.062	0.024	0.08
		S2	0.335	0.131	
		S3	0.054	0.021	
		S4	0.075	0.029	
		S5	0.213	0.083	
		S6	0.030	0.012	
		S7	0.145	0.057	
		S8	0.085	0.033	
Weaknesses	0.276	W1	0.305	0.084	0.09
		W2	0.122	0.034	
		W3	0.092	0.025	
		W4	0.096	0.026	
		W5	0.042	0.012	
		W6	0.180	0.050	
		W7	0.133	0.037	
		W8	0.030	0.008	
Opportunities	0.195	O1	0.240	0.047	0.07
		O2	0.224	0.044	
		O3	0.123	0.024	
		O4	0.199	0.039	
		O5	0.088	0.017	
		O6	0.054	0.011	
		O7	0.042	0.008	
		O8	0.029	0.006	
Threats	0.138	T1	0.213	0.029	0.09
		T2	0.166	0.023	
		T3	0.086	0.012	
		T4	0.062	0.009	
		T5	0.253	0.035	
		T6	0.054	0.007	
		T7	0.107	0.015	
		T8	0.058	0.008	

4.3. Analysis of the strategic space of the development of strategies for stabilizing the livelihood of smallholders

The results of the analysis of the strategic space of the development of strategies for stabilizing the livelihood of smallholders through non-farm activities revealed that strengths (0.391) were more important than weaknesses (0.276) in the internal environment and that opportunities (0.195) were more important than threats (0.138) in the external environment. Also, it was found that internal challenges (S + W = 0.667) were more important than external challenges (O + T = 0.333) in developing livelihood stabilization strategies. The beneficial environment (O + S = 0.586) was also found to dominate the risky environment (T + W = 0.414) (Table 4; Figure 8).

According to the ranking of the strategic zones, the first strategy is based on ST, i.e., the contingency strategy (max-min). This strategy tries to take advantage of the strengths to cope with the threats. It aims to maximize the strengths for tackling all threats. However, caution should be exercised in this strategy because the improper use of power can have undesirable effects. The second strategy is SO, i.e., the aggressive strategy (max-max) in which the whole system pursues a situation in which it can maximize both its strengths and opportunities. In these conditions, the organization aims to use its strengths for grasping the existing opportunities. The third strategy is based on WT, which is the defensive strategy (min-min). This strategy, which is also called the "survival strategy," is based on reducing the existing weaknesses in order to cope with the threats. Finally, the last strategy is based on WO, i.e., the adaptive strategy (min-max) which tries to reduce weaknesses in order to maximize the use of the existing opportunities. For example, an organization may detect some opportunities in its external environment, but cannot grasp them due to its weaknesses. In these conditions, the adaptive strategy can help take advantage of the opportunities (Figure 9).

TABLE 4 The external and internal factors in the SWOT matrix.

Internal points		External points	
Strengths	**Weaknesses**	**Opportunities**	**Threats**
• Low investment risk in non-farm businesses	• Capital-intensiveness of most non-farm businesses	• The helplessness of the smallholder agriculture sector in supplying rural livelihood	• Inadequacy of infrastructure and public facilities in some villages
• Lower dependence on climate and weather conditions than the agricultural sector	• Lack of career counselors to guide those interested in starting a non-farm business	• High risk of farm activities	• Lack of certain authority for rural development
• The possibility of creating added value in non-farm products	• Incompatibility of some non-farm businesses with the rural environment	• The existence of surplus manpower in the agricultural sector	• Cumbersome bureaucracy and rules for setting up non-farm businesses
• The possibility of developing the production level in non-farm businesses	• Lack of financing of rural non-farm businesses	• The reluctance of the young generation to work in smallholder agriculture	• Lack of support for the private sector to invest in non-farm businesses
• High return on capital in non-farm businesses	• Lack of rural non-farm business plans	• People's growing interest in tourism and the purchase of handicrafts and arts	• Lack of expertise of most villagers to get involved in non-farm businesses
• The ease of non-farm activities compared to farm activities	• Unprecedentedness of rural non-farm businesses	• Development of ICT in villages (access to the Internet in villages)	• International sanctions on the supply of some production inputs
• Higher non-farm income and profit and non-agricultural than farm income	• Hard acceptance of non-farm business by villagers	• Expansion of the use of social networks (Telegram, WhatsApp, and Instagram) in villages	• Lack of a suitable market for selling non-farm products
• The possibility of transferring surplus profits of the non-farm sector to the agricultural sector	• Modernizing and transforming the identity and nature of rural communities	• The possibility of benefiting from incentives related to rural employment creation laws	• The inability of villages to control and deal with epidemic viral diseases (such as the COVID-19)

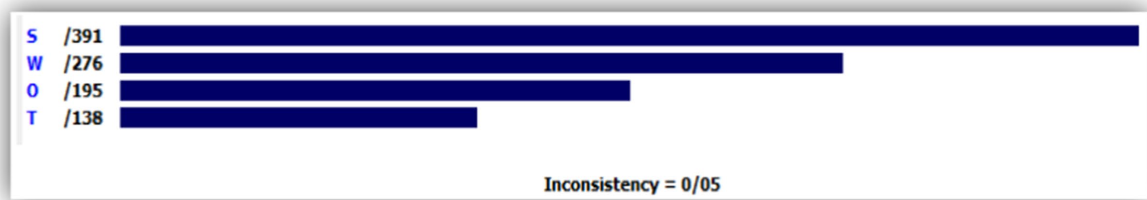

FIGURE 7
The weights of the SWOT criteria.

4.4. Developing and ranking livelihood stabilization strategy using the TOWS matrix

In this step, the strategic TOWS matrix was used to develop strategies for stabilizing the livelihood of smallholders through non-farm activities. The results are presented in Table 5. Accordingly, some strategies were developed for each zone. The result was 20 strategies for stabilizing the livelihood of smallholders through non-farm activities.

Table 6 presents the pairwise comparisons and the final weights of the factors at four strategic levels. It also specifies the sub criteria used in each strategy. According to the results, the most important strategies included "establishing and developing greenhouse cultivation based on the crop patterns considering the relative advantages of the villages" and "establishing microcredit foundations

TABLE 5 The TOWS matrix to determine strategies for formulating smallholders' livelihood stabilization strategies.

TOWS matrix	Opportunities (O)	Threats (T)
	(O1) The helplessness of the smallholder agriculture sector in supplying rural livelihood(O2) High risk of farm activities(O3) The existence of surplus manpower in the agricultural sector(O4) The reluctance of the young generation to work in smallholder agriculture(O5) People's growing interest in tourism and the purchase of handicrafts and arts(O6) Development of ICT in villages (access to the Internet in villages)(O7) Expansion of the use of social networks (Telegram, WhatsApp, and Instagram) in villages(O8) The possibility of benefiting from incentives related to rural employment creation laws	(T1) Inadequacy of infrastructure and public facilities in some villages(T2) Lack of certain authority for rural development(T3) Cumbersome bureaucracy and rules for setting up non-farm businesses(T4) Lack of support for the private sector to invest in non-farm businesses(T5) Lack of expertise of most villagers to get involved in non-farm businesses(T6) International sanctions on the supply of some production inputs(T7) Lack of a suitable market for selling non-farm products(T8) The inability of villages to control and deal with epidemic viral diseases (such as the COVID-19)
Strengths (S)	Aggressive strategies (SO)	Competitive strategies (ST)
(S1) Low investment risk in non-farm businesses(S2) Lower dependence on climate and weather conditions than the agricultural sector(S3) The possibility of creating added value in non-farm products(S4) The possibility of developing the production level in non-farm businesses(S5) High return on capital in non-farm businesses(S6) The ease of non-farm activities compared to farm activities(S7) Higher non-farm income and profit and non-agricultural than farm income(S8) The possibility of transferring surplus profits of the non-farm sector to the agricultural sector	(SO1) Involving rural people in rural employment creation programs(SO2) Identifying farmers who are susceptible to climate change and supporting them in launching and developing rural non-farm businesses as an alternative source of livelihood(SO3) Establishing microcredit foundations and funds to support the youth in getting involved in rural non-farm businesses(SO4) Using the capacity of social networks in marketing rural farm and non-farm products(SO5) Establishing and developing greenhouse cultivation based on the crop patterns considering the relative advantages of the villages	(ST1) Launching an non-farm extension sector along with the agricultural sector in the Organization of Agriculture and the Organization of Cultural Heritage, Tourism, and Handcraft(ST2) Holding specific skill training courses for non-farm businesses and agricultural processing industries in rural areas(ST3) Founding an organization for rural development for the optimal planning of all non-farm affairs in rural areas(ST4) Providing incentives for the return of rural immigrants for employment in the rural non-farm sector(ST5) Improving and developing infrastructure and general facilities in villages for facilitating the involvement of investors in rural non-farm entrepreneurship
Weaknesses (W)	Conservative strategies (WO)	Defensive strategies (WT)
(W1) Capital-intensiveness of most non-farm businesses(W2) Lack of career counselors to guide those interested in starting a non-farm business(W3) Incompatibility of some non-farm businesses with the rural environment(W4) Lack of financing of rural non-farm businesses(W5) Lack of rural non-farm business plans(W6) Unprecedentedness of rural non-farm businesses(W7) Hard acceptance of non-farm business by villagers(W8) Modernizing and transforming the identity and nature of rural communities	(WO1) Identifying the potential and *de facto* capacities of rural areas for creating and developing rural non-farm businesses(WO2) Supporting the development of processing industries considering the relative advantage of each region to prevent rural immigration(WO3) Providing low-interest loans and facilities to farmers in order to launch and develop non-farm businesses(WO4) Formulating and localizing non-farm business plans based on the environmental, social, economic, and cultural conditions of the village(WO5) Holding specific site visits to observe live on-farm and non-farm activities in rural areas	(WT1) Establishing a suitable organizational system for operationalizing smallholders' livelihood through non-farm activities using the regional infrastructure(WT2) Founding knowledge-intensive enterprising and using the graduates of different disciplines to provide consultation services to the rural people in order to grasp non-farm entrepreneurial opportunities in the region(WT3) Launching specific markets for rural handcraft in urban areas(WT4) Facilitating the process of issuing work permits for rural non-farm businesses

and funds to support the youth in getting involved in rural non-farm businesses," and the weakest ones included "facilitating the process of issuing work permits for rural non-farm businesses" and "improving and developing infrastructure and general facilities in villages for facilitating the involvement of investors in rural non-farm entrepreneurship."

5. Discussion

While some researchers (e.g., Markakis, 2004; Kinuthia and Wahome, 2019) argue that livelihood that is based on traditional farming and ranching is being ruined, others (e.g., Freier et al., 2012; Dehghanipour et al., 2018; Su et al., 2019; Savari et al., 2022) have investigated the reasons for the susceptibility of livelihood to external disruptions such as climate change and suggested that households are capable enough of achieving sustainable livelihood by the sound use of their capitals and the adoption of a suitable livelihood strategy (Savari and Shokati Amghani, 2019). Therefore, to retain the sustainability of their livelihood over time, households select their livelihood based on a combination of their capital (Jiao et al., 2017; Rockenbauch et al., 2019; Zhang and Fang, 2020).

It is worth noting that so far various strategies have been proposed for the supply of sustainable livelihood at the international level. A famous example is the formation of the Committee on Sustainable Development Goals by 193 UN member states in 2015, which aims to eradicate poverty from the world (Fritz et al., 2009; Christiaensen et al., 2013). There are, however, diverse barriers to achieving sustainable livelihood, which prevent the stabilization of

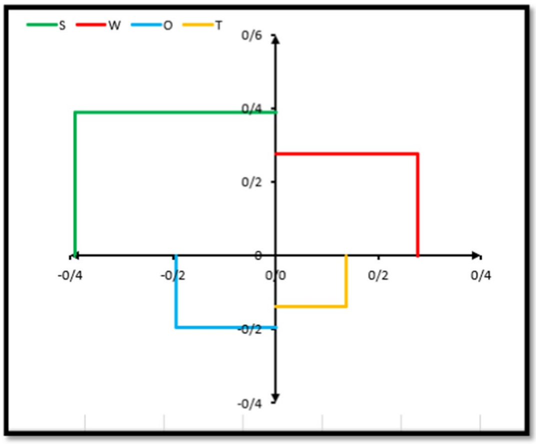

FIGURE 8
The status of the fourfold points of SWOT.

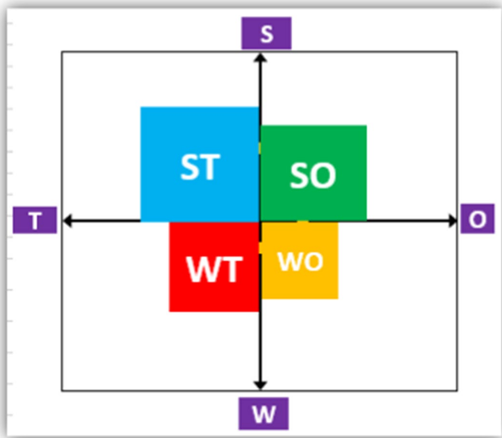

FIGURE 9
The analysis of the strategy space.

farmers' livelihood. An example is the seasonality of farm activities, making farmers dependent on seasonal and atmospheric changes, which is a big challenge to supplying their livelihood. In this respect, non-farm activities will be the most suitable complementary or alternative strategy (Abdollahzadeh et al., 2016). Also, the extensive climate change of recent decades has exposed the agricultural sector to multiple challenges, such as global warming, landslides, land subsidence, natural disasters like floods, fires, forest and pasture fires, drought, the invasion of plant diseases and pests like grasshoppers, and the salinization of groundwater resources and soils (World Bank, 2021; Savari et al., 2023a,b). Indeed, Iranian researchers have projected that the annual mean temperature in different parts of Iran will increase by 3.5–4.5°C whereas the mean annual precipitation will decrease by 7–14% by 2051. These changes will also be more extreme as one moves from the west to the east and from the north to the south. The temperature rise extends the agricultural growing season due to the increase in the number of frost-free days. The decline in precipitation will also increase dry season duration in a range from about 20 days in the western regions to over 30 days in the southern regions, which is of higher importance in rainfed cultivation areas. The temperature rise will also increase annual potential evapotranspiration by 18–30% by 2051. This will widen the difference between the precipitation rate and potential evapotranspiration, i.e., the precipitation shortage index, which will be mainly related to the increase in evapotranspiration (Koocheki et al., 2015). Considering the serious threats of water scarcity, drought has drawn scientists' attention in recent decades. Research around the world shows that this crisis has already started in China, Africa, India, Thailand, Mexico, Egypt, and Iran and the major rivers of the world including the Nile in Egypt, the Ganges in South Asia, the Yellow River in China, and the Colorado River in the US have seriously been threatened. Even, the water reserves of the 11 main rivers of the UK have decreased to one-third (Wines, 2014). In addition to the water loss of the rivers, the water resources of numerous lakes and inland and outland wetlands have already been dried completely or depleted severely. Examples include Lake Urmia, Bakhtegan Lake, Arzhan Lake, Tashk Lake, Parishan Lake, and Hamun Wetland in Iran, Poopó Lake in Bolivia, Colorado Lake in the US, the Aral Sea on the borderline of Kazakhstan and Uzbekistan, Lake Powell, Lake Chad, and many others, which have now no water, deeply challenging the life of humans, animals, and plants and consequently jeopardizing the supply of sustainable livelihood for local people (Lak et al., 2011). Accordingly, climate change is one of the most fundamental challenges of human communities, in addition to its effect on people's livelihoods. Drought, as one of the most important and costly climatic phenomena, has affected the livelihood of rural households by imposing more economic and social harms in arid regions (Nasrnia and Ashktorab, 2021). On the other hand, the partial and overall productivity of the agricultural sector has diminished and it cannot adapt to technological developments either because of the loss of agricultural lands due to land-use changes and the fragmentation of agricultural fields. So, the burden on the agricultural sector should be reduced by transferring surplus farmers to the industrial sector. In this regard, FAO statistics show that the agricultural land area has decreased from 1961 to 2019 (FAOSTAT, 2021). The data of the International Labor Organization regarding the share of the agricultural sector in total employment at the international level also reveals the fact that this sector is no longer capable of supplying the livelihood of the target community due to the challenges in exploiting basic production resources. Indeed, the share of this sector in global employment has decreased from 40% in 2000 to 28% in 2020 (ILOSTAT, 2021). Similarly, the agricultural sector has been the only sector with a negative growth rate (−3.9) in Iran based on a report of the national economic growth rate in the 9 months of 2021 provided by the Statistical Center of Iran. Unlike the agricultural sector, we are witnessing 7.1 and 5.1% economic growth rates in the industrial and service sectors, respectively, reflecting potential investment opportunities in these sectors at the national and rural levels (Statistical Center of Iran, 2022).

This research pursued two general objectives: (1) examining the status of the strategic environment of sustainable livelihood of smallholders through non-farm activities and (2) developing strategies for sustainable livelihood of smallholders through non-farm activities. So, the results can help countries that face the

TABLE 6 The ranking of the strategies for stabilizing the livelihood of smallholders through non-farm activities.

Strategies	Sub-criteria used for each strategy	TW	Rank
SO5	S1, S2, S3, S4, S5, S7, S8, O1, O2, O3, O4, O6, O7, O8	0.067	1
SO3	S1, S2, S3, S4, S5, S7, S8, O1, O2, O3, O4, O5, O8	0.064	2
SO1	S1, S2, S3, S4, S5, S6, S7, S8, O1, O2, O3, O4, O5, O8	0.060	3
SO2	S1, S2, S3, S4, S5, S6, S7, S8, O1, O2, O5, O8	0.035	4
SO4	S1, S3, S4, S5, S7, S8, O4, O5, O6, O7	0.018	5
WO5	W1, W2, W4, W6, W7, O1, O3, O4, O5, O6, O7, O8	0.036	6
WO2	W1, W2, W4, W5, W7, O1, O2, O3, O4, O8	0.030	7
WO1	W1, W2, W3, W6, O1, O2, O3, O4, O5, O8	0.029	8
ST6	S1, S2, S3, S4, S5, S6, S7, S8, T5, T7, T8	0.022	9
ST3	S3, S4, S5, S7, T1, T2, T3, T4, T5, T6, T7, T8	0.0205	10
ST2	S1, S3, S4, S5, S6, S7, T3, T5, T7, T8	0.0158	11
WT1	W2, W3, W4, W5, W6, W7, W8, T2, T3, T4, T6, T7, T8	0.0142	12
WO3	W1, W4, W5, W7, O3, O4, O5, O8	0.0136	13
ST1	S3, S4, S5, S6, S7, T2, T5, T8	0.0133	14
WT2	W2, W3, W5, W6, W7, W8, T4, T5, T6, T7, T8	0.0122	15
ST4	S1, S2, S3, S4, S5, S6, S7, S8, T4, T7	0.009	16
WO4	W2, W3, W5, W6, W7, W8, O5, O6, O7, O8	0.0069	17
WT3	W1, W4, W7, T4, T6, T7	0.004	18
ST5	S1, S3, S4, T1, T4, T7	0.003	19
WT4	W4, W5, W7, T2, T3, T4	0.003	20

unsustainability of smallholders' livelihoods to stabilize their livelihood by adopting these strategies. Furthermore, since no combined research has been conducted on our subject matter yet, the present research can contribute to the literature and fill the gap in previous studies.

In this research, we used the combined SWOT-AHP-TOWS index to specify the strategic status of smallholders' livelihood sustainability through non-farm activities. In the SWOT analysis, the measured weights of the factors are typically used to determine their effect on the strategy choices. The SWOT analysis does not provide the relative importance of the criteria in a systematic way and acts upon the examination of the decision alternatives in terms of the criteria. To cope with this shortage, the SWOT framework (conceptual model) is converted into a hierarchical structure, the model is integrated, and the AHP is used for analysis by calculating their eigenvalues. By integrating the AHP into the SWOT framework, it is intended to systematically rank the SWOT factors in terms of their importance (Savari and Amghani, 2022).

The assessment of the internal points (strengths and weaknesses) revealed that the most important strength in stabilizing the livelihood of smallholders through non-farm activities was "lower dependence on climate and weather conditions than the agricultural sector." Regarding this finding, it can be inferred that agriculture is a high-risk activity as farmers are faced with various types of climatic risks, pests, diseases, market risks, and raw material risks (Skees et al., 1999), whereas the diversity and severity of these risks are lower in non-farm activities. In other words, a wide range of risks influences farm income (Zhang et al., 2023), such as production risk, price or market risk, financial risk, and human risk. These risks vary in role and importance in different regions depending on the temporal and spatial conditions and government policies (Bielza et al., 2008). It should be noted that drought and severe heat (e.g., heat waves) among extreme conditions can be unbelievably destructive with extensive effects on different agricultural sectors, so they may lead to natural disasters and draw public attention. With the increase in the mean global temperature, the frequency and intensity of droughts and extreme heat have increased and are expected to keep increasing, posing plenty of risks to different sectors, including agriculture (Leng et al., 2015; Chen et al., 2018; Dai et al., 2020; Han et al., 2021).

The results of the internal assessment of the research also showed that the most important weakness in stabilizing the livelihood of smallholders through non-farm activities was "capital-intensiveness of most non-farm businesses." It can be interpreted that non-farm businesses are mostly of industrial type and sometimes need capital-intensive industrial manufacturing instruments that are unaffordable by rural households (Bordoloi, 2017, 2020). For example, a study in Bangladesh reported capital shortage as a key barrier to developing the rural non-farm sector (Rahbari et al., 2017).

Regarding the external points, "the helplessness of the smallholder agriculture sector in supplying rural livelihood" among the opportunities and "lack of expertise of most villagers to get involved in non-farm businesses" among the threats were the most important external factors influencing the development of strategies for stabilizing the livelihood of smallholders through non-farm activities. According to this finding, although the helplessness of the agricultural sector in supplying rural livelihood is by itself a threat to the community of smallholders, it can be an opportunity for entering into rural non-farm employment. There is a consensus in the literature of development studies that agriculture will fail to provide "productive employment" for the growing surplus rural population in the future decades. Here, the concept of "productive" employment can be well considered as achieving full and productive employment for all, including people in economically active age groups and women, as a part of the US 2030 agenda for sustainable development (United Nations, 2015). It is argued that despite the significant growth of agricultural production in several developing countries due to technological innovations, the capacity of the agricultural sector for workforce recruitment has not been satisfactory, especially in regions with inappropriate *per capita* land area and high rural population density (Lanjouw and Lanjouw, 1995; Simmons and Supri, 1997; Bhalla, 2005). Thus, a good deal of attention has been paid to the rural non-farm sector (RNFS) in the academic literature and in development planning and policy circles (Bordoloi, 2020). RNFS is an alternative for rural development in creating non-farm job opportunities in rural areas.

Regarding the lack of expertise among rural people to start non-farm businesses as a threat to stabilizing the livelihood of smallholders, it cannot be inferred that non-farm businesses are ambiguous, complicated, and unfamiliar for rural people because they did not use to exist in rural areas. So, most rural people have no adequate knowledge to get involved in non-farm businesses, and this is an obstacle to entering into this sector (Rahbari et al., 2017).

The analysis of the strategic space of the development of strategies for stabilizing the livelihood of smallholders through non-farm activities revealed that the strengths were more important than the weaknesses in the internal space and the opportunities were more important than the threats in the external space. Also, it was found that internal challenges are more important than external challenges in developing livelihood stabilization strategies. According to these results, the beneficial space dominates the risky environment. So, policymakers need to address the weaknesses and threats that threaten smallholders by adopting important policies as soon as possible as it will help farmers to stabilize their livelihood by promoting their strengths, alleviating their weaknesses, coping with the threats, and grasping the opportunities (Savari and Shokati Amghani, 2021; Savari and Amghani, 2022).

Finally, drawing on the TOWS matrix, the research developed 20 strategies for stabilizing the livelihood of smallholders through non-farm activities. The results in this section showed that the two strategies of "establishing and developing greenhouse cultivation based on the crop patterns considering the relative advantages of the villages" and "establishing microcredit foundations and funds to support the youth in getting involved in rural non-farm businesses" were the most important strategies for stabilizing the livelihood of smallholders through non-farm activities. In this regard, policymakers are recommended to take the strategies developed for livelihood stabilization seriously. Also, the following policies are recommended:

- Changing the approach of government support in the field of granting microcredits to smallholders: increasing production by providing credits and empowering smallholding units, and consequently, increasing employment and bringing economic balance between the agricultural and non-agricultural sectors.
- Developing infrastructural facilities and service: empowering the electricity grid in rural centers, facilitating the issuing of industrial power permits to the rural industrial activists, modifying roads and streets inside the rural areas, modifying roads connecting the farms, developing and expanding Internet access in rural areas, and developing warehouses and cold storage in central rural areas to preserve farm and non-farm products.
- Education: the development of non-farm employment requires suitable extension and educational programs. In this regard, it is necessary to provide technical and professional training for which governmental and non-governmental extension and educational institutions can be effective in developing non-farm employment because the certificates issued by the Technical and Professional Centers can be used to receive work permits and loans from the banking system.

6. Conclusion and Limitations

The purpose of the current study was to develop strategies for stabilizing the livelihood of smallholders through non-farm activities in four provinces of Alborz, Guilan, Hormozgan, and Yazd in Iran. To this end, the TOWS matrix was used, and 20 strategies were developed.

The main conclusion to be drawn from this study was the weights of the SWOT criteria were specified by their pairwise comparison. Based on the results, the strengths and weaknesses whose weights were 0.391 and 0.276, respectively had the greatest impact on the development of strategies for stabilizing the livelihood of smallholders through non-farm activities. Therefore, it is concluded that strengths can have the greatest impact in Developing strategies for stabilizing the livelihood of smallholder farmers through non-farm activities. Considering that the strengths are internal factors, it is possible to change and improve them in order to deal with the threats and also take maximum advantage of the opportunities. According to the ranking of the strategic zones, the first strategy is based on ST, i.e., the contingency strategy (max-min). This strategy tries to take advantage of the strengths to cope with the threats. It aims to maximize the strengths for tackling all threats. However, caution should be exercised in this strategy because the improper use of power can have undesirable effects. This study showed that presents the pairwise comparisons and the final weights of the factors at four strategic levels. It also specifies the sub criteria used in each strategy. The most obvious finding to emerge from this study was that, the most important strategies included "establishing and developing greenhouse cultivation based on the crop patterns considering the relative advantages of the villages" and "establishing microcredit foundations and funds to support the youth in getting involved in rural non-farm businesses," and the weakest ones included "facilitating the process of issuing work permits for rural non-farm businesses" and "improving and developing infrastructure and general facilities in villages for facilitating the involvement of investors in rural non-farm entrepreneurship."

In this research, it is true that we achieved valuable results that showed that non-agricultural activities can play an effective role in stabilizing the livelihood of smallholder farmers, but the important point is that the policymaking of non-agricultural activities is carried out in a separate organization from the agricultural organization. Unfortunately, they have no interaction or cooperation with each other. Even in some cases, these two organizations have a conflict of interest with each other. A clear example of that is agricultural land use change for the development of rural tourism. Therefore, countries will succeed in stabilizing farmers' livelihoods through non-farm activities if all matters related to sustainable rural development, including agricultural development and rural non-farm development, are planned and politicized through a single organization. Therefore, the feasibility of forming a rural development organization consisting of two agricultural and non-agricultural sectors can be considered by other researchers as future research.

Despite its important results, the research suffers from two limitations. First, it was conducted only in four Iranian provinces of Alborz, Guilan, Hormozgan, and Yazd, so we should be cautious in generalizing its results to other regions. Second, it was single-sectional in time. It is considerable that this research was conducted at a time when the entire country of Iran was involved in the COVID-19 epidemic, and for this reason, access to farmers and experts was very difficult.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the participants was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

JB, MSS, MSA, and AN contributed to the study's conception and design. Material preparation, data collection, and analysis were performed by JB, MSS, MSA, and AN. The first draft of the manuscript was written by MSS. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 24 August 2023
DOI 10.3389/fsufs.2023.1158946

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RECEIVED 04 February 2023
ACCEPTED 14 August 2023
PUBLISHED 24 August 2023

CITATION
Masuku MM, Mthembu Z and Mlambo VH (2023) Gendered effects of land access and ownership on food security in rural settings in South Africa.
Front. Sustain. Food Syst. 7:1158946.
doi: 10.3389/fsufs.2023.1158946

Gendered effects of land access and ownership on food security in rural settings in South Africa

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South Africa is one of the many countries that experience critical challenges regarding land issues, with rural women in particular having limited access to and ownership of land. This paper argues that land inaccessibility for women contributes significantly to their deprivation of economic opportunities. Secondary data on women and land ownership were extracted from main sources such as peer-reviewed articles and government gazettes. In the execution of this study, a comprehensive literature review (CLR) was conducted to illuminate the topic under investigation. The three phases (the exploration phase, the interpretative phase, and the communicative phase) of the comprehensive literature review method were adopted. The result of the review suggests that the gendered nature of land distribution contributes to the phenomenon of food insecurity that faces numerous women and their households in rural areas. The customary law is a key institutional factor that poses challenges for rural women in acquiring equal access to land ownership compared to men. The study recommends that the South African government should formulate better land policies that provide equal access to and ownership of land for both men and women.

KEYWORDS

food security, food insecurity, land access, rural areas, women

1. Introduction

Rural women face a plethora of challenges in accessing and owning land. Despite a Constitution that promotes human and women's rights, rural women in South Africa face numerous forms of oppression. Globally, numerous rural women are the key role players in and custodians of food security at the household level. They fulfil the roles of food producers, consumers, and family food managers. However, it has been observed that rural women still face a plethora of challenges such as limited access to ownership of land, cultural and traditional stigmatisation, a lack of access to support networking and, most importantly, limited access to financial backing (Mulusew and Mingyong, 2023). In African countries, most women may be considered poor and food insecure because they are bound by traditions that disallow them from possessing any assets. They habitually have to mediate access to land and finances through males who are the heads of households and the leaders in communities. This patriarchal attitude, which is dominant in most African cultures, marginalises women's constitutional rights. Rural African women's right to own land is vicarious, as they can only gain this right through men such as fathers, husbands, uncles, and sons. Zooming in on KwaZulu-Natal (KZN), it is evident that 29.67% (2.8 million hectares) of land in the province is governed by customary laws that give senior men the sole right to productive resources, which is a most prevalent practise in rural areas. Furthermore, this patriarchal attitude compels most African women to do all household tasks apart from tilling the land. They are unpaid and, consequently, marginalised and have limited influence in their households and communities.

In the South African context, it is well known that the persistent situation of land inequality amongst races and between genders has led to food insecurity at the household level. Sadly, little has been done to address this disconcerting observation (Masuku and Jili, 2017; OoNorasak et al., 2023). They lament the slow speed at which women have been given the support needed to ensure their growth in the agricultural sector. Therefore, this paper argues that gender inequality in accessing and controlling productive resources is a causative factor for food insecurity in rural areas. Although the South African democratic government has embarked on a number of equality-driven interventions to redress the injustices of a grossly skewed distribution of resources, access to ownership of land in rural settings remains elusive for the majority of women Mwambene et al., 2021).

The Food and Agriculture Organization (2015) indicates that, globally, not even 2% of the land is owned by women, whilst they produce between 60–80% of the food in rural settings. A substantial body of evidence indicates that women run less than 25% of agricultural businesses in developing nations. Moreover, "women in the developing world are five times less likely than men to own land, and [if they do] their farms are often smaller and less fertile" (Doss et al., 2015; Mokati et al., 2022). In this context, Agarwal (2018) argues that uneven access to ownership of land in rural areas, which is mandated by patriarchal-oriented customary norms, has resulted in low agricultural production and ongoing food insecurity in many households on the African continent.

García (2013) and Singh et al. (2022) both cite the FAO, arguing that, if women had the same opportunities for access to productive resources (such as arable land, seeds, fertilisers, tools, and loans) as men, they would have been able to increase agriculture yields by 20–30%. Mutangadura (2004) and Fagbadebo and Faluyi (2022) also note with concern that South Africa is well recognised as one of the leading African states that promote democratic values and civil liberties but that, even here, access to ownership of land is still dominated by men.

The number of female farmers is increasing as agriculture becomes more feminised, but if this process is expedited, it would improve intra-household nutritional allocations because owning a property naturally increases a woman's bargaining power within the family and community (Agarwal, 2018).

Therefore, this article examines the current situation in rural areas in relation to the distribution of the right to women to use and control land. In essence, the article argues that women are the major custodians of food security in their households and that this position should be acknowledged and respected.

2. Methodology

To investigate whether or not equal access to land ownership is a driving force for improving food security in rural South Africa, the design of this study was guided by a detailed, systematic, and comprehensive literature review (CLR) that focused on qualitative investigations. Three phases of CLR were adopted: (1) the exploration phase, which has 5 steps, (2) the interpretative phase, which has one step, and (3) the communicative phase, which also has one step (Williams, 2018). These phases are explained below:

2.1. Exploratory phase

2.1.1. Step 1: Exploring beliefs and topics

The search strategy was determined after identifying and establishing the research topic of interest. Search terms such as 'gender and food security in South Africa', 'gender and food security', 'agricultural', and 'women in agriculture' were used. The relevant results returned by the search were remarkable. Unfortunately, just a few articles on Google Scholar and Sabinet were ultimately manageable after performing additional screening of abstracts using the country's names to separate material that was not from South Africa.

2.1.2. Step 2: Initiating the search

In this step, sources of data were identified. Peer-reviewed articles in the English language published between 1994 and 2023 were identified by accessing two databases on the Internet (Sabinet and Google Scholar), and the results were analysed. The articles were screened using filters that considered the studies' location and context of land or food security. The initial search yielded 5,349 studies. After removing duplicates and deemed irrelevant studies, a rigorous review of 1705 research articles on women's role in land and food security was conducted. Upon further consideration of all the inclusion criteria (see section below), 67 studies were selected for analysis.

2.1.3. Step 3: Storing and organising information

Organising and storing the selected information was conducted in Google Forms, which is a technology-based strategy. A data extraction form was constructed to help extract information from each article on land, gender, and food security in rural settings in South Africa, as listed under the research objectives. The articles were divided according to the research methods the studies employed, namely qualitative, quantitative, and mixed methods. Many conceptual papers addressed the topic significantly, but they were discarded as they did not report on research.

2.1.4. Step 4: Selecting and deselecting information

2.2. Inclusion and exclusion criteria

Articles were sampled for the review based on a sampling criterion that only allowed articles from sub-Saharan African countries. All the articles that were ultimately included in this comprehensive literature review were based on empirical research and conceptual papers. The legal case and legislative frameworks related to this study were also included to have an insight into political will to address gender inequality and land rights issues. Another criterion was the area of the study. The articles selected had to represent communities in rural settings that were poor, vulnerable, underdeveloped, or located in remote areas. The gender of the sampled population had to include females, and the articles that were selected had to have been published after the advent of democracy in South Africa (1994 to 2023). The search went back that far as it intended to incorporate all relevant literature since 1994 on land access and food security. The search was done during 2022 and 2023. Table 1 provides details of the steps followed to identify articles for review.

Excluded articles were those that compared sub-Saharan countries with non-African countries. Articles published before 1994 were also not considered because the Constitution of the Republic of South Africa of 1996 was pivotal in this investigation as it was deemed the custodian of human rights in terms of gender disparities, racial discrimination, cultural diversity, and property rights. Articles written in non-English, non-traditional sources such as visual media and non-scholarly observations were excluded.

Step 5: The search was expanded using MODES a process that contributed to the addition of media, observations, documents, expert opinions, and other secondary data. MODES was therefore used as a vehicle to take the traditional literature review to the next level (Onwuegbuzie and Frels, 2015). For this review, Google Scholar and Sabinet were the most suitable databases to locate scholarly peer-reviewed sources that had immense significance in terms of gender, land access, and ownership in relation to food security in outlying areas.

2.3. Interpretive phase

2.3.1. Step 6: Analysing and synthesising information

Papers published after South Africa's democratic dispensation were taken into consideration as Section 25 of the South African Constitution (Republic of South Africa, 1996) asserts that all citizens, regardless of gender, race, and cultural diversity, should have equal access to land as one of their fundamental rights. As this was essentially a qualitative literature review, no specific comparator interventions or demographics were considered as the scope of the review was limited to certain criteria to achieve the objectives of the study. Therefore, a wide variety of study methodologies, including descriptive and exploratory/explanatory methods, were considered.

TABLE 1 Results of the preliminary literature search using databases.

Database	Total number of results	Peer-reviewed papers	Included for literature
SAGE journals	48	32	00
Google scholar	807	160	25
Social sciences citation index (Web of science)	300	157	00
EBSCOHost	458	200	00
Scopus	567	267	00
Sabinet	1,449	344	42
Web of science	652	252	00
Jstor	300	48	00
Springer link	768	245	00

Data were analysed using thematic analysis and the findings are presented under themed headings in this paper.

2.4. Communication phase

In the third and final part of the seven-step process, the researcher is required to deliver a presentation to an audience on the findings of the comprehensive literature review. Therefore, the information, analysis, conclusions, and implications of this study are communicated in writing in this journal paper, which is an approach supported by? Onwuegbuzie and Frels (2015).

3. Access to land ownership by rural women to address food security

The primary objectives of the Constitution Republic of South Africa of 1996, the White Paper on South African Land Policy of 1997, and a succession of relevant legislations are to redress racial and gender disparities in land ownership, develop the agricultural sector, and improve the livelihoods of the poor (Walker, 2005; Bayer, 2022). Most tribal authorities in rural settings discourage women from acquiring land. Thus, many women are obliged to acquire land through their husbands or other male relatives, which is an arrangement that leaves them with limited secured rights compared to those of their male counterparts (Cheteni et al., 2019). Gender inequality that disadvantages women in their quest to own land has not been adequately addressed at either the conceptualisation or implementation level using gender-responsive evaluations. This paper thus argues that the key to alleviating women's food insecurity and other poverty-related issues lies with their right to access and own land, which is entrenched in the Constitution. If this right is unequivocally granted, it will foster women's empowerment and growing awareness of their role in food security development.

For women, owning land provides a means to alleviate the 'evil twins' of food insecurity and poverty as it allows them to generate income and improve their livelihoods at the household level. In KwaZulu-Natal, most of the land redistributed for group resettlement schemes and communal grazing is of low quality. The private purchase of land in rural areas, which generally excludes women, distributes more land of high quality than government-assisted purchases. It is generally maintained that such patches of land that have been transferred to disadvantaged owners account for less than 6% of the total area transacted (Lyne and Darroch, 2001; Ngcobo, 2021; Zantsi et al., 2021). Of this small percentage of registered persons with land rights, women are the least secure regarding access to land rights (Akinola, 2018). Furthermore, Bob et al. (2018) argue that this inequality is an age-old socially constructed relationship between women and men that have shaped the perceptions and attitudes of society in South Africa and other part of the world. This is an indicator that major gaps exist between the law and practise which led tolimited potential for the growth and consolidation of women in agriculture.

Ironically, male politicians in developing countries acknowledge that women play a crucial role in food production and distribution but still turn a blind eye when women are denied access to land ownership in rural areas. This means that considerable attention should be directed at governments that have failed to address this highly debated and politicised issue for decades. Efforts to address this issue should be driven by state policy, which is greatly not well addressed in South Africa. In the absence of secure tenure, women's efforts to produce food in rural areas face the risk of not producing enough to address the problem of food insecurity in rural households. The absence of free access to ownership of land by women threatens future production opportunities and decent wages that are necessary to support the livelihoods of all members of rural households.

4. The effects of land inaccessibility and denied land ownership on women

Barriers to land ownership debilitate rural and urban women because culture within their environments offers limited economic-related opportunities, this led to less than 5% of Black women in South Africa own land (Thaba-Nkadimene et al., 2019). Moreover, there an inability or disinclination, to address the widespread cultural and traditional values that continue to suppress women. Furthermore, because women are still not benefitting from land interventions, it confirms that land reform policies that redress land disparities amongst previously disadvantaged groups have failed (Mubecua and Nojiyeza, 2019).

Whilst women are primarily responsible for ensuring that their families are food secure through agricultural reproduction despite limited access to land (Masuku and Jili, 2017 agricultural activities have become the primary source of income for rural populations to sustain their livelihoods. In contrast, individuals who are economically affluent, have purchasing power, and live a perceived high quality of life, are revered as their status is measured by their income (Casale and Posel, 2020; Fapohunda, 2022).

This is a great disadvantage as a lack of supportive agricultural associations prevents women from accessing the wider market to sell their produce. Barriers that impede women's ability to access and own land in rural areas.

Prevailing social behaviour in rural communities is also a barrier towards the realisation of women's right to access and own land. Bob (2008) and Guerny du and Topouzis (1997) emphasise the negative impact of societal attitudes amongst rural communities towards granting land ownership to women. Some studies have revealed that rural communities strongly share the sentiment that women must not be given the right to own land, despite the fact that they work on it every day. This conservative and gendered attitude towards land ownership has been documented in numerous studies, which again underlines the extent to which patriarchy is still prevalent in South African rural communities (Agarwal and Bina, 1994; Brottem and Ba, 2019; Khuzwayo et al., 2019; Meinzen-Dick et al., 2019).

This means that the Communal Land Rights Act 11 of 2004 has failed to address the issue of unequal opportunity for men and women to own land in rural areas. The inability of the former Act to adequately address the issue of women empowerment in land ownership has impacted negatively on women in rural areas and their ability to reduce food insecurity in their households. Jankielsohn and Duvenhage (2017) indicate that it is quite overwhelming and disappointing that, irrespective of legislation, laws, and various measures in place concerning women's empowerment, little change has been observed. They argue that the same challenges that underpinned the need for land reform and new legislation that gave effect to international instruments concerning human rights are still faced by women even today.

Wing and de Carvalho (1995), Bohler-Muller and Daniels (2009), and Scheidegger (2020) indicate that, due to rural communities' social systems and socialisation in general, rural women seem to remain ignorant of their constitutional rights, hence they continue to be victims of discrimination and oppression. Yngstrom (2002) supports this stance, indicating that rural women have been socialised into internalising their traditionally ascribed roles, therefore they fail to take their rights and opportunities into cognisance. However, this paper maintains that this socialisation, particularly in the South African context, cannot be viewed without incorporating the history of the country where colonialism and apartheid shaped how women were ideologically seen. In post-apartheid South Africa, itis a sad fact that women in rural societies are still often relegated to the kitchen and to the role of taking care of the man.

Derry (2015) argues that the social class of women in rural areas has also been seen as a barrier to land ownership. Furthermore, being a woman (especially an unmarried woman) in many societies does not guarantee empowerment or increased access to ownership of land. It is widely perceived that married or widowed women with children are better able to access land than their single counterparts (Kuusaana et al., 2013; Chigbu, 2019; Reddy, 2020). This is evident in most rural areas where single women occupy a lower social status than married or widowed women. Rural women are also confronted with unequal rights in family structures, as male children are seen as more deserving of land rights, and this customary view compounds the suffering of women. The issue of unequal rights in the family structure is a societal issue that has given rise to unequal access to productive resources such as land and capital, and it is also an issue of socialisation in a society where patriarchy is perpetuated. However, because little attention has been paid to gendered discrimination in terms of land rights in South Africa, some women continue to fight for equal rights in the context of land ownership, but they often lack the needed support.

It has also been argued that rural women lack knowledge about land reform processes and that this directly prevents them from owning land or being familiar with the processes that must be followed to acquire land. For instance, Moagi (2008) asserts that the failure of rural women to acquire vital knowledge about land reform processes and procedures often leaves them vulnerable and at the mercy of their male counterparts or the leadership structures within their communities?. In this regard, Paustian-Underdahl et al. (2014) hold the view that traditional leaders' perception of women's roles in their households, communities, and societies harms their ability to access ownership of land, their development, and their ability to sustain the livelihoods of their families.

5. The effects of customary law on gender equality

Mokgope (2000) holds the view that cultural beliefs and norms and culturally established social institutions prevent women from achieving emancipation. Furthermore, rural areas are characterised by age-old customary and social practises which, in most cases, serve as a stumbling block to women's empowerment and the realisation of their right to own land. The Constitution guarantees many critical rights for women such as the right to equality, freedom, education, property, and access to clean water, housing, health services, sufficient food, and social security (Francis and Webster, 2019). What is lamentable is that, despite the provisions in the Constitution, customary laws in rural areas still relegate women to a position of servitude to men, a relationship in which they are not entitled to inherit the land. Furthermore, Blom (2006) and Moyo (2013) highlight that it is disconcerting that, irrespective of laws and legislations that underscore equal rights and opportunities, customs and patriarchal structures still dictate norms and socially acceptable standards of living in rural areas. Traditional leaders are in charge of land distribution in rural areas, and they overlook the supreme law in favour of their traditions, customs, and patriarchal advantage. This is particularly evident in KwaZulu-Natal province where the Ingonyama Trust discriminates against women and violates the Constitution in favour of the traditional authority it advocates. The Trust has jurisdiction over millions of people living in rural areas (Rural women take the Ingonyama Trust to court, 2020), and it has been alleged that this Trust, which manages tribal land in KwaZulu-Natal, discriminates against women and denies them the right to land tenure (Shoba, 2021). Women thus experience prejudice in many forms and from many sources, including traditional leaders who collaborate with the Ingonyama Trust administration.

Ngomane (2016) notes with great concern that, as a result of customary and statutory legal systems, women have fewer benefits and greater burdens than men. Kehler (2001) shares the view that South African women in rural areas are constantly subjected to a lack of access to resources and basic services, arguing that this has led to women in rural areas learning to develop coping mechanisms to sustain their livelihoods by subjecting themselves to customary laws even though they are treated as minors. This is clearly in conflict with the Constitution, which is regarded as one of the most progressive in the world based on its emphasis on human, social, and economic rights. Gender equality is articulated in Chapter 1 Section 9(187), which is the pillar of any policy directive that government adopts regarding gender issues (Cold-Ravnkilde, 2019).

In Rahube (2018), the Constitutional Court had to decide whether a provision in the Upgrading of Land Tenure Rights Act No. 112 of 1991 was constitutionally invalid in that it automatically converted holders of land tenure rights into owners of property without allowing occupants and affected parties an opportunity to make submissions (Smith, 2008). Although this case concerned the invalidation of certain provisions of this legislation, it highlighted how the law had historically deprived women of ownership rights to property. As the court noted, "an African woman suffers three-fold discrimination based on her race, her class, and her gender" (Rahube, 2018). Although the situation has not been too dissimilar under customary law, some court decisions have made changes to the legal regime. Under customary law, land was historically allocated by the traditional authority to the head of a household who was, in all likelihood, a man such as a woman's father or her husband (Bekker et al., 2006).

The understanding of 'head of a household' also resonated in earlier legislation. Proclamation R293, which was promulgated in terms of the Black Administration Act No. 38 of 1927 (Parliament of South Africa, 1927) defined the head of the household in specifically gendered terms. As acting justice Goliath pointed out in the Rahube judgement, sections 8(1) and 9(1) of the Act envisaged "a situation where only men could be the head of the family, with women relatives and unmarried sons falling under their control." This left African women under customary law and colonial and apartheid legislation in a position where they could not legally be the owners of or exercise control over land. Although the aforementioned argument was generally accepted, Nhlapo (1995) argues that the development of customary laws under the Colonial and apartheid systems "usually took the form of an alliance between the colonial authorities and African males. This led to colonial and apartheid authorities and African males are holders of 'strategic' resources in the form of land, cattle, women, and children (and they) defended their vested interests by promoting the growth of rigid rules in place of custom when the latter system could no longer protect them from the effects of change." Customary laws have not only continued to prohibit the active participation of women in economic activities, but they have also prevented them from gaining ownership right to land and other resources. This paper argues that, although laws differ from county to county in respect of the extent of women's rights, a common feature is that most of these laws tend to view women as perpetual minors, and they thus fail to give them access to productive assets. Even if the Constitution does not discriminate against women, social norms, attitudes, and customary laws systematically marginalise women and prohibit them from having control over assets, particularly land. One practical example is inheritance laws that are patriarchal in nature as they give unequal succession rights to children on the basis of gender. This is based on the assumption that girls will eventually marry and have access to a husband's land, or that she will take her family's wealth to her husband's family. It has been noted that some civil society organisations have been advocating and lobbying for women's rights to be acknowledged in the Communal Land Rights Bill.

It is undeniable that the South African government, particularly the provincial government in KwaZulu-Natal, has made limited progress in allowing women to participate in decision-making structures. For instance, no woman has ever been appointed as a headman (Induna) or as a member of a traditional council regardless of the Constitutional Court handing down judgements that declared some customary laws and practises as invalid (Budlender et al., 2011; Khuzwayo et al., 2019).

6. Potential gains of improving land accessibility and ownership for rural women

The Food and Agriculture Organization (FAO) of the United Nations has consistently argued that improving women's access to productive resources such as land will boost the agriculture sector (Food and Agriculture Organization, 2011). Justino et al. (2020), the latter organization argues that increasing access and ownership to land will ultimately result in rural women being in a position to provide more food for their households, and therefore rural families will reap the benefits of better health through access to nutritious meals and education.

Most people in rural areas are women and children who live under the poverty line. Bob (2008) therefore emphasises that, by extending ownership of land to rural women, they will be empowered to have increased control of their lives through enhanced food production and reduced food insecurity. Cross and Friedman (1997) emphasise that, compared to men, women value land as a source of food production to sustain the livelihood of their households, whilst men may view it as a source of income for personal gain. This notion is informed by the fact that rural women contribute significantly to food production in South Africa and other African countries. Derry (2015) supports this notion, as he argues that granting rural women land ownership will increase their control of land through production mechanisms and enhance their effective and inclusive participation in decisions about land use. Authors such as Derry (2015), Akinola and Wissink (2019), Rehman et al. (2019), and Mwesigye et al. (2020) stress that secure access to and ownership of land has the potential to enhance intra-household bargaining power. By virtue of having ownership of land, rural women's status in households will be elevated, which also means that occurrences of domestic violence, conflict, and oppression will be minimised. This will, in turn, result in enhanced family relations as women will be afforded respect and recognition just like their husbands who own land. Galiè et al. (2019) suggest that the extension of ownership of land to women will result in increased confidence levels amongst rural women, ultimately empowering them in terms of their decision-making role in their families and households. 'An empowered woman is a powerful woman!' This saying suggest that women have the potential to become highly productive members of society who will contribute immensely to the economy. Derry and Diedong (2014) assert that increasing women's secure ownership of land will potentially improve the socio-economic status of rural households through the lessening of the burden on husbands who are the breadwinners. Two incomes are better than one; therefore, if women own productive land they will increase food security in their households and their communities which will be their markets.

In South Africa, the alleviation of rural food insecurity is a priority for the democratic government. With this being said, the government is not in a position to combat food insecurity on its own (Moyo, 2013), and it therefore needs to increase land ownership for women to ensure that they become active participants in the fight against all poverty-related issues. If land ownership for rural women is ensured and legally safeguarded, it will increase their productivity which will, in turn, lead to increased income generation and the creation of employment in rural areas. Such economic growth in rural areas has the potential to boost rural economic development. The importance of the role of women in the agricultural sector has been well documented and emphasised, and it is understood and acknowledged that rural households' access to food relies greatly on the work of rural women. Securing women's right to own land is therefore crucial in enhancing food security not only in rural areas but nationally as well.

7. Contribution to the field

Men and women are humans with different needs. The paper reveals that despite that South Africa is considered a democratic state, women in rural areas have suffered severe economic and social impacts from skewed access and ownership of land, which was determined through the country's patriarchal customary laws. The right to food security is meant to be enjoyed by all citizens including vulnerable groups such as women. However, the findings of this paper have exposed weaknesses of the government systems with reference to women's economic deprivation and their vulnerability due to injustices in the land discourse. This has made food security far-fetched for poor women.

8. Conclusion

The discourse has affirmed that rural women in South Africa have been barred from gaining ownership of land through customary laws, traditional perceptions, and gender inequality in rural areas. Access to and ownership of land by women are essential as women are the most vital resource for food production in rural communities. Owning land is essential in enhancing women's ability to make a meaningful contribution to rural economies as they engage in activities such as crop and livestock farming which is their only livelihood strategy. However, the process of implementing equal ownership of land is hampered by a lack of government interventions, persistent adherence to customary laws, and the perpetuation of patriarchal attitudes in rural areas. Therefore, this paper urges that women's right to land ownership, particularly in rural areas, should not be restricted by gender identity or inequality. Land ownership is a crucial physical asset for rural women who are mandated by tradition to ensure food security in their households. Unfortunately, this is compromised in rural areas where unequal distribution of land ownership prevails regardless of some efforts to address this as demanded by the Constitution. In rural areas, men have traditionally been favoured by customary law as the owners of land, and this situation has not changed much. In fact, the prevalence of customs that deny women access to and ownership of land has resulted in low agricultural production and has perpetuated food insecurity in many households. The dependency syndrome that prevents women from owning land undoubtedly exacerbates existing gender inequality in affected areas. Moreover, the limited access that women have to land ownership means that they are systematically marginalised and therefore excluded from decision-making processes related to productive resources and assets. Free access to tribal land and ownership of the areas they cultivate are crucial if rural women are to realise their potential as food producers who have the ability to engage in agricultural and non-agricultural activities. Only if this is achieved will women independently generate income that will alleviate food insecurity and dependency on their male counterparts. Conversely, the subordinate position of rural women in society has a negative impact on rural development as their needs are not met whilst their vulnerability to food insecurity and other related poverty issues is perpetuated. This situation has led to a growing number of landless women in rural areas, which is a situation that increases household food insecurity.

The paper argues that, in the South African context, women are systematically excluded from being beneficiaries of land reform due to a customary law that limits them from enjoying land rights on an equal footing with their male counterparts. However, it also acknowledges that the marginalisation and exclusion of women concerning land ownership is not peculiar to South Africa because land ownership is skewed across the African content where women's right to property is unequal to that of men. What is peculiar about the South African situation, however, is that this country has one of the most advanced democracy-based constitutions in the world, yet its rural women are locked behind the door of traditional male superiority. This means that, despite their pivotal role in agriculture and food production, rural women in South Africa continue to face discrimination as they are still barred from land and ownership rights as land titles are passed on almost exclusively down the male line. Withholding the right to own land from women does not only threaten progress in terms of gender equality, but it jeopardises sustainable and collective development as well.

In the context of the above discourse, the authors argue that customary law should not be understood as an advocate for exclusiveness; rather, it should be utilised to underscore the importance of gendered differences without denying women their right to own land. It is therefore recommended that the South African government should create a land distribution/ownership system that not only prioritises women's social and economic needs, but that also recognises their ability and power to create a viable rural economy based on their agricultural endeavours. Land ownership policies should therefore be revisited to advocate and give credence to the needs and skills of both genders in order to enhance equal access to and ownership of land. The ongoing challenge of gender inequality should thus be addressed by gender-responsive policies to undo the current unfair distribution of land. This will require an open-minded government that should devise interventions to address current skewed and gendered land rights to enhance rural women's economic empowerment and inclusive development.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

MM, ZM, and VM were responsible for all aspects of the paper's development from conceptualization and designing the study to identifying suitable studies via databases and registers, data extraction, and finalization. All authors contributed to the article and approved the submitted version.

Funding

This work is based on research supported by the National Institute for the Humanities and Social Sciences (NIHSS).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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frontiers | Frontiers in Sustainable Food Systems

TYPE Review
PUBLISHED 27 September 2023
DOI 10.3389/fsufs.2023.1241675

OPEN ACCESS

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RECEIVED 17 June 2023
ACCEPTED 12 September 2023
PUBLISHED 27 September 2023

CITATION
Mabhaudhi T, Chibarabada TP and Sikka A (2023) Status of integrated crop-livestock research in the mixed farming systems of the Global South: a scoping study. *Front. Sustain. Food Syst.* 7:1241675. doi: 10.3389/fsufs.2023.1241675

Status of integrated crop-livestock research in the mixed farming systems of the Global South: a scoping study

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Mixed farming systems (MFS) are the main food source and exist across almost all agroecological regions in the Global South. A systematic scoping review was conducted to identify the status of integrated crop-livestock research in MFS of the Global South. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses protocol was used to identify 210 studies (excluding reviews) addressing productivity, resilience, challenges, opportunities, and perceptions of integrating crops and livestock in the Global South from the Scopus and Web of Science database. Publication details, problem statement, experimental details and research outcomes of each study were extracted into an MS. Excel sheet. Descriptive methods such as frequency counting and the word frequency cloud were used to analyze the data and identify emerging themes. Integrated crop-livestock research was mostly conducted in sub-Saharan Africa and Asia and not much from North Africa and the Caribbean. The integrated research has been focused on farm production of human food and animal feed by smallholder farmers and soil productivity. Maize was the most dominant crop, while for livestock, it was sheep and cattle. The integrated crop-livestock research seeked to address various challenges, including the growing demand for food and fodder, water scarcity, land scarcity and degradation, climate change, disease outbreaks and social changes. The review summarized proposed strategies and approaches to improve the efficiency of MFS in the Global South. Under the current challenges, feed quality and supply can be improved through adoption of high biomass, climate smart and improved drought-tolerant fodder crops. Using crop residues incorporated in crop fields for improved soil organic matter and controlled grazing were some strategies suggested for land rehabilitation. Building the resilience of smallholder farmers in MFS can be done through diversification and ensuring access to information, markets and finance. Policies that promote the business component, i.e., markets, training, gender equality, private investments, tenure systems and technology adoption were identified for the sustainability of MFS. There is need for research that integrates crop-livestock systems and natural resource management innovations and that evaluates sustainable intensification strategies to meet productivity goals without compromising social and ecological outcomes in MFS.

KEYWORDS

cattle, crop-livestock systems, fodder, food, maize, sheep, soil fertility

1. Introduction

A mixed farming system (MFS) is whereby farmers keep crops and livestock on the same farm. In MFS, annual and perennial crops, tree species, ruminants and non-ruminants are integrated on the same farm to reduce production risks, improve food security and enhance income (Sumberg, 1998). In MFS, crop, livestock and/or fish production activities are managed by the same economic entity, such as a household, with animal inputs (for example, manure or draft power) being used in crop production (Rufino et al., 2006) and crop inputs (for example, residues or forage) being used in livestock production (Latham, 1997; Rufino et al., 2006). Mixed farming systems exist across almost all agroecological regions in the Global South despite various business models, research and training leaning toward specialized forms of farming (FAO, 2020). Mixed farming varies depending on social and cultural beliefs, market prices, local policies, technological advances and the environment.[1]

Mixed farming systems are the main food source in the Global South (see Footnote 1). Factors such as climate change (Thornton et al., 2009), population pressure, urbanization, water scarcity, changing diets, and volatile food prices (Steinfeld et al., 2006; Hazell and Wood, 2008; Seré et al., 2008) continue to threaten these systems together with livelihoods of smallholder farmers (Giller et al., 2021). Projections show that to meet the rising demand for food, agriculture (livestock and crop), global water consumption and agricultural land are expected to increase by 60% and approximately 70 million ha, respectively (Boretti and Rosa, 2019; High-Level Expert Forum, 2009; United Nations Convention to Combat Desertification, 2022). Crop–livestock systems must be transformed and intensified along productive and sustainable pathways. This aligns with achieving global targets such as the Sustainable Development Goals (SDGs).

Research, innovation and policy can achieve desirable pathways and mitigate undesirable impacts affecting MFS (González-García et al., 2012). Any prospects for sustainable intensification (SI) of mixed farming require understanding the vital interlinkages between crop and animal production and changes in these systems over time. The primary motivation behind this scoping review was to determine the status of integrated crop-livestock research within the Global South and to identify the factors influencing the viability of MFS. This will guide future research efforts into the SI of mixed farming. The scoping review aimed to synthesize integrated crop-livestock research in MFS of the Global South. Specifically, the review (i) identified the integrated crop-livestock research within MFS of the Global South, (ii) identified the problems and pressures that have been the subject of integrated crop-livestock research in MFS of the Global South and (iii) identified strategies and approaches that promote sustainability and social inclusion within MFS in the Global South.

2. Definition of terms

This review uses the Global South's boundaries, referring to countries classified by the World Bank as low or middle-income in Africa, Asia, Oceania, Latin America and the Caribbean (Figure 1; Dados and Connell, 2012). While Japan, Singapore and South Korea are in Asia, they are not considered Global South. Mixed farming systems which are synonymous with crop-livestock systems (Hou, 2014; Ryschawy et al., 2017), agro-pastoral systems (Hassen and Tesfaye, 2014) and integrated farming systems (Meena et al., 2022; Paramesh et al., 2022) were used in the context of a farming method in which farmers raise crops, livestock and or fish on the same piece of land, irrespective of scale. Systems integrating trees, livestock, fisheries, cash, and/or food crops were also included. Livestock is defined as domesticated terrestrial animals that are raised to provide a diverse array of goods and services such as traction, meat, milk, eggs, hides, fibers and feathers (fao.org), while crops are any cultivated plant, fungus, or alga harvested for food, clothing, livestock, fodder, biofuel, medicine, or other uses (fao.org). This review focuses on research that integrates both the crop and livestock systems and was conducted in MFS of the Global South.

3. Materials and methods

To collect literature on integrated crop-livestock research in MFS of the Global South, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol (Figure 1; Moher et al., 2009) was used. A scoping review approach was used as its strength lies in identifying the nature and extent of research and knowledge (Grant and Booth, 2009). A scoping review also determines the value of undertaking a full systematic review and refining subsequent research inquiries.

3.1. Information sources, search strategy, and data analysis

The literature was searched on scientific databases, Scopus[2] and Web of Science Core Collection (WoS).[3] The PCC [Population (or participants)/Concept/Context] framework was used to identify the main concepts and the framework that will inform the search strategy. The population the review intended to identify was from the Global South, while the concept was mixed farming systems. In terms of context, the review sought to identify studies that addressed productivity, livelihoods, challenges, perceptions, interventions, resilience, adaptation, food security and biodiversity. The same search syntax [TITLE-ABS-KEY (mixed-farming) OR TITLE-ABS-KEY (crop-livestock) OR TITLE-ABS-KEY (agro-pastoral) OR TITLE-ABS-KEY (integrated farming system) AND TITLE-ABS-KEY (Africa) OR TITLE-ABS-KEY (Asia) OR TITLE-ABS-KEY (Latin AND America) OR TITLE-ABS-KEY (Caribbean) OR TITLE-ABS-KEY (global AND south) OR TITLE-ABS-KEY (third AND world) OR TITLE-ABS-KEY (developing AND countries)] was used in Scopus and Web of Science databases on 11 December 2022. The Scopus database generated 630 results, while the Web of Science generated 598 results, creating a database with 1,228 studies. All

1 https://www.fao.org/3/y0501e/y0501e03.htm

2 https://www.scopus.com/

3 https://www.webofknowledge.com

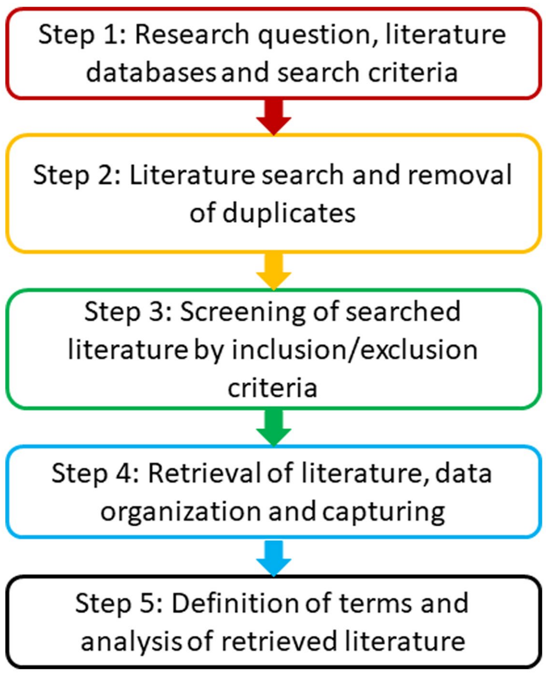

FIGURE 1
Methodology flowchart for systematic review using PRISMA protocol.

results obtained were exported to MS Excel and Mendeley. There were 359 duplicates in both databases, so they were immediately removed. At this stage, studies with titles only and no abstract or full text were removed. Eventually, 683 articles were subjected to abstract screening (Supplementary Figure 1).

3.2. Screening of literature, retrieval of literature, data organization, and capturing

The database was subjected to abstract screening by one author and was verified by another author using the criteria in Table 1 to include and exclude papers. Eventually, 210 articles were used in this study and were subjected to data extraction (Supplementary Figure 1). A data extraction sheet was designed in Microsoft Excel. Key data on the selected papers were extracted from the eligible studies and organized into a data extraction sheet. This was organized in columns including publication details (author, year, title), the problem being addressed, aim/objective, Data source (Primary, Secondary), Study type (Experimental, Conceptual, Cross-Sectional), Spatial Scale (Continental, Regional, National, City/Town, Household/Farm), Crops, Livestock, Data type (Qualitative, Quantitative), Measurements, Outcome. Where information was not given, it was left blank.

3.3. Data analysis and presentation

The database was organized into categories: year of publication, location, challenges the research is addressing (problems and pressures), crops and livestock included, and outcomes. Problem statements describe the problem or issue being addressed by the research study, hence problems and pressures were extracted from the problem statement. Studies identified one or more problems, and this was captured as is. Some problems and pressures were interlinked with others, and these interlinkages were captured. Descriptive methods such as frequency counting were used. A word cloud was prepared in NVivo 13 (QSR International Pty Ltd.) to identify emerging themes, using criteria of 1,000 most frequent words in the abstracts, with at least four letters. Word cloud visualizes word frequency and topical issues within a subject area. Most frequent terms were then used to identify major themes.

TABLE 1 Inclusion and exclusion criteria for the integrated crop-livestock research in mixed farming systems of the Global South database.

Criteria	Inclusion	Exclusion
Language	English	Any other language other than English
Location	Any location in the Global South	Any location outside the Global South
Farming system	Mixed farming systems/ Crop-Livestock System/ Agro-Pastoral/Integrated farming systems	Crop or livestock systems only
Type of article	Original research, opinion papers, technical reports	Reviews
Context	Productivity, livelihoods, challenges, perceptions, interventions, resilience, adaptation, resource use	

4. Results and discussion

4.1. Status of integrated crop-livestock research in mixed farming systems of the Global South

4.1.1. Annual distribution of integrated crop–livestock research in mixed farming systems of the Global South

In the Global South, research based on integrated crop-livestock systems dates back to the 1980s and showed a marked increase in the mid-90s (Figure 2). In 2002, there was a sharp increase in publications, doubling the previous average of 6 publications *per annum* (Figure 2). Integrated crop–livestock research began to rise, and the impacts of combining crop production and animal husbandry on soil fertility and the environment attracted great attention (Rufino et al., 2006; Herrero et al., 2010). The period from 2000 to 2010 was when the negative impacts of the green revolution on human nutrition and the environment became apparent (Pingali, 2012), thus the interest in integrated MFS and how to ensure productivity and sustainability of both the crop and livestock enterprises. 2020 had the highest number of publications (22; Figure 2).

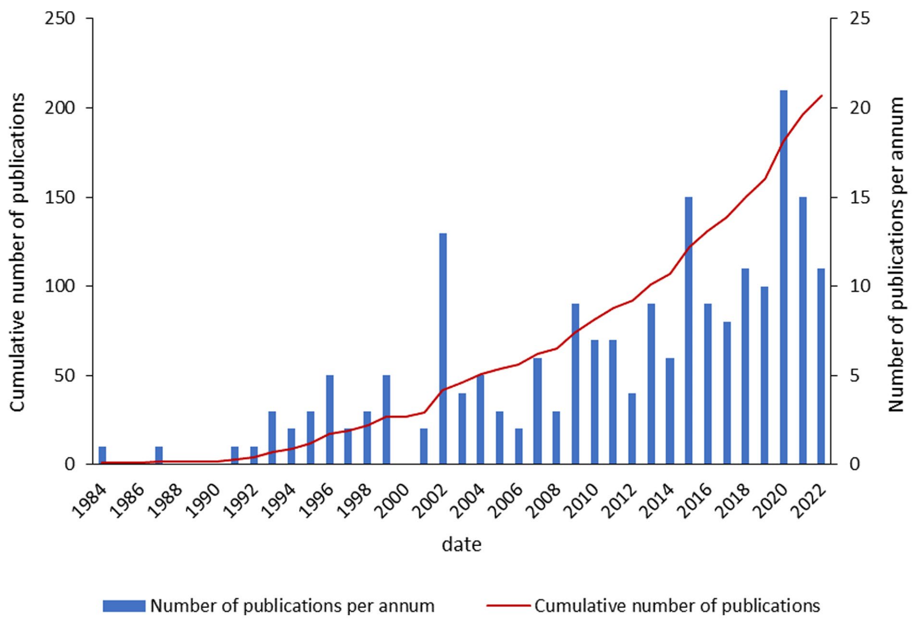

FIGURE 2
Annual distribution of integrated crop-livestock research in mixed farming systems of the Global South for the period 1984– 2022.

4.1.2. Geographical distribution of integrated crop-livestock research in mixed farming systems of the Global South

The geographical distribution of integrated crop-livestock research studies showed that Kenya and Ethiopia recorded the highest number of publications (22 and 28, respectively). This could be attributed to the strong presence of The International Livestock Research Institute (ILRI) in those countries and their mandate on livestock research. In Southern Africa, Zimbabwe and South Africa had the highest publications. For West Africa, several studies (19) were conducted in Nigeria, and others concentrated in the Sudanian savanna (Figure 3). In Asia, India (8) and China (7) had the highest number of publications (Figure 3). The study observed that water buffalos as part of domesticated livestock were unique to Asia, and no African countries mentioned buffalos in livestock enterprises (data not presented). Latin America had the least number of studies combined; however, with the region, Brazil and Cuba had the highest number of publications (2; Figure 3).

4.1.3. Word frequency in integrated crop-livestock research in mixed farming systems of the Global South

The word frequency search results showed that crop-livestock-based research focused on on-farm food and feed production by smallholder farmers and soil productivity (Figure 4). Two broad themes to summarize the word frequency were (i) the economic and social status of integrated crop-livestock research in MFS and (ii) the ecological status of integrated crop-livestock research in MFS. Under the former, studies looked at aspects such as availability of feed and feed, productivity, incomes and food security, while studies under the latter addressed nutrient cycling in MFS of the Global South. The farm was also a major word, suggesting that most studies were at the farm scale. Results also revealed that maize was frequently mentioned among integrated crop-livestock research studies, suggesting it is a major crop MFS for human and animal consumption (Figure 4). Cattle and sheep, both ruminants, were the most frequently mentioned livestock among crop-livestock-based research studies in MFS of the Global South.

4.1.4. Modelling crop-livestock systems in mixed farming systems of the Global South

Whole farm models are predictive tools that combine crop and livestock systems and can be used to help improve farming systems' efficiency and profitability. There has been progress in modelling mixed farming systems in the Global South. The review identified 10 simulation tools that have been explored to answer some research questions on MFS in the Global South (Table 2). Six of the tools [Vensim™ dynamic stock-flow feedback model, Whole-farm EPM (Econometric-process simulation model), Integrated Analysis Tool (IAT), The Simflex model, FarmDESIGN and CLIFS (Crop LIvestock Farm Simulator)] have a focus on aiding decision making for whole farm management of crop and livestock on an annual time scale from an economic point of view. Three models [TERRoir level Organic matter Interactions and Recycling model, GANESH (Goals oriented Approach to use No-till for a better Economic and environmental sustainability for Smallholders), Agent-based Model of Biomass flows in Agro-pastoral regions of West Africa (AMBAWA)] were developed to manage nutrients on the farm, especially determining the most efficient cycling of manure and crop residues (Table 2).

4.2. Problems and pressures addressed by the integrated crop-livestock research in mixed farming systems of the Global South

Studies mentioned one or more problems and pressures affecting MFS, including population growth, water scarcity, land scarcity,

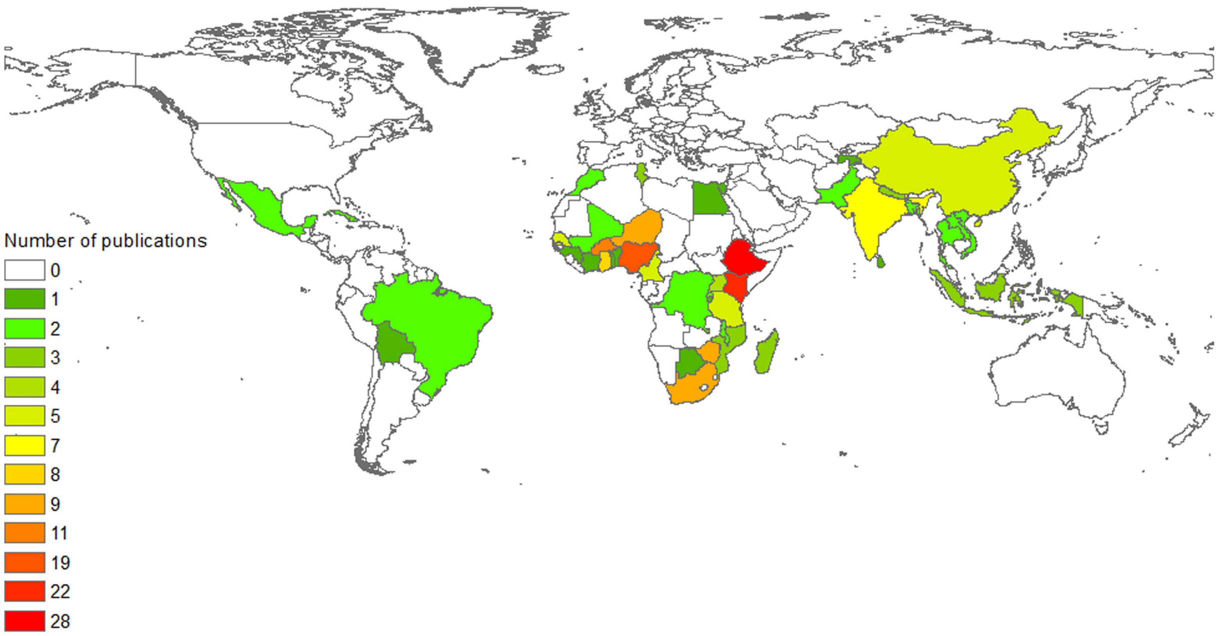

FIGURE 3
Geographical distribution of integrated crop-livestock research in the Global South [excludes studies with a regional (n = 7) or continent focus (n = 9)].

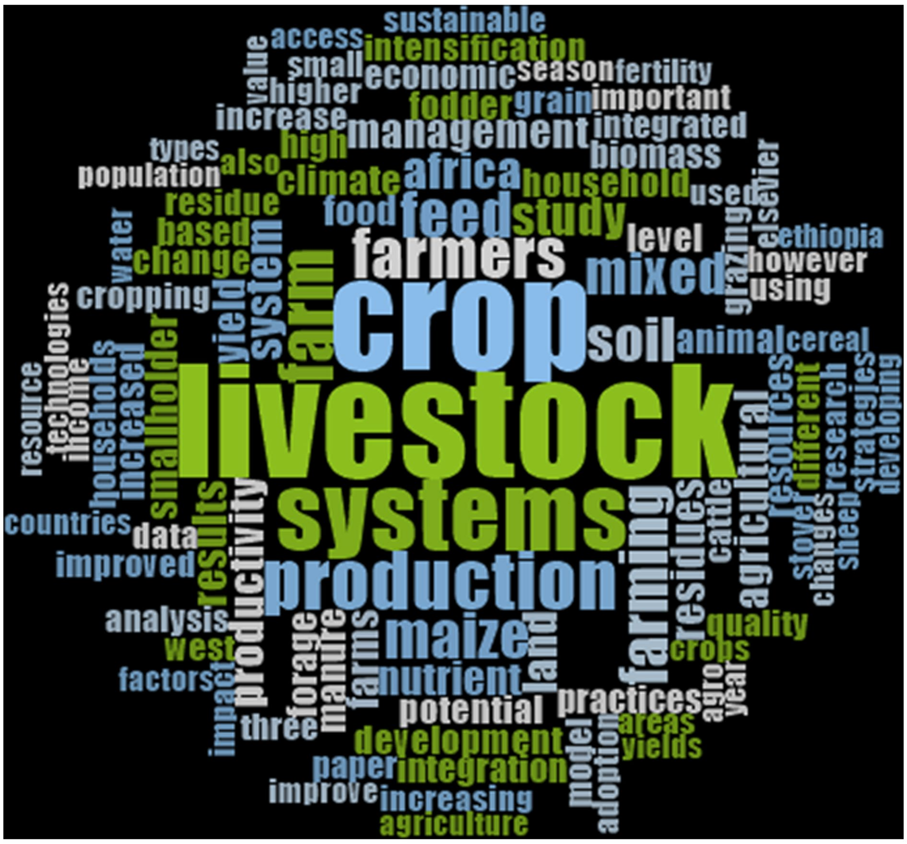

FIGURE 4
Word cloud generated from abstracts in an integrated crop-livestock research database for the Global South.

TABLE 2 Examples of mixed farming system modelling conducted in the Global South.

Name of simulation tool	Objective	Example case study	References
Goals oriented approach to use no-till for a better economic and environmental sustainability for smallholders (GANESH)	To explore the relationships between dairy production, different modalities of CA practices and biomass uses with economic income optimized at the farm level.	Explored tradeoffs and synergies between combinations of conventional and CA plots, different CA management options and the size of dairy cow herds in Madagascar	Naudin et al. (2015)
The nutrient use in animal and cropping systems – efficiencies and scales (NUANCES)	To assess ex-ante the feasibility, impact and tradeoffs of changing agricultural management in the short- and long-term, focusing on processes taking place at the farm rather than the single plot level.	Information from experimentation, soil types, livestock feeding and manure management were combined and used to design a strategy to restore the fertility of unproductive soils and improve livestock nutrition in a village in north-east Zimbabwe.	Giller et al. (2011)
Vensim™ dynamic stock-flow feedback model	To assess the biophysical and economic consequences of selected suites of management decisions and farming practices observed in the smallholder milpa-sheep system.	To assess the biophysical and economic consequences of selected suites of management decisions and farming practices observed in the smallholder milpa-sheep system of Yucatán State.	Parsons et al. (2011)
Whole-farm EPM econometric-process simulation model (EPM)	To estimate behavioral equations from econometric production models for each activity in the system and use these equations to simulate farmers' decisions as functions of farm characteristics, prices and policy.	Investigated the potential for interventions proposed by the Government of Kenya to meet the SDGs by 2030.	Valdivia et al. (2017)
Integrated analysis tool (IAT)	To assess crop, livestock, and socio-economic outcomes from different proposed intervention strategies and the level of risk to different components of the household resources.	Analyzed the impact of prospective farming systems change for a smallholder household in the eastern islands of Indonesia.	McDonald et al. (2019)
The Simflex model	Simulates farmers' decision rules governing the management of the cropping and livestock farm components, as well as crop and livestock production and farm gross margin.	Simulated current farm performance by assessing the cereal balance, the fodder balance and the whole farm gross margin in Burkina Faso.	Andrieu et al. (2015)
FarmDESIGN	Supports evaluation and re-design of mixed farm systems in planning processes used in this case for the calculation of nitrogen flow to, through and from a farm.	Quantified nitrogen flows, generate ENA indicators of integration, diversity and robustness, and explore the impact of crop intensification options on N networks across farm types in the mid-hills and lowland (Terai) of Nepal.	Alomia-Hinojosa et al. (2020)
TERRoir level organic matter interactions and recycling model	To assess soil fertility management and the nutrient recycling efficiency of agro-sylvo-pastoral landscapes.	Analyzed the organization of the N cycle and related impacts on soil fertility and N recycling efficiency in two contrasted villages in central Senegal: (i) an extensive system (Vext) based on free-grazing herds and a landscape structure favorable to herd mobility, and (ii) an intensive system (Vint) based on in-barn.	Grillot et al. (2018)
Crop LIvestock farm simulator (CLIFS)	To provide farmers with elements to consider and assess when considering a medium to a long-term development project for their farms.	Built scenarios of a farm's evolution and assessed them ex-ante by calculating several balances at the farm level (staple food, forage, manure) and their effects on the farm's economic results. The support process has been tested in several African and South American contexts.	le Gal et al. (2022)
Agent-based model of biomass flows in agro-pastoral regions of West Africa (AMBAWA)	To explore different scenarios of crop residue mulching on crop productivity at the field, farm, and village scales	Assessed the effects of crop residue management (mulching versus cattle feeding) on crop productivity in a village in central Burkina Faso	Berre et al. (2021)

economic growth, food insecurity, feed insecurity, land degradation, climate change, poor productivity, disease outbreaks and social change (Table 3). Table 4 summarizes the number of times the total studies mentioned each problem. Pre-1990, there were only two studies, and the problems and/or pressures identified were economic growth, land degradation and poor productivity (Table 4). During the 1990s, most of the research addressed the shortage of animal feed, land degradation and population growth that was driving increased food demand.

TABLE 3 Description of problems and pressures that the integrated crop-livestock research seeked to address.

Driver of change	Description
Population growth	The observed and projected population growth in the Global South. This will, in turn, increase the demand for food
Water scarcity	Water scarcity included all forms of water scarcity (economic and physical) plus droughts
Land scarcity	The shortage of land for both crop production and pastures. Small farm sizes
Economic growth	Included urbanization and rising incomes
Food security	Physical and economic access to sufficient, safe and nutritious food at all times that meets human dietary needs
Feed security	Physical and economic access to sufficient, safe and nutritious food at all times that meets livestock dietary needs
Land degradation	Declining soil quality (both physical and chemical soil quality), soil erosion
Climate change	Changes in weather patterns over time
Poor productivity	Low crop yields, low livestock weights, low livestock numbers
Social change	Rural to urban migration and dietary changes
Disease outbreaks	Animal disease outbreaks caused devasting deaths to livestock

TABLE 4 Problems and pressures identified in the problem statements of the integrated crop- livestock research studies from 1980 to date.

	1980–1990	1991–2000	2001–2010	2011–2020	2021 to date
	$n = 2$	$n = 24$	$n = 54$	$n = 99$	$n = 27$
Population growth	–	9	13	62	4
Water scarcity	–	3	5	29	2
Land scarcity	–	5	5	31	2
Economic growth	2	3	3	29	3
Food security	–	4	4	28	3
Feed security	–	10	5	39	4
Land degradation	1	7	17	61	6
Climate change	–	2	6	33	6
Poor productivity	1	5	12	56	8
Social change	–	3	1	12	1
Disease outbreaks	–	1	–	2	–

While it may be a surprise that the shortage of animal feed was the biggest problems in the 90s, this was because of significant land use changes during this period (Jagtap and Amissah-Arthur, 1999). Historically, livestock in smallholder MFS relied on grazing in rangelands, and these areas shrank significantly in favor of urbanization and extensification of crop production (Gavian and Ehui, 1999; Jagtap and Amissah-Arthur, 1999). Farmers were faced with the need to supplement grazing with feed. During this period, labor bottlenecks were also identified (Table 4). This coincides with the highest rural-to-urban migration period observed in developing countries (Lerch, 2020; Brown, 2021). From 2001 to 2010, the trend was the same, but studies that identified climate change as a problem for MSF in the Global South also started to increase.

Climate change directly affects MFS through seasonal shifts, climate variability and extreme weather events (Ahmad and Ma, 2020; Mihiretu et al., 2020; Mujeyi et al., 2022). Post-2010 studies addressing climate change rose approximately five times more. Farmer perceptions of climate change showed that farmers observed changes in weather variables and acknowledged climate change as a threat (Mihiretu et al., 2020). What remains a challenge is the low adaptive capacity to climate change (Ahmad and Ma, 2020; Mihiretu et al., 2020) and poor adoption of climate-smart interventions (Mujeyi et al., 2022). Food and feed insecurity were also topical from 2011 to 2020 (Table 4).

It is impossible to discuss problems or pressures in MFS as mutually exclusive. The review showed that problems or pressures in MFS were not mutually exclusive and were interlinked (Figure 5). One challenge can also perpetuate another. Problems or pressures can both be direct and indirect (Figure 5). Population growth is not only associated with increased demand for food but is a major driver in the water and land scarcity the world is currently facing. Smallholder agriculture is the major source of food in the Global South (Devendra and Thomas, 2002; Vanlauwe et al., 2014). Farm sizes in the Global South have decreased (Lowder et al., 2016), implying that any increase in crop production to mitigate food insecurity cannot be met through extensification, and livestock production cannot be sustained through rangelands and paddocks alone. Farmland degradation has been cited as one of the drivers of change in MFS. This has been attributed to unsustainable cropping and grazing practices. Unsustainable cropping practices include monoculture practices that mine nutrients in the soil, the use of synthetic fertilizers that increase soil pH and tillage practices that have contributed to soil runoff (Thorne and Tanner, 2002; Sumberg, 2003; Manlay et al., 2004; Semwal et al., 2004). Poor soil quality, among other factors such as water scarcity and climate change, has also contributed to low crop yields. Despite livestock showing potential to improve soil quality through manure, this is not fully exploited due to bottlenecks such as low livestock numbers and shortage of on-farm labor (Nkonya et al., 2005; Manyong et al., 2006; Onduru et al., 2007).

Farmers need to supplement livestock diets with expensive feed with shrinking grazing land and dry pastures during dry seasons. Alternative use of crop biomass as animal feed is not guaranteed as it depends on yield and often competes with other on-farm needs (Parthasarathy Rao and Hall, 2003). However, several studies assessed

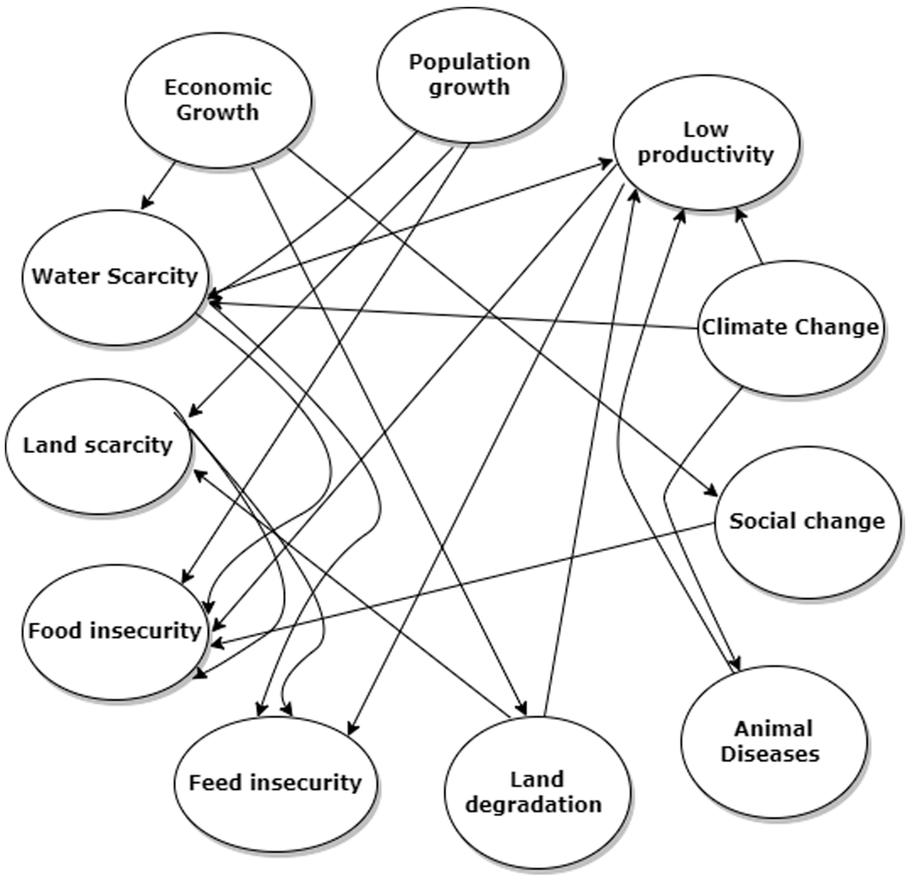

FIGURE 5
Linkages between problems and pressures driving integrated crop-livestock research in MFS of the Global South.

how to efficiently allocate these resources to balance healthy croplands and livestock nutrition (Naudin et al., 2015; Grillot et al., 2018; Berre et al., 2021). Growing fodder crops on cropland competes with food for human consumption. Economic growth, which also includes urbanization, has contributed to dietary changes. There is a growing preference for animal-based protein compared to plant-based protein (Herrero et al., 2010). Economic growth has also led to rural-to-urban migration of the economically active population, leading to a labor shortage for MFS (Zhou et al., 2020). Farmers have to prioritize labor allocation between the crop and livestock enterprises. Livestock disease outbreaks such as East Coast Fever and Trypanosome have also been observed to cause mortality and morbidity in livestock (Ejlertsen et al., 2012; Muhanguzi et al., 2014). Disease severance and frequency of outbreaks have been associated with climate change through conducive temperatures and other climatic conditions that encourage the reproduction and distribution of parasites and their vectors (Ali et al., 2020).

4.3. Strategies and approaches to improve mixed farming systems in the Global South

The review summarized proposed strategies and approaches to improve the efficiency of MFS in the Global South (Table 5). Interventions identified were classified into the following categories: feed and land management, food security, livestock management, climate change adaptation, policy and agribusiness (Table 5). The findings show that improving feed quality and supply through high biomass fodder and adopting improved drought-tolerant fodder crops can enhance feed production (Table 5). The availability of adequate feed resources and strategies for coping with feed scarcity ensure sustainable livestock production and food security (Mekonnen et al., 2019, 2022). With the increasing frequency and intensity of droughts in the Global South, it is important to utilize climate-smart forage grasses that combine nutrition and drought tolerance (Haileslassie et al., 2005; Descheemaeker et al., 2010). For instance, oat (*Avena sativa* L.)–vetch (*Vicia villosa* Roth) mixture, lablab [*Lablab purpureus* (L.) Sweet], vetch–desho grass (*Pennisetum pedicellatum* Trin.) intercropping, sweet lupin (*Lupinus albus* L.), alfalfa (*Medicago sativa* L.), and fodder beet (*Beta vulgaris* L.) showed high yield responses in farmers' fields and ultimately animal response trials showed an increase in milk yield (Mekonnen et al., 2022). Overexploitation of grazing resources and unsustainable cropping practices result in land degradation. Nutrient cycling and controlled grazing can sustainably control land degradation (Dougill et al., 2002; Ikpe and Powell, 2002; Haileslassie et al., 2007; Diarisso et al., 2015; Epper et al., 2020; Berre et al., 2021). Nutrient

TABLE 5 Strategies and interventions to improve mixed crop livestock systems.

Strategies	Proposed interventions	References
Feed management		
Improving feed quality	i) Cultivate fodder species or mixtures of species with useful nutritional qualities. ii) Introduction of leguminous cover crops	Larbi et al. (1999b); Devendra and Sevilla (2002); Blümmel et al. (2013); de Groote et al. (2013); Mupangwa and Thierfelder (2014); Mekonnen et al. (2022)
Improve feed quantity	i) Integration of high biomass crop genotypes for increased retained residues. ii) Introduction of new technologies such as legume-cereal mixture and use of indigenous species	Larbi et al. (1999b); de Groote et al. (2013); Notenbaert et al. (2013); Baudron et al. (2015); Komarek et al. (2015); Alomia-Hinojosa et al. (2020); Mekonnen et al. (2022)
Feed utilization	i) Reducing wastage through postharvest feed management and utilization options	Thorne and Tanner (2002); Tarawali et al. (2011); Mekonnen et al. (2022)
Improving feed water productivity	i) Considering the nutritional value, and drought tolerance in forage systems	Haileslassie et al. (2005); Descheemaeker et al. (2010)
Land management		
Nutrient cycling and soil fertility	i) Increased retention of crop residues ii) Conserve and manage waste to maximize nutrient cycling iii) Optimize the animals' time for foraging iv) Adopt high-value vermicompost production v) Introduction of leguminous cover crops	Dougill et al. (2002); Ikpe and Powell (2002); Haileslassie et al. (2007) Diarisso et al. (2015); Epper et al. (2020); Berre et al. (2021)
Grazing	i) Appropriate grazing management to prevent degradation ii) Location of watering points in rangelands iii) Head control of small ruminants	Taddese et al. (2002); la Rovere et al. (2005); Mekonnen et al. (2022)
Land rehabilitation	i) Controlled grazing ii) Zero-grazing iii) Increased retention of crop residues	MacLaren et al. (2019); Abdalla et al. (2021); Pfeiffer et al. (2022)
Food security		
Crop selection	i) Use of dual-purpose crops and varieties	Larbi et al. (1999b); Claessens et al. (2008); de Groote et al. (2013); Tui et al. (2015)
Improve crop productivity	i) Adopting new technologies such as Conservation Agriculture and Climate Smart Agriculture ii) Including improved climate-resilient crop breeds iii) Offer extension and agronomy support	Delgado (1989); Gavian and Ehui (1999); Andrieu et al. (2015); Henderson et al. (2018); Melesse et al. (2021); Moseley (2022)
Livestock management		
Improved animal health and livestock population	i) Focus breeding on improved, adapted local breeds ii) Access and delivery of appropriate artificial insemination iii) Veterinary service delivery in rural areas iv) Feed interventions v) Education and training	Bernués and Herrero (2008); Ejlertsen et al. (2012)
Improving the productivity of the livestock	i) Enhance farmers' access to relevant production and marketing information and improve crop-small-ruminant technologies ii) Integrating and intensifying feed and forage resources and postharvest innovations iii) Shortening the calving interval, improving disease resistance and working on factors that improve the vigor of the calves	Delgado (1989); Ajeigbe et al. (2010); Kassie et al. (2010); Ejlertsen et al. (2012); Asante et al. (2019)

(Continued)

TABLE 5 (Continued)

Strategies	Proposed interventions	References
Climate change adaptation		
Building resilience in communities	i) Develop appropriate drought adaptation strategies and avert the increasing degradation of woodlands ii) Agricultural diversification at the household level iii) Dissemination of information on climate change and adaptation strategies	Bernués and Herrero (2008); Moritz (2010); Fadina and Barjolle (2018); Henderson et al. (2018); Ahmad and Ma (2020); Conradie and Genis (2020)
Supportive institutions and policies		
Policies	i) Institutions to facilitate index-based livestock insurance ii) Investments in rural infrastructure iii) Enhancing profitability, efficiency and comparative advantage of indigenous cattle meat and milk production iv) An enabling environment for private investments in waste management v) Gender equality vi) Enhance access to farm resources and address barriers to input and output value chains vii) Legal land tenure systems	Jabbar (1993); Dougill et al. (2002); Devendra and Sevilla (2002); Devendra and Thomas (2002); Komarek et al. (2015); Ayantunde et al. (2018); El-Shater and Yigezu (2021)
Agribusiness		
Markets	i) Provide access to markets and relevant knowledge ii) Market segmentation analysis to enable identification of niche marketing of indigenous products iii) Access to the training facilities	Notenbaert et al. (2013); Mujeyi et al. (2022)
Technology adoption	i) Use of localized decision support tools to optimize farm productivity ii) Address barriers to input and output value chains; identify appropriate niches for technology development and intervention	Jabbar (1993); Giller et al. (2011); Naudin et al. (2015); Grillot et al. (2018); McDonald et al. (2019); Mekonnen et al. (2022)

budgets in MFS of Burkina Faso, showed partial balances of phosphorous were generally positive, which was also a result of phosphorous fertilizer use (Diarisso et al., 2015). Baudron et al. (2014) argued that the competition for cereal residues between livestock feeding and soil mulching should not deter conservation agriculture in MFS. Still, there is a need to strike a balance. To manage competition for food between humans and livestock, the use of dual-purpose crops such as groundnut, maize, millets and sweet potatoes was shown to ease this pressure and simultaneously improve food and fodder both in terms of quantity and nutritional quality (Larbi et al., 1999a; Claessens et al., 2008; De Groote et al., 2013; Tui et al., 2015).

Mixed farming systems in the Global South are threatened by livestock disease outbreaks that cause mortality to livestock and humans. Breeding for resistance and efficient veterinary services can prevent or control the prevailing diseases (Table 5; Bernués and Herrero, 2008; Ejlertsen et al., 2012). There is also a need to enhance farmers' access to relevant production and marketing information for improved livestock production. Policymakers in governments, extension services, research, and livestock development partners, and private sectors can formulate policy interventions that promote access to finance and markets for subsistence MFS (Table 5; Delgado, 1989; Ajeigbe et al., 2010; Kassie et al., 2010; Ejlertsen et al., 2012; Asante et al., 2019).

Climate change presents a challenge to the productivity, sustainability and profitability of MFS. Building the resilience of smallholder farmers is important to ensure the sustainability of these systems. Diversifying production practices and using drought-tolerant crop varieties and livestock breeds are strategies for farmers to adapt to the changing climate (Table 5; Bernués and Herrero, 2008; Moritz, 2010; Fadina and Barjolle, 2018; Henderson et al., 2018; Ahmad and Ma, 2020; Conradie and Genis, 2020). Smallholder farmers need access to funds to finance adaptation practices. Climate information is also critical in guiding the adaptation needs of farmers at a local level. There should be efforts to address inequalities in MFS and support all smallholder farmers to access information, markets and finance (Devendra and Sevilla, 2002; Dougill et al., 2002; Ayantunde et al., 2018). The adoption of technologies to close the labor gap and to improve farm efficiency was identified as a strategy to improve MFS; however, there is generally poor adoption of technologies by farmers. There is a need to identify appropriate niches for technology development and interventions to improve adoption (Jabbar, 1993; Grillot et al., 2018). Decision support tools were identified as potential solutions to improve decision-making in farm design and managing limited resources for greater economic returns and land conservation (Giller et al., 2011; Naudin et al., 2015). These tools were, however, still in development and evaluation; there were no publications detailing how they have been extended to the end users (farmers and extension services).

5. Limitations of review

The review used the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to identify, select, appraise, and synthesize studies. Due to the choice and combinations of predefined search terms, some literature may have been excluded. The review only searched for literature in scientific databases (WoS and Science Direct), thus excluding other potential sources of "gray literature" such as dissertations and reports. Asia may also have been underrepresented in this study. Authors believe that some work is done by the Indian Council of Agricultural Research on Integrated farming system research, but most of this work has not yet been published; hence is not reflected in this review. The authors also acknowledge that there is a lot of research conducted in MFS; however, only integrated crop and livestock research was selected for this review.

6. Conclusion and recommendations

A scoping review was conducted to synthesize integrated crop-livestock research in MFS of the Global South. Crop-livestock research in the Global South dates back to the 1980s. Economic growth, land degradation and poor productivity sparked research interest in these systems during that time. In the 1990s, the shortage of animal feed was topical due to land use changes that shrunk grazing rangelands. Geographically, crop-livestock-based research was concentrated in Ethiopia, Kenya, Nigeria and the Sudanian savanna of West Africa. The focus of the crop-livestock research was on-farm production of food and feed by smallholder farmers and soil productivity, with maize being the most frequently mentioned crop and sheep and cattle being the frequently mentioned livestock. The review identified 10 simulation tools explored in the Global South to address aspects such as farm design, nutrient cycling and operational decision-making. These tools are still in the research and development phase, and there was no evidence to suggest that farmers and extension services are utilizing these tools. Piloting these technologies to the intended users and addressing any limitations that may hinder their adoption is necessary.

Problems and pressures affecting MFS included population growth, land degradation, climate change, water scarcity, economic growth, etc., but cannot be viewed individually as they are interlinked. For example, climate change can directly influence climate change through extreme events affecting crops and livestock. Indirectly, climate change promotes livestock diseases that affect the viability of MFS. It is worth mentioning that there are many other challenges affecting viability of MFS that were not addressed by this literature database. These include international trade and globalization of markets, shifts in country policies, shortening market chains, property rights, market rights and declining human health (malnutrition; Hazell and Wood, 2008; Herrero et al., 2012). Our database comprised of studies mostly addressing biophysical aspects of integrated crop-livestock research. The review identified interventions to improve viability and sustainability in MFS. These included managing land for feed and food security by introducing legume cover crops, drought-tolerant crops, forage grasses, and dual-purpose crops. Strategies such as using indigenous breeds and access to veterinary services were proposed to manage livestock mortality and morbidity. The need for appropriate policies and business models that create an enabling environment for MFS in the Global South was highlighted. While there were suggestions of coming up with the right policies for markets, investments and tenure systems, there is still need for research that unpacks any unforeseen tradeoffs, so that the policies have the intented consequence's on farmers in MFS.

The review concludes by highlighting some gaps that can guide future research in MFS. Considering that MFS exist across almost all agroecological regions in the Global South, authors felt there was limited literature integrating crop-livestock systems. As we were doing literature screening, there was a lot of research on individual crop or livestock components. This fails to capture any synergies and tradeoffs between the two components. There is a need for research that integrates crop-livestock systems and natural resource management innovations that can be scalable under different agroecology's of the Global South. The interaction between MFS and agricultural water management was almost lacking in the literature. Since water is a scarce resource and often limiting in smallholder systems, it is important to consider how MFS strategies respond to combinations of water management strategies and how such measures can improve production and water use efficiency (WUE). Multiple-use water services and systems (MUS) have emerged as a promising way to enhance single-water use systems' productivity but are yet to be exploited in MFS. Water footprints have been evaluated separately for crops (Mekonnen and Hoekstra, 2011; Chu et al., 2017) and livestock (Ibidhi and Salem, 2020) and research opportunities exist for evaluating water footprints in MFS. The sustainable intensification of MFS is critical to meeting productivity goals without compromising social and ecological outcomes. Diversification in mixed systems also remains important, especially its potential to buffer against risks of climate change and the prospects of multiple ecosystem services. No single practice or strategy will suffice to achieve sustainable intensification of MFS, but rather an ensemble of approaches calibrated for local contexts and environmental conditions.

Author contributions

TM: conceptualization and critical analysis. TC: conceptualization, methodology, data curation, and writing – original draft preparation. AS: critical analysis. All authors contributed to the article and approved the submitted version.

Acknowledgments

The authors would like to acknowledge contributions from the reviewers of this review, and funding from the One CGIAR Sustainable Intensification of Mixed Farming Systems (SI-MFS) Initiative, which is grateful for the support of CGIAR Trust. Fund contributors: www.cgiar.org/funders.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2023.1241675/full#supplementary-material

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TYPE Original Research
PUBLISHED 27 September 2023
DOI 10.3389/fsufs.2023.1189451

OPEN ACCESS

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RECEIVED 19 March 2023
ACCEPTED 07 September 2023
PUBLISHED 27 September 2023

CITATION
Tian S and Mei Y (2023) Emergency regional food supply chain design and its labor demand forecasting model: application to COVID-19 pandemic disruption.
Front. Sustain. Food Syst. 7:1189451.
doi: 10.3389/fsufs.2023.1189451

Emergency regional food supply chain design and its labor demand forecasting model: application to COVID-19 pandemic disruption

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The COVID-19 pandemic has severely disrupted the global food supply chain through various interventions, such as city closures, traffic restrictions, and silent management. Limited research has been conducted on the design of emergency regional food supply chains (ERFSC) and its labor demand forecasting under government-mandated interventions. This paper applies emergency supply chain management theory to analyze the business processes of the ERFSC and proposes a multi-level ERFSC network tailored to different risk levels. Additionally, a food demand forecasting model and a mathematical model for stochastic labor demand planning are constructed based on the development trend of regional epidemics. An empirical analysis is presented using Huaguoyuan, Guiyang, China, as an example. The results demonstrate that the proposed ERFSC design and its labor demand forecasting model can achieve secure supply and accurate distribution of necessities in regions with different risk levels. These findings have important policy and research implications for the government and practitioners to take interventions and actions to ensure food supply for residents in the context of city closure or silent management. This study serves as a pilot study that will be further extended by the authors from geographical and policy perspectives.

KEYWORDS
COVID-19, emergency regional food supply chain (ERFSC), public health emergencies, necessities, end-delivery services, labor demand forecasting, interchange state

1. Introduction

During the COVID-19 pandemic, many countries have implemented extensive lockdowns, economic interventions, and health system measures to mitigate the spread of the virus (Ivanov and Dolgui, 2020; Hale et al., 2021). Several recent studies have concluded that the lockdown has posed a threat to food security, leading to reduced yields, disruptions in food supply chains, restricted trade flows, and reduced dietary choices (Devereux et al., 2020; Fan et al., 2020). The interventions implemented to contain COVID-19 have significantly impacted the food value chain, resulting in difficulties in purchasing necessities and insecurity of basic needs for the population in the outbreak region (Hobbs, 2020; Narayanan et al., 2020). In urban areas that rely on external supplies to meet their needs, sudden disruptions in food supply and panic buying behavior caused prices to soar and triggered social panic (Davila et al., 2021). On the supply side, the lockdown may lead to a reduction in vegetable production and also lengthen the food distribution cycle, particularly impacting some perishable commodities such as fruit, meat products, and fresh vegetables (Harris et al., 2020; Yu et al., 2020; Huang et al., 2021). On the demand side, the outbreak of the COVID-19 crisis may cause social panic and potential hoarding of food, leading to two extremes of over-buying and under-buying that can impact the basic livelihood security of people quarantined at home (Goddard, 2020; Nicomedes and Avila, 2020; Zhang et al., 2020).

The pandemic has exposed the vulnerabilities of global food supply chains and disrupted the flow of food from producers to consumers (Christiaensen et al., 2021; Yin et al., 2021; Alabi and Ngwenyama, 2023). The regional food supply chains are becoming a viable alternative for food security due to easier access to local food (Cristiano, 2021; Thilmany et al., 2021). Regional food supply chains are based on local food production and demand and are characterized by fewer intermediaries, shorter distribution times, greater agility, and more sustainability in economic, environmental, and social terms than conventional food production (Berti and Mulligan, 2016). They are also favored by consumers for reasons such as fresher, safer, more nutritious food supplies and support for local economic development (Schnell, 2013; Feldmann and Hamm, 2015). The efforts are underway to reconfigure and innovate the current food supply chain and strengthen the urban-rural integration of food supply to build a more stable, resilient, and sustainable food supply chain (Mollenkopf et al., 2021; Sharma et al., 2021). The Food and Agriculture Organization of the United Nations has emphasized the importance of regional supply chains in countering large-scale disruptions in food supply chains caused by the COVID-19 crisis (Food and Organization, 2020; Rosenzweig et al., 2020). Strengthening regional food supply chains is also being considered as a viable option for dealing with the impact of uncertainty (Mahajan and Tomar, 2021). Singh et al. (2021) proposed a public distribution system consisting of a central warehouse, state warehouse, district warehouse, and fair price shop to quickly recover the food supply in the region.

The COVID-19 crisis has resulted in labor shortages in the food supply chains due to lockdowns, movement restrictions, quarantines, and illnesses (Hobbs, 2020; Saul et al., 2020). As labor is a crucial input for the functioning of every supply chain network, this can lead to increased costs, lower profits for firms, higher prices for consumers, and unfulfilled demand (Bhattarai and Reiley, 2020). To cope with sudden labor demands during an outbreak, redundancy within the supply chain system or finding new alternatives can be a way forward (Coopmans et al., 2021). Nagurney (2021) developed a supply chain network optimization framework that explicitly includes labor as a variable in the economic activities of supply chain networks, such as production, transportation, storage, and distribution. Community organizations are using local information, networks, and relationships to distribute food to community residents during the pandemic (Aday and Aday, 2020). In emergency supply chain management, the establishment of self-organization with efficient management and transparency of information is crucial (Zebrowski, 2019; Banerjee et al., 2021; Mutebi et al., 2021). Shareef et al. (2019) argue that volunteers play an important role in emergency disaster rescue and provide access to a government-run network of volunteer requisitioners. Some studies suggest that an integrated system of simultaneous truck and drone distribution in high-risk zones can efficiently meet demand distribution without close contact (Jeong et al., 2019; Das et al., 2020). In addition, outdoor spaces are being designated in different parts of the city as alternative locations for traders and farmers to conduct sales transactions during retail closures (Singh et al., 2021). Therefore, the rapid recovery or reconstruction of the food supply chain in the region during public health emergencies requires the consideration of the population, distribution location, risk area division, interchange state (IS) setting, operator requirements and end-delivery strategy, which is a complex system project.

By analysing the literature, resilience and sustainability were found to be the most critical themes, and the application of various innovative technologies such as digital twins, artificial intelligence, blockchain and the Internet of Things in the management of supply chains suffering from sudden disruptions was more studied (Moosavi et al., 2021, 2022; Montoya-Torres et al., 2023). However, it was discovered that there has not been sufficient discussion on how to quickly construct an ERFSC, particularly in the context of a logistics park outbreak and city-wide silent management. Although researchers have proposed several ideas for restoring the food supply chain during a pandemic, the practicality of these ideas is limited due to different premises considered in previous studies (Fan et al., 2020; Chitrakar et al., 2021; Dixon et al., 2021; Huang et al., 2021). This research gap includes the lack of food supply chain network design, end-delivery services strategies, and labor demand forecasting models under lockdown conditions. To address this gap, we present a multi-level regional food supply chain system solution adapted to different risk levels, which is being introduced for the first time. Finally, we construct an ERFSC framework of agricultural suppliers, distribution centres (DCs), ISs, and residents as an example, focusing on Huaguoyuan in Guiyang City, China, to achieve secure supply and accurate distribution of necessities in areas with varying risk levels. This study makes important contributions to the field, including:

(i) It proposed a more practical strategy for safeguarding the supply of necessities to regional residents during a regional pandemic outbreak, namely a regional food supply chain design based on dynamic demand for essential supplies, labor demand forecasting and end-delivery strategies to achieve risk management and emergency response during emergencies such as food supply chain disruptions.

(ii) It studied the development of a demand forecasting model for necessities and a labor forecasting model for regional food supply chain operation requirements and end-delivery services strategy based on the risk trend of the epidemic in the region under silent management interventions, which improved the efficiency and quality of ERFSC management.

(iii) The proposal of an ERFSC labor demand forecasting algorithm that takes into account uncertain parameters and fully considers the random distribution properties of these parameters.

Our study serves as an important theoretical foundation for future research on ERFSC reconfiguration and labor demand forecasting during emergency situations. Additionally, it provides valuable recommendations for government agencies, businesses, and social organizations involved in emergency response.

2. ERFSC network design

The ERFSC is a temporary alliance formed by the government in response to emergencies to integrate various advantageous resources of society. In addition to the characteristics of the general regional food supply chain, the ERFSC has variations in the operation items of each activity link in the supply chain and temporary cooperation and coordination among them. This is also the key factor determining the operational efficiency of the ERFSC (Shah Alam Khan, 2008; Dwivedi et al., 2018). An effective emergency regional supply chain should be able to make rapid assessments and decisions based on actual dynamic demand (Dwivedi et al., 2018).

There are several issues in emergency supply chain operations, such as mapping existing emergency supply chains, demand forecasting and assessment, procurement, inventory management, logistics management, and relief distribution (Wang and Zhang, 2016). Therefore, it is necessary for the government to set up a supply assurance team to optimize the distribution of resources to transport agricultural products to designated farmers' markets, retailers, or sell them directly to residents.

Generally, food supply chains consist of a three-tier structure of supplier-DC-retailer, and the farmer-consumer model is also more common in regional food supply chains (Thilmany et al., 2021). During an outbreak in an urban area, interventions such as city closures, movement restrictions, and home quarantines can lead to the city being divided into smaller zones for management, such as administrative boundaries, communities, and neighborhoods. In such cases, DCs become the main source of supplies for the city's residents. To achieve full coverage and precise distribution of food while complying with epidemic prevention policies that reduce movement, we propose an ERFSC network with DCs as the source, as depicted in Figure 1. Here, each DC is responsible for a certain range of retailers/ISs, and each retailer/IS is responsible for supplying food to residents in a designated zone.

During the epidemic, unexpected transport restrictions and labor shortages disrupted the urban food supply chain (Hobbs, 2020; Sukhwani et al., 2020). Availability of labor, including loading and unloading, delivery, sorting, and processing labor, as well as smooth logistics, became the crucial factors in maintaining the food supply chain. For some companies, the inability of employees to return to work became a bottleneck (Singh et al., 2021; Tarra et al., 2021). Therefore, the goal of the ERFSC is to distribute the necessary supplies in infected areas with minimum labor, within a reasonable time and cost.

2.1. Description and analysis of the ERFSC

To optimize the allocation of labor in the ERFSC, we have developed a scenario as shown in Figure 2. Our analysis focuses on the optimal allocation of labor in the ERFSC in urban areas, specifically from the DCs to the residents. The DCs receive goods from outside, distribute them based on the downstream retailers' demand, and arrange vehicles or engage third-party logistics to transport them to each retailer. The retailers receive shipments from DCs, sort and prepack the food according to customer requirements, and hand them over to riders or carriers for delivery to residents. Residents get their food via self-purchase, pick-up or home delivery, depending on the risk level of their zone, as shown in Figure 3.

2.1.1. Market demand forecast

Forecasting models play a crucial role in precision marketing, aiding in the comprehension and fulfillment of customer needs and expectations (You et al., 2015). Various statistical analysis techniques, such as time-series analysis and regression analysis, have been employed for demand forecasting in supply chain management (Wang et al., 2016). The utilization of AI techniques, such as artificial neural networks and evolutionary computation, has become prevalent in demand forecasting due to the advancements in computing technologies (Lin et al., 2018). In addition, big data analysis in supply chain management is receiving increasing attention (Ali et al., 2017; Nguyen et al., 2018). As data for the parameters in the model were readily available, we chose to use statistical analysis to forecast food demand.

Normally, the total food demand in a region is mainly determined by the number of people and remains relatively stable when the population changes little. However, during an outbreak, the total food demand in the region fluctuates due to changes in the risk zones. Let N_0 denote the number of permanent residents in the region and d_0 denote the normal daily per capita food requirement. If the number of people classified as high and medium risk zones is n_{hr} and n_{mr}, respectively, then the total food demand $D(t)$ in the region during an outbreak can be expressed as

$$\begin{aligned} D(t) &= [\alpha \cdot n_{hr} + \beta \cdot n_{mr} + (N_0 - n_{hr} - n_{mr})] \cdot d_0 \\ &= [N_0 + (\alpha - 1) \cdot n_{hr} + (\beta - 1) \cdot n_{mr}] \cdot d_0, \alpha > \beta > 1 \end{aligned} \quad (1)$$

Here, α and β are the perturbation factors for the demand for food by people in high and medium risk zones, respectively, which can be interpreted as the shopping cycle.

2.1.2. Efficiency of end-delivery services

Convenience plays a crucial role in consumers' food purchasing choices (Morganosky and Cude, 2000). Traditional grocery stores have implemented various methods to offer convenient delivery options to their customers, such as online shopping, door-step home deliveries, and drive-through pick-ups (Raison and Jones, 2020). Additionally, studies have shown that consumers are willing to pay a small fee for enhanced convenience, like home delivery services (Anesbury et al., 2015). During an epidemic, it is crucial for ERFSCs to devise a delivery strategy that ensures residents have access to food while minimizing the risk of mutual exposure. To achieve an efficient and safe end-delivery strategy, we propose a differentiated approach based on the level of risk zones, which is depicted in Figure 3. In

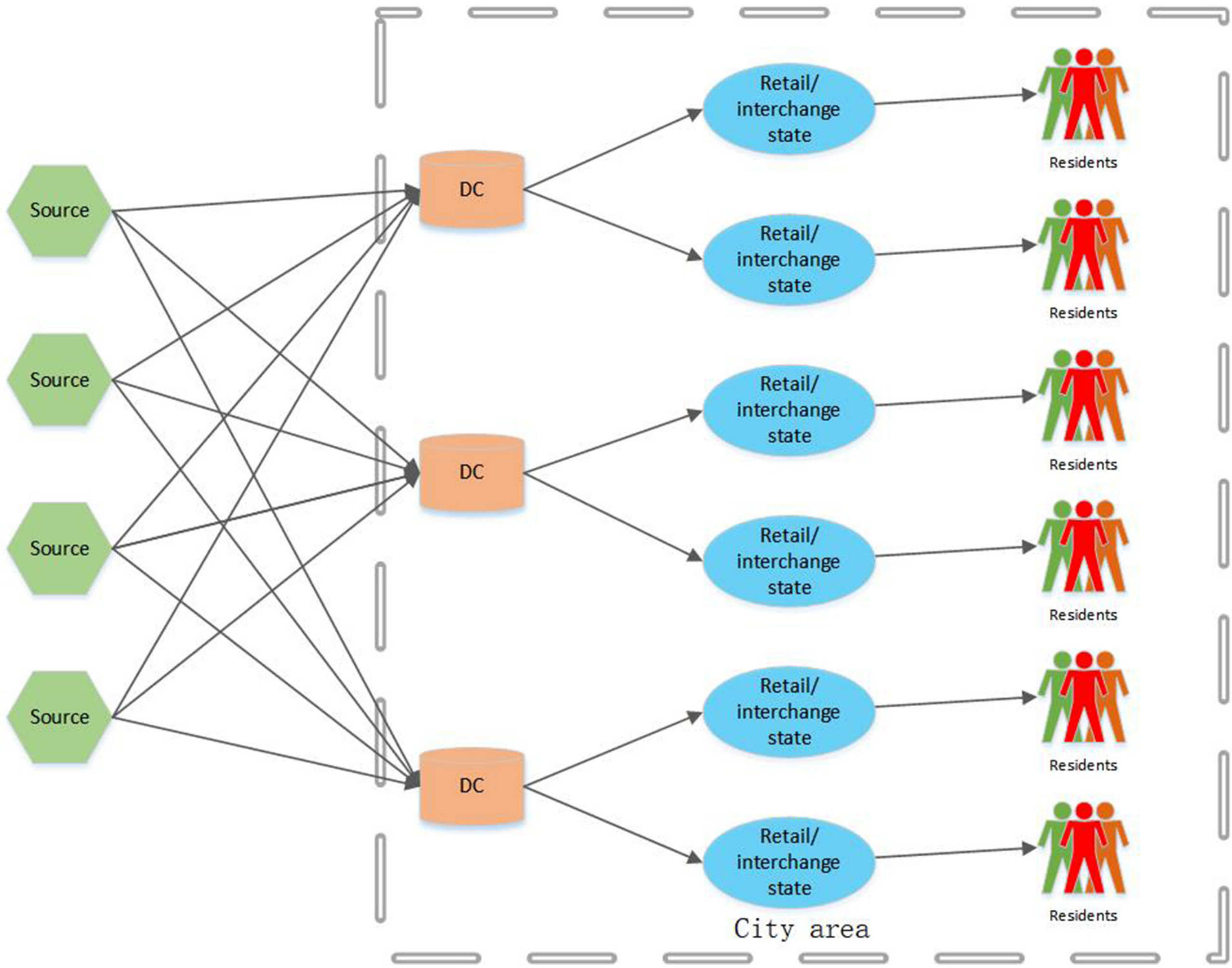

FIGURE 1
The ERFSC network.

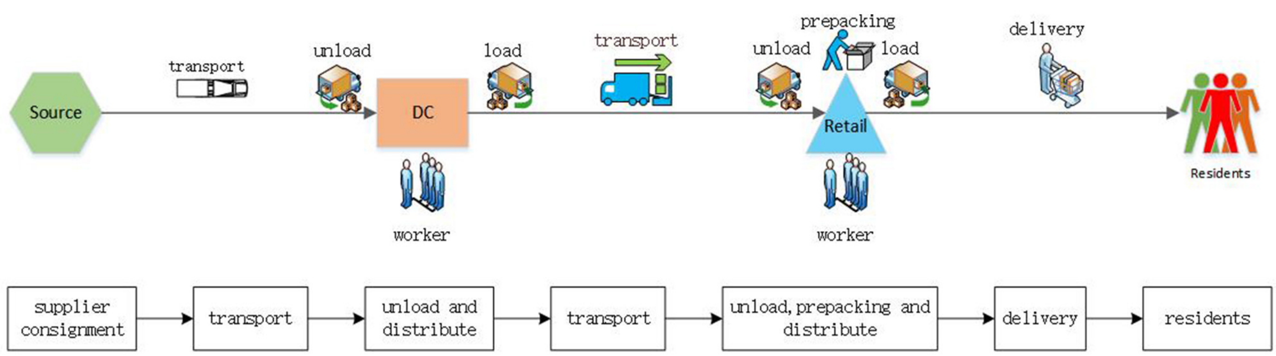

FIGURE 2
The description and analysis of the ERFSC.

low-risk zones, residents can opt for offline shopping, visiting physical stores to purchase their food. For those in medium-risk zones, a convenient option would be to have their food delivered to designated locations where they can pick it up in an orderly manner. Finally, residents in high-risk zones should receive home delivery, ensuring minimal contact and maximum

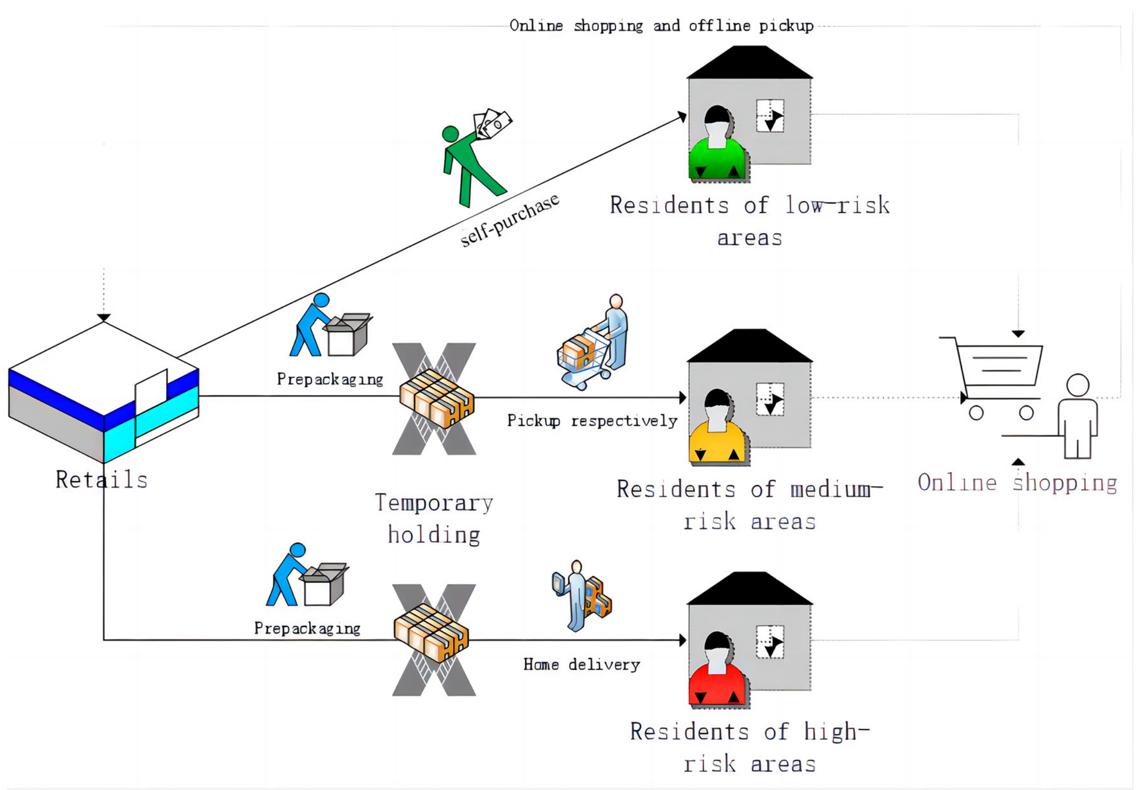

FIGURE 3
The shopping process for residents in different risk zones.

safety. The efficiency of the end-delivery service is defined as the weight of goods delivered per unit time from retailers/ISs to residents according to the demand list. Generally, the delivery time for high-risk zones is longer than for medium-risk zones. Therefore, the end-delivery service efficiency can be expressed as

$$EDE_{hr} = \frac{AW}{t_{hr}} \tag{2}$$

$$EDE_{mr} = \frac{AW}{t_{mr}} \tag{3}$$

where AW is the average weight of goods per delivery and follows a uniform distribution $U(a, b)$; t_{hr} and t_{mr} are the time required to deliver a batch of goods to high-risk and medium-risk zones, respectively, and follow normal distributions $N(\mu, \delta^2)$.

2.1.3. Labor efficiency and transport efficiency

labor is a crucial element in the functioning of any supply chain network, and the efficiency of work directly affects the overall effectiveness of the network (Jaillet et al., 2019; Bhattarai and Reiley, 2020). In general, labor efficiency can be represented by the time required for each task and the number of tasks completed within a certain period of time. During an epidemic, it becomes imperative to choose the appropriate type and size of vehicles to achieve transport efficiency and meet supply chain objectives. Larger vehicles may decrease the frequency of transportation, but they also have a lower turnover rate for perishable goods, which can lead to increased spoilage. On the other hand, smaller trucks have a lesser carrying capacity but are more agile, making them suitable for emergency situations where quick transport dispatch is essential (Marusak, 2021). Assuming that the time required for each task follows a normal distribution, we can derive the average and standard deviation of labor efficiency for each task from historical data. Therefore, we can represent the average labor efficiency of unloading, prepacking, loading and transportation tasks of goods in the food supply chain by UL, $Prep$, L, Tr and follow some random distribution.

2.1.4. Supply chain delivery window

The supply chain delivery window is the time required from the supply side of raw materials to delivery to the consumer. It has received a lot of focus from researchers, particularly in the areas of production planning and delivery routing optimisation (da Silveira and Arkader, 2007; Benjamin and Beasley, 2010; Yeung et al., 2011). Uniquely, this paper aims to study the issue of supply chain delivery windows from a different perspective, with a particular focus on the allocation of labor in the food supply chain. Generally, the relief supplies dispatch centres cannot distribute all the relief supplies to the affected areas at once, and successive multi-batch are a time-saving supply method, as depicted in Figure 4. Suppose there are n nodes in the supply chain, each with an operating time t_i, and let $t_{es(j,i)}$ denote the earliest start time of batch j at node i. Then we can calculate the earliest start time of batch j at node i as follows

$$t_{es(j,i)} = \max(t_{es(j,i-1)} + t_{i-1}, t_{es(j-1,i)} + t_i), i = 1, 2, \cdots, n; j = 1, 2, \cdots \quad (4)$$

Recursively, the supply chain delivery window for successive j batches are

$$t_{jq} = \max t_{es(j,n)} + t_n = (j-1)t_{i\_max} + \sum_{i=1}^{n} t_i \quad (5)$$

Here, t_{i_max} is the maximum value in the sequence t_i.

3. Mathematical modeling of labor demand forecasting

Humanitarian relief efforts are critical during disasters, such as providing food, water, and medical care. It is essential to distribute relief supplies quickly, fairly, and accurately to rescue scenes (Starr and Van Wassenhove, 2014; Çankaya et al., 2019). The COVID-19 pandemic and quarantine interventions have disrupted the labor market and made it difficult for existing food supply chains to operate effectively. Despite labor being a key input in the food industry, it is often overlooked in food supply chain assessments (Wijnands and Ondersteijn, 2006). However, forecasting the workforce required for the operation of the ERFSC is crucial, as it is a vital input to the operation. In an ERFSC scenario that involves labor changes in the DCs, Details, and Deliveries, a mathematical model has been developed to optimize the allocation of the labor force, ensuring that the dispatch and distribution of the demanded food quantity are completed within the specified time period.

3.1. Assumptions

Considering the complexity of the model, the following assumptions were made:

(1) Only a few essential foodstuffs (rice, pulses, non-perishable vegetables, etc.) were studied and were well stocked.

(2) The total demand of the population is based on the resident population and is calculated according to the healthy dietary provisions per capita.

(3) Prepackaging processing and preserving residents' food demand orders to be delivered by weight.

(4) Government-authorized green passes are given to vehicles, and there are no restrictions on vehicle transport.

(5) Logistics vehicles and drivers are adequate and have uniform vehicle sizes.

(6) The completion time of the labor force is subject to a certain random distribution.

(7) Successive operations at each activity node are achieved through shift changes.

(8) The food supply chain is designed using lean logistics ideas, i.e. inventory is not considered here.

To facilitate the narrative, the symbols and their descriptions are presented as follows.

$D(t)$: Total daily food demand in the region (kg).

$d0$: Daily average food requirement per capita (kg).

n_{a0}: Number of available workforce per shift in the DC.

n_{r0}: Number of available workforce per shift in retail stores.

n_{d0}: Number of available workforce per shift in end-delivery.

n_{hr}: Number of people in high-risk areas within the supply range.

n_{mr}: Number of people in medium-risk areas within the supply range.

α: Perturbation factor for food demand in high-risk areas.

β: Perturbation factor for food demand in medium-risk areas.

V: Maximum capacity of logistics vehicles (kg).

ρ: Transportation batch.

EDE_{hr}: End-delivery efficiency in high-risk areas (kg/h).

EDE_{mr}: End-delivery efficiency in medium-risk areas (kg/h).

UL: Unloading efficiency (kg/h).

$Prep$: Pre-packing efficiency (kg/h).

L: Loading efficiency (kg/h).

Tr: Transportation efficiency (kg/h).

T_0: Demand cycle (h).

n_a: Number of personnel required in the DC.

n_r: Number of personnel required in retail stores.

n_d: Number of personnel required in end-delivery.

3.2. Modeling

$$Min \quad n_a + n_r + n_d \quad (6)$$

$$\text{s.t.} \quad \frac{V}{n_a}\left(\frac{1}{UL} + \frac{1}{L}\right) + \frac{V}{Tr} + \frac{V}{UL \cdot n_r}\left(\frac{1}{UL} + \frac{1}{Prep} + \frac{1}{L}\right) + \left(\frac{\alpha \cdot n_{hr} \cdot d_0}{EDE_{hr} \cdot n_d} + \frac{\beta \cdot n_{mr} \cdot d_0}{EDE_{mr} \cdot n_d}\right) \cdot \frac{1}{\rho} + (\rho - 1) \cdot t_{i\_max} \le T_0 \quad (6\text{-}1)$$

$$D(t) = [N_0 + (\alpha - 1)n_{hr} + (\beta - 1)n_{mr}] \cdot d_0 \quad (6\text{-}2)$$

$$\rho = \lceil \frac{D(t)}{V} \rceil \quad (6\text{-}3)$$

$$t_{i\_max} = max\left\{\frac{V}{n_a}\left(\frac{1}{UL} + \frac{1}{L}\right), \frac{V}{Tr}, \frac{V}{UL \cdot n_r}\left(\frac{1}{UL} + \frac{1}{Prep} + \frac{1}{L}\right), \left(\frac{\alpha \cdot n_{hr} \cdot d_0}{EDE_{hr} \cdot n_d} + \frac{\beta \cdot n_{mr} \cdot d_0}{EDE_{mr} \cdot n_d}\right) \cdot \frac{1}{\rho}\right\} \quad (6\text{-}4)$$

$$0 \le n_a \le n_{a0} \quad (6\text{-}5)$$

$$0 \le n_r \le n_{r0} \quad (6\text{-}6)$$

$$0 \le n_d \le n_{d0} \quad (6\text{-}7)$$

$$n_a, n_r, n_d \quad \text{is integer}$$

In the model, the objective function (6) is the minimum labor demand to ensure the normal operation of the ERFSC; constraint

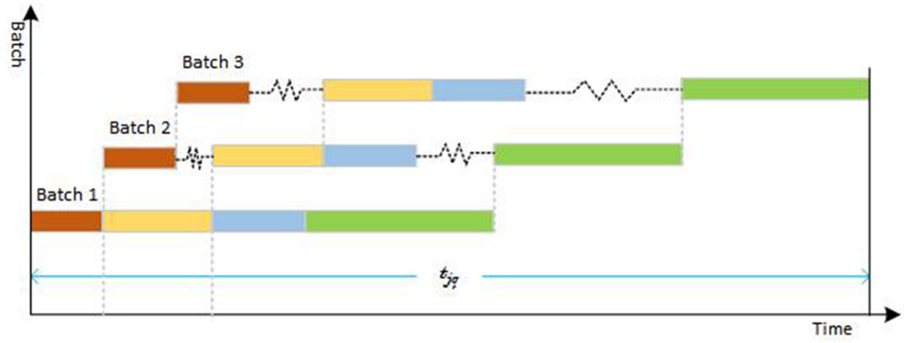

FIGURE 4
Successive multi-batch supply.

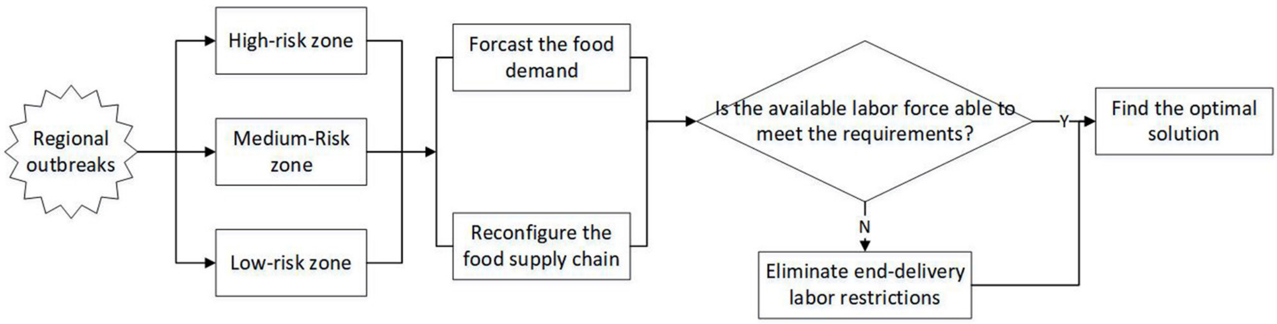

FIGURE 5
The solution design technology roadmap.

(6-1) is the time to complete the full supply of regional food within a specified period of time; constraint (6-2) is the total dynamic demand for regional food; constraint (6-3) is the determination of transport batches based on total food demand and logistics vehicle capacity; Constraint (6-4) is the longest time spent by a node in the ERFSC; and constraints (6-5), (6-6), and (6-7) are the labor constraints at each activity node of the ERFSC.

3.3. Scenario design

The decrease in operators and increase in demand for food distribution following a regional outbreak has created difficulties in the operation of the ERFSC. Based on an analysis of the ERFSC operation description, it was found that DCs and retailers require workers with higher skills, while end-delivery services requires fewer skills. Therefore, to alleviate the labor shortage problem, volunteers can be recruited for end-delivery services work, thus shifting the bottleneck factor of labor shortage to the end-delivery services. In other words, when all available personnel are involved in the supply chain operation but the task cannot be completed, we lift the restriction on the number of end-delivery services workers and, in practice, solve the staff shortage by recruiting volunteers or community residents. The solution design technology roadmap is shown in Figure 5.

3.4. Solution

In optimising food supply chains, the main objectives generally include minimum transportation cost, minimum wastage rate, and minimum cycle time. To achieve this, the problem is usually modelled and solved using different machine learning techniques, including genetic algorithms, simulated annealing algorithms, ant colony algorithms, neural network algorithms, and mixed integer programming (Tarhan and Grossmann, 2008; Peidro et al., 2009; Govindan and Cheng, 2018; Chan et al., 2020; Altun et al., 2022). However, the complexity of the optimisation problem increases with the spatial and temporal scale of the supply chain, involving numerous participants and different operation cycles, as well as uncertainties such as policies, natural disasters, wars, and epidemics. To address this, complex supply chain design and optimisation have been made possible by the development of computing performance and various optimisation algorithms (Conti et al., 2009; Scott et al., 2013).

The mathematical model presented in Equation (6) reflects the changes in total demand and distribution schedules due to changes in personnel at risk in the region. The optimal matching of the number of laborers at each node of the food supply chain is required in order to meet the supply of basic household goods to the residents of the region within a specified time frame, which is a dynamic integer non-linear programming problem that can be solved by Algorithm 1.

The primary objective of this algorithm is to ensure the smooth operation of the emergency regional food supply chain, particularly during public health emergencies. It aims to determine the minimum labor force required for essential stages such as DC, retail, and end-delivery. The input parameters encompass personnel count, changes in the number of at-risk individuals, vehicle capacity, labor efficiency, transportation efficiency, and delivery efficiency. These data can be derived from historical and dynamically updated data analysis, making the algorithm user-friendly. The primary output is the labor demand for each operational node, which varies due to the random distribution of input parameters. To address this issue, we employ multiple iterations and average calculations to forecast labor requirements.

input:
- C1: the maximum capacity of the transported vehicles
- C2: the number of repeating calculations
- C3: the total number of individuals in the region
- μ_1, σ_1: mean and standard deviation for UL
- μ_2, σ_2: mean and standard deviation for L
- μ_3, σ_3: mean and standard deviation for Prep
- $Tr_1, Tr_2, \ldots$: list of values for Tr
- $d0_1, d0_2, d0_3, d0_4, \ldots$: list of values for d0
- μ_4, σ_4: mean and standard deviation for EDE_{hr}
- μ_5, σ_5: mean and standard deviation for EDE_{mr}
- $N_{hr_1}, N_{hr_2}, \ldots, N_{hr_n}$: list of values for N_{hr}
- $N_{mr_1}, N_{mr_2}, \ldots, N_{mr_n}$: list of values for N_{mr}
- n: research duration (days)
- α, β: coefficients for calculating Dt (where Dt is the total number of people in the study area)

output:
- avgdd: average value of the objectives
- $-obj_1, obj_2, obj_3$: separate grouping of the C2 repetitive calculation solutions for each objective
- $-mx_1, mx_2, mx_3$: maximum values of each objective
- mn_1, mn_2, mn_3: minimum values of each objective

procedure DEFINE SUB-FUNCTION
    function $f = fun1(x)$
        $f \leftarrow \sum_{i=1}^{3} x_i$
    end function
    function $[g, h] = fun2(x)$
        $t\_max \leftarrow \max[V \times (\frac{1}{UL} + \frac{1}{L})/x[1], V/Tr, V \times (\frac{1}{UL} + \frac{1}{Prep} + \frac{1}{L})/x[2], d0/rou \times (\frac{\alpha \times n\_hrt}{TDE\_hr} + \frac{\beta \times n\_mrt}{TDE\_mr})/x[3]]$
        $g \leftarrow V \times (\frac{1}{UL} + \frac{1}{L})/x[1] + V/Tr + V \times (\frac{1}{UL} + \frac{1}{Prep} + \frac{1}{L})/x[2] + d0/\rho \times (\frac{\alpha \times n\_hrt}{TDE\_hr} + \frac{\beta \times n\_mrt}{TDE\_mr})/x[3] - 24 + (\rho - 1) \times t\_max$
        $h \leftarrow []$
    end function
end procedure
procedure GLOBAL VARIABLES AND INITIALIZATION
    $[V, UL, L, Prep] \leftarrow [C1, \mathrm{ceil}(normrnd(\mu_1, \sigma_1)), \mathrm{ceil}(normrnd(\mu_2, \sigma_2)), \mathrm{ceil}(normrnd(\mu_3, \sigma_3))]$
    $[Tr, d0, EDE\_hr, EDE\_mr] \leftarrow [\mathrm{randsrc}(1, 1, [Tr_1, Tr_2, \ldots]), \mathrm{randsrc}(1, 1, [d0_1, d0_2, d0_3, d0_4, \ldots]), \mathrm{ceil}(normrnd(\mu_4, \sigma_4)), \mathrm{ceil}(normrnd(\mu_5, \sigma_5))]$
    $[N_{hr}, N_{mr}] \leftarrow [[N_{hr_1}, N_{hr_2}, \ldots, N_{hr_n}], [N_{mr_1}, N_{mr_2}, \ldots, N_{mr_n}]]$
    $[\rho, t] \leftarrow [zeros(1, n), zeros(3, n)]$
    $[value, x0, sumdd] \leftarrow [zeros(1, n), \mathrm{rand}(1, 3), zeros(3, n)]$
end procedure
procedure CALCULATE OPTIMIZATION OBJECTIVES
    for $i \leftarrow 1$ to C2 **do**
        for $j \leftarrow 1$ to n **do**
            $[n_{hr}, n_{mr}] \leftarrow [N_{hr}(j), N_{mr}(j)]$
            $Dt \leftarrow C3 + \alpha \cdot n_{hr} + \beta \cdot n_{mr}$
            $\rho \leftarrow \mathrm{ceil}(Dt/V)$
            $[x, y] \leftarrow \mathrm{fmincon}('fun1', x0, [], [], [], [], [0, 0, 0], [\mathrm{inf}, \mathrm{inf}, \mathrm{inf}], 'fun2')$
            $[t(:, j), value(j)] \leftarrow [x, y]$
        end for
        $[dd(i, 1), vv(i, 1), sumdd] \leftarrow [t, value, sumdd + dd(i, 1)]$
    end for
end procedure
procedure CALCULATE AVERAGE AND EXTREMES
    $avgdd \leftarrow \mathrm{sumdd}/C2$
    $[obj_1, obj_2, obj_3] \leftarrow [zeros(C2, n), zeros(C2, n), zeros(C2, n)]$
    for $h \leftarrow 1$ to C2 **do**
        $obj_1(h, :) \leftarrow dd(h, 1)(1, :)$
        $obj_2(h, :) \leftarrow dd(h, 1)(2, :)$
        $obj_3(h, :) \leftarrow dd(h, 1)(3, :)$
    end for
    $[mx_1, mx_2, mx_3] \leftarrow [\max(obj_1), \max(obj_2), \max(obj_3)]$
    $[mn_1, mn_2, mn_3] \leftarrow [\min(obj_1), \min(obj_2), \min(obj_3)]$
end procedure

Algorithm 1. The ERFSC labor demand forecasting algorithm.

The fmincon function is a powerful optimization tool widely used for nonlinear constrained optimization problems. Its flexibility and versatility enable users to customize settings based on specific problem characteristics, resulting in effective optimization outcomes (Chuan et al., 2014). However, due to the limited research on labor demand forecasting in ERFSC, further data is needed to verify the validity of our proposed model across different scenarios.

In summary, the algorithm presents a viable solution for forecasting the minimum labor requirements in the main stages of ERFSC. Its readily available input parameters contribute to its broad applicability. Moreover, the algorithm can be customized for various scenarios, such as forecasting quantities for additional stages by including corresponding constraints in the model. However, the algorithm's repeated use of nested loops increases time and space complexity, signaling areas for further improvement in future studies. Additionally, reliance on the quality and accuracy of input data is an important consideration. Implementing techniques like data cleaning, preprocessing, multi-source data fusion, domain expertise application, error handling, and fault tolerance mechanisms can enhance the algorithm's reliability and robustness.

4. Case study

4.1. Background of the case

The Huaguoyuan region of Guiyang, China, which is known as the Asia's largest community, covers over 6,000 acres of land, with 12 main municipal roads, 10 shopping malls, and 27 subdivisions with 220 high-rise buildings. The area has a population of 430,000 residents and 1 million daily transients. In September 2022, an outbreak occurred between September 1 and September 30, 2022, making the Huaguoyuan region a representative and significant case study.

4.2. ERFSC network design

To address the challenge of supplying necessities to the residents of Huaguoyuan, a "multi-level distribution and pick-up" strategy was proposed. The strategy involves establishing a temporary DC in Huaguoyuan, adding additional ISs based on zone division and retailer operation status, and setting up buffer areas by buildings to form a straight-through organizational structure for the ERFSC. The DC location plays a crucial role in supply chain efficiency for aggregating and distributing products (Ge et al., 2022). The agricultural products DC is positioned on the primary traffic road and in the centre of Huaguoyuan to facilitate the flow of goods and allow only government-authorized vehicles and labor for supply assurance.

The ISs are placed close to the community to reduce the frequency and distance of residents moving outward. The buffer areas are situated in the open area directly adjacent to buildings and are managed by community managers or volunteers for order pick-up and/or home delivery. Figure 6 shows the design of the ERFSC, and Figure 7 demonstrates the workflow for the operation of the regional food distribution network in Huaguoyuan.

4.3. Labor demand forecasting model development and optimization

4.3.1. Data collection and analysis

Following the outbreak in Huaguoyuan, the local government implemented silent management and city closure interventions, and the total population of the region remained relatively constant at 430,000. The number of people at high and medium risk in the Huaguoyuan region was collected using various methods, such as telephone consultations with the community and internet searches, as shown in Table 1.

Other parameters derived from historical data from DCs, logistics companies, retailers, and delivery staff are presented in Table 2.

4.3.2. Mathematical modelling

To develop the labor demand forecasting model, it is important to consider the surge in demand for necessities during the epidemic, which led to residents stockpiling food due to the lack of a well-established food supply chain. The total demand for necessities in an area is proportional to the resident population, and fluctuations caused by the epidemic can be eliminated by designing an efficient food supply chain and delivery cycle. Assuming disturbance coefficients of 3 and 2 for food demand by residents in high and medium risk zones, respectively, and a required delivery cycle of 1 time per day, the model is developed as follows.

$$Min \quad n_a + n_r + n_d \tag{7}$$

$$\text{s.t.} \quad \frac{5000}{n_a}\left(\frac{1}{UL}+\frac{1}{L}\right)+\frac{5000}{Tr}+\frac{5000}{UL\cdot n_r}\left(\frac{1}{UL}+\frac{1}{Prep}+\frac{1}{L}\right) + \left(\frac{3\cdot n_{hr}\cdot d_0}{EDE_{hr}\cdot n_d}+\frac{2\cdot n_{mr}\cdot d_0}{EDE_{mr}\cdot n_d}\right)\cdot\frac{1}{\rho}+(\rho-1)\cdot t_{i\_max}\le T_0 \tag{7-1}$$

$$D(t) = [430000 + 2n_{hr} + n_{mr}]\cdot d_0 \tag{7-2}$$

$$\rho = \left\lceil \frac{D(t)}{5000} \right\rceil \tag{7-3}$$

$$t_{i\_max} = max\left\{\frac{5000}{n_a}\left(\frac{1}{UL}+\frac{1}{L}\right), \frac{5000}{Tr}, \frac{5000}{UL\cdot n_r}\left(\frac{1}{UL}+\frac{1}{Prep}+\frac{1}{L}\right), \left(\frac{3\cdot n_{hr}\cdot d_0}{EDE_{hr}\cdot n_d}+\frac{2\cdot n_{mr}\cdot d_0}{EDE_{mr}\cdot n_d}\right)\cdot\frac{1}{\rho}\right\} \tag{7-4}$$

$$0 \le n_a \le 30 \tag{7-5}$$

$$0 \le n_r \le 80 \tag{7-6}$$

$$0 \le n_d \le 100 \tag{7-7}$$

$$n_a, n_r, n_d \quad \text{is integer}$$

4.3.3. Model solution

The problem is a stochastic programming problem, and the optimal solution is characterized by stochasticity and instability due to the multiple stochastic parameters. To tackle this, it is proposed to use a sampling average approximation to obtain the expected value of the optimal solution, which will demonstrate the validity of the model and forecast the demand for labor at each activity node. This will provide an auxiliary scientific decision for practical work. First, by optimising the solution according to the available labor, i.e. with restrictions on n_a, n_r and n_d, which determines whether volunteers need to be recruited. Secondly, if there is a shortage of labor, the restriction on n_d is removed and the number of additional volunteers needed is solved optimally. The problem is solved using Algorithm 1, and a sample of 1000 random optimal solutions are selected to calculate the mean value. The results are shown in Tables 3, 4.

4.3.4. Results

4.3.4.1. Content analysis

It can be seen from Tables 3, 4 that the demand for labor in the DCs, retailers and end-delivery services nodes of

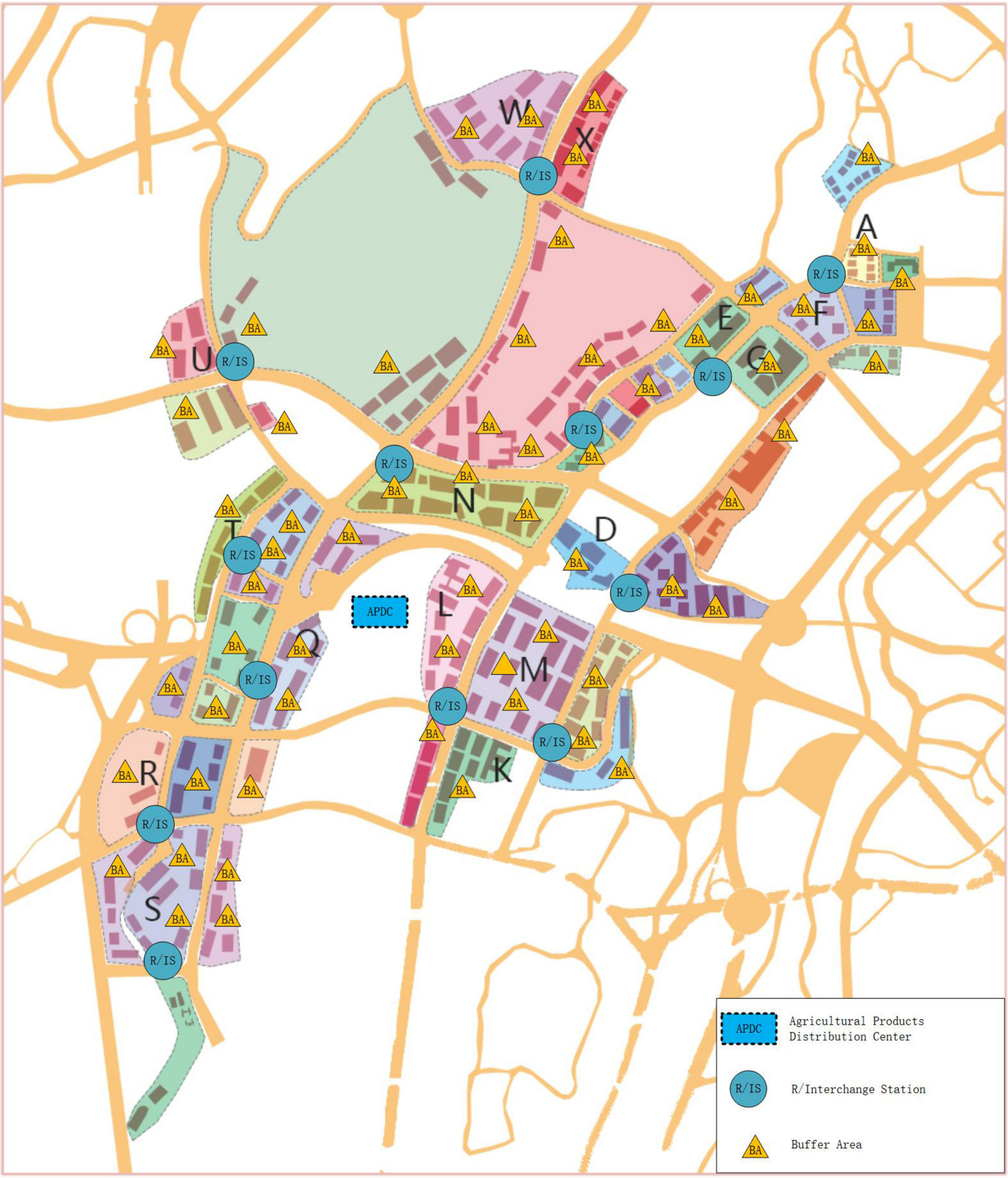

FIGURE 6
The ERFSC network design for Huaguoyuan.

ERFSC changes with variations in the number of high- and medium-risk zones in the region. The demand for end-delivery services labor is particularly more sensitive to such changes, as illustrated in Figure 8. When there are no high- or medium-risk zones in the region, there is no need for additional end-delivery services staff. However, during periods of city-wide silent

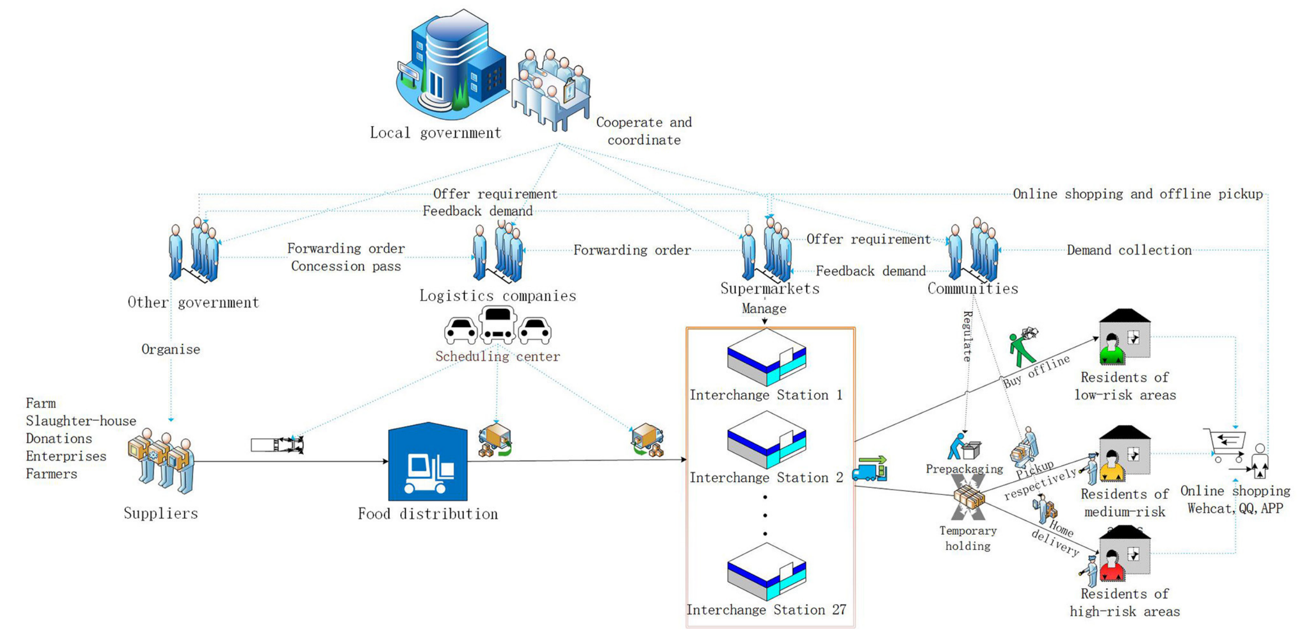

FIGURE 7
The operation process of ERFSC.

TABLE 1 Number of residents in high- and medium-risk zones of Huaguoyuan.

Date	n_{hr}	n_{mr}	Date	n_{hr}	n_{mr}
1-Sep-22	0	0	16-Sep-22	96,900	155,800
2-Sep-22	0	0	17-Sep-22	96,900	155,800
3-Sep-22	430,000	0	18-Sep-22	76,000	144,400
4-Sep-22	430,000	0	19-Sep-22	85,500	131,100
5-Sep-22	430,000	0	20-Sep-22	76,000	114,000
6-Sep-22	17,100	7,600	21-Sep-22	58,900	74,100
7-Sep-22	17,100	7,600	22-Sep-22	15,200	89,300
8-Sep-22	17,100	7,600	23-Sep-22	15,200	77,900
9-Sep-22	17,100	7,600	24-Sep-22	9,500	66,500
10-Sep-22	17,100	7,600	25-Sep-22	5700	30,400
11-Sep-22	17,100	7,600	26-Sep-22	0	9,500
12-Sep-22	79,800	142,500	27-Sep-22	0	9,500
13-Sep-22	93,100	157,700	28-Sep-22	0	9,500
14-Sep-22	89,300	161,500	29-Sep-22	0	0
15-Sep-22	112,100	140,600	30-Sep-22	0	0

TABLE 2 The parameters data.

$d_0(kg)$	n_{a0}	n_{r0}	n_{d0}	$EDE_{hr}(kg/h)$	$EDE_{mr}(kg/h)$
$\sim U(0.8, 1.2)$	≤ 30	≤ 80	≤ 100	$\sim N(50, 5^2)$	$\sim N(200, 20^2)$
V(kg)	UL(kg/h)	Prep(kg/h)	L(kg/h)	Tr(kg/h)	
5000	$\sim N(5,000, 100^2)$	$\sim N(1,000, 20^2)$	$\sim N(4,000, 80^2)$	[10,000, 15,000, 20,000]	

TABLE 3 Labor demand forecasting for the ERFSC in Huaguoyuan under the constraints of n_a, n_r and n_d (persons/shift).

Date	n_a	n_r	n_d	Date	n_{hr}	n_{mr}	n_d
1-Sep-22	8	26	0	16-Sep-22	30	80	100
2-Sep-22	8	26	0	17-Sep-22	30	80	100
3-Sep-22	30	80	100	18-Sep-22	30	80	100
4-Sep-22	30	80	100	19-Sep-22	30	80	100
5-Sep-22	30	80	100	20-Sep-22	30	80	100
6-Sep-22	9	30	47	21-Sep-22	30	80	100
7-Sep-22	9	30	47	22-Sep-22	11	36	77
8-Sep-22	9	30	47	23-Sep-22	11	34	72
9-Sep-22	9	30	47	24-Sep-22	10	32	53
10-Sep-22	9	30	47	25-Sep-22	9	30	28
11-Sep-22	9	30	47	26-Sep-22	9	27	5
12-Sep-22	30	80	100	27-Sep-22	9	27	5
13-Sep-22	30	80	100	28-Sep-22	9	27	5
14-Sep-22	30	80	100	29-Sep-22	8	26	0
15-Sep-22	30	80	100	30-Sep-22	8	26	0

TABLE 4 Labor demand forecasting for the ERFSC in Huaguoyuan with the removal of n_d restrictions (persons/shift).

Date	n_a	n_r	n_d	Date	n_{hr}	n_{mr}	n_d
1-Sep-22	8	26	0	16-Sep-22	30	80	319
2-Sep-22	8	26	0	17-Sep-22	30	80	319
3-Sep-22	30	80	1430	18-Sep-22	30	80	260
4-Sep-22	30	80	1430	19-Sep-22	30	80	279
5-Sep-22	30	80	1430	20-Sep-22	30	80	247
6-Sep-22	9	30	47	21-Sep-22	30	80	185
7-Sep-22	9	30	47	22-Sep-22	11	36	77
8-Sep-22	9	30	47	23-Sep-22	11	34	72
9-Sep-22	9	30	47	24-Sep-22	10	32	53
10-Sep-22	9	30	47	25-Sep-22	9	30	28
11-Sep-22	9	30	47	26-Sep-22	9	27	5
12-Sep-22	30	80	269	27-Sep-22	9	27	5
13-Sep-22	30	80	310	28-Sep-22	9	27	5
14-Sep-22	30	80	302	29-Sep-22	8	26	0
15-Sep-22	30	80	352	30-Sep-22	8	26	0

management, the demand for labor at each activity node of the ERFSC reaches its maximum, and the demand for end-delivery services staff increases dramatically, making it difficult for the existing end-delivery services system to cope, leading to delayed deliveries.

As the silent management interventions are lifted, residents in low-risk zones can shop offline, thereby reducing the demand for labor at each activity node of the ERFSC. In Table 3, when n_a, n_r and n_d all reach a threshold value, it indicates that the current labor force cannot complete the required task and must be increased. Table 4 provides the amount of labor required per shift, which can serve as a basis for adjusting the total labor demand for multiple shifts while planning staff requirements. Overall, the results of the analysis demonstrate the validity of the developed model and provide a scientific basis for decision-making in practical work. The use of the sampling average approximation technique enables the estimation of the expected value of the optimal solution, taking into account the stochastic nature of the problem and the instability caused by multiple parameters, thereby providing valuable insights for the management of labor resources in ERFSC.

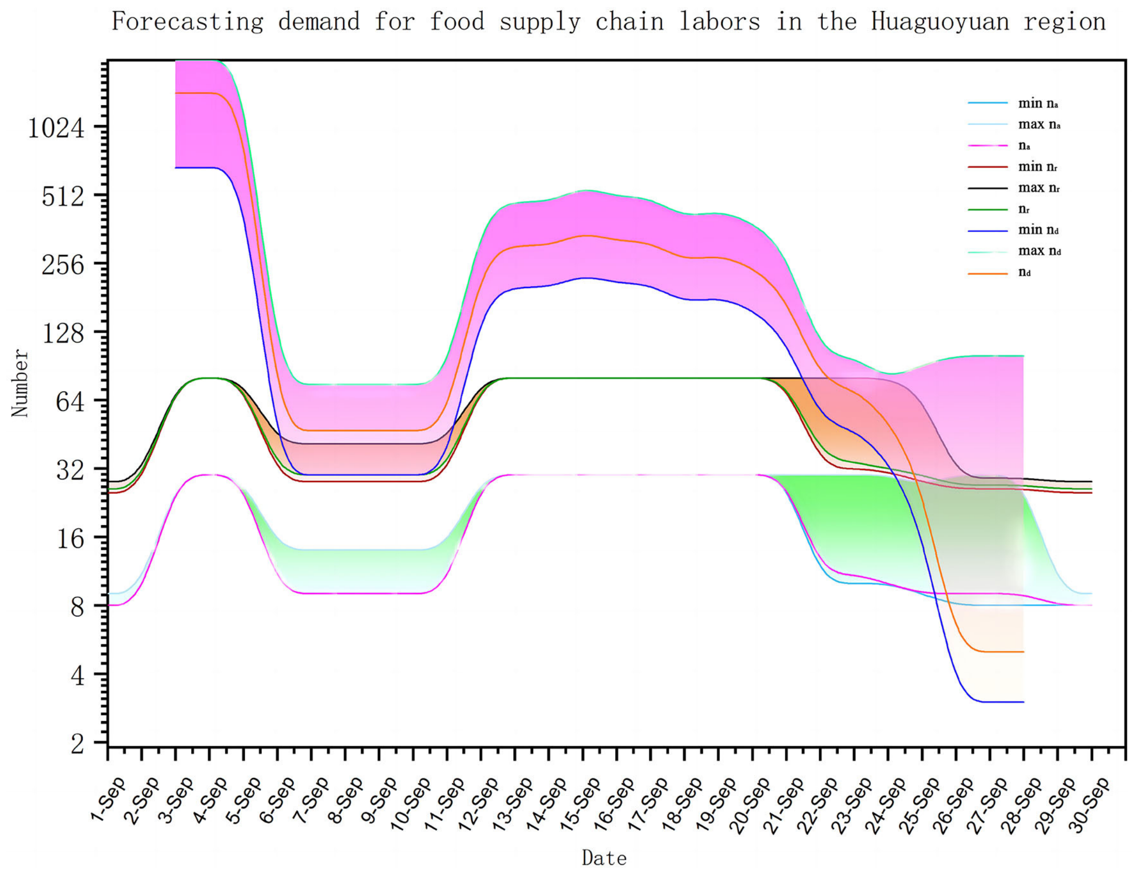

FIGURE 8
The ERFSC labor demand forecasting in the Huaguoyuan region.

TABLE 5 Correlation analysis between risk zones and the number of personnel in each node of ERFSC.

	n_a	n_r	n_d
n_{hr}	0.77 (0.000***)	0.971 (0.000***)	0.996 (0.000***)
n_{mr}	0.309 (0.097*)	0.215 (0.253)	0.063 (0.742)
n_{lr}	−0.835 (0.000***)	−0.973 (0.000***)	−0.926 (0.000***)

***, *Represent 1%, 10% significance levels, respectively.

4.3.4.2. Correlation analysis

To investigate the influence of the number of individuals in the risk area on the number of staff required at each node of the ERFSC, this study adopted Pearson correlation analysis combined with Tables 1, 4 to provide a quantitative description. Pearson correlation analysis is a statistical method used to measure the closeness of the linear relationship and the direction of correlation between two variables (Asuero et al., 2006; Sedgwick, 2012). Based on the calculations, as shown in Table 5, without controlling for variables, we found that n_{hr} had correlation coefficients of 0.77, 0.971, and 0.996 with n_a, n_r, and n_d, respectively. This indicates a strong positive correlation between n_{hr} and these three variables, all of which are statistically significant at a level below 0.01 (p-values: 0.000). Thus, we can reject the null hypothesis and conclude that there is a strong positive correlation between n_{hr} and n_a, n_r, and n_d.

Similarly, we found that n_{lr} had correlation coefficients of -0.835, -0.973, and -0.926 with n_a, n_r, and n_d, respectively. This suggests a strong negative correlation between n_{lr} and these three variables, all of which are statistically significant at a level below 0.01 (p-values: 0.000). Therefore, we reject the null hypothesis and conclude that there is a strong negative correlation between n_{lr} and n_a, n_r, and n_d. However, for the correlation between n_{mr} and n_a, n_r, and n_d, we found correlation coefficients of 0.309, 0.215, and 0.063 respectively, with corresponding p-values of 0.097, 0.253, and 0.742. This indicates that in the specific context of this study, we cannot reject the null hypothesis and conclude that there is no correlation between n_{mr} and n_a, n_r, and n_d. This conclusion may contradict our intuition. We speculate that this may be due to the smaller β values set in the model. However, the setting of β values must align with the actual situation and cannot be arbitrarily increased. Therefore, in the specific scenario of this study, our conclusion is valid.

The correlation analysis results mentioned above hold significant academic implications for studying the impact of the number of personnel in high-risk areas on the personnel requirements at various nodes of the emergency food supply chain. By exploring the strong positive correlation between n_{hr} and n_a, n_r, and n_d, as well as the strong negative correlation between n_{lr} and n_a, n_r, and n_d, we gain a better understanding of how changes in personnel numbers affect different nodes of the emergency food supply chain. Additionally, although no correlation was found between n_{mr} and n_a, n_r, and n_d, this provides guidance and inspiration for further research to delve into the complex relationships among these variables.

In general, the analysis results confirm the efficacy of the developed model and provide scientific basis for decision-making in practical work. Given the stochastic nature of the problem and the instability caused by multiple parameters, a sampling average approximation method can be used to estimate the expected value of the optimal solution (Kleywegt et al., 2002; Verweij et al., 2003), providing valuable insights for labor resource management in the ERFSC.

These research findings hold academic significance as they demonstrate the potential of the model in managing food supply chains during emergencies. Moreover, the reliability and accuracy of the model serve as the foundation for further improvement and development by researchers. Future research can explore ways to optimize the parameter settings of the model in order to enhance its predictive performance and application scope.

5. Discussion

The outbreak of a public health emergency requires the establishment of an emergency food supply chain to ensure the basic needs of the population. In this study, we focused on constructing an ERFSC and distribution network to meet both the requirements of epidemic prevention and food supply guarantee. We emphasized the importance of labor force planning and assignment in the food supply chain, especially during times of crisis such as the outbreak of a pandemic. The scarcity of labor force in the food supply chain was identified as a critical challenge that needed to be addressed (Luckstead et al., 2021; Nagurney, 2021).

To overcome this challenge, we proposed to accurately forecast labor demand in each activity of the ERFSC by establishing labor demand forecasting models, which could provide valuable insights for companies to effectively manage and allocate their labor resources, ensuring the normal operation of the food supply chain and guaranteeing food security in society.

Furthermore, we highlighted the need for diversification in agricultural suppliers and the establishment of long-term strategic cooperation agreements with agricultural provinces and import agents. Additionally, involving local farmers and farms as suppliers can not only ensure regular food supply but also cater to the demand during emergencies. The role of supply and marketing cooperatives as local aggregation centers for high-quality locally grown products was also emphasized to strengthen the link between urban and rural food supply.

The optimization of layout distribution centers and connection points was identified as a necessary measure to be taken in case of disruptions in the existing food supply chain. Moreover, community engagement and mobilization of residents to participate in end-delivery were suggested as a practical solution when there is a shortage of labor force. In the long run, enhancing the development of the necessities industry chain and the construction of an information platform will promote the sharing of emergency material information resources and facilitate integration with the national emergency platform.

6. Conclusions

In this study, we have presented a comprehensive approach to address the disruptions in food supply chains during public health emergencies. Our research focuses on the design of ERFSC and the forecasting of labor demand, aiming to ensure the provision of necessities to affected areas.

To achieve this goal, we have proposed a multi-level ERFSC framework that can effectively adapt to different risk levels. The framework leverages local manufacturing and nearby sourcing strategies to enhance the resilience and sustainability of the supply chain (Alhawari et al., 2021; Boehme et al., 2021; Burgos and Ivanov, 2021). By utilizing local resources and optimizing logistics and supply chain infrastructure, the framework enables the rapid establishment of a coordinated ERFSC network. This network can dynamically adjust the food supply according to changes in the regional risk level, ensuring the continuous operation and efficient distribution of necessities such as food and protective equipment.

To accurately forecast food demand, we have developed a model that incorporates the trend of regional outbreaks. This model enables us to forecast the required food quantities for different risk level regions. By aligning the supply chain operations with the predicted demand, we can effectively meet the needs of disaster-affected populations for necessities.

Furthermore, we have formulated a stochastic planning model to determine the labor demand in the food supply chain during emergencies. This model allows for the swift allocation of the required workforce for the distribution of emergency food supplies. It ensures that the labor force is properly allocated based on the fluctuating demands, guaranteeing the timely delivery of relief food.

To validate the effectiveness of our proposed approach, we conducted a case study in the Huaguoyuan area of Guiyang, China. The results demonstrated that our models and frameworks are practical and effective in ensuring the provision and accurate distribution of necessities in regions with varying risk levels. The significance of this research rests in its contribution to the field of emergency management by providing a systematic and practical solution for the construction of ERFSC. By combining local resources and optimizing supply chain networks, our approach effectively addresses the challenges of food security and precise distribution during public health emergencies. Government agencies and practitioners can utilize our findings as a theoretical foundation for informed decision-making in developing food security measures and action plans.

While we have made important strides in this study, there are areas for future research. One such aspect is the need to further expand and refine our food demand forecasting model, particularly by considering additional factors such as geographical variations and policy frameworks. Moreover, the scalability and adaptability of our approach should be thoroughly examined in different geographical contexts and under various emergency scenarios.

In summary, our research provides valuable insights and practical guidance for designing ERFSC during public health emergencies. The proposed models and frameworks offer an effective means to ensure the continuous provision and efficient distribution of necessities This study contributes to the existing body of knowledge in emergency management and holds promise for practical applications.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: https://figshare.com/s/be2fc1e2039086f76444.

Author contributions

YM contributed to study concepts, data acquisition, manuscript revision/review, and manuscript final version approval. ST contributed to study design, literature research, experimental studies, data acquisition, data analysis/interpretation, statistical analysis, manuscript preparation, manuscript editing, and manuscript final version approval. All authors contributed to the article and approved the submitted version.

Funding

This research received partial support from the Growth Project of Young Scientific and Technological Talents in Colleges and Universities of Guizhou Province (Grant Qian Jiao he KY Zi [2021] 113). Additionally, it was supported by the Science and Technology Projects of Guizhou Province (QKHJCZK2022YB195, QKHJCZK2023YB143, and QKHPTRCZCKJ2021007), as well as the Natural Science Research Project of the Education Department of Guizhou Province (QJJ2023061 and QJJ2023012).

Acknowledgments

The authors would like to thank the management of the companies involved and the people who took time to attend interviews and complete questionnaires.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 13 October 2023
DOI 10.3389/fsufs.2023.1197228

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RECEIVED 30 March 2023
ACCEPTED 15 September 2023
PUBLISHED 13 October 2023

CITATION
Kang Y, Wabyona E, Etienne K, Allarabaye M, Bakoi A and Doocy S (2023) Temporal trends of food insecurity in Chad, 2016–2021. *Front. Sustain. Food Syst.* 7:1197228.
doi: 10.3389/fsufs.2023.1197228

Temporal trends of food insecurity in Chad, 2016–2021

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Introduction: Considering persistently high levels of poverty and food insecurity in Chad, this study examines food insecurity trends from 2016 to 2021 and identifies risk factors for food insecurity in 2020 and 2021.

Methods: Data from six cross-sectional Enquête Nationale sur la Securité Alimentaire (ENSA) surveys from 2016 to 2021 collected in rural areas were used. The linear regressions for food consumption score (FCS), reduced coping strategy index (rCSI), and livelihood coping strategy index (LCSI) and logistic regressions for "*poor food consumption*" were used to estimate the annual rate of change. Risk factor analysis was conducted with demographic, socio-economic, and pandemic-related economic indicators in univariate models, and subsequent multivariate models were used to produce adjusted odds ratios.

Results: At a national level, there was a gradual decrease in FCS (1.16 points per year), an increase in LCSI (0.11 points), and an increase in the proportion of households with poor food consumption from 18.5% to 25.3% (1.55 percentage point) during 2016–2021; a similar trend for FCS and LCSI for worsened food insecurity was observed in the Sudanian zone. There was no significant change in rCSI during that time at the national level, but there was a reduction in the Saharan zone and an increasing trend in the Sahélian zone. Risk factors for poor food consumption in 2020–2021 included lower wealth status, a single income source, an illiterate household head, and Sahelian zone residence. The only characteristic significantly associated with increased coping mechanism use in both years was having a disabled household head.

Discussion: The results provide evidence of worsening food security in Chad in the past 6 years, both nationally and including the agricultural Sudanian zone. Food insecurity was consistently the highest in the Sahelian zone. While some risk factors for poor food consumption and diet-related coping mechanism use were consistent between 2020 and 2021, there were differences among other risk factors, likely a reflection of the impacts of the COVID-19 pandemic. A strategic shift in humanitarian and development programming is required to mitigate the rise in food insecurity at the national and regional levels, with a particular emphasis on the Sahelian zone.

KEYWORDS
COVID-19, Chad, food security, food consumption score, diet-related coping strategy

Introduction

Chad is a landlocked Sahelian country with high levels of poverty and food insecurity. Chad is 190th out of 191 countries on the Human Development Index (HDI), and 42.3% of the population lives in poverty [United Nations Development Programme (UNDP) and Oxford Poverty and Human Development Initiative (OPHI), 2022; United Nations Development Programme (UNDP), 2023]. In 2022, more than 5.3 million people suffered from food insecurity (Hoinathy and Delanga, 2022), and approximately 2.1 million were in severe food insecurity [Système d'Information sur la Sécurité Alimentaire et d'Alerte Précoce du TCHAD (SISAAP) et al., 2022]. On the Global Hunger Index, Chad is ranked 117th of 121 countries, and 40% of Chadian children are stunted, a marker of chronic undernutrition (Institut National de la Statistique et al., 2014-2015; Global Hunger Index, 2023).

In addition to the high prevalence of poverty, one of the main drivers of food insecurity in Chad has been erratic agricultural production owing to increasing climate change and variability in a context of high dependence on subsistence agriculture (SISAAP, 2022). The Notre Dame Global Adaptation Index ranks Chad as the most vulnerable to climate change, ranked 185th of 185 countries (Notre Dame Global Adaptation Initiative, 2023). There was a continued rise in prices of cereals, up to 30–40% in the past 5 years, which is in part due to erratic production.

The recurrence of shocks and stressors at national and global levels, such as floods, dry spells, and economic shocks, has been frequent, not allowing households enough time to recover between shocks (Système d'Information sur la Sécurité Alimentaire et d'Alerte Précoce du TCHAD, 2020; Hassen and Bilali, 2022).

There was a forced displacement of over 400,000 people (as of December 2021) in some parts of the country due to the presence of non-state armed groups [United Nations High Commissioner for Refugees (UNHCR), 2021]. The violent Boko-Haram insurgency in Northeastern Nigeria resulted in displacements and movement restrictions and disrupted many agricultural activities including major crops such as maize, sorghum, and millet (Musa et al., 2022). Chad is one of the largest refugee-hosting countries, with over 1 million forcibly displaced people and conflict-affected refugees (UNHCR, 2023). The inflow of refugees increased the ongoing food insecurity and put constraints on scarce resources (Médecins Sans Frontières, 2022). Such displacement hinders agricultural production, affects access to employment opportunities, and interferes with market and trade activities.

Globally, the COVID-19 pandemic had immense impacts on food insecurity. Common consequences of the 2020 lockdowns that were enacted by governments to reduce COVID-19 transmission included increased unemployment, loss of household income, and economic recession (Béné et al., 2021). Supply chain disruptions, rising food prices coupled with declining incomes, and movement restrictions collectively contributed to reduced access to both an adequate diet and appropriate health and nutrition services. The Food and Agriculture Organization (FAO) estimated that globally an additional 112 million people fell into undernutrition because of the COVID-19 pandemic, and food insecurity attributed to COVID-19 lockdowns disproportionately affected socio-economically vulnerable groups (FAO et al., 2022). Kang et al. (2023) found that nearly two-thirds of households in Chad reported an income reduction due to the pandemic, which was in turn associated with increased use of livelihood coping strategies. The household economic impacts of the pandemic in Chad were most pronounced in urban areas in 2020, whereas in 2021, there was a geographic shift and household economies in rural areas were more negatively affected (Kang et al., 2023).

Measures taken to alleviate hardship at the household level included the temporary suspension of electricity and water bills, expansion of the national food distribution program, establishment of a youth entrepreneurship fund, and a solidarity fund for the vulnerable population. In 2020, fiscal policies allowed for reductions in business license fees and taxes, agricultural sector subsidies, and simplification of import requirements for food and other necessities. In January 2021, a gradual re-opening included allowing the use of public transportation; re-opening of markets, shops, schools and universities, places of worship, and restaurants for carry-out; and re-opening of land borders and air travel (International Monetary Fund, 2022).

In Chad, by mid-2022, an estimated 2.1 million people faced crisis or above levels of food insecurity largely due to the convergence of the aforementioned factors and the Government declared a state of emergency due to the food crisis in the country [Food Security Information Network (FSIN) and Global Network Against Food Crises, 2022; Tchana et al., 2022].

Many theoretical frameworks showing the pathways through which household food security or local food systems are affected by COVID-19 economic recession are available [Béné et al., 2021; High Level Panel of Experts on Food Security and Nutrition (HLPE), 2021; Ghosh-Jerath et al., 2022]. The theoretical framework of this study is generated by adopting available frameworks (Supplementary Figure 1).

Although food insecurity in Chad has been widely reported, and this is loosely attributed to climate change, conflict, and pandemics, there is a lack of systematic evidence on the long-term trend of food security and the statistical association or risk factors for food insecurity. To this gap, this study examines the long-term spatial and temporal trends of food security among rural households in Chad from 2016 to 2021 and identifies risk factors for food insecurity during the 2020 to 2021 COVID-19 pandemic. We hypothesize that food security in the country has deteriorated over the study period. Given increasing food insecurity, the study is expected to inform the strategic orientation of humanitarian and development programs that can draw on the evidence to holistically address food insecurity and, more broadly, social protection for the most vulnerable.

Literature review

The World Food Summit of 1996 defined food security as a situation that exists when all people, at all times, have physical and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life (FAO, 1996). Food security is a multi-dimensional concept, encompassing physical food availability, economic and physical access to food, food utilization, and stability of the other three dimensions (Peng and Berry, 2019). It is therefore impacted by, among other things, the development of the countries, political instability, and climate change (Brown et al., 2015). Due to Chad's low positioning on social, economic, and climate indicators as earlier described and summarized by the World Bank, 2023, the country faces unique food security challenges in each of the dimensions (World Bank Group, 2023).

Food availability

Historical data available through the FAOSTAT database show that between 2000 and 2021, there was an 83% increase in the surface cultivated, a 53% increase in cereal yields, and a 182% increase in overall production, nonetheless marked by some years of deficit agriculture (Food Agriculture Organization, 2023). However, 83% of the increases in production for the period 1990–2016 can be explained by expansions in harvested area (Nilsson et al., 2000). A review of the Cadre Harmonisé (SISAAP, 2022) analyses nonetheless shows that in recent years (2018–2022), there was a notable (10%) reduction in production and there remains a cereal deficit of 276,911 tons, considering imports.

It is widely documented that agricultural production in Chad is primarily subsistence-based (with about 80% of the population engaged in smallholder farming and reliant on agriculture for food security) and rain-fed (GIZ, 2020; CIAT, 2021). Accordingly, food availability has been documented as dependent on rainfall (and overall climate) variability (CIAT, 2021). Notwithstanding, in their analysis of various production data on Chad, Nilsson et al. (2020) found that changes to crop water availability from rainfall are largely decoupled from the long-term increases in crop production. On the other hand, their analysis shows that population changes and international aid can explain differences in long-term changes between Chad's regions. Nilsson et al. (2020) also identified stochastic factors such as farm support programs, market prices, access to new markets, and accommodation of refugees as important to grasp abrupt changes in crop production, potentially explaining (in part) the erratic trends.

Access to food

Poverty in Chad is omnipresent and severe, of which 89% of poor households live in rural areas (The World Bank, 2021). Nonetheless, there was a notable reduction in the national poverty prevalence from 45.5% in 2014 to the present 42.3% (The World Bank, 2021). This inevitably means that fundamentally, a significant part of the population (estimated at 2.4 million people in 2018) is not able to meet basic nutritional needs per day. Further to this, it is notable that Chad has experienced a continuous rise in food prices over the last 2 years, further restraining access to food. The most widely consumed foods experienced increases throughout 2021, with millet, maize, sorghum, and berbere closing the year at 36.2, 36.5, 41.3, and 41.5%, respectively, above the 5-year average (WFP, 2022). The analysis attributes these price increases to, among other things, the drop in cereal production experienced during the 2021/2022 crop year, insecurity in parts of the country causing displacement of people, and production losses that led to a drop in food stocks in households and on the markets (WFP, 2022).

Food utilization

According to a review of the national food security assessment (ENSA) reports (SISAAP, 2022), the quantity and quality of household food consumption have deteriorated continuously since 2016, with a marked difference in the levels between the agroecological zones. For instance, in the Soudanien zone, the food consumption score declined from 66.4 in 2016 to 53.3 in 2022. In terms of quality, the reports show consistently higher consumption of grains, sugar, oil, and vegetables across the years at the expense of the more nutritious foods (SISAAP, 2022).

Food insecurity is the main reason for poor infant and young child feeding practices in Chad (Wuehler and Nadjilem, 2011). This combined with relatively poor sanitary standards in the country as well as the existence of socio-cultural barriers that impede the use of good nutrition practices particularly among children exacerbates poor utilization of food (WFP Chad, 2022). Thus, among children, the percentage of children who meet the minimum acceptable diet remains very low, at 33.8% according to the SMART survey report (Govt. Chad et al., 2023).

The national prevalence of stunting in Chad was staggered high between 32.4% in 2017 and 30.4% in 2021 without improvement (Govt. Chad et al., 2022). A study in N'Djamena with a sample of 881 children of 6–59 months of age (25.5%) reported that household food insecurity (16.6%) was related to child stunting (Gassara et al., 2023). Overall, a synthesis of data presented by the SMART nutrition surveys and the global nutrition report of 2022 indicates that Chad is faced with the triple burden of malnutrition with a high level of global acute malnutrition, a high prevalence of micronutrient deficiencies with anemia prevalence of 60% among children under 5 years, and relatively high prevalence of overweight and obesity, particularly among women, at 32 and 11%, respectively (Global Nutrition Report, 2022).

Food stability

The ND-GAIN index (Notre Dame Global Adaptation Initiative, 2023), which summarizes a country's vulnerability to climate change and other global challenges in combination with its readiness to improve resilience, classifies Chad as the country that is most vulnerable to climate change in the world, ranking 185th of 185 countries.

According to Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) (Funk et al., 2015), there has been an increase in total annual precipitation over the past 40+ years, and the last 6 years have all been above the long-term average with the highest quantity over the last 40 years recorded in 2022. Yet, according to research, all recent decades have been marked by reports of drought in the Sahel (Funk et al., 2015). Chad's unpredictable rainfall patterns, flooding, and droughts cause economic and social problems, exacerbating conflict and contributing to migration and internal displacement (American University, 2021). In addition to climate and conflict-related shocks, a recent study by Kang et al. (2023) showed that the COVID-19 pandemic also significantly affected food security by disrupting livelihoods in both rural and urban areas. As noted by the IMF 2022 (Baptista et al., 2022), successive shocks from the war in Ukraine and the COVID-19 pandemic have increased food prices and depressed incomes, raising the number of people suffering from high malnutrition and unable to meet basic food consumption in sub-Saharan Africa.

Methods

Data source

Secondary analysis was conducted using data from the 2016 to 2021 Enquête Nationale de la Sécurité Alimentaire (hereafter referred to as ENSA), which are national food security surveys conducted annually in the last quarter of the year (Système d'Information sur la Sécurité Alimentaire et d'Alerte Précoce du TCHAD, 2020). The ENSA is organized by the Government of Chad in partnership with WFP, FAO, and NGOs. The original focus of the survey was rural areas; however, in 2020, the ENSA was expanded to include urban populations in N'Djamena. The detailed procedure of data collection in ENSA surveys was described elsewhere (Système d'Information sur la Sécurité Alimentaire et d'Alerte Précoce du TCHAD, 2020). ENSA surveys employ probability-based sampling where each of the 68 departments is a stratum, with two-stage sampling including community and household selection. The ENSA sampling frame consists of the list of villages obtained during the 2009 Chad Population and Housing Census (Système d'Information sur la Sécurité Alimentaire et d'Alerte Précoce du TCHAD, 2020). The ENSA sample size in rural areas (i.e., outside N'Djamena) ranged from 9,165 to 9,544 households between 2016 and 2019 and increased to 13,208 and 14,761 in 2020 and 2021, respectively. Trained enumerators administered a standard questionnaire using the Open Data Kit (ODK) platform in the randomly selected households, interviewing the household head or other adult member present. The household questionnaire covered a range of topics including household assets, agricultural practices, sources of income, level of food stocks, food consumption, expenditures, household shocks, and coping mechanisms.

Outcome variables

The three outcome measures used for analysis were food consumption score (FCS), reduced coping strategy index (rCSI), and livelihoods coping strategy index (LCSI). The FCS reflects the diversity and frequency of household food and nutritional intake consumed in the 7 days preceding the survey and is an indicator used globally (INDDEX Project, 2018). The consumption frequency of eight food groups is assessed in the preceding 7 days, and weighted scores for each food group are summed to calculate the FCS; a higher FCS score indicates better food security. Household food security status is categorized using the following thresholds: 0–28 poor; 28.5–42 borderline; and >42 acceptable. For this analysis, a binary FCS variable (acceptable vs. poor/borderline) was generated and used as an additional outcome measure. The rCSI is a proxy indicator of household food insecurity that reflects both the frequency and severity of coping behaviors in the past week (Maxwell and Caldwell, 2008). The index is calculated based on five food-related coping behaviors including eating less preferred/costly foods; adult reduction of portion size to enable children to eat; reducing portion size at the household level; skipping meals; and borrowing food or relying on help from family/friends. Each question is scored based on frequency in the preceding 7 days, and scores are weighted by severity; a higher rCSI score indicates worse food insecurity. Household coping mechanism use is categorized based on the rCSI score where 0–3 is acceptable, 4–18 crisis, and 19–56 emergency level. For this analysis, a binary rCSI variable (acceptable vs. emergency/crisis) was generated and used as an additional outcome measure. The livelihoods coping strategies index (LCSI) was used to assess the use of livelihood-related coping mechanisms in the preceding month (WFP, 2022) with three severity levels (stress, crisis, and emergency). The LCSI was then computed for each household by weighting by severity level and adding all coping mechanisms used.

Statistical analysis

Statistical analysis was conducted using STATA/SE 17.0. Descriptive statistics included means, proportions, and confidence intervals which were analyzed separately for each survey to account for survey design and sampling weights, with trends over time illustrated at the national and ecological zone levels. Continuous outcome variables were checked for normality by quantile–quantile (Q-Q) plot and Shapiro–Wilk test (all $p > 0.05$).

Temporal trend analysis

For the temporal trend analysis with continuous FCS, rCSI, and LCSI outcomes, linear regression models with a time variable (survey year) were first fitted to estimate the annual change in these outcomes ($y_i = \beta_0 + \beta_1^* time_t + \ldots. + e_t$). A binary outcome (poor/borderline food consumption) was first specified by a logistic regression model ($\text{logit } y_i = \beta_0 + \beta_1^* time_t + \ldots. + e_t$). Second, quadratic models were fitted by adding a quadratic variable of time for the continuous outcomes ($yi = \beta 0 + \beta 1^* time_t^* time_t + \ldots. + et$) and the binary outcome ($\text{logit } yi = \beta 0 + \beta 1^* time_t^* time_t + \ldots. + e_t$).

In the quadratic models, the average marginal effect of the time that averaged the slopes of the change across six data points (years) was used to estimate the annual change in the score of continuous outcomes or an annual rate of change for the binary outcome. The average marginal effect of time (absolute percentage points) is approximately equal to the β1 coefficient when a model is fitted with a linear probability model. The annual score/rate change from the linear or logistic models was generally consistent with the results from time quadratic models.

One advantage of our approach is that the annual rate of change in the outcomes is estimated from the average marginal effect of time. The average marginal effects account for any variability or non-linearity in changes for the study period, by averaging the slopes of the change in outcome rates across all six rounds of survey data points.

The percentage change per year was estimated at the country level and for each agroecological zone (Saharan Zone, Sahelian Zone, and Sudanian Zone) (Figure 1). All linear, logistic, and quadratic regression models at the national level were adjusted for the ecological zone, literacy, gender, and age of household head, family structure, and wealth. A wealth quintile was generated using propensity score analysis based on assets.

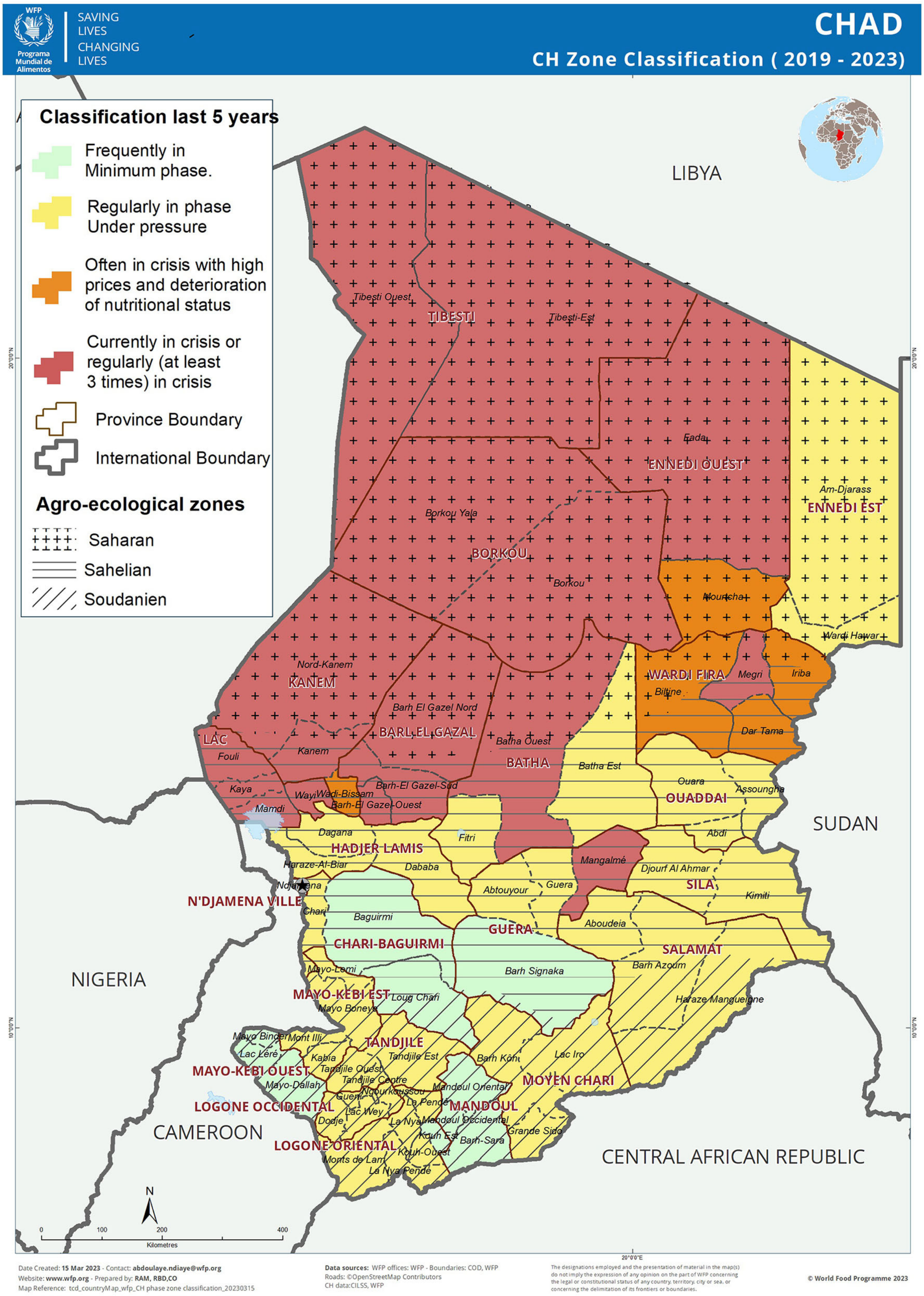

FIGURE 1
Map of the ecological zones and food security status in Chad.

Risk factor analysis

Univariate logistic regressions were first conducted to test the association between each of the potential risk variables and outcome variables in 2020 and 2021 (poor/borderline food consumption and diet-related coping mechanism use). Potential risk variables to be tested in univariate logistic regression included the household head's age, gender, marital status, literacy, disability, and occupation, family size, family structure (monogamous/polygamous/divorced), living conditions (dwelling type; energy, cooking sources and type of drinking water), three agroecological zones, change in COVID-related income, change in the number of income sources, primary income source, and LCIS. If there was a significant relationship in univariate regression models ($p < 0.10$), the variable was included in the multivariate regression analysis. The variables that presented significance ($p < 0.05$ or 95% CI not including 1.0) at multivariable analysis were considered significant risk factors. Differences in the factors between 2020 and 2021 were described separately for urban and rural populations for each year. The values of the variation inflation factor (VIF) for the final multivariate models were between 1.17 and 1.21, which indicated low multicollinearity. There was no heteroskedasticity for the final regression models tested by the Breusch–Pagan test ($p > 0.05$).

Ethical clearance

This study was reviewed by the Johns Hopkins Bloomberg School of Public Health Institutional Review Board and deemed to be exempt because it involved only secondary data analysis of acronymized data.

Results

Descriptive statistics for rural households participating in the 2016 to 2021 ENSA are presented in Table 1. The sample was concentrated in Sahelian and Sudanian zones, which is reflective of the population distribution. Mean household size ranged from 7.1 to 8.0, and 39.4% to 48.1% of households were considered large (defined as 8+ members) each year. Most households were monogamous (58.3–62.3%), though polygamous families (26.4–32.9%) were also common, and, to a lesser extent, households headed by divorced/widowed/single individuals (8.4–12.4%). The age distribution of household heads was relatively consistent across years with similar proportions (∼22–28%) of household heads in the 25–34 year, 35–44 year, and 45–55 year age groups; older (>55 years) and younger (<25 years) household heads accounted for ∼18–21% and 5–7% of the sample, respectively. The proportion of female-headed households was slightly lower in 2016 (15.6%) and 2021 (17.9%) as compared to other years when female-headed households comprised 21.2–21.9% of the sample. The proportion of illiterate household heads was higher in 2016–2019 (41.6–44.3%) and decreased to 36.6–37.3% in 2020/21.

Trends in food security and coping mechanism use, 2016–2021

We present the average marginal effect of time based on quadratic models as the annual change in FCS, CSI, and LCSI or annual rate change in the prevalence of poor/borderline food consumption (Table 2). The mean FCS significantly decreased from 60.3 points in 2016 to 54.9 points in 2021, indicating a declining trend in food security with an average reduction of 1.16 points in the FCS annually ($p < 0.01$). When examined by zone, there was no statistically significant change in FCS in the Saharan and Sahelian zones. However, there was a notable peak in poor food consumption in 2020 in the Sahelian Zone. In contrast, households in the Sudanian zone had a statistically significant decline in food security, with mean FCS decreasing from 66.4 in 2016 to 59.6 in 2021, which translates to a yearly reduction of 1.23 points in FCS ($p < 0.01$).

Similarly, the proportion of poor or borderline food consumption increased from 18.5% in 2016 to 25.3% in 2021 at the national level, which equates to a 1.55% (CI: 0.31–2.79%; $p = 0.014$) increase per year ($p = 0.014$; Table 2 and Supplementary Table 1). In the Sudanian zone, the proportion of households with poor/borderline food consumption increased significantly from 7.9% to 16.7%, which translates to an average annual increase of 1.33% (CI: 0.44–2.25%; $p = 0.01$). There was no statistically significant change over time in the proportion of households with poor/borderline food consumption in the Sahelian and Saharan zones (Figure 2).

The mean CSI score did not show any significant change between 2016 and 2021 at the national level ($p = 0.15$ and $p = 0.19$, respectively; Table 2, Figure 3, and Supplementary Table 1). There was a statistically significant annual improvement in CSI score with an average of 0.57 in the Sahelian zone and worsening with an average of 0.38 score per year in the Saharan zone. There was no significant time trend in CSI in the Sudanian zone. This trade-off trend of rCSI between Saharan and Sahelian zones resulted in no significant change at the national level.

The mean LCSI-Livelihoods-related coping mechanism use worsened over the years with a 0.11 score increase per year at the national level (Table 2, Figure 4, and Supplementary Table 1). The worsening in LCSI was significant in Sahelian with an annual increase of 0.14 score ($p = 0.004$) and in the Sudanian zone with an annual increase of 0.08 in LCSI; $p = 0.01$). There was no significant change in the Saharan zone. There was a peak in livelihood-related coping mechanism use in Feb 2021.

Risk factors for poor food consumption

Household characteristics that were significantly associated with increased risk of poor food consumption in both 2020 and 2021 included having an illiterate household head, being in a lower wealth quintile, having a single income source, and residence in the Sahelian zone (Table 3). The likelihood of poor food consumption increased with poorer wealth quintiles in a dose–response manner in both years and had the strongest association. As compared to the top quintile, in 2020 and 2021, households in

TABLE 1 General characteristics of the rural ENSA survey population in Chad, 2016–2021.

Survey date	Oct-16[1]	Oct-17[1]	Oct-18[1]	Oct-19[1]	Oct-20[1]	Oct-21[1]
Sample size	9,456	9,019	9,443	9,483	13,208	14,730
Geographic distribution of households						
Agroecological zone						
Saharan zone	4.4%	8.1%	8.7%	6.8%	3.4%	6.0%
Sahelian zone	48.7%	48.6%	48.9%	45.6%	46.4%	46.3%
Sudanian zone	46.9%	43.4%	48.9%	47.7%	50.2%	47.7%
Household demographic characteristics						
Household size						
Mean	7.7	8.0	7.6	7.1	7.1	7.7
Large (8+ members)	45.9%	48.1%	45.1%	43.1%	39.4%	44.2%
Household structure						
Monogamy	58.5%	58.7%	58.3%	61.2%	62.3%	62.3%
Polygamy	32.6%	32.9%	31.6%	26.4%	26.7%	28.7%
Divorced/widowed/single	9.0%	8.4%	10.1%	12.4%	11.1%	9.0%
Household head characteristics						
Household head age						
<25y	6.9%	6.5%	7.2%	5.7%	6.2%	4.9%
25–34y	26.9%	26.0%	24.5%	23.1%	23.8%	22.4%
35–44y	26.3%	25.7%	27.5%	28.1%	25.7%	28.5%
45–54y	21.7%	21.9%	21.5%	23.1%	22.8%	23.1%
≥55y	18.2%	19.9%	19.3%	19.9%	21.5%	21.2%
Female household head	15.6%	19.6%	21.9%	21.2%	21.9%	17.9%
Illiterate household head	42.7%	44.8%	41.6%	44.3%	36.6%	37.3%
Disabled household head	–	–	–	–	10.2%	8.3%

the poorest quintile were 4.64 and 3.68 times more likely to have poor food consumption, respectively ($p < 0.01$ for both years). All other quintiles had significantly increased odds of poor food consumption in both years as well ranging from 3.00 to 3.75 for the 2nd quintile, 2.33 to 2.75 for the 3rd quintile, and 1.35 to 1.86 for the 4th quintile. All quintiles had larger odds ratios in 2020 as compared to 2021, which aligns with the 2020 peak in poor food consumption at the national level. The agroecological zone was also very strongly associated with increased risk of poor/borderline food consumption, where households in the Sahelian zone had a 2.61 (CI: 1.47–4.61) and 2.51 (CI: 1.54–4.10) odds of poor food consumption in 2020 and 2021, respectively, as compared to households in the Sudanian zone which was consistently the most food secure. In 2020, when there was a peak in poor food consumption and coping mechanism use in the Saharan zone, households were 4.16 (CI: 1.58–11.0) times more likely to have poor food consumption as compared to those in the Sudanian zone, but in 2021, the situation resolved.

Apart from wealth quintile and residence location, household characteristics significantly associated with increased risk of poor food consumption in both years were having a single income source and an illiterate household head. In 2020 and 2021, respectively, households with a single income source were 1.83 (CI: 1.38–2.34) and 1.43 (CI: 1.11–1.85) times more likely to experience poor food consumption compared to those with multiple income sources. Households with illiterate heads were 1.48 (CI: 1.10–1.99) and 1.34 (CI: 1.03–1.75) times more likely to have poor/borderline food consumption in 2020 and 2021, respectively, as compared to households with literate heads. The only characteristic that was protective against poor/borderline food consumption in both years was an increase in the number of household income sources. Households reporting diversification of income (compared to the preceding year) were one-third less likely to have poor/borderline food consumption in both 2020 and 2021 (2020 OR = 0.68, CI: 0.52–90; 2021 OR = 0.67, CI: 0.48–0.95).

More household characteristics were significantly associated with poor food consumption in 2020 as compared to 2021. In 2020, polygamous household structure (OR = 1.24, CI: 1.01–1.54) and non-agricultural income sources including skilled/unskilled labor (OR = 1.49, CI: 1.04–2.13) and households reliant on humanitarian assistance and remittances (OR = 2.16, CI: 1.35–3.45) faced an increased risk of poor food consumption. In contrast, being in a larger household with eight or more members was protective (OR = 0.72, CI: 0.55–0.94).

TABLE 2 Trends in food consumption and diet-related coping mechanism use from ENSA surveys, 2016–2021.

Survey date	Oct-16	Oct-17	Oct-18	Oct-19	Oct-20	Oct-21	Annual rate of change[a]			
N	9,456	9,019	9,443	9,483	13,208	14,730	Linear model[a]		Quadratic model[b]	
Food consumption score (mean, 95% CI)							Adjusted ß[f]	*p*-value	Adjusted ß[f]	*p*-value
National level	60.3	58.9	55.7	56.3	58.3	54.9	**−1.16**	**<0.01**	**−1.16**	**<0.01**
	(57.8, 62.9)	(56.3, 61.6)	(53.0, 58.4)	(55.3, 60.2)	(56.3, 60.4)	(52.6, 57.3)	**(−1.88, −0.43)**		**(−1.88, −0.43)**	
Saharan zone	65.4	62.5	58.7	56.8	48.2	49.9	−2.46	0.14	−2.46	0.14
	(50.0, 80.8)	(54.2, 70.8)	(51.5, 65.9)	(54.4, 59.3)	(38.4, 58.0)	(46.6, 53.2)	(−5.73, 0.81)		(−5.73, 0.81)	
Sahelian zone	54.1	52.7	51.6	52.7	54.4	50.8	−1.02	0.13	−1.02	0.13
	(50.1, 58.0)	(48.7, 56.6)	(46.8, 56.5)	(48.2, 57.1)	(51.3, 57.5)	(47.0, 54.5)	(−2.33, 0.29)		(−2.33, 0.29)	
Sudanian zone	66.4	65.3	59.8	62.8	62.6	59.6	**−1.24**	**<0.01**	**−1.23**	**<0.01**
	(63.7, 69.1)	(62.3, 68.3)	(56.9, 62.7)	(60.2, 65.4)	(60.1, 65.1)	(56.2, 63.1)	**(−1.99, −0.48)**		**(−1.99, −0.48)**	
Diet-related coping mechanism use—rCSI (mean, 95% CI)							Adjusted ß[f]	*p*-value	Adjusted ß[f]	*p*-value
National level	3.8	5.1	5.1	4.3	4.3	4.3	0.15	0.19	0.15	0.19
	(3.1, 4.6)	(4.1, 6.1)	(4.0, 6.1)	(3.2, 5.4)	(3.4, 5.3)	(3.6, 5.1)	(−0.07, 0.37)		(−0.07, 0.37)	
Saharan zone	6.1	3.4	3.2	3.8	5.6	2.8	−0.57	0.02	−0.57	0.02
	(5.1, 7.2)	(2.6, 4.2)	(1.6, 4.8)	(2.6, 5.1)	(3.6, 7.6)	(1.6, 4.0)	(−1.05, −0.09)		(−1.05, −0.09)	
Sahelian zone	3.6	5.2	4.6	4.5	4.5	5.1	0.39	0.01	0.38	0.01
	(2.9, 4.3)	(3.8, 6.5)	(3.6, 5.6)	(3.5, 5.6)	(3.3, 5.7)	(3.8, 6.3)	(0.08, 0.69)		(0.07, 0.69)	
Sudanian zone	3.9	5.3	6.0	4.2	4.1	3.9	0.01 (−0.34, 0.36)	0.98	0.10 (−0.35, 0.36)	0.98
	(2.6, 5.1)	(3.7, 6.9)	(3.8, 8.2)	(2.2, 6.2)	(2.7, 5.5)	(2.8, 4.9)				
Livelihoods-related coping mechanism use—LCSI (mean, 95% CI)							Adjusted ß[f]	*p*-value	Adjusted ß[f]	*p*-value
National level	0.71	1.28	1.53	0.99	0.79	1.25	**0.11**	**<0.001**	**0.11**	**<0.001**
	(0.61, 0.82)	(1.01, 1.55)	(1.09, 1.97)	(0.74, 1.23)	(0.61, 0.96)	(1.00, 1.51)	**(0.06, 0.17)**		**(0.06, 0.17)**	
Saharan zone	0.72	0.91	1.73	1.03	1.29	1.95	0.17		0.17	0.12
	(0.41, 1.03)	(0.68, 1.14)	(0.86, 2.61)	(0.85, 1.21)	(0.20, 2.79)	(0.62, 3.28)	(−0.04, 0.37)	0.12	(−0.04, 0.37)	
Sahelian zone	0.75	1.52	1.39	0.79	0.79	1.32	**0.14**	**0.004**	**0.14**	**0.004**
	(1.04, 1.79)	(1.08, 1.97)	(0.95, 1.83)	(0.60, 0.97)	(0.60, 0.97)	(1.00, 1.65)	**(0.05, 0.23)**		**(0.05, 0.23)**	
Sudanian zone	0.67	1.19	1.50	0.59	0.75	1.10	**0.08**	**0.01**	**0.08**	**0.01**
	(0.56 0.78)	(0.74, 1.64)	(0.62, 2.39)	(0.31, 0.88)	(0.47, 1.04)	(0.71, 1.49)	**(0.02, 0.15)**		**(0.02, 0.15)**	
							Logistic model[c]		Quadratic model[d]	
Poor or borderline food consumption (percent, 95% CI)							Adjusted OR[f]	*p*-value	Adjusted ß[f]	*p*-value
National level	18.8	22.0	25.1	22.2	18.2	25.3	**1.11**	**0.02**	**1.55**	**0.01**
	(15.0, 23.3)	(18.3, 26.2)	(20.6, 30.3)	(18.1, 27.0)	(14.6, 22.4)	(20.9, 30.2)	**(1.02, 1.22)**		**(0.31, 2.79)**	
Saharan zone	14.5	18.0	17.3	18.8	44.5	21.6	1.16	0.42	1.81	0.39
	(2.7, 50.6)	(8.9, 32.9)	(8.8, 31.0)	(15.1, 23.0)	(26.1, 64.5)	(13.4, 32.9)	(0.81, 1.66)		(−2.37, 5.99)	
Sahelian zone	29.8	32.3	36.5	33.9	26.5	34.6	1.09	0.19	1.64	0.18
	(23.1, 37.4)	(26.1, 39.2)	(28.2, 45.8)	(26.1, 42.7)	(19.9, 34.3)	(25.8, 44.6)	(0.96, 1.23)		(−0.76, 4.05)	
Sudanian zone	7.9	11.1	13.6	11.5	8.7	16.7	**1.17**	**0.01**	**1.33**	**0.01**
	(4.7, 12.8)	(8.0, 15.3)	(9.9, 18.4)	(8.1, 16.3)	(6.0, 12.6)	(12.9, 21.2)	**(1.03, 1.33)**		**(0.41, 2.25)**	

[a]Bold text denotes statistical significance in adjusted models.

[b]Fitted to linear regression models with a time variable (each survey year).

[c]Fitted to quadratic models with an additional square term of the time variable (each survey year*each survey year) to the linear regression. The average marginal effect was derived by differentiating dy/dx.

[d]Fitted to logistic regression models with a time variable (each survey year).

[e]Fitted to quadratic models with an additional square term of the time variable (each survey year*each survey year) to the logistic regression. The average marginal effect is derived by differentiating dy/dx.

[f]All regression models were adjusted for household head's literacy, marital status, sex, and age, household wealth status, family size, main income source, energy source, and wall materials of household building.

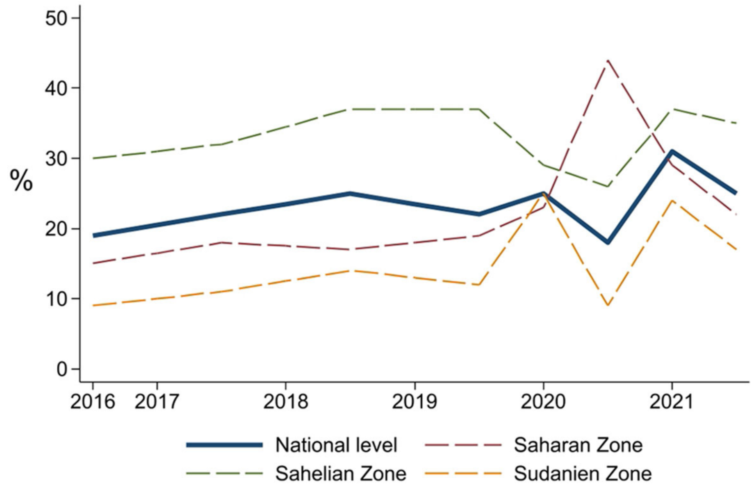

FIGURE 2
Temporal trends in the proportion of households with poor or borderline food consumption 2016–2021.

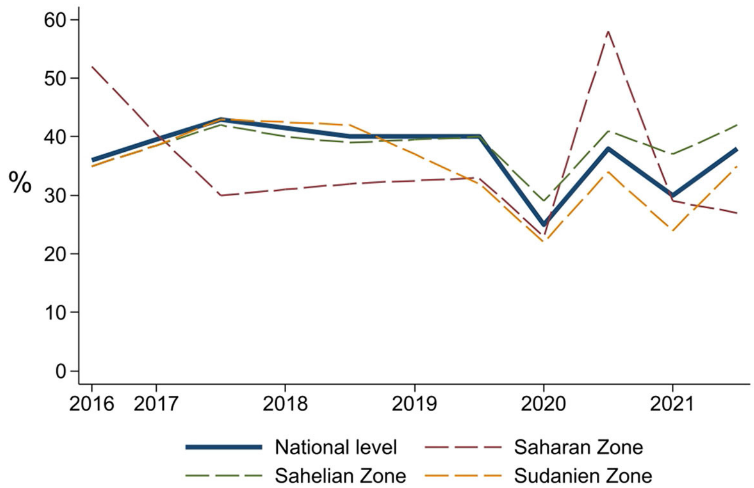

FIGURE 3
Temporal trends in diet-related coping mechanism use in Chad, 2016–2021.

Risk factors for diet-related coping mechanism use

There was little consistency in risk factors for diet-related coping mechanism use in 2020 and 2021 (Table 4). The only household characteristics significantly associated with increased coping mechanism use in both years were having a disabled household head and the livelihoods coping strategy index score. In 2020, polygamous family structure (OR = 1.21; CI: 1.01, 1.46), having a disabled household head (OR = 1.42; 95% CI: 1.02, 1.97), and the use of an unimproved drinking water source (OR = 1.59; CI: 1.17, 2.17) were associated with an increased risk of using diet-related coping mechanisms. The household economic characteristics associated with increased use of diet-related coping mechanisms in 2020 included belonging to the poorest wealth quintile (OR = 1.78, CI: 1.17–1.21) and a decrease in the number of income sources compared to the preceding year (OR = 1.61, CI: 1.21, 2.14). While the livelihood coping strategy index score was positively associated with diet-related coping mechanism use (OR = 1.59, CI: 1.20, 2.12), the use of emergency livelihood coping mechanisms, which include begging and selling land or the last breeding stock, was protective against the use of diet-related coping mechanisms (OR = 0.38, CI: 015, 0.95).

Similar to 2020, households with disabled heads were more likely to use diet-related coping mechanisms (OR = 1.36, CI: 1.03, 1.79). In 2021, older household head age was significantly associated with lower diet-related coping mechanism use. Compared to the 25–34 years age group, household heads aged 35–44 years (OR = 0.87, CI: 0.76, 0.99) and >55 years (OR = 0.84, CI: 0.73, 0.97) were less likely to use diet-related

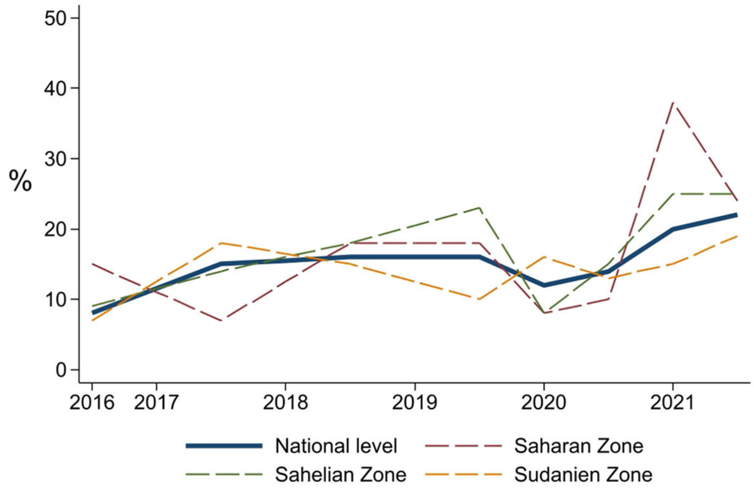

FIGURE 4
Proportion of households using emergency/crisis livelihoods coping strategies in Chad, 2016–2021.

coping mechanisms. The use of a non-electric energy source (OR = 2.65, CI: 1.65, 4.28) and reliance on external aid (OR = 1.44, CI: 1.06, 1.97) were also positively associated with the use of diet-related coping mechanisms in 2021 (but not 2020). Both LCSI (OR = 1.29, CI: 1.09, 1.54) and the use of crisis-level coping mechanisms (OR = 3.07, CI: 1.61, 5.87), including harvesting immature crops, removing children from school, and reducing health and education spending, were positively associated with diet-related coping mechanisms.

Discussion

This study examined spatial and temporal trends of food consumption and diet-related coping mechanisms use from 2016 to 2021 in Chad and identified risk factors related to these food security outcomes. At the national level, there were significant declines in food security during the 5-year evaluation period, including in the pre-COVID period. The proportion of households with poor or borderline food consumption increased by 6.8% between 2016 and 2021, with an average annual increase of 1.3%; food consumption scores decreased by an average of 1.16 points during this period. In examining trends over time, the proportion of households with poor and borderline food consumption rose from 18.8% in October 2016 to 22.2% in October 2019, before the pandemic. There were no significant trends in rCSI at the national level. However, a significant temporal trend in rCSI was observed with an average decrease of 0.57 points per year in the Saharan zone (improving) and an increase of 0.38 points per year in the Sahelian zone (worsening) during this period. The trend of LCSI was consistent with FCS, overall worsening at the national level and the Saharan and Sahelian zonal levels. The observed decline in food security occurs within a deteriorating macroeconomic situation which is attributed to political instability and efforts to combat terrorism; declining oil prices, trade revenues, and investment; and high food prices [Famine Early Warning Systems (FEWS) Network, 2021; Food Security Information Network (FSIN) and Global Network Against Food Crises, 2022].

During the earlier part of the pandemic in October 2020, the proportion of households with poor/borderline food consumption declined to a 5-year low of 18.2% in October 2020 before jumping drastically to a 5-year high of 30.7% in February 2021, after which there was a decline to 25.3% in October 2021 (the final time point in the analysis). The early pandemic low in food insecurity could be partially related to the scaling of the national food distribution program and other government fiscal and policy interventions (International Monetary Fund, 2022). It should also be noted that the negative impacts of the pandemic on household economies were most pronounced in urban areas in 2020 and rural areas in 2021, which aligns with our finding of deteriorating food insecurity in the rural ENSA coverage areas in 2021 (Kang et al., 2023).

Examination of food consumption at a regional level showed that the Sudanian zone had the highest levels of food consumption, yet it was the only zone to have a statistically significant decrease in food consumption, where the proportion of households with poor/borderline food insecurity rose by 8.8% over the 5-year period with an average annual increase of 1.3%. Despite the decreasing trend in food consumption, the proportion of households with poor/borderline food insecurity in 2021 in the Sudanian zone (16.7%) was approximately half that of the Sahelian zone, where more than one-third (34.6%) of households had poor/borderline food consumption. This is probably due to relatively higher agricultural production in the Sudanian zone hence relatively higher household food availability and access. However, the increasing climate variability and the fact that this zone is prone to weather extremes such as flooding likely affect production which is progressively negatively impacting household food security. Roughly half of the survey participants from the Sahelian zone belonged to the poorest quintile, and this region is particularly affected by climate change and limited natural resources [Food Security Information Network (FSIN) and Global Network Against Food Crises, 2022]. The Sahelian zone consistently had the lowest

TABLE 3 Risk factors for poor or borderline food consumption during the COVID-19 pandemic in Chad[a].

	October 2020			October 2021		
	Adjusted OR	(95% CI)	*p*-value	Adjusted OR	(95% CI)	*p*-value
Household demographic characteristics						
Large household 8+ Members (Ref:≤7)	**0.72**	**(0.55, 0.94)**	**0.02**	1.01	(0.88, 1.16)	0.87
Households structure (Ref: Monogamous)	1.00			1.00		
Polygamous	**1.24**	**(1.01, 1.54)**	**0.05**	0.92	(0.78, 1.08)	0.31
Divorced/widowed/single	0.97	(0.75, 1.27)	0.85	1.23	(0.95, 1.60)	0.11
Household head characteristics						
Household head age (Ref: 25–34 years)				1.00		
<25 years	–			1.09	(0.89, 1.34)	0.42
35–44 years	–			1.05	(0.90, 1.24)	0.50
45–54 years	–			1.13	(0.89, 1.43)	0.30
≥55 years	–			1.09	(0.88, 1.37)	0.42
Female household head sex	0.92	(0.68, 1.24)	0.59	0.82	(0.59, 1.14)	0.23
Illiterate household head	**1.48**	**(1.10, 1.99)**	**0.01**	**1.34**	**(1.03, 1.75)**	**0.03**
Disabled household head				1.29	(0.99, 1.67)	0.06
Residence location and living conditions						
Agroecological zone (Ref: Sudanian)	1.00			1.00		
Sahelian zone	**2.61**	**(1.47, 4.61)**	**<0.01**	**2.51**	**(1.54, 4.10)**	**<0.01**
Saharan zone	**4.16**	**(1.58, 11.0)**	**<0.01**	0.91	(0.44, 1.90)	0.80
Non-electric/gas energy source	**1.56**	**(1.06, 2.29)**	**0.02**	1.45	(0.87, 2.40)	0.15
Low-quality wall materials	0.76	(0.55, 1.04)	0.09	1.19	(0.81, 1.74)	0.37
Household economy						
Wealth quintiles (Ref: 5th/wealthiest)	1.00			1.00		
4th	**1.86**	**(1.21, 2.84)**	**0.01**	**1.35**	**(1.01, 1.82)**	**0.05**
3rd	**2.75**	**(1.82, 4.17)**	**<0.01**	**2.33**	**(1.81, 3.00)**	**<0.01**
2nd	**3.75**	**(2.38, 5.93)**	**<0.01**	**3.00**	**(2.21, 4.08)**	**<0.01**
1st	**4.64**	**(3.05, 7.07)**	**<0.01**	**3.68**	**(2.57, 5.26)**	**<0.01**
COVID-related income decrease[b]	1.26	(0.98, 1.62)	0.08	1.28	(0.98, 1.68)	0.07
Change in number of income sources[b]	1.00			1.00		
Increased	**0.68**	**(0.52, 0.90)**	**0.01**	**0.67**	**(0.48, 0.95)**	**0.03**
Decreased	0.95	(0.73, 1.24)	0.71	0.87	(0.60, 1.26)	0.45
Only one income source	**1.83**	**(1.38, 2.43)**	**<0.01**	**1.43**	**(1.11, 1.85)**	**0.01**
Primary income source (Ref: Agriculture)[c]	1.00			1.00		
Livestock	0.87	(0.55, 1.35)	0.52	0.68	(0.44, 1.04)	0.08
Small trade	1.13	(0.72, 1.79)	0.58	1.04	(0.64, 1.70)	0.86
Skilled/unskilled/artisanal labor	**1.49**	**(1.04, 2.13)**	**0.03**	1.00	(0.68, 1.48)	1.00
Humanitarian aid/remittances	**2.16**	**(1.35, 3.45)**	**<0.01**	1.36	(0.86, 2.15)	0.18
Others	**3.68**	**(1.94, 6.96)**	**<0.01**	1.25	(0.84, 1.86)	0.26
Livelihoods coping strategies index score	1.06	(0.99, 1.14)	0.08	–		
Crisis coping mechanism use (any)[d]	–			–		
Emergency coping mechanism use (any)[d]	–			–		

[a]Only covariates significant at the $p < 0.10$ level in univariate models are included in multivariate models; bold text denotes statistical significance in adjusted models.
[b]Compared to the preceding year.
[c]Included if reported as one of the top three household income sources.
[d]Crisis coping mechanisms include harvesting immature crops, removing children from school, and reducing health and education spending; emergency coping mechanisms include begging and selling land or the last breeding stock.

TABLE 4 Risk factors for emergency/crisis coping strategy use during the COVID-19 pandemic in Chad[a].

	October 2020			October 2021		
	Adjusted OR	(95% CI)	*p*-value	Adjusted OR	(95% CI)	*p*-value
Household demographic characteristics						
Households structure (Ref: Monogamous)						
Polygamous	**1.21**	**(1.01, 1.46)**	**0.04**	0.88	(0.73, 1.05)	0.15
Divorced/widowed/single	1.02	(0.78, 1.34)	0.86	1.01	(0.76, 1.33)	0.96
Household head characteristics						
Household head age (Ref: 25–34 years)	–					
<25 years	–			0.87	(0.72, 1.06)	0.16
35–44 years	–			**0.87**	**(0.76, 0.99)**	**0.04**
45–54 years	–			0.91	(0.75, 1.09)	0.29
≥55 years	–			**0.84**	**(0.73, 0.97)**	**0.02**
Female household head sex	1.26	(0.93, 1.70)	0.14	1.00	(0.77, 1.32)	0.97
Disabled household head	**1.42**	**(1.02, 1.97)**	**0.04**	**1.36**	**(1.03, 1.79)**	**0.03**
Residence location and living conditions						
Agroecological zone (Ref: Sudanian)						
Sahelian zone	1.07	(0.56, 2.02)	0.84	–		
Saharan zone	1.56	(0.76, 3.21)	1.59	–		
Non-electric/gas energy source	1.23	(0.91, 1.67)	0.18			
Inefficient cooking source	4.74	(0.95, 23.8)	0.06	**2.65**	**(1.65, 4.28)**	**<0.001**
Low-quality wall materials	0.96	(0.71, 1.31)	0.81	–		
Unimproved drinking water source	**1.59**	**(1.17, 2.17)**	**<0.01**	–		
Household economy						
Wealth quintiles (Ref: 5th/wealthiest)						
4th	0.97	(0.77, 1.23)	0.81	1.04	(0.78, 1.38)	0.78
3rd	1.03	(0.78, 1.35)	0.85	0.79	(0.58, 1.09)	0.15
2nd	1.28	(0.92, 1.77)	0.14	0.92	(0.63, 1.34)	0.65
1st	**1.78**	**(1.17, 2.71)**	**0.01**	1.23	(0.77, 1.96)	0.39
COVID-related income decrease[b]	1.13	(0.87, 1.47)	0.34	1.21	(0.89, 1.64)	0.21
Change in number of income sources[b]						
Increased	0.91	(0.58, 1.43)	0.67	–		
Decreased	**1.61**	**(1.21, 2.14)**	**0.01**	–		
Only one income source	1.32	(0.93, 1.85	0.12	–		
Primary income source (Ref: Agriculture)[c]						
Livestock	–			0.82	(0.60, 1.11)	0.20
Small trade	–			1.06	(0.77, 1.44)	0.73
Skilled/unskilled/artisanal labor	–			1.26	(0.92, 1.73)	0.15
Humanitarian aid/remittances	–			**1.44**	**(1.06, 1.97)**	**0.02**
Others	–			0.93	(0.61, 1.42)	0.73
Livelihoods coping strategies index score	**1.59**	**(1.20, 2.12)**	**0.01**	**1.29**	**(1.09, 1.54)**	**0.01**
Crisis coping mechanism use (any)[d]	1.05	(0.48, 2.33)	0.90	**3.07**	**(1.61, 5.87)**	**0.01**
Emergency coping mechanism use (any)[d]	**0.38**	**(0.15, 0.95)**	**0.04**	0.64	(0.31, 1.34)	0.24

[a]Only covariates significant at the $p < 0.10$ level in univariate models are included in multivariate models; bold text denotes statistical significance in adjusted models.
[b]Compared to the preceding year.
[c]Included if reported as one of the top three household income sources.
[d]Crisis coping mechanisms include harvesting immature crops, removing children from school, and reducing health and education spending; emergency coping mechanisms include begging and selling land or the last breeding stock.

food consumption scores and the highest proportion of the population with poor/borderline food consumption (26.5–37.4%). The exception was in October 2020 when food insecurity peaked in the Saharan zone, and the proportion of households with poor/borderline food consumption spiked to 44.5%. During this time frame, the northernmost areas of the country moved from stress to crisis levels of food insecurity, which aligns with the end of a severe pastoral lean season [Famine Early Warning Systems (FEWS) Network, 2021].

In the risk factor analysis for poor food consumption, having an illiterate household head, being in a lower wealth quintile, having a single income source, and Sahelian zone residence were significantly associated with poor/borderline food consumption in both 2020 and 2021. Households with illiterate household heads have been shown to have reduced income, limited access to information on jobs and prices, and increased expenses, which lead to higher food insecurity (Asesefa Kisi et al., 2018; Park et al., 2020). Additional characteristics associated with poor/borderline food consumption only in 2020 included being in a smaller (<7 members) or polygamous household, or a household [Food Security Information Network (FSIN) and Global Network Against Food Crises, 2022] that relied on skilled/unskilled labor or humanitarian assistance/remittances as a primary income source were observed during the peak of the COVID-19 pandemic in 2020. Similar to this study, FCS was predicted by job status/income levels and socio-economic status, age group within the context of the COVID-19 pandemic in both Ethiopia and Lao PDR (Gonella et al., 2022; Head et al., 2022). Consistent with findings from this analysis, there is substantial evidence that low-wage and low-skilled workforce lost their jobs or experienced income reduction during the initial lockdowns of COVID-19 (Nechifor et al., 2021). Without significant home production, it follows that laborers are more likely to face challenges accessing food than farming households that produce and sell or consume staple grains (Kang et al., 2021). In the 2020 ENSA, large household size was related to having multiple income sources; thus, larger household size was protective against food insecurity during COVID-19. In Nigerian agricultural households, polygamous families had better dietary diversity due to having more women engaged in farming activities pre-COVID-19 (Owoo, 2018). A similar casual pathway may exist in Chad, where at the national level in 2020, larger households were less vulnerable to food insecurity due to having more labor available and greater diversity in income sources. Interestingly, female-headed households were not at increased risk for poor food consumption or diet-related coping mechanism use in this analysis which is inconsistent with global trends (FAO et al., 2022).

Limitations

First, the ENSA collects a variety of food security indicators, but not all measures (e.g., household food insecurity access scale, household hunger score, or individual dietary diversity) are collected; thus, food security status as measured by FCS could not be crossed-checked against other dimensions such as access, stability, or sustainability [High Level Panel of Experts on Food Security and Nutrition (HLPE), 2021]. Second, although the sampling approach was consistent over time, it is possible that access issues may have influenced the representativeness of the sample in given years and that some of the temporal variations in food security indicators could be attributed to such sampling errors. Third, the short 7-day recall period of the rCSI may have been inadequate to fully assess a diet-related coping mechanism use, particularly given that this is likely to vary greatly in relation to household income flows and harvests. Fourth, the generalizability of findings is limited to the rural population of the country as urban households were included in the ENSA survey from 2020.

Finally, while the ENSA dataset provides repeat observations over time and incorporated an additional module on COVID-19 modules in 2020 and 2021, the scope of questions on COVID-19 impacts was limited; however, the dataset remains unique in that it provides a perspective on food insecurity both pre- and post-COVID.

Conclusion

The observed trends in food consumption suggest a small and gradual increase in food insecurity that began before the COVID-19 pandemic, and substantial variability in food insecurity in 2020 and 2021, both by region but also with respect to profiles of households at risk for poor food consumption. Many of the risk factors observed in 2020 were mitigated in 2021 as the pandemic impacts began to subside.

In a context where the driving factors of food insecurity persist, a strategic shift in humanitarian and development programming is needed to reverse the trend. The national response plan to food insecurity during the lean season typically prioritizes short-term assistance to food-insecure populations in the form of food and nutrition assistance and livelihood support. While this is vital, evidence in this study suggests that it is insufficient to meet the objectives. Notably, food insecurity being higher among the poorer quintiles and among households with illiterate household heads suggests the need for longer-term responses that address both chronic and acute food insecurity. Applying a social protection lens to interventions could enable the required strategic shift, potentially encompassing predictable safety nets that are shock-responsive, as well as school-based interventions and labor market programs.

Future policy should consider not only long-term trends but also risk factors for food insecurity within the most current years for which data are available. In addition to social protection and humanitarian assistance programs that focus on meeting immediate basic needs, longer-term development projects and policies that consider the challenges of the current economic environment and the impacts of climate change and also systematically promote social investment are urgently needed to enable more households to move out of poverty and food insecurity.

Data availability statement

The datasets presented in this study may be made available with the permission of World Food Programme, Chad (https://www.wfp.org/countries/chad).

Ethics statement

Ethical approval was not required for the study involving human participants in accordance with the local legislation and institutional requirements. Written informed consent to participate in this study was not required from the participants in accordance with the national legislation and the institutional requirements.

Author contributions

SD and EW conceptualized the study and were involved in obtaining funding. YK led data curation and analysis with support from MA, AB, and KE. YK led the drafting of the manuscript. EW, KE, MA, AB, and SD provided support during manuscript development and critical review. All authors participated in data analysis, review, and decision-making around the presentation of findings. All authors contributed to the article and approved the submitted version.

Funding

This study was funded by the World Food Programme, Chad.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2023.1197228/full#supplementary-material

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frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 30 October 2023
DOI 10.3389/fsufs.2023.1241850

OPEN ACCESS

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RECEIVED 17 June 2023
ACCEPTED 10 October 2023
PUBLISHED 30 October 2023

CITATION
Desta G, Legesse G, Agegnehu G, Tigabie A, Nagaraji S, Gashaw T, Degefu T, Ayalew B, Addis A, Getachew T, Managido D, Bazie Z, Abathun T, Abera A, Dache A, Adissie S, Sebnie W, Feyisa T, Yakob G, Amede T, Van Rooyen A, Jat ML and Harawa R (2023) Landscape-based nutrient application in wheat and teff mixed farming systems of Ethiopia: farmer and extension agent demand driven approach. *Front. Sustain. Food Syst.* 7:1241850. doi: 10.3389/fsufs.2023.1241850

Landscape-based nutrient application in wheat and teff mixed farming systems of Ethiopia: farmer and extension agent demand driven approach

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Introduction: Adapting fertilizer use is crucial if smallholder agroecosystems are to attain the sustainable development goals of zero hunger and agroecosystem resilience. Poor soil health and nutrient variability characterize the smallholder farming systems. However, the current research at the field scale does not account for nutrient variability across landscape positions, posing significant challenges for targeted nutrient management interventions. The purpose of this research was to create a demand-driven and co-development approach for diagnosing farmer nutrient management practices and determining landscape-specific (hillslope, mid-slope, and foot slope) fertilizer applications for teff and wheat.

Method: A landscape segmentation approach was aimed to address gaps in farm-scale nutrient management research as well as the limitations of blanket recommendations to meet local nutrient requirements. This approach incorporates the concept of interconnected socio-technical systems as well as the concepts and procedures of co-development. A smart mobile app was used by extension agents to generate crop-specific decision rules at the landscape scale and forward the specific fertilizer applications to target farmers through SMS messages or print formats.

Results and discussion: The findings reveal that farmers apply more fertilizer to hillslopes and less to mid- and foot slopes. However, landscape-specific fertilizer application guided by crop-specific decision rules via mobile applications resulted in much higher yield improvements, 23% and 56% at foot slopes and 21% and 6.5% at mid slopes for wheat and teff, respectively. The optimized net benefit per hectare increase over the current extension recommendation was \$176 and \$333 at foot slopes and \$159 and \$64 at mid slopes for wheat and teff (average of \$90 and \$107 for wheat and teff), respectively. The results of the net benefit-to-cost ratio (BCR) demonstrated that applying landscape-targeted fertilizer resulted in an optimum return on investment (\$10.0 net profit per \$1.0 investment) while also enhancing nutrient use efficiency across the three landscape positions. Farmers are now cognizant of the need to reduce fertilizer rates on hillslopes while increasing them on parcels at mid- and foot-slope landscapes, which have higher responses and profits. As a result, applying digital advisory to optimize landscape-targeted fertilizer management gives agronomic, economic, and environmental benefits. The outcomes results of the innovation also contribute to overcoming site-specific yield gaps and low nutrient use efficiency, they have the potential to be scaled if complementing innovations and scaling factors are integrated.

KEYWORDS

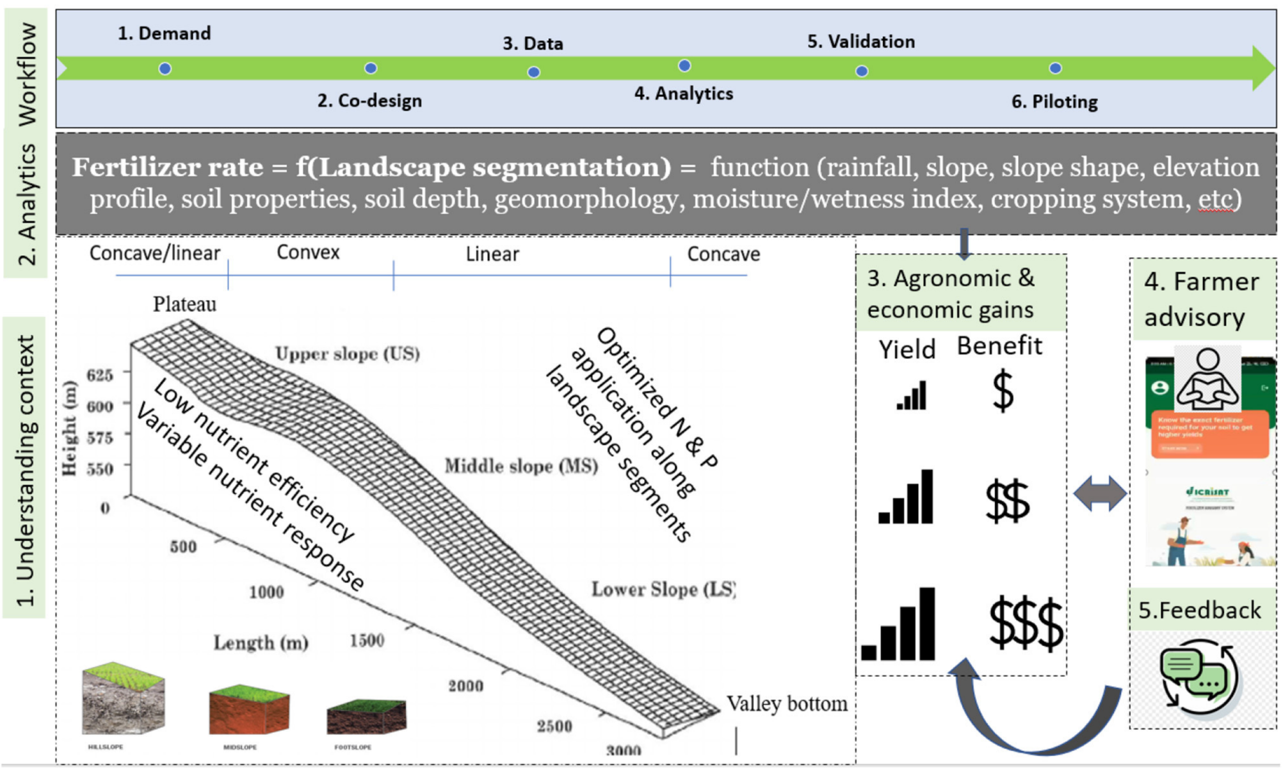
landscape segmentation, site-specific, optimized fertilizer use, agronomic gains, economic gains

Highlights

- Farmers practiced more fertilizer application on shallow hillslopes than lower slopes.
- A landscape segmentation approach enables a localized nutrient management for smallholders.
- Landscape-specific fertilizer application improved agronomic and economic gains.
- The BCR revealed an optimum return on investment along landscapes.
- The landscape specific digital advisory must be enabled by bundled innovations.

1. Introduction

Soil fertility is critical for long-term agricultural production and food systems. Depletion of soil nutrients within farms and across landscape positions is a major problem constraining crop productivity in smallholder farms of sub-Saharan Africa and it is a contributor to the change in agricultural landscapes and become a major sustainability concern (García-Martín et al., 2021). Nitrogen (N) and phosphorus (P) are the nutrients that most often limit crop yields, yet widespread use of soluble N and P fertilizers contributes to climate change via greenhouse gas emissions, and water pollution, both of which, in turn, threaten future food production and human health (Blesh et al., 2022; Drinkwater and Snapp, 2022). Agricultural landscape change is driven by a multitude of processes, which are typically closely interlinked. Local-level agricultural landscape changes – manifested as nutrient depletion, water scarcity, land use, and productivity changes - are driven by the interaction of natural and farming systems and socioeconomic settings of farming communities (Steffen et al., 2015). On the other hand, rising societal needs for food also lead to an intensification of agriculture (Erb et al., 2013). Soil nutrient management by smallholder farmers is thus one of the major elements of localized agricultural landscape sustainability influenced by the interaction



GRAPHICAL ABSTRACT Schematic presentation of the contents of the paper depicting five aspects. (1) Context of the landscape feature, (2) Analytical workflow to develop landscape nutrient advisory, (3) Agronomy and economic gains (KPIs), (4) The fertilizer advisory, and (5) Feedback.

of natural and farmers' socio-economic systems and deeply linked to local productivity, soil ecosystem services, soil health quality, and economic opportunity.

Soil nutrient management is critical for maximizing agricultural yield and protecting soil health for long-term productivity. Soil fertility challenges include the mining of soil nutrients and very little restoration of organic and inorganic soil amendments (Karaca et al., 2018). According to assessments of the soil's nutrient balance, nutrient losses in central Ethiopia reached 122 kg nitrogen, 13 kg phosphorus, and 82 kg potassium ha^{-1} y^{-1}(Haileslassie et al., 2005). Aluminum toxicity and phosphorous fixation are two additional constraints in Ethiopian soils that are visible at pH values lower than 5.5, which worsen nutrient limitations and toxicity (Agegnehu and Amede, 2017). Furthermore, steep slope agriculture in Ethiopia resulted in severe topsoil erosion, resulting in one of Africa's highest rates of nutrient depletion (41, 6, and 26 kg ha^{-1} y^{-1} of nitrogen, phosphorus, and potassium, respectively) (Smaling et al., 1993; Stoorvogel et al., 1993).

Other factors affecting productivity, in addition to soil depletion, include cropping patterns, fertilizer management, topography and geomorphologic changes, and fluctuations in rainfall conditions (Yokamo et al., 2022). Natural variations in soil fertility can be attributed to complex interactions between geology, climate, and soil use (Mzuku et al., 2005; Yasrebi et al., 2008; Yadav et al., 2023). Furthermore, topography influences the storage of soil organic matter and nutrients due to microclimate, runoff erosion, evaporation, and transpiration (Raghubanshi, 1992). Changes in vegetation species and soil nutrient concentrations occur frequently along the altitudinal gradient in crop-livestock mixed agricultural systems (He et al., 2016). All of these factors interact to create soil fertility variability and the resulting site-specific yield gaps (Njoroge and Zingore, 2022).

The variety of soil qualities, such as soil texture, soil structure, and organic matter, influences fertilizer use efficiency. Topographic gradients and soil moisture availability are also important factors in regulating the use of fertilizer (Martinez-Feria and Basso, 2020). Landscape positions explained by a variety of variables, including soil, slope, geomorphology, cropping system, and soil moisture, respond differently to agricultural productivity (Amede et al., 2020). In addition to natural factors, inadequate fertilizer use by smallholder farmers is caused by input access at the wrong time and place, excessive input prices, inaccessibility, and unavailability, as well as inadequate extension services, and limited access to credit (Yokamo et al., 2022). These barriers to fertilizer management could explain differences in fertilizer marginal returns and low adoption rates. These factors, as well as the mismatch between requirement and application, are expected to have a major impact on crop output. To inform fertilizer management decisions, it is critical to implement soil nutrient management techniques that are specifically adapted to local soil fertility needs and soil nutrient management drivers under varied agroecologies and farming systems.

The mean yield of maize, wheat, sorghum, and teff, which are grown by 16 million farmers, is 6.8, 2.7, 2.5, and 1.7 t/ha, respectively (Central Statistical Agency, 2021), while the yield of testing crops, wheat, and teff, is lower than the global average yield of 3.9 t/ha (Yokamo et al., 2022). A balanced fertilizer dose must be applied to any crop in order to achieve the desired yield (Elias et al., 2020; Yokamo et al., 2022). Regardless of the average fertilizer use rate among farmers who have adopted fertilizer, most farmers use and manage inorganic fertilizer inefficiently due to a lack of specific understanding of the site context and soil nutrient requirements. This could lead to a misalignment between soil nutrient requirements and fertilizer treatments (Abay et al., 2021). For example, the application of fertilizers to non-responsive and marginal areas, such as hillslopes and acidic soils (Amede et al., 2020; Abay et al., 2021), and low rainfall regimes (Martinez-Feria and Basso, 2020), impeded fertilizer use efficiency.

Current fertilizer recommendations frequently disregard the variability of production characteristics across time and space, only favoring crop responses in some farming systems. This results in blanket fertilizer recommendations that can be extended to other agricultural systems. Given the great range of soils and landscape features (topographies, elevation differences), the variability of agroecologies and farming systems, and the lack of digital extension services, it is important to address site-specific yield gaps for smallholder farmers. Creating landscape-specific fertilizer management and application strategies, as well as optimizing fertilizer application, necessitate an understanding of and evidence of crop response to fertilizer under varied topographies and crop management systems.

Thus, the current study was designed to address issues of localized yield gaps and extension service delivery problems, specifically: (1) Farmers currently apply fertilizer based on blanket recommendations that are based on extrapolating advice from one site to another without taking into account variation in climate, soil, and ecological setting; (2) There is little coverage of marginal lands (>15% in current national on-farm studies on nutrient management);. (3) The current crop technology scaling is heavily centered on variety and excludes localized nutrient management and agronomic practices as well as disregarding collaborative and farmer-centered innovation procedures; and (4). Due to several restrictions in the enabling conditions, the provision of extension services has not yet been digitized. Therefore, the goal of the current study was to demonstrate and highlight user-validated and demand-driven fertilizer management and use at the landscape scale. The specific objectives were to: (1) comprehend the evolution of fertilizer extension and current localized fertilizer use and agronomic practices of smallholder farmers; (2) assess the effects of combined N and P fertilizer applications across landscape positions on agronomic gains, agronomic efficiency, economic benefits, and optimized return on investment; and (3) draw lessons on a demand-driven and co-developed research process, a landscape scale nutrient management approach, and the requirements for scaling as a long-term remedy to address yield gaps, enhance nutrient use efficiency, and reduce costs.

2. Materials and methods

2.1. Target area description

This study was based on long-term landscape-targeted nutrient management on-farm field trials conducted in teff and wheat cropping systems in different districts of the country (see Figure 1).

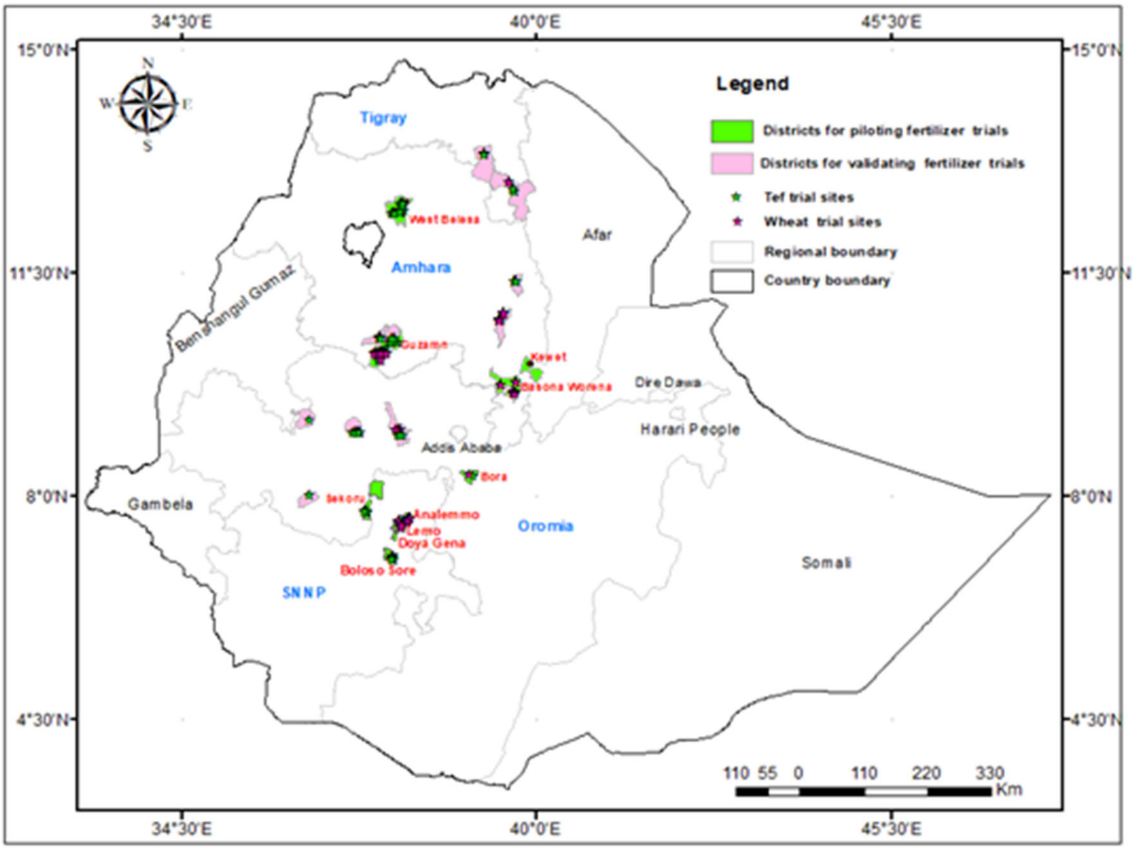


FIGURE 1
Location map of target areas where landscape-specific nutrient application is implemented: teff and wheat on-farm field trails, validation, and piloting trials.

Later, a digital advice tool co-developed by partners was validated and implemented in representative districts. The districts were chosen to represent two rainfall regimes (low to medium and high rainfall with 700–1500 mm mean annual rainfall), a variety of soil systems (Nitisols, Vertisols, Cambisols), and primarily teff and wheat cropping systems. Most smallholder farmers in the target areas are low-input users, using fertilizer only for a few market-oriented grain crops and very little or no fertilizer for sorghum and barley. These farmers, who regularly use fertilizer, have limited access to fertilizer, which on average ranges from 50 to 200 kg per hectare per season for various cereal crops planted on all of their plots. However, due to a 130–150% increase in fertilizer prices, this trend of application was substantially reduced and, in some instances, halted in 2022. During times of scarcity, farmers are accustomed to prioritizing the usage of urea for specific crops. Smallholder agricultural production in the target areas is characterized by low output, a lack of infrastructure, little technical knowledge, and a reliance on rainfall availability. Low crop yields are becoming a serious concern in the target areas as soil fertility deteriorates. Research findings revealed that the country's nutrient balance exhibited a depletion rate of 122, 13, and 82 kg ha^{-1} y^{-1} of nitrogen, phosphorus, and potassium, respectively (Haileslassie et al., 2005). Wheat and teff growing areas are distinguished by flat to undulating terrains that range in altitude from low to high.

2.2. Concepts and co-development approach

This research focuses on the agronomy at scale innovation development process used in the Fertilizer Ethiopia Use Case as part of the CGIAR's Excellence in Agronomy (EIA) initiative. To achieve an agronomic solution at scale, the research employs a conceptual framework of interconnected socio-technical components such as understanding and analyzing current practices, co-development, co-validation, and scaling of innovations and knowledge systems (Figure 2), all of which are linked by monitoring, evaluation, and a learning loop. An assessment of existing practices is undertaken to understand the gaps in research innovation and extension service delivery, as well as how current agricultural practices affect landscape-scale production levels and ecosystem services. The conceptual framework included in a co-development process is guided by seven principles, including context and demand-driven, on-farm data-driven, local farmer knowledge-centered, digitized extension services, capacity building, a multi-partner scaling network, and feedback loop mechanisms. The needs for fertilizer application, as well as experiences with digital extension services, were investigated and assessed through focus group conversations with farmers, extension agents, subject matter specialists, and researchers. Participatory procedures, technical

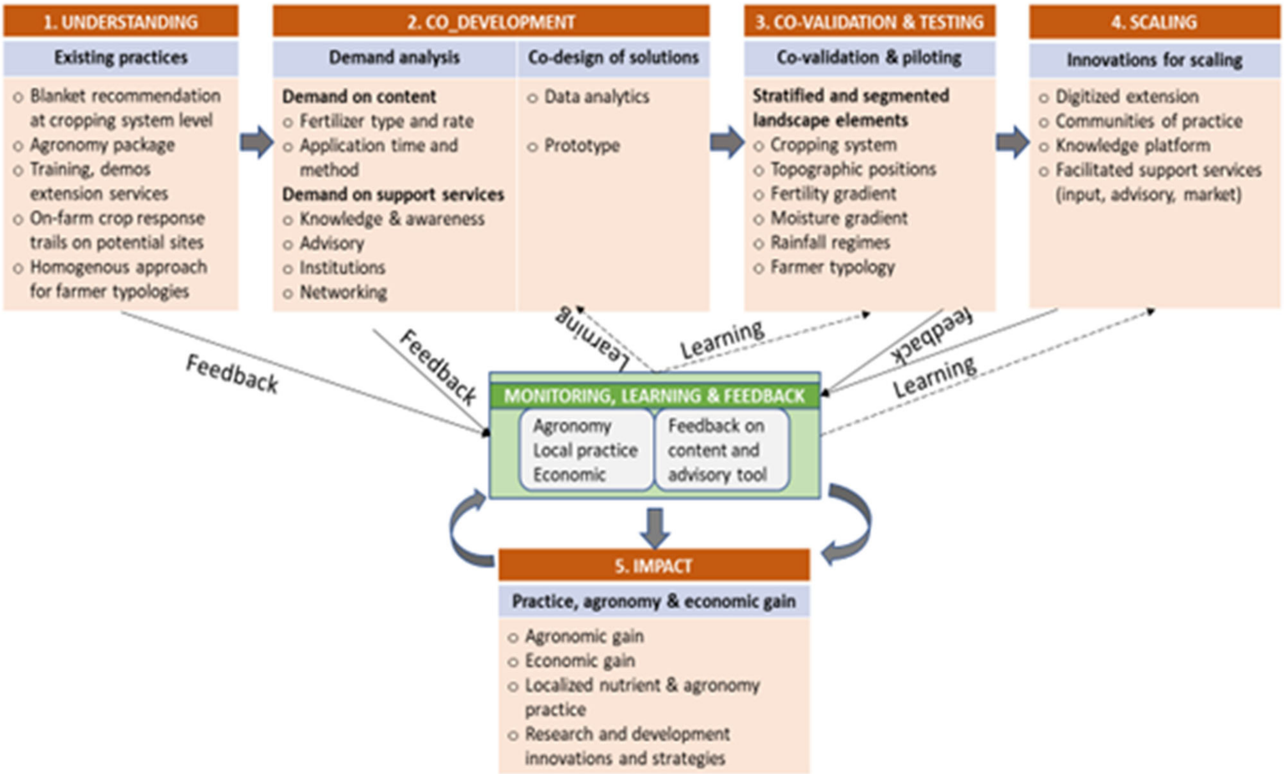


FIGURE 2
A conceptual framework for demand-driven and co-development of farmer and extension agent-centered landscape specific fertilizer application.

solutions, and scaling pathways were co-designed based on specific situations and demands of the farmers.

The current crop response to fertilizer on-farm data and other exploratory environmental data were translated and modeled into a digital advising tool for a localized landscape-specific fertilizer application based on the articulated user demand and gap analysis. This advisory was later scientifically co-validated in 2021 by testing on 260 farmers' fields in 15 districts, mostly with farmers and extension agents, as well as national soil and agronomy specialists. Later, in 2022, a verified advisory was co-piloted on 1,154 farmers' fields across 10 districts in 24 locations. The co-development method centered on farmers and extension agents. In addition to technical validation, farmer focus group conversations were held to better understand local knowledge of agronomic techniques and fertilizer use in landscapes. This local knowledge is combined with technical fertilizer knowledge to increase the relevance, acceptance, and adoption of landscape-targeted fertilizer applications in the local community. Extension agents, researchers, and decision-makers provided further feedback through field day events and social media communities of practice. The interactive and knowledge-based interaction strategy, which adheres to user-centered design principles, was designed with farmers and extension agents in mind. Partners at the forefront of technology development, input supply, digital solutions, and extension advisory must collaborate for improved and integrated innovations and knowledge that consider partners' perspectives and thus deliver bundled digital advisory solutions across the value chain in order to achieve an effective impact pathway and change outcomes.

2.3. Demand assessment

Focus group conversations with local stakeholders in several districts were utilized to examine farmers, extension agents, researchers, and district-level expert demands on fertilizer management elements. The requirements were investigated and specified in terms of information and knowledge gaps, fertilizer source and rate practices, digital advisory services, and other types of information and knowledge services. The focus group discussions were used to refine the research questions that would be the content of the intended innovation and analyzed the constraints of current extension services as well as the gaps and opportunities of digital advisory solutions. Thus, the demand was articulated, and a solution for wheat and teff cropping systems in dry and wet rainfed and mixed highland environments was offered.

2.4. Prototype development, validation, and piloting

The study team created the problem statement to formulate the research question after identifying the need for context-specific types and rates of fertilizer. At the landscape scale, the problem statement was to build decision rules and figure out fertilizer composition that returns the highest average yield with the least quantity of fertilizer application for each crop. Thus, the fertilizer management solution for wheat and teff cropping systems is designed with user demands, landscape positions on a spatial scale, and dry and wet rainfed domains in mind. The system can also make use of current crop response to fertilizer information.

The prototype was built using two datasets. First, we used data from a multilocation crop response on-farm trials for wheat, teff, and sorghum crops deployed from 2014 to 2021 and implemented along landscape scales classified into three positions: hillslope, mid-slope, and foot slope (refer to detailed descriptions in Amede et al., 2020; Desta et al., 2022). Second, based on the geolocation of on-farm agronomy data, we employed soil, climatic, and topographic online data sources from ISRIC, EthioSIS spatial nutrient map, and CHIRPS. Before performing analytical modeling, the data was cleaned, enriched, transformed, and labeled. The data was coded at three levels to assist the analysis steps: (1) Experimental IDs were defined to identify similar sets of environmental domains such as soil characteristics, rainfall, terrain, cropping systems, and so on. (2) Trial IDs, within an experiment, the various nutrient application rates of the on-farm trials were considered as different trials; and (3) Replication IDs, within the same experiment, a trial was replicated across farmer fields to average out factors outside the control. Each landscape position and crop type had its labeling. Machine learning techniques were utilized to construct decision rules that run on a prediction engine and produce specific fertilizer recommendations for each landscape stratum based on queries of essential attributes (i.e., entropy is used to evaluate randomness and disorder or uncertainty). So, for each experiment, the analytical algorithm was developed, and the trial with the highest average yield (within the 5% yield range) and the least amount of nutrients was labeled as the recommendation for each landscape position. The decision criteria were transformed into an app-based digital decision support tool that conveys farmers' text messages on landscape-targeted fertilizer applications for each crop.

In the 2021 cropping season, a technical validation protocol for extension agents was developed and implemented in 5 districts for teff and 4 districts for wheat. The validation trials were designed to contrast the fertilizer decision rules (prototype) that return specific fertilizer recommendations at each landscape stratum within a homogeneous environmental domain against the current extension fertilizer recommendation (as a control). The current extension fertilizer recommendation represents a research recommendation included as an agronomic extension package at the district level or it is a national blanket recommendation where there is no local research recommendation. Four farmer fields were chosen for validation in each landscape stratum (hillslope, mid-slope, and foot slope). In each farmer's field, two 10 m by 10 m field plots are laid out side by side for landscape-specific decision rules (prototype) and control treatments (extension fertilizer recommendation). Data on agronomic variables, production costs, and output prices were collected. Additional long-term yield monitoring data on farmer practices was collected from the target areas to serve as a baseline.

During the validation process, demand partners and research teams shared roles and responsibilities. The implementation was coordinated by the district agriculture office. Farmers who participated in the validation had to provide information on farm history, agronomic approaches, and cultivation costs. The extension agents were responsible for actively engaging farmers to collect agronomic and production cost data from the validation trials, facilitate farmer-to-farmer exchange visits, and organize field day events among farmers and district agriculture partners. Researchers in the national research system provided technical assistance to extension agents, such as validation method training, feedback surveys, and data collection. After updating the advisory using the validation trial data, the stakeholder participatory process continued during the 2022 cropping season when the fertilizer advisory tool was piloted in 24 Kebeles in 10 districts (i.e., there are 4 overlapping districts for two test crops) of the three regional states (Amhara, Oromia, and South) (Figure 1). The piloting activities were conducted in six districts across 13 locations on 516 farmer fields for wheat and eight districts across 18 locations on 587 farmer fields for teff.

2.5. Feedback survey

During the validation and piloting phases, four feedback strategies were utilized. Twenty participants from each Kebele were randomly selected from both participant and non-participant farmers, including individuals of different genders and ages, for focus group discussions (FGD). Each participant farmer was given an equal opportunity to answer each question. They were asked to share their thoughts on the specific context of their parcels. The FGD participants provided contextualized information that helped in providing feedback on the performance of nutrient applications and agronomic techniques. In addition, field day events were organized to allow local partners and participant farmers to exchange their reflections and insights. Furthermore, a social media platform (a Telegram group) was created in each district, which included extension agents, experts, decision-makers, and researchers, to form communities of practice that facilitate the exchange of new knowledge, problem-solving, sharing of thoughts, and sharing of testimony. Finally, a formal feedback survey was conducted that included extension agents and a mix of participant and non-participant farmers using the feedback and event registration tool in ODK.

2.6. Data analysis

The co-development of a landscape-specific fertilizer recommendation by demand partners was measured in terms of improving farmers' fertilizer use behaviors, agronomic gains, and economic benefits. Agronomic and economic data from the validation trial were used to evaluate yield improvement, benefit-to-cost ratio (net benefit per total cost), profitability, and agronomic efficiency to existing extension fertilizer recommendations. The relative yield increase of the landscape-targeted fertilizer recommendation was analyzed and compared to the control and district-level baseline data, as well as the agronomic efficiency (yield increase per unit of nutrient application) and net benefit, using probability analysis. Farmers and extension agents provided comments on the content application and usability of the digital advisory to examine the acceptability and relevance of the fertilizer recommendations at the landscape scale and the digitalized extension advisory tool.

3. Results

3.1. Evolution of fertilizer research and extension

This section seeks to present the current state and trends in fertilizer extension during the previous five decades, as well as information about gaps and current practices. The evolution of fertilizer extension is depicted in Supplementary Figure S1. From the late 1960s until the mid-1980s, fertilizer application levels remained low. Between 1986 and 1995, during the launch of the Peasant Agricultural Development Program (PADEP), fertilizer consumption slightly increased. A variety of initiatives have since changed Ethiopia's fertilizer supply. One of the gaps in fertilizer adoption until recently was the blanket application of fertilizer with little respect for specific nutrient requirements based on soil type, climatic conditions, and crop type. The need for site-specific fertilizer recommendations was discovered during the implementation of the first agricultural minimum package project in the early 1970s (Degefie and Tamene, 2017).

The second minimal package program, which operated from 1980 to 1984, aimed to increase crop productivity by increasing fertilizer use. Under the supervision of the Ministry of Agriculture's (MoA) Agricultural Development Department (ADD) and National Fertilizer Input Unit (NFIU), intensive fertilizer response studies, including 2.5-hectare field trials, on-farm fertilizer, and integrated plant nutrition testing, were conducted during PADEP. Based on an economically optimal nutrient rate, these studies produced regional fertilizer recommendations for a broader soil category (FAO, 1997). During this time, the Institute of Agricultural Research (IAR) also conducted crop response research with N and P. Participatory demonstration of inputs was carried out as part of the Participatory Demonstration and Training Extension System (PADETES) from 1993 to 1999.

SG2000 used a high-input approach—integrated use of seeds, fertilizer, financing, and extension—in the early 2000s to double or triple crop yields and increase profitability by two to three times (Spielman et al., 2011). Soil fertility and soil health received governmental attention following this time, particularly during the first Growth and Transformation Plan (GTP I, 2011–2015), and became one of the Agriculture Investment Framework (PIF) strategic objectives. As a result, several soil nutrient-related projects, including EKN-WUR by EIAR (2010–2011), EthioSIS by ATA (since 2012), CASCAPE by universities (2012–2015), OFRA by AGRA (2015–2019), and Africa Rising by CGs (2014–2022), have been initiated. This period is also marked by the invention of blended fertilizers. Significant soil sets have been discovered since 2010. Since 2010, the national research system and agriculture offices have launched major sets of soil test-based fertilizer experiments and fertilizer response demonstrations across the country. ICRISAT has been active in and contributed to the creation of fertilizer response trials over this period and has initiated landscape-targeted fertilizer response experiments for wheat, teff, sorghum, and maize crops. The refining of varied nutrient sources and rates through validation studies, as well as the promotion of integrated nutrient management through the ISFM framework, are currently driving the evolution of fertilizer management and use. Nonetheless, throughout the last four decades, the issue of targeting site-specific fertilizer applications has gone unresolved.

3.2. Local demands and nutrient management practices

3.2.1. Demands for fertilizer management

Extension experts employed a variety of approaches to determine and advise farmers on fertilizer sources and application rates. Extension experts examine local crop diversity, land size, the extent of fertilizer use in prior years, farmer purchasing capacity, and the number of lead farmers when assessing total fertilizer demand. Soil fertility maps (EthioSIS maps) are used to determine the forms of fertilizer sources. The amount of annual fertilizer delivery finally determines the actual fertilizer demand in the districts. Crop-specific fertilizer use or application rates are determined using fertilizer recommendations included in district extension package guidelines. Most farmers made location-specific fertilizer applications based on the experiences of other lead farmers. Farmers are hesitant to use extension recommendations unless they are motivated by location-specific factors, as they are associated with risks such as increasing fertilizer prices, delivery delays, rainfall variability and drought, and diseases and pests. Farmers, extension officers, and researchers expressed their local needs and requirements about fertilizer management. The critical requirements included: (1) methods for assessing and deciding on local fertilizer requirements based on soil, topography, climate, and farmer type; (2) data and information gaps on soil fertility depletion rates by cropping system; and (3) fertilizer application guidelines and tools.

3.2.2. Farmers' agronomic practices along landscapes

Understanding and describing how farmers use fertilizer and agronomic techniques in landscape positions is required for laying the basis for targeted fertilizer application and nutrient use efficiency. We examined the relationship between scientific data and farmers' contextual knowledge in this study. Farmers from 24 different areas participated in a focus group discussion to analyze their present use of fertilizer and agronomic techniques. According to the results of focus group interviews with farmers, farmers often describe their parcels or the locality's collective croplands in terms of the soils' long-term productivity, water-holding ability, crop appropriateness, and tillage and planting requirements. It is recognized that converting a wide range of soil and crop attributes into spatially variable landscape sections with varying production levels is thus an important nutrient management strategy for meeting localized demand, increasing fertilizer use efficiency, and reducing nutrient loss (Haneklaus and Schnug, 2000).

The focus groups evaluated soil conditions, cropping systems, and planting dates along different landscape domains, as well as fertilizer use in varied situations. Soil depth is used by farmers as a local indicator to assess soil fertility in general and the potential for the production of parcels that correspond to different landscape segments in particular. In comparison to the mid-and foot-landscape sites, hillslopes have minimal soil depth (Supplementary Figure S2). Farmers distinguish landscape sites by employing spatially explicit cropping systems and planting dates, as shown in Supplementary Figure S3. When planted in hillslope conditions, both wheat and teff cropping systems often use cereal-pulse cultivation cycles (Supplementary Figure S3). Cycling from one cereal to another was common on foot slopes in teff planting systems. Planting dates and cropping patterns differ depending on landscape position, which is linked to slope, soil fertility status, and moisture retention capacity.

While teff and wheat crops were planted on the foot slopes during a period of saturated soil moisture conditions, farmers with plots on the hillslopes planted early under sub-optimal moisture conditions. Teff can be planted from the first decade of July to the third decade of August, whereas wheat can be planted from the first decade of June to the first decade of August (Supplementary Figure S3). Planting dates vary from a week to a decade within each landscape position. Changes in agronomic methods (planting dates and crop rotation) are generally ascribed to soil depth changes and the accompanying ability of landscape locations to retain water. Thus, the various attributes of landscape segments in terms of cropping systems and planting dates, as well as variance in soils, topography, and geomorphologic features, indicate the importance of landscape position as a decisive element in farmers' agronomic and fertilizer management.

3.2.3. Farmers' fertilizer management practices along landscapes

National agricultural extension services recommended 87/46 kg ha^{-1} N/P2O5 for wheat (Alemu et al., 2016; Lelago, 2016; Elias et al., 2019; Desta and Almayehu, 2020) and 46/46 kg ha^{-1} N/P2O5 for teff (Kenea et al., 2021). However, the extension fertilizer recommendation has been changed to account for little rainfall and acidic conditions. In low-rainfall areas, the blanket recommendation for teff is 41/46 kg ha^{-1} N/P2O5, whereas, in acidic soils, the recommendation is 180/92 kg ha^{-1} N/P2O5 for wheat and 80/46 kg ha^{-1} N/P2O5 for teff. Although there are guidelines for extension recommendations for many crops, farmers often contextualize to their farm conditions and adapt their own fertilizer application practices. Following in-depth interviews with farmer groups in 24 different locations, it was determined that landscape aspects had a significant impact on fertilizer applications and agronomic practices such as planting dates, cropping systems, and crop rotations.

Farmers' fertilizer utilization strategies differ depending on crop type and landscape position. Farmers put varying amounts of fertilizers on hillslopes, mid-slopes, and foot slopes (Figure 3). Farmers were accustomed to applying more fertilizer to the wheat crop than to the teff crop. Regardless of landscape position, farmers utilized extremely variable rates of 5–100 and 4–35 kg ha^{-1} nitrogen and phosphorus for teff and 50–200 and 10–35 kg ha^{-1} nitrogen and phosphorus for wheat. For hill slope, mid-slope, and foot slope positions, farmers applied 8–100, 5–80, and 5–65 Kg ha^{-1} of nitrogen and 6–76, 3–57, and 8–38 Kg ha^{-1} of phosphorus to teff, respectively. In contrast, for hillslope, mid-slope, and foot slope applications, respectively, 65–150, 50–130, and 50–180 Kg ha^{-1} of nitrogen and 38–75, 25–75, and 30–75 Kg/ha^{-1} of phosphorus are added to wheat. Farmers' diverse fertilizer applications show that, in contrast to the fertilizer recommendations provided by extension services, they are accustomed to engaging in localized fertilizer management. Overall, most farmers used less nitrogen and more phosphorus fertilizers. Farmers used relatively high fertilizer rates on farms located on hillslopes and vice versa on farms located on foot slopes. This variation in the utilization of fertilizer showed the necessity for tailored fertilizer use based on farmer type and landscape positions. According to the most current CSA agricultural survey reports (FAO, 1997), the average national teff and wheat fertilizer application were 67/20 and 90/25 kg ha^{-1} nitrogen and phosphorus, respectively. The significant disparity in application rates between farmer practices and the national average demonstrates the importance of locally tailored fertilizer management. Even though farmers used a lot of fertilizer on hillslopes, the measured yield data revealed a decrease in the trend from foot slopes to hillslopes (Figure 2). Given the relatively high rate of fertilizer application and poor grain output on hillslopes, fertilizer appears to be used inefficiently, resulting in marginal returns on investment.

Figure 3 depicts farmers' current fertilizer use for teff and wheat in three different landscapes. The resulting partial factor of productivity (PFP) of N and P was found to be significantly varied both within and between landscape positions due to farmers' differing application rates. The existing farmers' practice results in the inefficient use of nutrients due to the high rate of fertilizer usage on hillslopes and the concomitant fall in agronomic efficiency from foot slopes to hillslopes. As a result, the total yield response is larger on foot slopes and lower on mid- and hillslopes (Figure 4). While the yield response on reasonably fertile flat lands increases through a wide range of fertilizer rates, the response on hillslopes diminishes as the rate of application increases. Farmers' fertilizer application in their fields is ineffective because they lack sufficient knowledge of the nutrient management required under particular conditions. As a result, it is critical to improve farmers' fertilizer usage patterns for them to apply an appropriate amount of fertilizer, resulting in high productivity.

3.3. Agronomy and economic gains at the validation stage

3.3.1. Agronomic gains

The validation trials were designed to contrast fertilizer decision rules that return specific fertilizer recommendations at each landscape stratum within a homogeneous environmental domain with the extension fertilizer recommendation (as a control). Taking all farmer fields planted for teff across all districts, the average nitrogen application generated by the decision rules was 110, 75, and 55 kg ha^{-1} at foot slope, mid-slope, and hillslope, respectively, compared to the 60, 60, and 55 kg ha^{-1} average extension recommendation (control treatment). The average nitrogen application of teff by the decision rule increased by 84 and 27% at the foot slope and mid-slope, respectively,

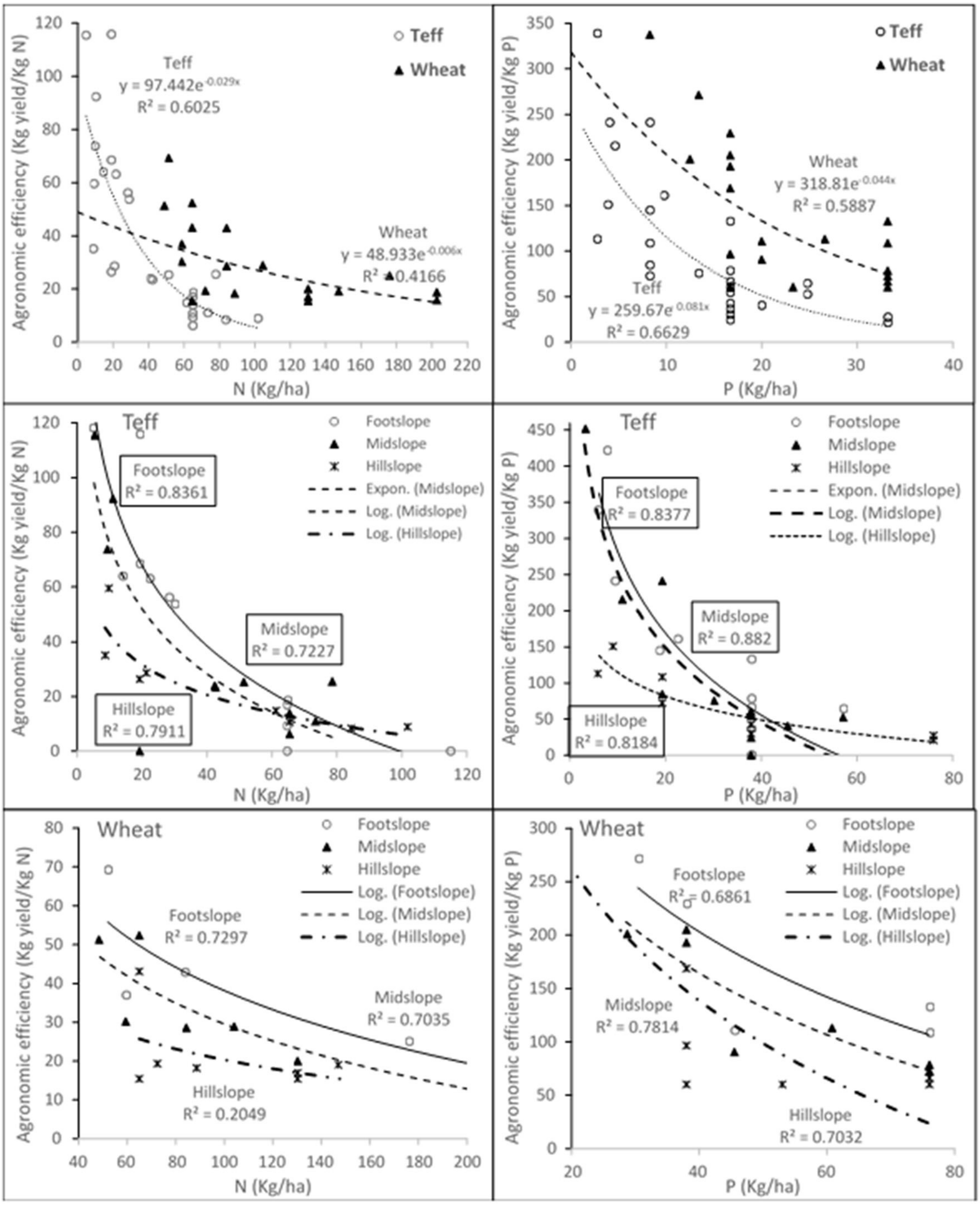


FIGURE 3
Partial factor of productivity of N and P fertilizers for teff and wheat under farmer management practice.

over the extension application, while it remained the same at the hillslope. The average phosphorus applications for teff were 33, 21, and 15 kg ha^{-1}, respectively, compared to the average extension recommendation of 17 kg ha^{-1}. The phosphorus rate increased by 93 and 22% on the foot slope and mid-slope, respectively, and reduced by 16% on the hillslope. The average nitrogen application generated by the decision rules for wheat was 135, 112, and 60 kg ha^{-1} at the foot slope, mid-slope, and hillslope, respectively, compared to 107, 105, and 117 kg ha^{-1} for the control treatment. The landscape recommendation increased by 26 and 7.7% at the foot and mid slopes, respectively, but decreased by 49% at the hillslope. The average phosphorus application to wheat was 34, 29, and 15 kg ha^{-1}, compared to the 20 kg ha^{-1} average extension requirement, resulting in 72 and 47% increases at the foot and mid slopes, respectively, and a 29% decrease at the hillslope. In general, the landscape approach increased nitrogen

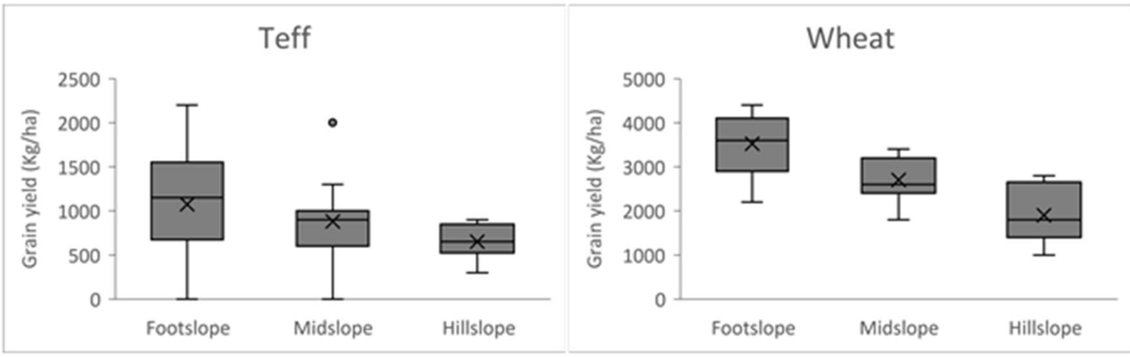


FIGURE 4
Grain yield information on farmers' fields which are generated from farmer focus group discussions.

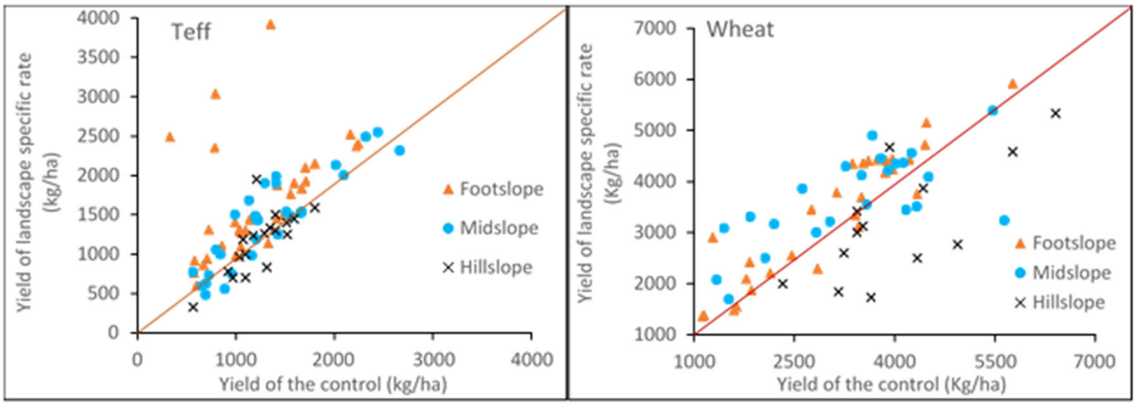


FIGURE 5
The grain yield relationship of the landscape-specific fertilizer application and the control or extension recommendation.

and phosphorus application rates for teff and wheat by 45 and 4%, respectively, over the existing recommendation rate.

When compared to extension recommendations, using a landscape-specific fertilizer rate increased average wheat and teff yields by 100 (15%) and 146 (20%) kg ha^{-1}, respectively (Supplementary Figure S4). The yield response varied among landscape sections (Figures 5, 6), with wheat and teff yielding 23 and 56% greater than the control on foot slopes, respectively. Wheat and teff yield increases were 21 and 6.5% on mid slopes and −17 and −10% on hillslopes, respectively (Figures 6B, D). The yield comparison, using probability distributions, also shows that the landscape-specific fertilizer innovation generated higher yields than current extension fertilizer advises in ~65% of the farmer's fields (Figures 6B, D). A significantly negative yield gain was seen on fields located on hillslopes where the yield of the extension fertilizer application exceeded the landscape-specific recommendation (Figures 5, 6). The low pH-induced nutrient imbalance was a typical source of negative yield gain in acidic soil sites when the extension recommendation advised using extra fertilizer to compensate for unavailable nutrients. Figure 6 showed that landscape-specific fertilizer recommendations exceeded both extension fertilizer recommendations (control) and the baseline yield derived from district-wide long-term yield monitoring. A landscape-specific rate produced a higher yield than the extension recommendation under the same cumulative probability of occurrence. Teff's yield increase is larger than that of wheat. However, when compared to long-term yield data, wheat and teff farms that received landscape-specific rates showed considerable yield enhancement (Figure 6). This demonstrates that landscape-targeted fertilizer treatments boosted teff yield. Wheat yield responded slightly to landscape-targeted rates because existing fertilizer application has resulted in varied wheat production in acidity-affected sites. Thus, the yield comparison indicated that the yield response varied based on the landscape positions and the specific context of the locations. Farmers are encouraged to reduce fertilizer rates on depleted and shallow soils on hillslopes and increase them on lower slopes where the response is better, resulting in a considerable improvement in crop yield over the present fertilizer extension practice.

Other research discovered that crop yields increased in response to N and P applications (Chivenge et al., 2010; Gebremaria and Assefa, 2014; Abera et al., 2017). These researches revealed a linear relationship between N and P rates and grain yield, underlining the need to increase grain yield through the application

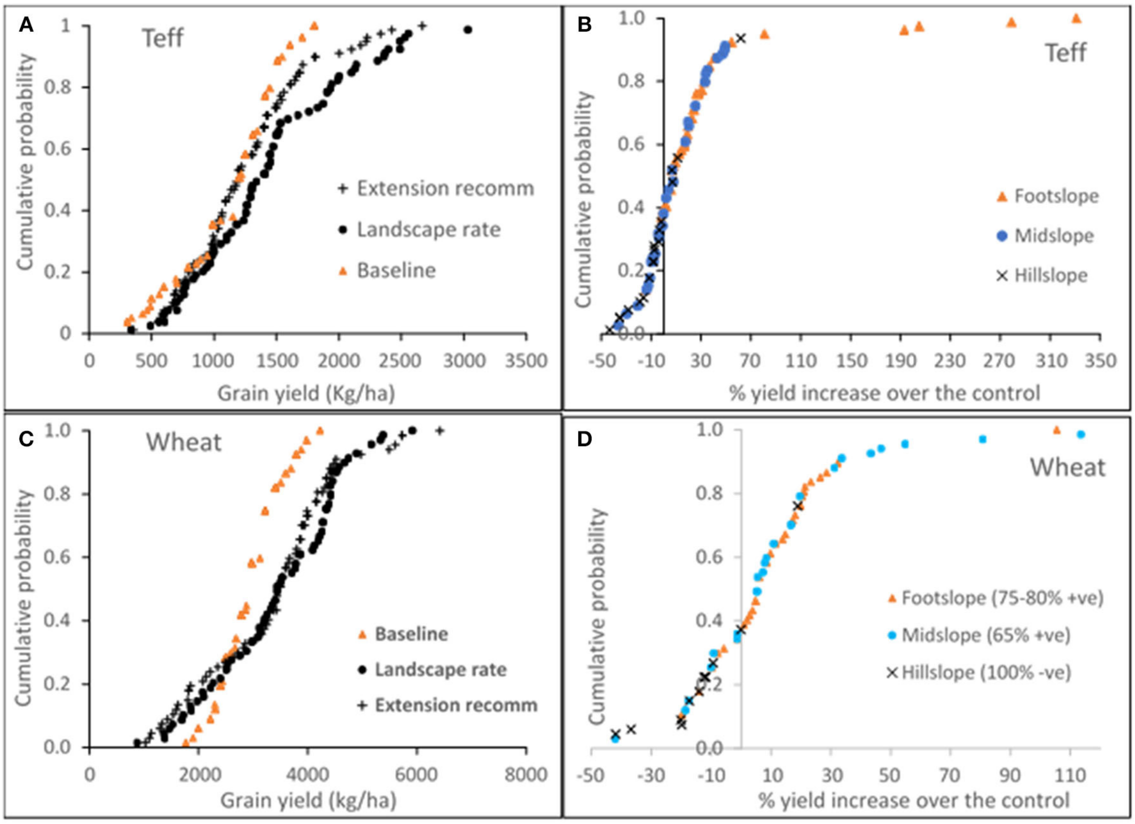


FIGURE 6
Comparison of cumulative probability of yield response from landscape-specific rate and extension recommendations for teff **(A)** and wheat **(C)** and percent yield increase over the control yield of teff **(B)** and wheat **(D)** at the validation stage.

of high N and P rates. The yields of crops rise with N and P fertilizer application due to the critical importance of these macronutrients and the ability to replenish low soil nitrogen levels (Yokamo et al., 2022). However, the relationship between N and P rates and grain yield along landscape positions produced variable and non-linear responses in the present study. On foot slopes, higher yield response was recorded for wide and large amounts of N and P applications, but only at a small range of N and P rates on hillslopes. The magnitude of the yield response has also been shown to vary based on soil nutrient availability, soil type, soil organic carbon content, landscape positioning, and seasonal rainfall amount (Yokamo et al., 2022). However, because several of these essential characteristics determining yield response were not investigated in this study, future research should concentrate on selected or combination explanatory variables that influence yield and nutrient use efficiency.

3.3.2. Agronomic efficiency

Figure 7 displays the agronomic efficiency of N and P for teff and wheat (i.e., increase in yield over control per nutrient use). Foot slopes and mid slopes had higher agronomic efficiency than hillslopes, indicating that moderate to flat slopes and fertile soils responded better to fertilizer. The decreasing status of soil depletion was highlighted by the negative nutrient utilization efficiency on hillslopes. Phosphorus efficiency is notably low on hillslopes. Increased current extension fertilizer use on acidic soils is most likely the cause for lower P efficiency in wheat on hillslopes. For example, under problematic soils such as acidic and waterlogged soils. The application of inorganic fertilizer alone does not improve the nutrient use efficiency of crops; rather, it is required to integrate nutrient and crop improvement practices to sustain soil health. This calls for the use of integrated organic and inorganic fertilizer management, as well as land and water management and agronomic practices on hillslopes.

3.3.3. Economic gains

Aside from crop yield benefits, economic factors such as profit and net benefit-to-cost ratio were evaluated for optimizing fertilizer application over landscape positions. Although landscape nutrient management innovation resulted in a yield gain in 65% of the overall observations (Figure 6), economic benefits were found in all of the yield observations in the three landscape positions, as shown in Figure 8. Despite an increase in average nitrogen application of 45 and 4% for teff and wheat, respectively, and 42% for phosphorus over the extension recommendations, an additional net benefit was realized over the extension recommendations. Landscape tailored nutrition recommendations increased profitability by $90 (ET Birr 4383) and $107 (ET Birr 5300) per hectare for wheat and teff, respectively, over extension recommendations. Compared to the net benefit of the extension recommendation, a net benefit that increased by $176 (ET Birr 8526) and $159 (ET Birr 7728) for wheat and $333 (ET Birr 16133) and $64 (ET Birr 3125) for teff was measured at the foot slope and mid-slope, respectively; whereas there was a respective decrease of -$64 (ET Birr—3125) and -$69 (ET Birr—3360) for wheat and teff at hillslopes. The corresponding net benefit-to-cost ratio (i.e., a net benefit of 5.0 and 2.6 Birr per

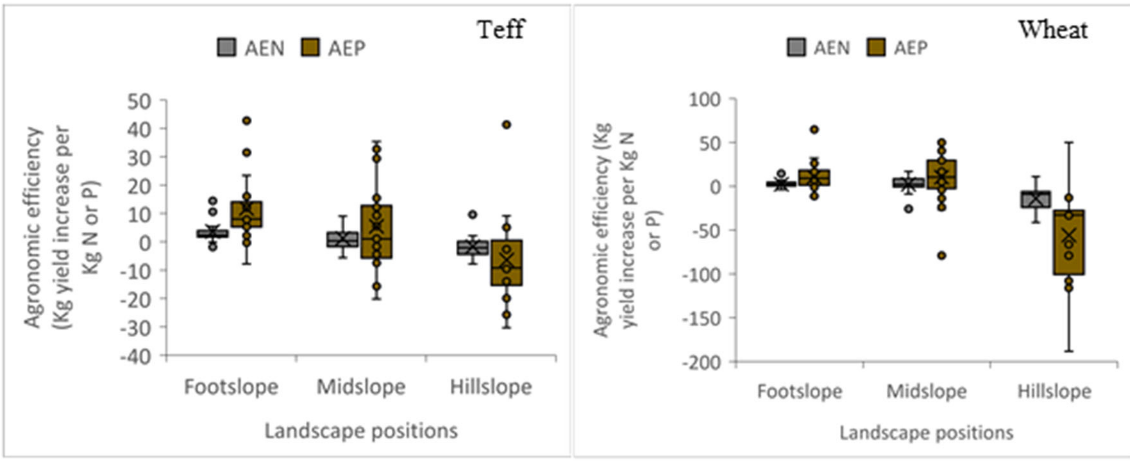


FIGURE 7
Agronomic efficiency of N and P (change in yield over the control per N and P fertilizer applied) for teff and wheat along landscape positions.

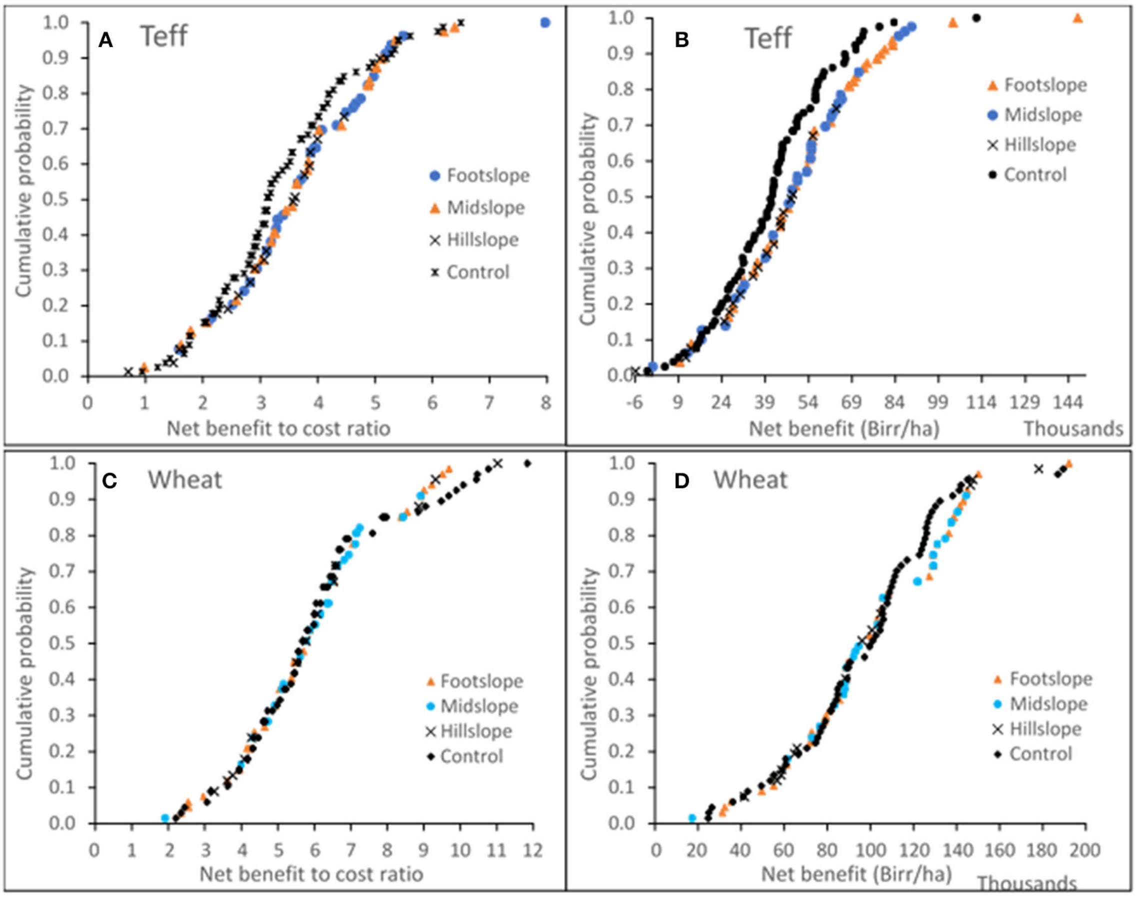


FIGURE 8
Comparison of economic responses using the cumulative probability of net benefits and net benefit to cost ratio (BCR) from landscape-specific rate and extension recommendations for teff **(A, B)** and wheat **(C, D)** measured at the validation stage.

one unit of investment for wheat and teff, respectively) also reveals the most favorable economic return on investment across the three landscape positions (Figure 9). Teff produced large economic gains above and beyond the extension recommendations. Whereas, greater overall economic net benefit has been estimated for wheat simply based on high yields of crops and comparatively modest nutrient application. Farmers saved a portion of the fertilizer used on hillslopes while benefiting from production gains and economic profits from optimal fertilizer use on mid-slopes and foot slopes, as demonstrated by the comparative benefit-to-cost ratio (Figure 9). Alternative land and soil health strategies and improved practices on hillslopes, such as manure, crop residues, green manures, and land conservation practices, could help to improve soil quality, allow crops to grow better, respond better to applied nutrients, and ensure a positive return on investment for fertilizer in degraded hillslope landscape positions.

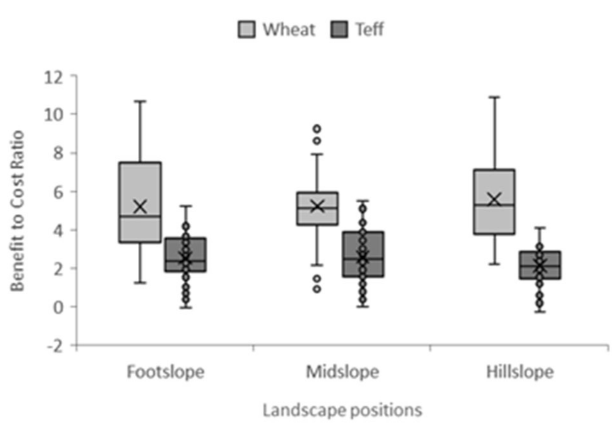


FIGURE 9
Net benefit to cost ratio (BCR) at the three landscape positions for wheat and teff measured in the validation trials.

3.4. Agronomic and economic benefits of the landscape fertilizer innovation: piloting stage

The validated landscape-specific fertilizer application was piloted in 1,154 farmer fields across 24 sites in 2022. The average N/P rates for foot slope, mid-slope, and hillslope during the piloting of landscape fertilizer rates for teff were 73/24, 61/18, and 51/15 kg ha^{-1}, respectively. Moving from hill slope, mid-slope to foot slope landscape positions resulted in better teff grain yield response and increased profitability of $1180, $1462, and $1745 per hectare (ET Birr 62639, 77512, and 92523), respectively (Figure 10). The yield response was considerably stronger in high-rainfall locations than in low-rainfall areas. Except for a modest decrease in N use efficiency at hillslopes, partial factor productivity (PFP) of N and P for teff has been equal on the foot slope and mid-slope positions. The net benefit-to-cost ratio (BCR) of applying landscape-specific fertilizer for teff has around the same average values across the three landscape positions (ET Birr 10.0 net benefit per one-birr expenditure). During the piloting trials for wheat, average N/P rates of 137/30, 108/30, and 67/18 kg ha^{-1} for foot slope, mid-slope, and hillslope were used. As depicted in Figure 11, despite the poor net benefit, the PFP of N and P for wheat demonstrated high efficiency at hillslopes, which was likely due to the lower rate of N and P applications at hillslopes. At hillslopes, mid slopes, and foot slopes, the net benefit was $2228, $2261, and $2746 per hectare (ET Birr 118067, 119842, and 145546), respectively (Figure 11). The average net benefit to cost ratio (BCR) of applying landscape-specific fertilizer to wheat was ET Birr 10.8 for one-birr investment (10.3, 9.6, and 14.9 at the foot slope, mid-slope, and hillslope, respectively). The benefit-to-cost ratio results showed that a landscape-scale nutrient management approach can result in the more cost-effective fertilizer application than the extension recommendation.

Using farm gate prices for grains and fertilizers in 2021, the landscape-specific fertilizer recommendation was determined to be agronomically and economically effective. During the piloting stage in 2022, the recommendation was further evaluated agronomically and economically following an increase in fertilizer prices due to the Ukraine war. The average grain price of wheat and teff across the implementing areas at harvesting time was ET Birr 2950 and ET Birr 3980 in 2021, respectively, and ET Birr 4125 (a 40% increase) and ET Birr 5150 (a 29% increase) in 2022. Following the harvesting period, the price of teff increased by 150–200%, which was not factored into the fertilizer advisory's economic analysis. The fertilizer price was raised from ET Birr 16.00 in 2021 to ET Birr 38.5 in 2022, representing a more than 140% increase. Despite a rise in fertilizer costs in 2022, the landscape-specific fertilizer recommendation showed an economically profitable fertilizer application that provided an average of ET Birr 10.00 profit per unit of investment (Figures 10, 11). Furthermore, the effectiveness of fertilizer use on hillslopes could be improved and optimized by combining integrated soil health activities with inorganic fertilizer.

3.5. Users feedback

Smallholder farmers and extension agents are the intended end users of this landscape-targeted fertilizer innovation. They took part in awareness-raising activities, digital advisory tool training, validation trials that compared the landscape fertilizer rate to the extension recommendation, and field day events. Farmers were impressed with the performance of landscape-targeted nutrient management, including fertilizer rates and application times when compared to their local practices in adjacent farmer fields. Farmers discovered that crops that received landscape-specific fertilizer rates performed much better than adjacent fields. They rectified their erroneous thinking that they applied a substantial amount of fertilizer to deteriorated hillslopes and a small amount to foot slopes. Following the validation demonstrations, most farmers in various parts of the South Regional State who did not previously apply nitrogen fertilizer to teff changed their practices. As a result of these innovations in fertilizer application, farmers sought the profitability of the appropriate rates of fertilizer along the landscape. Farmers, extension workers, and experts were aware of the relevance of bundled agronomic practices (time of fertilizer application, seed rate, variety, and weeding) that greatly

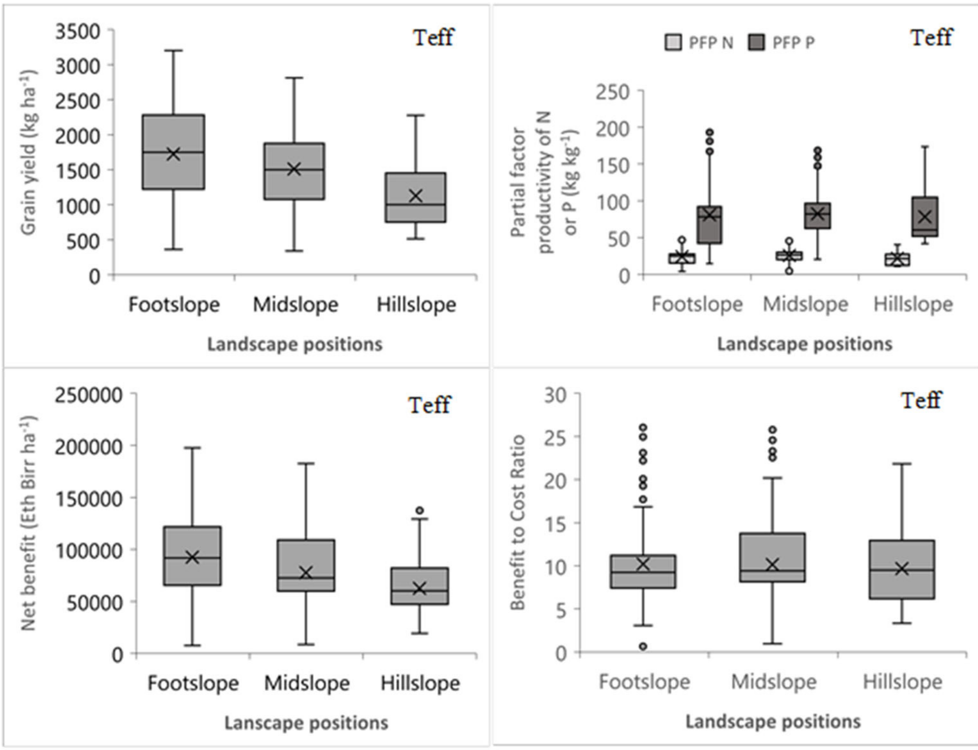


FIGURE 10
Agronomic and economic benefits of a validated landscape-specific fertilizer application using the digital advisory tool for teff at the piloting stage.

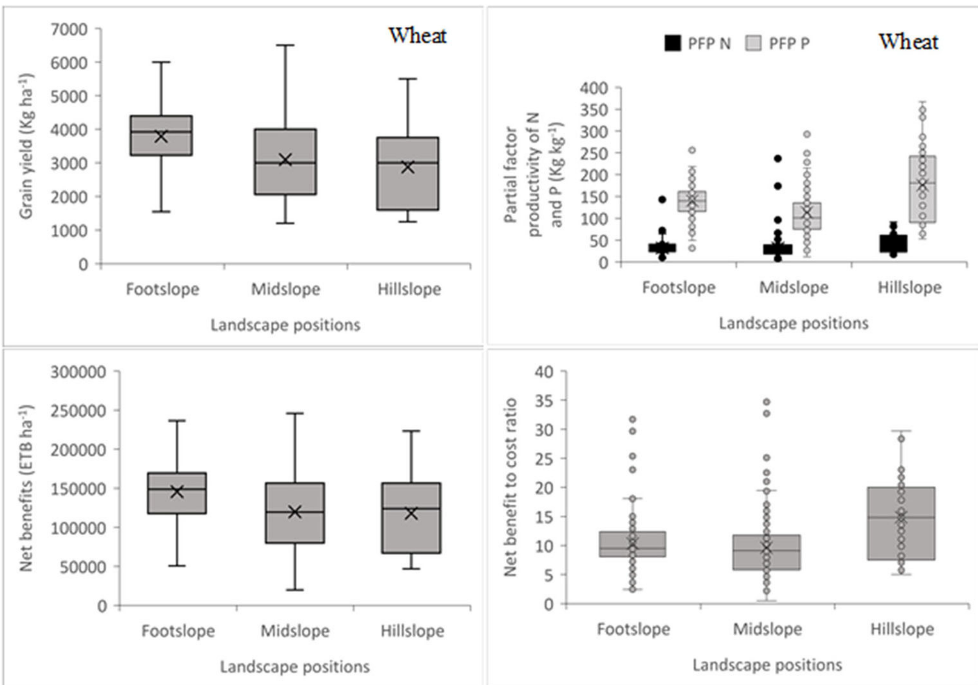


FIGURE 11
Agronomic and economic benefits of a validated landscape-specific fertilizer application using the digital advisory tool for wheat at the piloting stage.

contribute to higher crop yields in addition to landscape-based nutrient management. In addition, the innovation encourages NARS researchers to reevaluate their pre-extension and pre-scaling operations to incorporate demand partners into the co-development process. Because fertilizer management is crucial to crop productivity, the innovation will attract and involve a wide range of stakeholders in the fertilizer value chain.

4. Discussions

4.1. The relevance of landscape approach for site-specific nutrient management

In recent years, the national research system has been involved in coordinated fertilizer trials as a result of the emphasis on the validation of different fertilizer sources and the necessity of location-specific fertilizer application. Extensive evaluation and validation of various blended fertilizers, nutrient omission trials, and rate trials have been carried out in various cropping systems. Even though cropland uses in the country covered all slope classes, nearly 90% of these on-farm fertilizer trials were conducted on fields with <10% slope gradients (Supplementary Figure S5). The existing recommendations have a limited representation of the country's actual cropping systems and topographic features. This misrepresentation will result in inefficient fertilizer use in farmers' fields across all slope ranges, including non-responsive degraded soils. Yoo et al. (2006) found that varied surface landforms and soil types are associated with various crops and fertilizer management techniques. Furthermore, landscape-scale chemical fertility gradients were found to have a significant impact on nutrient management and yield variability (Turner and Hiernaux, 2015). Changes in soil depth have an impact on nitrogen and water management at the landscape scale (Bufebo et al., 2021). Thus, converting a variety of soil and crop attributes into spatially varied landscape segments is an important nutrient management strategy for satisfying localized demand, improving nutrient use effectiveness, and reducing fertilizer losses (Haneklaus and Schnug, 2000). To fill these gaps in fertilizer research, given the current context and the variety of soil and crop attributes along landscapes, a spatially explicit and stratified landscape strategy based on homogeneous segments of soils, topographies, and soil moisture levels along the topo-sequence is required. This involves the formulation of optimal fertilizer recommendations that account for the vast range of fertilizer responses found throughout the terrain. Furthermore, because it influences local fertilizer use and agronomic practices (see also Section 3.2), the landscape is an important scale for farmers. Overall, this localized landscape fertilizer management approach gives lessons for the relevance of integrated and localized sustainable management of landscapes.

4.2. Benefits of landscape-optimized fertilizer application and co-development approach

Because landscape effects are not considered, the effect of fertilizer application on yield response is frequently limited to plot and farm field research. Most Ethiopian farmlands are undulating and rolling landscapes with varying levels of soil moisture and fertility at different slope positions (Yimer, 2017; Seifu et al., 2020; Bufebo et al., 2021), which influence grain micronutrient concentrations (Manzeke-Kangara et al., 2023) and crop production (Amede et al., 2020). Natural variety and landscape nutrient interactions in agricultural field landscapes must be recognized and documented (Jowkin and Schoenau, 1998; Amede et al., 2020; Desta et al., 2022). In this study, regardless of crop types, landscape-specific fertilizer applications revealed a variable yield response along landscape positions which is further dictated by soil nutrients, soil moisture levels, cropping system, topographic, soil acidity levels, and field agronomic management factors. A landscape-specific fertilizer application through smart mobile applications which is guided by crop-specific decision rules resulted in a positive crop yield response, a 15 and 20% yield increase over the extension recommendations, and an optimized net benefit increase of $90 and $107 per hectare for wheat and teff, respectively.

The landscape nutrient management approach yielded ET Birr 10.0 net profit per unit of investment. The agronomic and economic improvement is greater when compared to the 12% yield gain and 15% profitability reported by a meta-analysis study in Sub-Saharan Africa (Chivenge et al., 2021). When compared to average farmers' use of N and P, the benefits of landscape-segmented fertilizer application were significant. This emphasizes the importance of demand-driven, site-specific nutrient management in providing localized solutions for smallholder farmers, with increased productivity and sustainability as co-benefits. However, for the digital advising tool to provide landscape-specific recommendations to smallholder farmers, digital support must be enabled by digital innovation platforms that integrate data, delivery infrastructure, input services, and stakeholder alliances.

A segmented landscape approach demonstrated that yield potential is lower in hillslope soils even with higher fertilizer rates, whereas mid slopes and foot slopes will continue to produce higher yields with optimal fertilizer rates; as a result, farmers gained a positive return on investment and changed their fertilizer use practices along the way. These findings contribute to the adoption of contextualized nutrient requirements based on the needs of local farmers. Other research has found that hillslope or shoulder placements produce lower yields than other slope positions (Amede et al., 2020; Desta et al., 2022) due to low soil nitrogen and crop N uptake (Jowkin and Schoenau, 1998).

To recap, the farmer and extension agent-centered landscape optimized fertilizer application approach emphasizes: (1) A landscape is a farmer-relevant scale that fits well with their local knowledge of soil and agronomic practices such as planting date and cropping system; (2) A landscape is a biophysical scale ideal for capturing nutrient and water flows; (3) The landscape approach raised the understanding of decision makers, extension agents, and farmers about localized fertilizer use and agronomy, as well as its use as part of a variety scaling package; (4) By contextualizing the advisory tool with local farmers' agronomic and nutrient management knowledge and practices, the fertilizer recommendation content became more relevant, and the tool's maturity to scale was improved; (5) The approach allows for optimal nutrient use efficiency while causing no environmental (leaching) loss or economic cost; and 6) An integrated digital fertilizer solution for soil health across landscape scales, value chain sectors, and disciplines is critical to increasing sustainable nutrient use and productive agro-food systems. Thus, optimizing landscape fertilizer management at the farmer-relevant scale resulted in a higher return on fertilizer investment, enhancing system production by closing spatial yield gaps with fertilizer and other agronomic practices.

4.3. Innovation requirements for scaling landscape-based nutrient management

The agronomic and economic benefits of the digital advising tool for landscape-targeted fertilizer recommendations have been validated using experimental data (i.e., technical validation with current extension recommendations). The landscape fertilizer application was further piloted to demonstrate the efficacy of the landscape-specific fertilizer prescriptions in creating localized and sustainable solutions. The knowledge of local farmers was also utilized to improve the validity of the fertilizer application. The landscape-specific fertilizer application was supplemented with farmers' local agronomic techniques, such as cropping systems, planting dates, and nutrient management, to achieve local customization. It is because establishing a feedback loop with end users through a demand-driven and bottom-up strategy, as well as contextualizing the landscape fertilizer advisory with local knowledge, increased the recommendations' relevance and acceptance, as well as the advisory's maturity to scale.

To actualize the impact of research and development at scale, scaling innovations requires a systemic and multi-perspective approach, as well as performance management of the scaling processes (Sartas et al., 2020). Landscape-targeted fertilizer application, according to this scaling idea, is not a stand-alone practice; it is a component of other innovative elements that impact the design and delivery of the fertilizer application and the advising tool, as well as its scaling readiness. These components include awareness and knowledge services, data development, enabling institutions and networking services, digital knowledge platforms, practices, and other modeling tools (Pircher et al., 2022). These technological and societal innovations are important to the commercialization of landscape-targeted fertilizer applications. We recommend meeting these needs and reviewing the landscape fertilizer recommendations. We propose meeting these prerequisites and examining the landscape fertilizer recommendation's scalability as a long-term approach to address site-specific production gaps and increase nutrient usage efficiency for maximum benefit to smallholder farmers.

Technically, one of the components is the pooling of data from practical research encompassing several system domains, which is used to produce and update knowledge on landscape nutrient management using fertilizer optimization algorithms. Additional digital tools or models that enable the assessment and integration of information on land characteristics and land management techniques can provide a bundle of solutions at the landscape scale for achieving integrated soil health. Long-term collaboration among multiple demand partners with diverse needs and capabilities in fertilizer research, extension, and input services can improve fertilizer recommendation delivery and ownership while allowing for the scaling of the landscape-targeted fertilizer recommendation and delivery system. Collaboration between agronomy and soil research and extension teams (for content development) and extension communication and digital teams (for extension advisory delivery) within the agriculture sector and input supply entities (input supply services) is a critical requirement as an enabling mechanism for scaling the validated application. Social media platforms, such as Telegram groups, can serve as a community of practice for practitioners (researchers, extension agents, experts, and decision-makers). The community of practice platform is intended to promote partner awareness of digital solutions, facilitate knowledge exchange and communication for landscape-targeted fertilizer applications, and implement digital solutions. It is also required to evaluate additional demand requirements for bundled solutions from farmers, extension agents, the national research system, input providers, cooperatives, and others.

These innovation requirements are meant not only to facilitate innovation scaling but also to achieve sustainable production at the landscape scale. It is vital to assess and define goals for optimal nutrient use efficiency and reduce yield gaps while minimizing environmental and economic costs. These are important indicator of designing a site-specific soil nutrient management strategy and optimizing fertilizer recommendations. So, designing strategy for increasing sustainable nutrient use in a landscape approach necessitate actions at multiple levels, sectors, and disciplines along the fertilizer use value chain. To achieve sustainable nutrient use in a landscape approach, operational and policy support requirements must be facilitated. First, the national research on crop response to nutrient application needs to be reoriented in a landscape approach so that localized optimal fertilizer recommendations can be ensured. Second, fertilizer use guidelines have been prepared based on priorities and needs to guide the fertilizer input supply and extension services and provide feedback to the national fertilizer investment. These guidelines can also consider fertilizer use for problematic soils taking into account inefficiencies and environmental losses. Third, the landscape-targeted fertilizer management approach has to be embedded with an integrated soil health approach to foster sustainable soil use and sustainable food systems at the landscape scale.

5. Conclusion

Over the last five to six decades, fertilizer research and extension services in Ethiopia have evolved through distinct phases marked by distinct approaches and project investments. While several soil health support initiatives were in place at present time, the demands for site-specific fertilizer management and digitized extension services were not met. Until now, fertilizer recommendations were frequently based on crop responses in specific cropping systems, regardless of how topographic features and other production factors changed over time and space. As a result, current extension fertilizer recommendations are provided regardless of changes in terrain, soil, or cropping system. Fertilizer application effects on yield response are often limited to plots and individual farmer fields. While several of Ethiopia's farmlands are undulating and rolling landscapes with varying levels of soil moisture and fertility at various slope positions, landscape influences are rarely considered. Landscape placement also has a significant impact on crop yield. The key research and development issues are thus assessing whether actual fertilizer demand in these types of landscapes is impeded by low fertilizer efficiency or because fertilizer profitability is simply too low to justify its use. Farmers have limited incentive to invest in inputs on sloping and undulating fields because of the low crop response and low profitability.

A demand-driven and co-validated landscape-specific fertilizer application led by crop-specific decision criteria using smart mobile application tool resulted in positive teff and wheat yield responses and an increase in net benefit of teff and wheat production over the extension fertilizer recommendations. It optimizes the amount of fertilizer investment across the landscape positions while also improving agronomic use efficiency. In the face of the current global fertilizer price increase, targeted landscape fertilizer application remains lucrative and provides an adequate and considerable return on investment. The advisory tool is a mobile app-based digital decision support tool that assists extension workers and farmers in targeting landscape-specific fertilizer applications. As a result of the innovation, farmers' fertilizer management practices have changed. Farmers reduce fertilizer rates on hillslopes that have deteriorating and shallow soils while raising them on lower slopes that have higher responses and profitability. It has also influenced local practitioners' views on the value of agronomy and local knowledge. Therefore, landscape-specific nutrient management provides agronomic, environmental, and economic benefits while integrating readily with local farmers' cropping strategies. As a result of an optimal landscape-targeted fertilizer management solution across landscape positions, as well as a farmer- and extension agent-centered strategy, long-term nutrient utilization, and productive agro-food systems are improved. However, this paper has limitations to account for the detailed environmental and social benefits as it is beyond the scope of the paper.

This paper specifically lays out the scientific basis and localized fertilizer management options across landscape positions to sustainably manage soil fertility, with particular attention to smallholder subsistence farmers under humid mixed farming systems. A landscape-targeted nutrient management has immense contributions along landscapes where nutrient and water flows make differences in crop performances under different farming systems both in humid and dry land conditions and varying topographies and landforms. It is therefore strongly suggested to test the landscape fertilizer advisory tool in similar geographies and integrate it with existing learning landscape initiatives in Africa and upgrade the advisory to a different level by bundling other soil health elements. This localized landscape fertilizer management approach highlights the leverage points for promoting localized sustainable management of landscapes and suggests pathways for ecological nutrient management and fostering landscape sustainability.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

GD: conceptualization, methodology, formal analysis, writing–original draft preparation, visualization, supervision, and project administration. GL: software, investigation, writing—review and editing, and visualization. GA: conceptualization, investigation, formal analysis, and writing – review and editing. AT: investigation and writing—review and editing. SN: software, writing—review and editing, and data curation. TGa and TD: methodology and investigation. BA, AAd, TGe, DM, ZB, TA, AAb, AD, SA, and WS: investigation. TF and GY: project administration. TA: conceptualization and methodology. AV: supervision and writing—review and editing. MJ: supervision. RH: supervision and fund acquisition. All authors contributed to the article and approved the submitted version.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. This work (the validation and piloting study for fertilizer advisory) was supported by the Bill and Melinda Gates Foundation, Seattle, WA (grant number INV-005431) through the Excellence in Agronomy (EIA) CGIAR initiative led by IITA.

Acknowledgments

We acknowledge the Ministry of Agriculture, the demand partner of the use case, particularly the district agriculture offices and extension agents in the districts of Basonawerana, Gozamin, West Belesa, Kewet, Lemo, Analemo, Doyogena, Bolososore, Sekoru, and Bora. Special thanks go to National Agriculture Research System (NARS) partners as well as the collaborating research centers, for their contributions to the validation and piloting activities. We appreciate the farmers who volunteer to work with us.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2023.1241850/full#supplementary-material

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frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 03 November 2023
DOI 10.3389/fsufs.2023.1236581

OPEN ACCESS

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RECEIVED 07 June 2023
ACCEPTED 10 October 2023
PUBLISHED 03 November 2023

CITATION
Assani Seidou A, Offoumon OTLF, Sanni Worogo SH, Houaga I, Koara Yarou A, Azalou M, Adambi Boukari FZ, Idrissou Y, Houinato M and Alkoiret Traoré I (2023) The effect of the silvopastoral system on milk production and reproductive performance of dairy cows and its contribution to adaptation to a changing climate in the drylands of Benin (West-Africa). *Front. Sustain. Food Syst.* 7:1236581.
doi: 10.3389/fsufs.2023.1236581

The effect of the silvopastoral system on milk production and reproductive performance of dairy cows and its contribution to adaptation to a changing climate in the drylands of Benin (West-Africa)

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Knowledge about dairy cows raised in small-scale agroforestry systems in dryland areas is of paramount importance to inform policy and decision making in the dairy production sector in the current context of climate change. The aim of this study was to evaluate the effect of integrated farming systems on daily milk yield and demographic traits of dairy cows in drylands. A study conducted on 447 dairy cows was carried out to compare their milk yield and demographic parameters under different small-scale agroforestry systems in drylands of Benin: traditional silvopasture (TSS); Improved silvopasture (ISS); Small Integrated Agrosilvopasture (SIAS) and Large Integrated Agrosilvopasture (LIAS). The type of cattle farms had a significant effect ($p < 0.05$) on daily milk yield and demographic traits. Dairy cattle from ISS farms had the highest daily milk yield regardless of the type of dairy cow breed. Demographic traits of herds were significantly ($p < 0.05$) influenced by the type of dairy cattle farms. The proportion of lactating cows was higher ($p <$ 0.05) in herds of ISS (48.4%) followed by those in TSS and LIAS (36.1 and 25.0% respectively) while SIAS was the lowest in (14.4%). The pre-weaning mortality rate was higher ($p < 0.05$) in TSS and LIAS farms (18.3 and 17.6 % respectively) compared to SIAS and ISS farms (5.20 and 4.60 % respectively). The fertility rate was higher ($p < 0.05$) in ISS and SIAS farms (92.3 and 89.6% respectively) compared to TSS and LIAS farms (68.3 and 74.2% respectively). The weaning productivity was higher ($p < 0.05$) in ISS and SIAS (88.6 and 85.8 % respectively) than in TSS and LIAS farms (66.1 and 67.6 % respectively). This study showed that ISS farms are characterized by higher milk yield and demographic parameters. ISS systems can then be promoted in smallholder cattle farming to improve milk production and reproductive performance of dairy cows in drylands.

KEYWORDS

dairy cattle, integrated systems, climate change, fodder trees, milk yield

1. Introduction

In Sub-Saharan Africa, livestock farming plays important economic and social role for rural households. The livestock sector contribution to the agricultural Gross Domestic Product of African countries was estimated to be 40% and ranging from 30 to 80% depending on the country (Panel, 2020). However, despite its importance, livestock development faces enormous constraints. In fact, climate change (CC) has a serious impact on dairy cattle farming through the rise of drought and temperature (Idrissou et al., 2019). In general, CC has direct impacts on livestock by influencing animal performance and indirect impacts when it affects pastoral resources (Idrissou et al., 2019). The shortage of fodder in the dry season is of particular concern for pastoralists and agro-pastoralists. Direct effects of CC include temperature-related diseases and deaths, and animal morbidity during extreme weather events (Nardone et al., 2010). In fact, global warming in tropical environments causes secondary problems due to acclimatization: the reduction of food intake, respiratory rate and water consumption in the immediate term and a hormonal disturbance affecting the reactivity of target tissues to environmental stimuli (Lacetera, 2019; Magiri et al., 2020).

To address the adverse effects of CC in drylands of Benin, smallholder dairy farmers have developed feeding strategies integrating tree or shrub species to feed cattle during feed shortage. In fact, ligneous fodder represents an appreciable source of supplementary food used in ruminant feed in the dry season (Koura et al., 2021). In Benin, trees grow sometimes spontaneously in naturally or are planted and generally maintained. The woody fodder species encountered may be exotic or result from domestication and selection by local populations. Access to woody fodder is either by direct browsing of the leaves, twigs and fruits, or after cutting the branches (Houérou, 1980; Franzel et al., 2014). Woody fodder species also play an important role in production systems, particularly for their quality, their seasonal availability and the protection they offer to the herbaceous layer (Paul et al., 2020).

Livestock-tree integration practices have been the subject of several studies in sub-Saharan Africa (Sarr et al., 2013; Koura et al., 2015; Sèwadé et al., 2016). In fact, agroforestry parklands in this region of Africa are agricultural systems combining trees, crops and livestock. These agroforestry parks allow small farmers to reduce vulnerability to the risks of CC (Thorlakson and Neufeldt, 2012). Animals feed on crop residues, leaves, fruits and pods of trees; and contribute to the recycling of nutrients by the deposition of their droppings (Vandermeulen et al., 2018). In Nigeria, Amonum et al. (2009), identified three types of livestock-tree integration systems: Alley farming, Shelterbelts and Home gardens. In southern Benin, the integration of farm animals in oil palm tree plantations has also been identified by Koura et al. (2015) among smallholder farmers of taurine cattle breeds to ensure the cleaning of the plantations by grazing and to fertilize the soil. The presence of tress in dairy cows grazing/feeding systems also reduces the heat stress through provision of a favorable microclimate (Vieira et al., 2020; Skonieski et al., 2021). Thus, silvopastoralism and agrosilvopastoralism constitute an option for grazing-based cattle farming systems that promote soil-animal-fodder-tree interactions, improving the productivity of dairy cows and reducing heat stress (Broom et al., 2013; Zeppetello et al., 2022). Despite the importance of these systems, there is a lack of knowledge about dairy cows raised in agrosilvopostaoral and silvopastoral systems in drylands, thus emphasizing the importance of new studies aiming at elucidating the effect of these integrated farming systems on the productivity of dairy cows in drylands. Therefore, the aim of the study was to evaluate the effects of different small-scale agroforestry systems (agrosilvopastoral and silvopastoral) on daily milk yield and demographic parameters of dairy cows in drylands.

2. Materials and methods

2.1. Study area

The study was conducted on smallholder dairy cattle farms in two ecological regions of Benin (arid Sudanian and semi-arid Sudano-Guinean regions). The arid Sudanian region (7° 30-9° 30 N) is characterized by annual rainfall of 800 to 1,100 mm and a vegetation growing season of 145 days, while the semi-arid Sudano-Guinean region (9° 30-12° N) receives annual rainfall of 1,100–1,300 mm and a vegetation growing season of 200 days. The villages of Founougo, Goumori, Bagou and Sori were selected in the arid Sudanian region and the villages of Ouénou, Sirarou, Kika and Béterou in semi-arid Sudano-Guinean region for twelve-month farm monitoring (Figure 1). Dairy farmers of these regions are known for their practice of adaptation to CC based on the integration of animals with trees or shrubs. The herds of farmers who participated in this study were those who had at least two cows at the early lactation and who had participated in the previous study initiated by Assani et al. (2023). The previous study identified four types of smallholder dairy cattle farms namely traditional silvopasture (TSS); Improved Silvopasture (ISS); Small-scale Agrosilvopasture (SIAS) and Large Integrated Agrosilvopasture (LIAS). The characteristics of the four identified type of farmers in dryland areas of Benin are presented in Supplementary Table S1 (Assani et al., 2023). In TSS, farmers had an average of 26 Tropical Livestock Unit (TLU). They did not own land and they used trees and shrubs from the rangelands. They used native trees (*Khaya senegalensis, Afzelia Africana and Pterocarpus erinaceus*) as feed supplements for dairy cattle in natural rangelands during dry season (Figure 2). In ISS, farmers had a mean of 11 TLU per herd. They owned land (4.2 ha) and associated livestock, forage plants (*Panicum maximun C1, Pennisetum purperium and Brachiaria ruziziensis*) and trees/shrubs plantation (*Khaya senegalensis, Afzelia Africana, Pterocarpus erinaceus, Cajanus cajan, Gliricidia sepium, Acacia auriculiformis, Leucaena leucocephala, Stylosanthes guianensis Mucuna pruriens*) in pasturelands (Figure 3). Fodder trees are utilized throughout the year. The SIAS farmers adopted the integration of agriculture, ruminant livestock and trees. They owned a small area of land (3.0 ha) and low size of herd (6 TLU). SIAS farmers used native trees/shrubs fodder (*Cajanus cajan, Acacia auriculiformis, Leucaena leucocephala, Stylosanthes guianensis, Mucuna pruriens*) and crop residues (Maize stover, rice straw, sorghum straw and Cowpea haulms) as feed supplements for dairy cattle during dry season (Figure 4). In LIAS, farmers tilled large portions of land (9.3

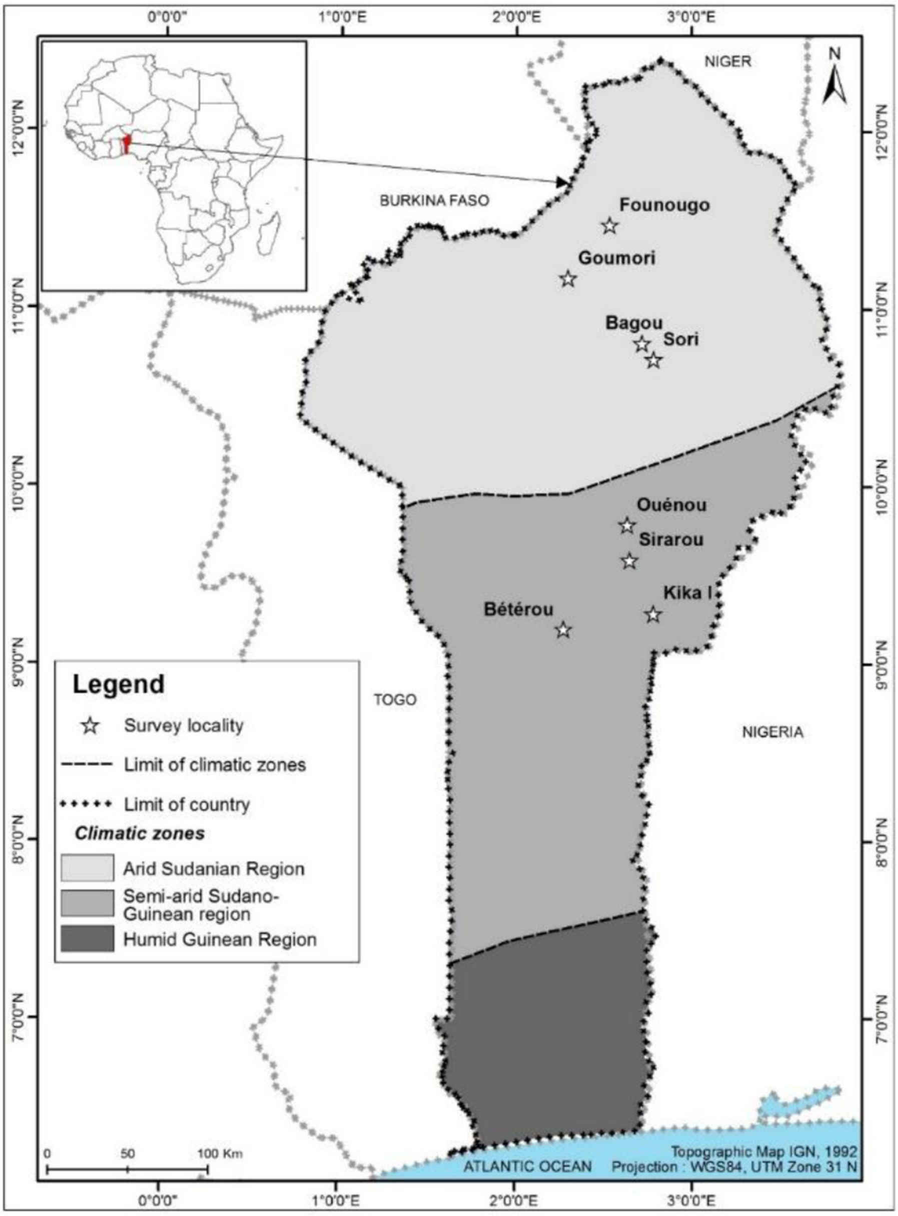

FIGURE 1
Map of Benin showing the locations investigated in dryland zones of Benin.

ha) and had a mean of 18 TLU. Leguminous fodder trees (*Khaya senegalensis, Afzelia Africana, Pterocarpus erinaceus, Cajanus cajan, Acacia auriculiformis, Leucaena leucocephala, Stylosanthes guianensis, Mucuna pruriens*) and crop residues (Maize stover, rice straw, sorghum straw and Cowpea haulms) are utilized to feed ruminants during the dry season (Figure 5).

2.2. Milk yield data collection

Monitoring of ten (10) farms per type of farming system identified in dryland areas of Benin i.e. 40 farms was carried out from March 2021 to January 2022. Daily milk yield data were collected from 113, 103, 102 and 129 cows respectively on the TSS, ISS, SIAS and LIAS farms, giving a total of 447 dairy cows. On each farm, dairy cows were selected according to breed (Borgou, Crossbreed, Gudali and White Fulani) and lactation rank (lactations 1, 2, 3, 4, 5 and more). Table 1 gives more details on the number of cows monitored during this study in each type of farming system according to breed and lactation number. The chosen cows were given an identification number or name to facilitate monitoring. All animals lost (mortality, sale, etc.) during monitoring were not counted in this number. Milk was collected once a week during 305 days of lactation. Hand milking is carried

FIGURE 2
Traditional silvopastoral system on rangelands in dryland areas of Benin.

FIGURE 3
Improved silvopastoral of Khaya senegalensis and forage plants in dryland areas of Benin.

FIGURE 4
Agrosivopastoral systems- integration of trees (*Khaya senegalensis*), crops (maize) and animals in dryland areas of Benin.

out twice a day twice a day, in the morning at 7 a.m. before leaving for pasture, and in the evening at 6 p.m. when return from pasture. Once the milk had been collected, the quantity was measured on a weighing balance and recorded on the data collection sheet. Daily milk yield is the sum of the morning and evening milk collections.

2.3. Demographic parameters data collection

The demographic parameters in TSS, ISS, SIAS and LIAS farming systems are studied on the basis of information collected on the movement of cattle on the farm during the year (initial cattle numbers, birth, purchase, mortality, sale, donation, exchange, slaughter and final cattle numbers), farm cattle composition (female calves, heifers, lactating cows, dry cows, male calves, subadult bulls and reproductive bulls), reproduction parameters (advanced gestation, abortion and calving) and viability-mortality parameters (stillbirths, age-specific mortality and live offspring at weaning). The 40 farms monitored for milk production were also used to collect one-year demographic data (from March 2021 to February 2022). Farm monitoring for demographic parameters data collection was done once a week. During each visit, all events concerning demographics parameters (number of cows present, number of cows in lactation, number of births, number of abortions, number of dead animals, number of animal entries and exits) were recorded using monitoring sheets. The animals were identified beforehand

FIGURE 5
Khaya senegalensis trees around fields for dairy cattle feed in dryland areas of Benin.

TABLE 1 Number of dairy cows monitored according to breed and lactation rank in each farming system identified in dryland areas of Benin.

	TSS	ISS	SIAS	LIAS	Total
Farm	10	10	10	10	40
Total cow	113	103	102	129	447
Cow breed					
Borgou	25	26	31	43	125
Crossbreed	21	23	17	31	92
Gudali	26	42	15	27	110
White Fulani	41	12	39	28	120
Lactation rank					
Lactation 1	23	26	25	40	114
Lactation 2	31	28	31	28	118
Lactation 3-4	35	34	24	33	126
Lactation 5 and more	24	15	22	28	89

TSS, Traditional silvopastoral systems; ISS, Improved silvopastoral systems; SIAS, Small Integrated agrosilvopastoral systems; LIAS, Large Integrated agrosilvopastoral systems.

taking into account the name of the animal or identification number, the breed and the date of birth. Demographic parameters were calculated using the formula proposed by Lhoste (2001):

Reproductive rates

Rate of abortions = Number of abortions ∗ 100/Number of cows

Calving rate = Number of calving ∗ 100/Number of cows

Fertility rate = Number of alive born calves ∗ 100/Number of cows

Mortality rates

Stillbirth rate = Number of stillborn calves ∗ 100/Number of calves born

Pre-weaning mortality rate = Number of pre-weaning dead calves ∗ 100/number of calves born alive

Global mortality rate = Number of dead animals ∗ 100/Average herd size

Numerical weaning productivity = number of alive weaned calves ∗ 100/Number of cows

Management rates

Offtake rate (OR) = Number of exploited animals ∗ 100/Average size of the cattle herd

Intake rate (IR) = Number of imported animals ∗ 100/Average size of the cattle herd

Net offtake rate = OR – IR.

2.4. Chemical analyses

To know more about the composition of the most fodder trees/shrubs, forage plants and crop residues used as feed supplements for dairy cattle in each farming system during dry season, the feed samples were collected to determine the chemical composition. Leaves samples were collected from several branches in the canopy. The samples (500 g) for each forage and crop residues were oven-dried at a temperature of 60°C for 72 h for dry matter, then ground and sieved. Analysis was carried out using the AOAC method (AOAC, 1990). The samples were analyzed in triplicate in accordance with approved methods (AOAC, 1990) to determine Dry matter (DM), ash, crude protein (CP) and ether extract (EE) (AOAC procedure 2001.12, 930.05, 978.04 and 920.39 for DM, ash, CP and EE, respectively). The fiber contents (NDF and ADF) were analyzed using the Velp Scientifica™ FIWE 3 Fiber Analyzer according to Van Soest et al. (1991) methods. *In vitro* evaluation of DM digestibility was based on the two-step technique of Tilley and Terry (1963).

2.5. Data analysis

To assess the effects of different small-scale agroforestry systems (TSS, ISS, SIAS and LIAS) on daily milk yield, we used the General Linear Model (GLM) in R.4.2.1 software (R Core Team Development, 2022). The model used was:

$$Yijk = \mu + Si + Pj + Rk + Si{*}Pj + Si{*}Rk + Eijk$$

Where, Yijk = Response variable (Milk yield);

μ = overall mean;

Si = fixed effect of the silvopastoral system (4 classes; TS = 1, 2, 3, 4);

Pj = fixed effect of season (P = dry season, wet season; 2 classes) or fixed effect of lactation number of cows (P = L1, L2, L3-4, L ≥ 5; 4 classes);

TABLE 2 Chemical composition and nutritional value of tree/shrub leaves, forage plants and crop residues used to feed dairy cows in each farming system identified in the drylands of Benin.

Species	DM	Ash	CP	NDF	ADF	EE	DMd %
		% DM					
Khaya senegalensis	92.62[a]	8.92[c]	13.15[c]	51.69[d]	33.54[cd]	2.55[c]	59.10[a]
Afzelia africana	94.10[a]	6.58[d]	16.14[b]	68.45[b]	65.32[a]	3.24[b]	52.40[a]
Pterocarpus erinaceus	90.20[a]	7.86[cd]	14.86[b]	54.70[c]	37.25[c]	4.62[a]	48.62[c]
Cajanus cajan	93.56[a]	7.52[cd]	23.80[a]	49.21[de]	31.40[d]	4.75[a]	56.12[a]
Gliricidia sepium	89.20[b]	10.01[b]	18.21[a]	39.46[ef]	26.52[e]	4.86[a]	51.88[b]
Acacia auriculiformis	90.21[a]	7.62[cd]	14.33[c]	46.82[de]	34.65[d]	3.52[b]	48.47[c]
Leucaena leucocephala	92.10[a]	6.82[cd]	22.61[a]	58.67[c]	41.10[b]	3.04[b]	49.84[c]
Panicum maximum C_1	91.10[a]	5.84[de]	8.89[d]	68.20[b]	38.42[cd]	2.34[c]	42.32[d]
Pennisetum purperium	91.30[a]	8.98[c]	8.75[d]	70.02[a]	42.06[b]	2.85[c]	55.20[a]
Brachiaria ruziziensis	89.20[ab]	8.42[c]	7.98[d]	65.13[b]	46.21[b]	3.01[b]	53.80[a]
Stylosanthes guianensis	90.10[a]	8.65[c]	15.20[b]	51.30[d]	37.25[cd]	2.65[c]	57.45[a]
Mucuna pruriens	92.82[a]	6.58[cd]	18.58[a]	66.40[b]	36.50[c]	1.82[cd]	52.64[b]
Maize stover	93.10[a]	7.20[cd]	3.50[e]	74.20[a]	49.80[ab]	1.10[cd]	49.20[b]
Rice straw	92.80[a]	14.2[a]	4.40[e]	64.70[b]	45.10[ab]	1.20[cd]	48.52[c]
Sorghum straw	91.40[a]	7.10[cd]	2.80[e]	74.60[a]	43.30[b]	0.80[d]	43.51[d]
Cowpea haulms	94.30[a]	7.43[cd]	11.60[c]	47.85[e]	32.46[cd]	1.86[cd]	63.20[a]

[a,b,c,d,e,f]Within a column, values with different superscript letters are significantly different at $p \leq 0.05$.
DM, dry matter; CP, crude protein; NDF, neutral detergent fiber; ADF, acid detergent fiber; EE, ether extract; DMd, dry matter degradability.

Rk = fixed effect of cow breed (R = Borgou, Crossbreed, Gudali, White Fulani; 4 classes);

Si∗Pj = interaction of the silvopastoral system and the season;

Si∗Rk = interaction of the silvopastoral system and the cow breed;

Eijk = error.

Average milk yields for each type of farming system were compared using the least significant difference (LSD) test with *agricolae* package (de Mendiburu, 2021) to see if there was a significant difference at the 5% level.

To understand how different small-scale agroforestry systems impact the demographic parameters, we compared the following variables between farming system (TSS, ISS, SIAS and LIAS): reproductive rates (rate of abortions, calving rate and fertility rate), mortality rates (stillbirth rate, pre-weaning mortality rate, global mortality rate and numerical weaning productivity) and management rates (offtake rate, intake rate and net offtake rate). As the data for each of these variables were not normally distributed, the Kruskal-Wallis test was used for these analyses.

3. Results

3.1. Chemical composition and nutritional value of tree/shrub leaves, forage plants, and crop residues used as feed supplements for dairy cattle

Table 2 shows the chemical composition and nutritional value of tree/shrub leaves, forage plants and crop residues used as feed supplements for dairy cattle in dryland areas of Benin. The crude protein values of tree/shrub leaves, forage plants and crop residues range from 2.80% (Sorghum straw) to 23.80% (*C. cajan*). Crude protein values for tree/shrub leaves, forage legumes (*S. guianensis* and *M. pruriens*) and Cowpea haulms are above 10%. The lowest and highest NDF values were obtained in *G. sepium* (39.46%) and Sorghum straw (74.60%), respectively. Dry matter digestibility values ranged from 42.32 to 63.20%, respectively.

3.2. Milk yield

3.2.1. Milk yield of cows according to different cow breeds, seasons of the years and type of farm

The type of integrated cattle farming had a significant effect ($p < 0.01$) on milk yield (Tables 3, 4). Regardless of the cattle breed, cows from farms practicing ISS produced more daily milk (2.2, 4.1, 2.6, 2.4 kg/day/cow for Borgou, Gudali, White Fulani and crossbred cow, respectively) ($p < 0.05$), followed by cows from farms practicing LIAS (1.4, 3.1, 1.4, 1.6 kg/day/cow for Borgou, Gudali, White Fulani and crossbred cow, respectively) and finally SIAS (1.0, 1.8, 1.2, 1.1 kg/day/cow for Borgou, Gudali, White Fulani and crossbred cow, respectively) and TSS (0.9, 1.5, 1.1, 1.0 kg/day/cow for Borgou, Gudali, White Fulani and crossbred cow, respectively) whose milk yield was identical. Compared with other systems, ISS dairy cattle show better daily milk yields during the dry season (Table 4).

3.2.2. Milk yield of cows according to lactation rank and type of farm

Figure 6 compares the milk yield of cows according to lactation rank within each practice type of integration of the tree adopted by the farmer to cope with CC. Regardless of the integration of pasture in the trees for livestock feeding adopted by the farmer to cope with CC, the effect of number of lactations on milk production was significant ($p < 0.05$). The milk yield in young cows (Lactation 1 and 2) were low ($p < 0.05$). While it was higher ($p < 0.05$) in cows whose number of lactations was between 3 and 4, followed by those with 5 or more lactations.

TABLE 3 Effects of silvopastoral system, cow breed and seasons of the years on milk production (kg/day/cow).

Sources of variation	Daily milk yield	*p-value*
Silvopastoral system		*0.001*
Traditional silvopastoral systems (TSS)	1.0 ± 0.18^{d}	
Improved silvopastoral systems (ISS)	$2,8 \pm 0.63^{a}$	
SIAS = Small Integrated agrosilvopastoral systems (SIAS)	$1,2 \pm 0.26^{c}$	
Large Integrated agrosilvopastoral systems (LIAS)	$1,8 \pm 0.61^{b}$	
Cow breed		*0.001*
Borgou	1.1 ± 0.42^{c}	
Gudali	$2,6 \pm 0.95^{a}$	
White Fulani	$1,6 \pm 0.50^{b}$	
Crossbreed	$1,5 \pm 0.47^{b}$	
Season		*0.002*
Dry season	1.95 ± 0.92^{b}	
Wet season	$2,95 \pm 0.25^{a}$	

[a,b,c,d]Means with different superscript letters on the same column differ significantly ($p < 0.05$). *p*-value means the value of probability.

3.2.3. Milk yield per month of lactation according to type of farm

Regardless of breed, milk yield per month of lactation was significantly higher in the ISS cows than in the others (TSS, LIAS and SIAS) (Figure 7). The highest daily milk production was observed in the second month of lactation and the third month of lactation respectively in taurine and crossbred cows (Borgou and crossbreed) and zebu cows (Gudali and White Fulani). The lowest daily milk yield was obtained in the eleventh month regardless of the type of agroforestry systems practiced.

3.3. Demographic features

3.3.1. Herd structure

Herd structure of cattle according to type of farms integrated trees in cattle farming identified in drylands of Benin is presented in the Table 5. The type of farms statistically significant effect ($p < 0.05$) on the different cattle categories (Table 5). With regard to females, the proportion of lactating cows, total female and dry cows were higher ($p < 0.05$) in ISS herds compared with TSS, SIAS and LIAS. However, the proportion of heifers in SIAS herds was lower ($p < 0.05$) than in TSS, ISS and LIAS herds (Table 5). The proportions of female calves were similar in the four small-scale agroforestry systems.

When considering males, the type of agroforestry system had also a significant effect ($p < 0.05$) on male proportions. The reproductive bulls' proportions and total males in SIAS herds was higher ($p < 0.05$) than those of TSS, ISS and LIAS. The proportions of male calves were similar in the 4 types of agroforestry systems. The average herd size of TSS was 5, 2.6 and 1.8 times greater ($p < 0.05$) than that of SIAS, ISS and LIAS cattle herds, respectively.

3.3.2. Demographic parameters

Cattle herds in ISS and SIAS had the best ($p < 0.05$) demographic parameters (Table 6), characterized by high fertility, parturition and weaning productivity rates ($p < 0.05$) and low ($p < 0.05$) abortion and mortality rates (pre-weaning, stillbirth and overall mortality rates).

TABLE 4 Effects of interaction of silvopastoral system and cow breed or seasons of the years on milk production (kg/day/cow) across the type of farm.

	TSS	ISS	SIAS	LIAS	*p-value*
Silvopastoral system*breed					
Borgou	0.9 ± 0.18^{c}	2.2 ± 0.16^{a}	1.0 ± 0.15^{c}	1.4 ± 0.17^{b}	*0.02*
Gudali	1.5 ± 0.21^{d}	4.1 ± 0.22^{a}	1.8 ± 0.22^{c}	3.1 ± 0.24^{b}	*0.001*
White Fulani	1.1 ± 0.16^{c}	2.6 ± 0.24^{a}	1.2 ± 0.23^{c}	1.4 ± 0.18^{b}	*0.002*
Crossbreed	1.0 ± 0.20^{c}	2.4 ± 0.18^{a}	1.1 ± 0.26^{c}	1.6 ± 0.19^{b}	*0.02*
Silvopastoral system*season					
Dry season	0.9 ± 0.23^{d}	3.8 ± 0.23^{a}	1.2 ± 0.12^{c}	1.9 ± 0.21^{b}	*0.001*
Wet season	1.3 ± 0.16^{d}	5.2 ± 0.21^{a}	2.1 ± 0.16^{c}	3.2 ± 0.26^{b}	*0.001*

[a,b,c,d]Means with different superscript letters on the same row differ significantly ($p < 0.05$). TSS, Traditional silvopastoral systems; ISS, Improved silvopastoral systems; SIAS, Small Integrated agrosilvopastoral systems; LIAS, Large Integrated agrosilvopastoral systems. *p*-value means the value of probability.

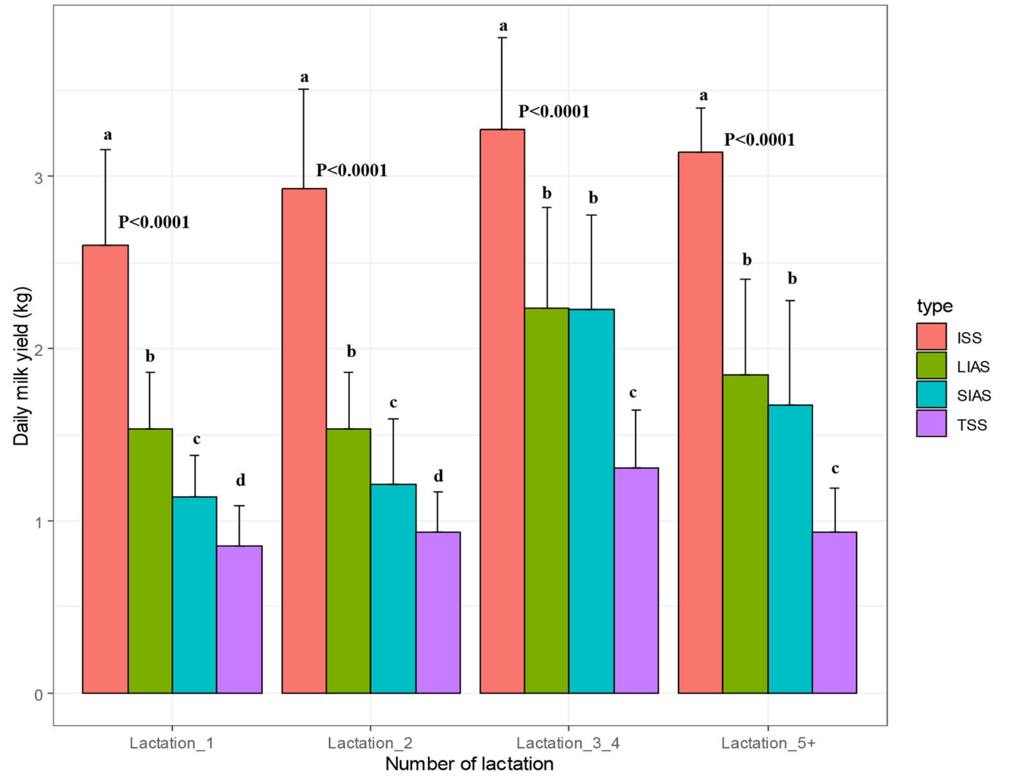

FIGURE 6
Milk production (kg/day/cow) of cattle cows according to lactation rank and type of farm. Barplots with different superscript letters differ significantly ($p < 0.05$). TSS, Traditional silvopastoral systems; ISS, Improved silvopastoral systems; SIAS, Small Integrated agrosilvopastoral systems; LIAS, Large Integrated agrosilvopastoral systems.

TABLE 5 Herd structure (%) by the type of farms with integration of trees in cattle farming identified in drylands of Benin.

Cattle categories	TSS	ISS	SIAS	LIAS	*p-value*
Female (%)					
Female calves	13.4^a	10.2^a	10.0^a	11.2^a	0.086
Heifers	11.2^a	10.6^a	7.20^b	11.4^a	0.001
Lactating cows	36.1^b	48.4^a	14.4^c	25.0^b	0.0001
Dry cows	10.1^b	12.0^a	6.20^c	11.2^b	0.01
Total Female	70.8^b	81.2^a	37.8^c	58.8^b	0.0019
Male (%)					
Male calves	8.20^a	7.50^a	9.70^a	7.30^a	0.110
Subadult bulls	9.60^b	2.10^c	18.3^a	8.70^b	0.0013
Reproductive bulls	11.4^c	9.20^c	34.2^a	26.2^b	0.0020
Total Male	29.2^c	18.8^d	62.2^a	42.2^b	0.0018
Herd size (heads)	68^a	26^c	13^d	38^b	0.001

[a,b,c,d]Frequences with different superscript letters on the same row differ significantly ($p < 0.05$). TSS, Traditional silvopastoral systems; ISS, Improved silvopastoral systems; SIAS, Small Integrated agrosilvopastoral systems; LIAS, Large Integrated agrosilvopastoral systems.

The offtake rate was higher ($p < 0.05$) in ISS herds. The intake rate in ISS and SIAS were higher ($p < 0.05$) than those of TSS and LIAS farms. The net offtake rate was positive in the TSS, ISS and LIAS herds and high ($p < 0.05$) than those of SIAS which was negative.

4. Discussion

4.1. Milk yield

The daily milk yield was higher in cows from farms adopting ISS compared to those practicing LIAS, SIAS and TSS. In fact, the animals from ISS farms benefit from a supplementation of woody fodder at any time of the year, which allows them to produce more milk. The effects of fodder trees or shrubs in improving milk production have been demonstrated in several studies (Mangesho et al., 2017; Salifou et al., 2017; Agani et al., 2022). Certain trees and shrubs are lactogenic in local dairy cows. In Benin, traditional cattle farmers use roots, leaves, bark, fruits and seeds to stimulate milk production in cows (Salifou et al., 2017). In northern Benin, certain woody fodder such as *Afzelia Africana, Khaya senegalensis and Pterocarpus erinaceus* are prized but *Afzelia africana* is the most sought after because it would increase milk production (Houehanou et al., 2008). This result corroborates those of Ibrahim et al. (2005) who reported that dairy cows fed on shrub forage produced an impressive daily milk yield without the use of supplemental concentrates. Furthermore, a study of Cohen-Zinder et al. (2016) on lactating cows revealed that milk production was improved by 2% if cows were fed on *Moringa oleifera* silage instead

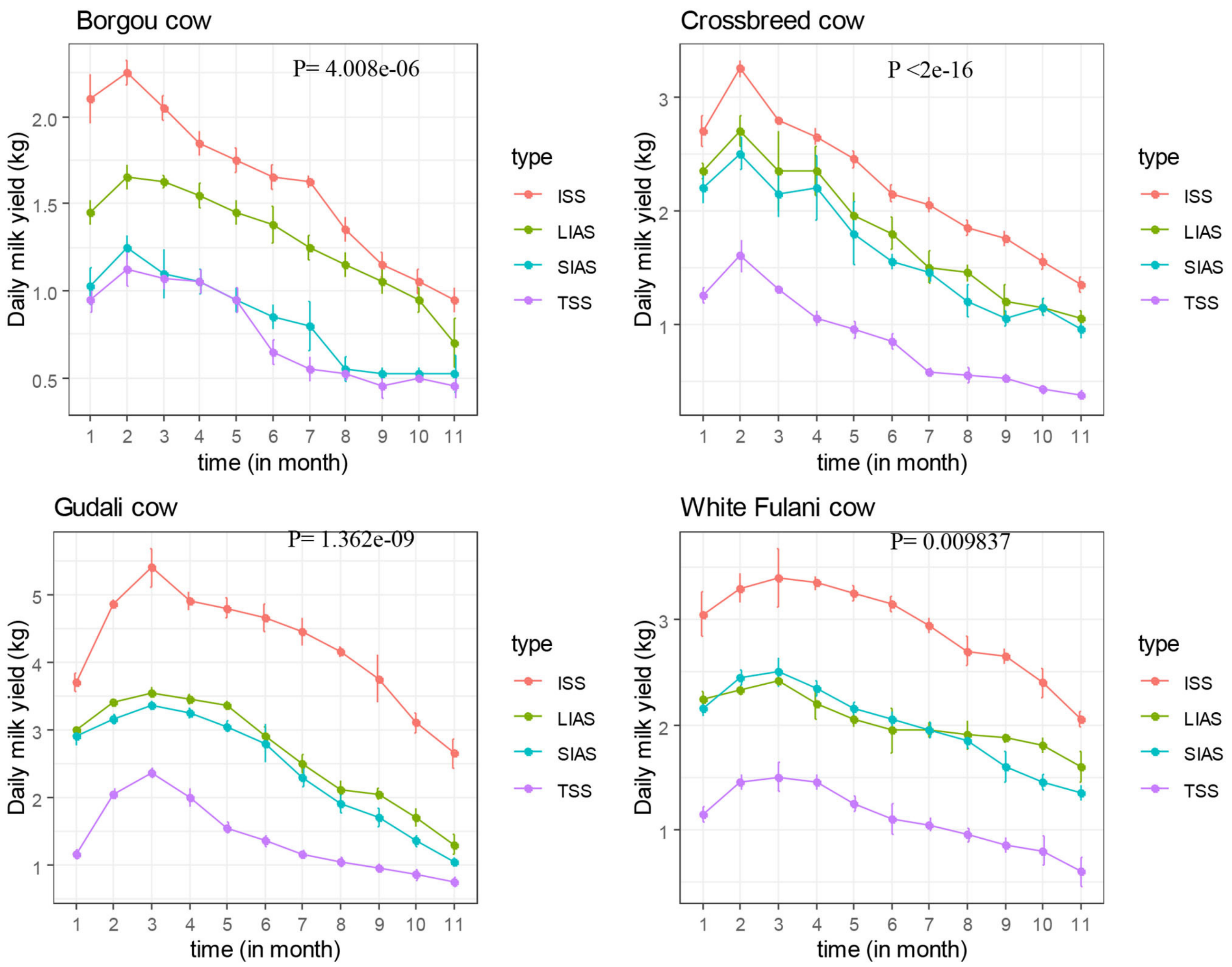

FIGURE 7
Evolution of milk production per month of lactation according to type of farm for each cattle breed in drylands of Benin. TSS, Traditional silvopastoral systems; ISS, Improved silvopastoral systems; SIAS, Small Integrated agrosilvopastoral systems; LIAS, Large Integrated agrosilvopastoral systems.

of wheat silage. Zhang et al. (2018) showed that the milk production of cows increased by 5% supplementing the diet with 6% *Moringa oleifera* in lactating multiparous Holstein dairy cows. *Leucaena leucocephala* supplementation also improved animal performance by increasing their proportion in cattle diet (Stifkens et al., 2022). Fodder trees are fodder resources for animals in dry periods. Their protein and vitamin content makes them the main fodder resource for livestock in the dry season to meet the maintenance and production needs of animals (Njidda and Ikhimioya, 2010; Mebirouk-Boudechiche et al., 2014; Sidi Imorou et al., 2016). In the Agrosilvopastoral territory of Nétéboulou in Senegal, the crude protein content of the leaves of *Pterocarpus erinaceus* can reach 15 to 20% of the dry matter (Mbaye et al., 2003). Trees and shrubs could then be used as alternative sources of protein for ruminants, which can lead to higher milk yield in native cows (Alam et al., 2009).

The highest daily milk yield obtained in the ISS, LIAS, SIAS farms compared to TSS cattle farm could also be due to the importance of woody fodder in the regulation of the body temperature of dairy cows. In fact, the presence of trees in the pastures can reduce heat stress, with positive effects on food consumption and milk production (de Abreu, 2002).

The amount of milk obtained from each local cattle bred based on tree integration practices in this study is greater than that obtained by Worogo et al. (2021) in traditional dairy cattle in northern Benin. This could be explained by the farming method practiced. In fact, the cattle farmers included in their study did not feed their cows with leaves from trees on their farm. Moreover, the quantity of milk produced by local cows in the TSS systems are similar to those reported by Kassa et al. (2016). This could be explained by the fact that the cows monitored by these authors practice extensive farming with seasonal exploitation of trees and shrubs on natural rangelands. Milk production increases gradually from the 1st to the 4th lactation where it reaches the peak and drops gradually from the 5th lactation. The development of mammary tissues during the reproductive life of the cow could explain this increase in milk according to the rank of birth (Rivière, 1991). From the 5th lactation, the milk production of dairy cows decreases, this

TABLE 6 Demographic parameters by the type of farms with integration of trees in cattle farming identified in drylands of Benin.

Parameters, %	TSS	ISS	SIAS	LIAS	*p-value*
Reproductive parameters:					
Rate of abortions	7.80[a]	1.80[b]	2.10[b]	6.20[a]	0.02
Calving rate	72.6[b]	94.2[a]	87.6[a]	77.6[b]	0.001
Fertility rate	68.3[b]	92.3[a]	89.6[a]	74.2[b]	0.001
Mortality parameters:					
Stillbirth rate	8.40[a]	2.10[b]	2.60[b]	6.10[a]	0.002
Pre-weaning mortality rate	18.3[a]	4.60[b]	5.20[b]	17.6[a]	0.001
Global mortality rate	5.80[a]	2.30[b]	2.40[b]	5.20[a]	0.004
Numerical weaning productivity	66.1[b]	88.6[a]	85.8[a]	67.6[b]	0.001
Management rates:					
Offtake rate	3.30[b]	8.80[a]	2.80[b]	3.80[b]	0.0001
Intake rate	1.20[b]	2.50[a]	3.60[a]	1.30[b]	0.01
Net offtake rate	2.10[b]	6.30[a]	−0.80[c]	2.50[b]	0.002

[a,b,c,d]Frequences with different superscript letters on the same row differ significantly ($p < 0.05$). TSS, Traditional silvopastoral systems; ISS, Improved silvopastoral systems; SIAS, Small Integrated agrosilvopastoral systems; LIAS, Large Integrated agrosilvopastoral systems.

could be due to the aging of the mammary tissues (Kassa et al., 2016). The parity number is therefore a physiological factor in the variation of milk production (Rivière, 1991). Several authors also reported the effect of parity number on cow milk production in Benin (Alkoiret et al., 2010; Assani et al., 2015; Worogo et al., 2021).

4.2. Herd structure

Monitoring the structure of a dairy herd provides important insights into herd profitability and farm dynamics (Muller, 2018). This study showed that herd structure varied with integrated production systems. The high proportion of lactating cows and dry cows in ISS herds is related to the main production objective of this farm (Assani et al., 2023). In fact, ISS farmers specialize in dairy production and direct their production toward the market or semi-dairies. This could be explained by the large number of dairy cows present on this type of farm. This herd structure, where the proportion of lactating cows is around 50%, confirms the specialization of herds in dairy production. Milk, in fact, represents an essential constituent of the food ration of human populations in Benin and provides a regular income to breeders of this type (Ogodja et al., 1991). Similar results were observed by Akpa et al. (2012) who showed that it is for milk production purpose that farmers raise a greater proportion of cows.

The largest proportions of adult males were found in the LIAS and SIAS types compared to the other types. This could be explained by the fact that the animals of these types are kept by agro-pastoralists and have a high number of draft oxen. Worogo et al. (2021) came up with similar observation where Borgou cattle were widely used for animal-drawn cultivation in northern Benin by agro-pastoralists. The composition of TSS cattle herds is on average 29.2% males and 70.8% females. This result is similar to those obtained in traditional cattle farms in Benin (Dehoux and Hounsou-Ve, 1993; Alkoiret et al., 2010; Assani et al., 2015; Worogo et al., 2021). According to these authors, the herds consist of one male for three females in traditional farms.

4.3. Demographic features

The superiority of the reproduction parameters of the ISS herds compared to the other types could be explained by the improvement of practices for the integration of livestock with the installation of fodder plots and the planting of fodder trees and shrubs adopted by farmers of this type. In fact, the presence of plantations of fodder trees and shrubs in livestock farms allows farmers to cope with feed shortages during the dry season, which improves cow productivity (abortion rate, parturition rate and fertility rate). Feeding influences all stages and components of reproduction in females (puberty, cyclicity and heat, mating, gestation, drying off, postpartum, and lactation) and males (puberty, libido, sperm and spermogram) (Meyer, 2009; Martins et al., 2021). In the Sahel, Diawara et al. (2017) observed a deterioration in reproductive performance in less mobile animals that do not receive enough feed supplements. ISS farms were more characterized by high fertility (92.3%), parturition (94%) and lowest abortion rate (1.8%). The results obtained in this type of dairy farming are similar to those obtained by Worogo et al. (2021) at the Okpara breeding farm. On the other hand, Dehoux and Hounsou-Ve (1993) obtained similar values of the fertility rate (65.4%) and the abortion rate (4%) in northern Benin within traditional beef herds corresponding to the performance of TSS.

The mortality parameters were also low in the ISS and SIAS type herds, this could be linked to the improvement of farming practices in this type. The study conducted at the Okpara breeding farm by Youssao et al. (2000) showed the reduction of mortality of the young animals to 2.5% by a program of regrouping of the births, a good feed and a good weaning. On the other hand, another study carried out in South Africa showed that most deaths are often caused by diseases (50%) and drought (34%) (Motiang and Webb, 2016). This is also the observation made in this study where the highest mortalities were obtained in the TSS and LIAS farms. This could be explained by the fact that there is a weak integration of the tree in this farming system, limited only to the exploitation of the trees natural range already very degraded in drylands of Benin which could cause a feeding imbalance and heat stress. In fact, heat stress increases respiration and mortality, reduces fertility, alters animal behavior and suppresses the immune and endocrine systems, thereby increasing the susceptibility of animals to certain diseases (Thornton et al., 2022). Furthermore, the mortality rate results obtained in this study are better than those found by others (Alkoiret et al., 2010; Assani et al., 2015; Worogo et al., 2021) in traditional cattle farming where the mortality rate youth ranged from 14 to 33%. These authors also confirmed that mortality rates are higher in traditional farming due to undernourishment and the absence or insufficiency of sanitary and medical prophylaxis. The main causes of mortality are almost the same for all farming systems in the study area and are of viral, bacterial, parasitic, feed or traumatic origin. Management rates vary depending on the type of farming systems. The superiority of the net offtake rate of the ISS herds would be linked to the low mortality rates recorded and to their objective of producing milk so that the several males are sold. Mortality being higher in the TSS and LIAS type, these herds have fewer animals to sell. The SIAS type consists of small herds, selling very few animals to achieve the goal of increasing numbers. They are also agro-pastoralists, they buy more young male cattle, which could explain the very high intake rate in this type. The numerical exploitation of cattle herds in drylands of Benin is consistent with that of traditional herds (Assani et al., 2015). According to these authors, the numerical exploitation rate of sedentary herds varied between 2 and 9%. Numerical exploitation also varies according to livestock categories: males are often sold very young in ISS farms, while females are kept for a long time for breeding in TSS and LIAS farms (Alkoiret et al., 2010). The low growth rates of herds in TSS and LIAS could be explained by the poor reproduction and mortality parameters associated with high numerical exploitation recorded in these herds. ISS-type herds that had the highest reproductive and exploitation parameters and the lowest mortality parameters had the highest numerical yield. In South Africa, some authors (Scholtz and Bester, 2010; Meissner et al., 2014) also reported that the high herd mortality of small-scale livestock keepers is the main cause of low productivity and low animal off-take rates.

4.4. Policy implications for sustainable animal production

Improved silvopastoral is adaptive to drought because foliage production from trees and shrubs is less affected by varying precipitation, temperature and other climatic variables thus enabling farmers to sustain livestock production even during extreme weather conditions (Papanastasis et al., 2008). The results show that dairy farming can be practiced in the drylands of Benin even during the dry season. The Benin government being aware of the great threat that climate change poses to the country's sustainable development, has drawn up National Action Programs for Adaptation to Climate Change (NAPA). Agrosilvopastoral and silvopastoral practices is one of the priority actions in this context, equally contributing to the adaptation and mitigation of climate change, as well as to food security. It is then necessary to:

- take into account agrosilvopastoral and silvopastoral systems and their potential in any development of national, sectoral and local policies on climate change;
- facilitate access to rural land for livestock smallholder farmers,
- promote tree plantations on small-scale pastoral farms in drylands;
- promote traditional and technical innovations adapted to each integrated animal production system identified;
- delineate animal corridors, including restoration of degraded rangeland with fodder trees;
- rehabilitate good management practices for silvopastoral resources, including capacity building for stakeholders (farmers, technicians, agricultural institutions, NGOs, etc.) and
- valorize indigenous knowledge of adaptation of livestock smallholder farmers to climate change.

5. Conclusions

The findings of this study showed that the silvopastoral system (ISS) increased milk production and improved demography parameters in dairy cattle. This type of feeding strategy can be promoted on dairy farms in the drylands of Benin. The adoption of this agroforestry technology is very linked to access to land, we recommend that policy-makers create the conditions necessary (facilitate access to rural land for livestock smallholder farmers, promote tree plantations on small-scale pastoral farms in drylands, training sessions on good practices of silvopastoral system, etc.) for the large-scale adoption of this agroforestry technology on cattle farms, in order to promote sustainable livestock production. Further studies are needed to assess the carbon footprint and sequestration capacity of each feeding strategy to select sustainable adaptation strategies to climate change in sub-Saharan Africa.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

AA, IH, and SS: conceptualization, methodology, validation, and investigation. AA, IH, SS, AK, and MA: writing—original draft preparation. AA, IH, SS, MA, MH, IA, OO, and YI: writing—review and editing. AA and IA: supervision, project administration, and funding acquisition. OO: supervision and funding acquisition. YI: supervision. All authors read and approved the final manuscript.

Funding

This research received German Academic Exchange Service (DAAD) funding through Climate Research for Alumni and Postdocs in Africa (ClimapAfrica) programme.

Acknowledgments

The authors express their gratitude to the German Academic Exchange Service (DAAD) for funding this study through Climate Research for Alumni and Postdocs in Africa (ClimapAfrica) programme and the livestock keepers for their frank and valuable cooperation during this study.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2023.1236581/full#supplementary-material

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Frontiers in Sustainable Food Systems
TYPE Original Research
PUBLISHED 08 January 2024
DOI 10.3389/fsufs.2023.1332595

OPEN ACCESS

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RECEIVED 03 November 2023
ACCEPTED 18 December 2023
PUBLISHED 08 January 2024

CITATION
He J, Ran D, Tan D and Liao X (2024) Spatiotemporal evolution of cropland in Northeast China's black soil region over the past 40 years at the county scale. *Front. Sustain. Food Syst.* 7:1332595. doi: 10.3389/fsufs.2023.1332595

Spatiotemporal evolution of cropland in Northeast China's black soil region over the past 40 years at the county scale

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This study investigates the 40-year spatiotemporal evolution of cropland in Northeast China's black soil region at the county scale. Utilizing land use/cover maps from 1980 to 2020 with a 30 m × 30 m resolution, we employed various analytical methods, including mathematical statistics, GIS spatial analysis, land use transition matrix, landscape pattern analysis, and hotspot analysis. The findings of this study are as follows: (1) Cropland area expanded by 51,976.76 km2 from 1980 to 2020, mainly concentrated in the Sanjiang Plain, Songnen Plain, and Liaohe Plain. Notably, areas near prefecture-level city locations experienced a decrease in cropland, while regions farther from cities witnessed an increase. (2) Cropland primarily transitioned from woodland, grassland, and unused land to cropland, covering substantial areas. Conversely, cropland was converted mainly into woodland, built-up land, and grassland. (3) Over the same period, cropland in the region exhibited increased elevation and slope, with average altitude rising by 2.06 m and average slope increasing by 0.0369 degrees. (4) The study revealed an increase in cropland proportion, predominance, and aggregation, alongside more irregular shapes and reduced subdivision. These findings highlight significant changes in the cropland landscape in Northeast China's black soil region and offer insights for policy recommendations and land management strategies. The research findings of this paper can offer valuable insights for the protection and utilization of cropland in the region. They can provide scientific references for the formulation of policies related to China's food security.

KEYWORDS

cropland, remote sensing, land use transition matrix, landscape pattern, hot spot analysis, Northeast China

1 Introduction

Research on land use change is a crucial aspect of global change studies and remains a prominent area of investigation (Turner et al., 1995; Liu et al., 2003; Ning et al., 2018; Chen et al., 2021). Among the various facets of land use change, the study of cropland change holds particular significance, because grain needs to be produced from cropland (Guo et al., 2023). Cropland is the most basic natural resource, which is a basic necessity for human survival, and the Chinese government is always focused on protecting cropland (Lichtenberg and Ding, 2008; Zhou et al., 2021). With the development of industrialization and urbanization, many problems arise, such as a large amount of cropland converted to non-agricultural land, non-grain production on cropland, decrease in quality of cropland, subdivision of cropland, soil pollution, and other problems (Deng et al., 2011; Yu et al., 2018; Liu et al., 2019; Qiu M. et al., 2020; Qiu B. et al., 2020; Chen et al., 2021, 2022; Wang et al., 2021; Guo et al., 2022; Ran et al., 2022). The black soil region of Northeast China as the third largest black soil region in the world is very important for China's food security, and the Outline of the Northeast Blackland Conservation Plan (2017–2030) shows its grain production accounts for 1/4 of the country, grain commodity volume accounts for 1/4 of the country, and grain transfer accounts for 1/3 of the country. To protect the black soil in the black soil region of Northeast China, the Black Soil Protection Law of the People's Republic of China was adopted after a vote at the closing meeting of the 35th standing committee session of the 13th National People's Congress on June 24, 2022. The law take effect on Aug. 1, 2022. Therefore, it is important to study the spatiotemporal changes of cropland in the black soil area of northeast China for the protection of cropland in this region.

The cropland changes study's contents include the process characteristics, the spatiotemporal heterogeneity and intensity, different modes, and driving mechanisms of the cropland expansion (Pendrill and Persson, 2017; Zhang et al., 2017; Ma et al., 2019; Cai et al., 2021; Chen et al., 2022; Wang et al., 2022), and cropland use efficiency (Zhou et al., 2022), and cropland land multifunction assessment (Jiang et al., 2020; Li et al., 2023), cultivated land use protection pressure (Chen et al., 2017), cultivated land quality evaluation (Wang et al., 2012; Shi et al., 2020; Song et al., 2022), and etc. From the impact of cropland change. Some scholars studied the impacts of cropland expansion on carbon storage (Tang et al., 2020; Huang et al., 2022), forests (Ngoma et al., 2021), grassland (Pool et al., 2014; Wimberly et al., 2017), ecosystem services (Lu et al., 2017), water quantity and quality (Fitton et al., 2019; Hu et al., 2019), agricultural pests (Zhao et al., 2015), surface air temperature (Xiong, 2015), soil erosion (Mancino et al., 2016), climate change (Abera et al., 2020), biodiversity conservation (Moraes et al., 2017), and etc. From the causes of the change in cropland. Andrade de Sá et al. found that agriculture competes with forests for land in Brazil (Andrade de Sá et al., 2013). Wang et al. found that more than 80% of total cultivated land consumption in Shanghai, Tianjin, and Beijing is satisfied by other provinces (Wang et al., 2021). Xi et al. found that land occupied by rural settlements/residential land resulted in the loss of cultivated land (Xi et al., 2012). Radwan et al. found that cities expansion led to the large decrease in the cultivated land (Radwan et al., 2019). From the study scale, including global, national, provincial, county, basin, and etc. Hu et al. found that China was the only country which experienced cropland decrease on Global the cropland expansion based on GlobeLand 30 (Hu et al., 2020). Liu et al. found that croplands were the primary contributor to urban expansion with a sample of 75 cities in China (Liu et al., 2019). Wang et al. found that large areas of cropland expansion were mainly clustered in the middle of this area in the Yangtze River Economic Belt (Wang et al., 2022). Wang et al. found that croplands were the primary contributor to urban expansion in Shandong Province (Wang et al., 2021). Meng et al. found that croplands were the primary contributor to urban expansion in Chengdu (Meng et al., 2022). Xiong et al. found that cultivated land area increased originally and subsequently decreased from 2000 to 2020 in Qishan County, China (Xiong et al., 2022). From the cropland protection policy, some scholars studied the role of the requisition–compensation balance of farmland (Song and Pijanowski, 2014; Shen et al., 2017; Wu et al., 2017), basic farmland protection system (Wu et al., 2017), and linking the increase in urban construction land with a decrease in rural construction land (Liu et al., 2019) on quality of cropland protection were minimally, and the policy evolution of cultivated land use (Wang et al., 2018), land use and rural transformation (You et al., 2018).

This paper addresses these shortcomings by conducting a comprehensive analysis, using nearly four decades of land use/cover maps from 1980 to 2020 with a 30 m × 30 m resolution. The study employs various analytical methods, such as mathematical statistics, GIS spatial analysis, land use transition matrix, landscape pattern analysis, and hotspot analysis, to systematically and thoroughly examine the spatiotemporal evolutionary characteristics of cropland quantity, spatial distribution, conversion patterns, altitude, slope, and landscape pattern within Northeast China's black soil region at the county scale. The research findings of this study can offer scientific references for the protection of arable land in the Northeast Black Soil Region. Additionally, they can serve as scientific references for the national food security policies targeted at this region.

2 Materials and methods

2.1 Study area

The black soil of northeast China is one of the four largest black soil areas in the world and is mainly located in Northeast China in Heilongjiang Province, Jilin Province, Liaoning Province, and Inner Mongolia's four eastern leagues (Figure 1). The black soil area of northeast China covers 1.09 million km^2, accounting for 12% of the total global black soil area, and its total grain production accounts for a quarter of the country. "Black Soil Protection Law of the People's Republic of China" was adopted to protect the black soil of northeast China. Therefore, it is important to explore the spatial and temporal characteristics of cropland in the black soil area of northeast China for the conservation of the black soil area.

2.2 Data sources

The data were collected from the following sources: (1) land use/cover maps data include six land use/cover types as follows, cropland, woodland, grassland, water body, built-up land, unused land in 1980, 1990, 1995, 2000, 2005, 2010, 2015, and 2020, with a cell size of 30 m × 30 m, from the Resource and Environmental Sciences and Data Center, Chinese Academy of Sciences ([1]accessed on 5 June 2022); (2) Altitude, slope data from OpenTopography, with a cell size of 30 m × 30 m ([2]accessed on20 November 2022); (3) administrative boundary data from the National Basic Geographic Information Center ([3]accessed on 5 June 2022).

1 https://www.resdc.cn
2 https://portal.opentopography.org
3 http://www.ngcc.cn/ngcc/

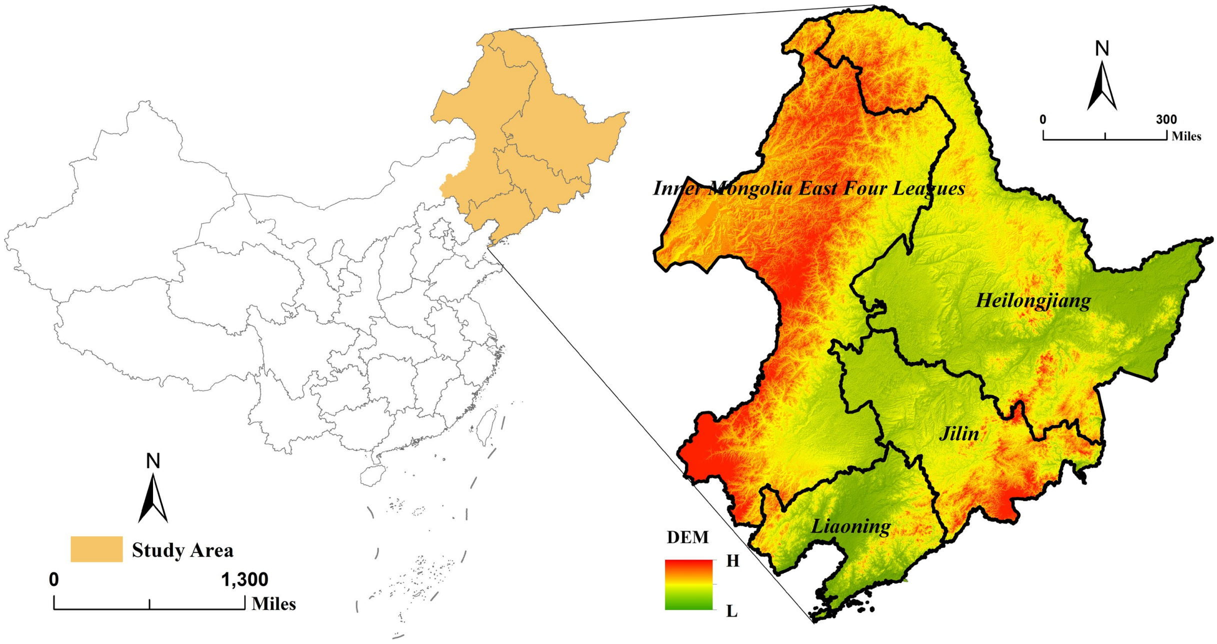

FIGURE 1
Location of the study area.

2.3 Methods

To understand the spatiotemporal evolution characteristics of cropland in the Northeast Black Soil Region, the transformation features between cropland and other land use types, the variations in cropland with respect to altitude and slope, as well as the landscape pattern characteristics of cropland under human influence, various tools and analyses can be employed.

A land use matrix can provide insights into the transformation features between cropland and other land use types. Zonal statistics as table can be applied to comprehend the characteristics of cropland changes with respect to altitude and slope. Landscape pattern indices can reveal the features of cropland landscape patterns under human influence. Hotspot analysis tools can be utilized to understand the changing characteristics of the aforementioned features. The above methods can provide us with a comprehensive understanding of the characteristics of cropland changes in the Northeast Black Soil Region.

2.3.1 Land use transition matrix

The land use matrix, which defines the transition among various land use types at the beginning and end of a period of time, is crucial for analyzing the change in land types in a region (Shi et al., 2018; Zhu et al., 2021). The Equation 1 is as follows (Zhang et al., 2023):

$$L = \begin{bmatrix} L_{11}\ L_{12} \cdots L_{1j} \\ L_{21}\ L_{22} \cdots L_{2j} \\ :::: \\ L_{i1}\ L_{i2} \cdots L_{ij} \end{bmatrix} \quad (1)$$

where L represents the area, L_{ij} indicates the area in transition from landscape i to j at the beginning and end of a period of time.

2.3.2 Zonal statistics as table (spatial analyst)

Summarizes the values of a raster within the zones of another dataset and reports the results as a table. We used this tool to calculate the change in altitude and slope of cropland in a region. Please refer to **Arc Gis 10.8** software for the details of the zonal statistics as table tool.

2.3.3 Analysis of cropland using landscape metrics

Landscape metrics are frequently used methods for quantitatively describing regional landscape pattern changes. We analyzed the spatial variation characteristics of cropland in the black soil area of northeast China in five dimensions: landscape proportion, landscape shape, landscape predominance, landscape subdivision, and landscape aggregation (Li et al., 2005; Zhang et al., 2016; Dadashpoor et al., 2019; Yin et al., 2022). Therefore, five class-level metrics were chosen to reflect these spatial characteristics of cropland landscape patterns, including percentage of landscape (PLAND), landscape shape index (LSI), largest patch index (LPI), landscape division index (DIVISION), and clumpiness index (CLUMPY). Table 1 contains a list of each of the chosen landscape metrics, and landscape metrics were calculated in **Fragstats4.2.1 (University of Massachusetts in Amherst, Amherst, MA, United States)** (McGarigal and Marks, 1995). Please refer to **Fragstats4.2.1** software for more details on the five metrics.

2.3.4 Hot spot analysis

The hot spot analysis tool identifies statistically significant spatial clusters of high values (hot spots) and low values (cold spots) (Tran et al., 2017; Singh et al., 2021; Zhou et al., 2023). we used this tool to analyze the hot and cold spot distribution characteristics of statistical significance in the changes in PLAND, LSI, LPI, DIVISION, and CLUMPY of cropland. Please refer to **Arc Gis 10.8** software for the details of the hot spot analysis tool.

3 Results

3.1 Spatiotemporal characteristics of cropland

3.1.1 Spatial distribution of cropland

Figure 2 shows the spatial distribution of cropland in 1980 and 2020. From the geographical distribution, cropland in the black soil region of northeast China was mainly located in Sanjiang Plain, Songnen Plain, and Liaohe Plain in 1980 and 2020.

From the administrative distribution, cropland in the black soil region of northeast China in 2020 was predominantly located in areas including Qiqihar, Suihua, Daqing, Jiamusi, Shuangyashan, Qitaihe, Jixi, east-central Hegang, and west-central and north Harbin of Heilongjiang Province, Changchun, Siping, Songyuan, Baicheng, and Liaoyuan of Jilin Province, North-central Tieling, Shenyang, Jinzhou, Panjin, Dalian, west-central Liaoyang and northwestern Yingkou of Liaoning Province, and the regions of Inner Mongolia East Four Leagues neared Heilongjiang Province, Jilin Province, and Liaoning Province. From 1980 to 2020, the increase in cropland in the Sanjiang Plain of Heilongjiang Province and the regions of Hulunbuir, Inner Mongolia neared Heilongjiang Province were very significant.

3.1.2 Spatiotemporal characteristics of cropland change

Figure 3 and Table 2 show the cropland area, change value, and change ratio in the black soil area of northeast China from 1980 to 2020. During 1980–2020, Changes in cropland area in the black soil region of northeast China showed an increasing trend, the cropland area increased from 319,480.75 km^2 to 371,457.51 km^2, the change value was 51,976.76km^2, and the change ratio was 16.27%. By study period, the value and ratio of change of 1980–1990, 1990–1995, 1995–2000, 2000–2005, 2005–2010, and 2010–2015 showed an increasing trend, and the value and ratio of change of 2015–2020 showed a decreasing trend. The order of the size of the changes in the values and ratios of cropland area in each study period is as follows: 1990–1995 (22063.20 km^2, 6.57%), 1980–1990 (16377.12 km^2, 5.13%), 1995–2000 (12088.53 km^2, 3.38%), 2015–2020 (−2202.73 km^2, −0.59%), 2000–2005 (1706.38 km^2, 0.46%), 2005–2010 (1137.60 km^2, 0.31%), 2010–2015 (806.66 km^2, 0.22%). The value and ratio of change of cropland in the black soil area of northeast China in the first three study periods were significantly higher than those in the last four study periods. The value and ratio of change of cropland land in the black soil area of northeast China showed a decreasing trend in each study period, except for 1980–1990.

Figure 4 displays the spatial distribution of changes in cropland amounts, featuring three types of information: increase (in red), decrease (in green), and change values. In the first step, changes in cropland area were categorized into two groups based on whether they increased or decreased. In the second step, the values of all periods that had been classified were categorized into five categories using the natural breakpoint method.

Based on the trends in cropland change values from 1980 to 2020, Figure 4 (1980–2020) displays the locations of prefecture-level city locations and their surrounding areas where cropland change values exhibited either a decreasing trend or a non-significant increasing trend. Notably, areas with an increasing trend in cropland change values were situated at a considerable distance from the prefecture-level city locations. Prefecture-level cities experiencing an increasing trend in the value of cropland area change were primarily concentrated in Heilongjiang Province, the four eastern leagues of Inner Mongolia, and Jilin Province. In contrast, prefecture-level cities with a decreasing trend in the value of cropland area change were mainly found in Liaoning Province and certain parts of Jilin Province. Additionally, Figure 4 (1980–2020) identifies regions with a significant increasing trend in the value of cropland change (≥441.18 km^2). These regions were primarily located in the Sanjiang Plain, Heihe, Harbin, Qiqihar, Heilongjiang Province, as well as in the northwest and southeast of Tongliao, the east of Chifeng, and east-central Hulunbuir in Inner Mongolia. Similar trends extended to Baicheng in Jilin Province, Yanbian Korean Autonomous Prefecture in Jilin Province, and other areas. Conversely, regions with a decreasing trend in the value of cropland change were mainly concentrated in Siping, Jilin Province, as well as in Chaoyang, Huludao, Dandong, Shenyang, and other areas in Liaoning Province.

TABLE 1 The landscape metrics selected in this study.

Abbr	Metrics	Range	Units
PLAND	Percentage of Landscape	0 < PLAND≦100. PLAND approaches 0 when the corresponding patch type (class) becomes increasingly rare in the landscape. PLAND = 100 when the entire landscape consists of a single patch type; that is, when the entire image is comprised of a single patch.	Percent
LSI	Landscape Shape Index	LSI ≥ 1, without limit. LSI = 1 when the landscape consists of a single square patch of the corresponding type; LSI increases without limit as landscape shape becomes more irregular and/or as the length of edge within the landscape of the corresponding patch type increases.	None
LPI	Largest Patch Index	0 < LPI≦100. LPI approaches 0 when the largest patch of the corresponding patch type is increasingly small. LPI = 100 when the entire landscape consists of a single patch of the corresponding patch type; that is, when the largest patch comprises 100% of the landscape.	Percent
DIVISION	Landscape Division Index	0≦DIVISION<1. DIVISION = 0 when the landscape consists of single patch. DIVISION approaches 1 when the focal patch type consists of single, small patch one cell in area. As the proportion of the landscape comprised of the focal patch type decreases and as those patches decrease in size, DIVISION approaches 1.	Proportion
CLUMPY	Clumpiness Index	-1≦CLUMPY≦1. CLUMPY equals −1 when the focal patch type is maximally disaggregated; CLUMPY equals 0 when the focal patch type is distributed randomly, and approaches 1 when the patch type is maximally aggregated. Note, CLUMPY equals 1 only when the landscape consists of a single patch and includes a border comprised of the focal class.	Proportion

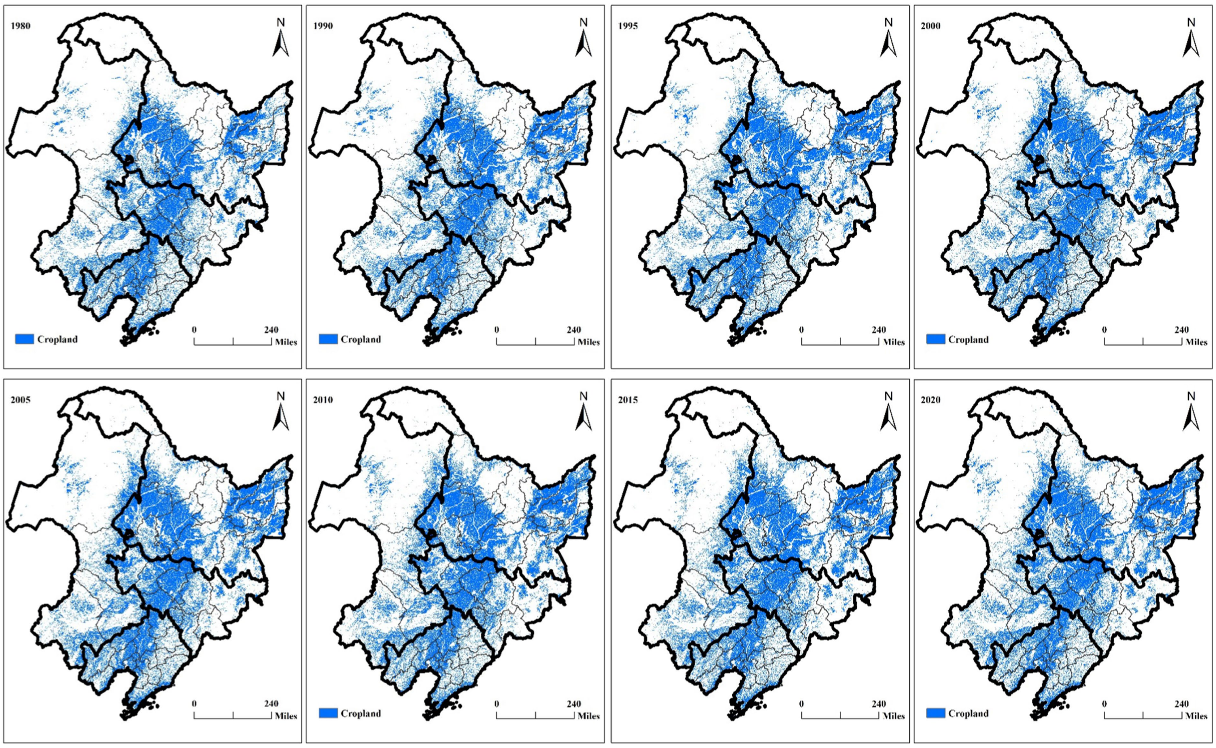

FIGURE 2
Spatial distribution of cropland. The thick black line is the provincial boundary (Including the four eastern leagues of Inner Mongolia), and the thin black line is the prefecture-level city boundary.

The trend of spatial movement of the regions with a high increase in the change in the value of cropland area (≥441.18km^2) was from the east (Figure 4, 1980–1990) to the west (Figure 4, 1990–1995) and then to the north (Figure 4, 1995–2000). Figure 4 (1980–1990, 1990–1995, 1995–2000) show the regions with a high increase in the change in the value of cropland area (≥441.18km^2) were mainly located in the Sanjiang Plain, Heihe, Heilongjiang Province, and Jilin, Jilin Province (Figure 4, 1980–1990), and the regions with a high increase in the change in the value of cropland area (≥441.18km^2) were mainly located in Xing'an League and Tongliao City in Inner Mongolia, Daqing, Harbin, Heihe, Suihua, and Hegang in Heilongjiang Province, Baicheng and Songyuan in Jilin Province, etc. (Figure 4, 1990–1995), and the regions with a high increase in the change in the value of cropland area (≥441.18km^2) were mainly located in Hulunbeier East Region, Inner Mongolia, and Heihe, Heilongjiang Province (Figure 4, 1995–2000). Figure 4 (2000–2005) shows the change value of cropland was not significant.

Figure 4 (2005–2010, 2010–2015, 2015–2020) show that there were more areas with a decreasing trend in the value of cropland change. This includes the number of regions and the size of change values.

The regions with a decreasing trend in the change in the value of cropland area were mainly located in Chaoyang, Huludao, Fuxin, Shenyang, Tonghua, and most other regions in Liaoning Province, as well as Tongliao, Chifeng, and other regions in Inner Mongolia, Baicheng, Siping, Jilin, and other regions in Jilin Province, and Suihua, Qiqihar, Harbin, Yichun, Shuangyashan, and other regions in Heilongjiang Province. During the period of 2010–2015, these regions were mainly located in central Heilongjiang Province, central and southeastern Jilin Province, and Liaoning Province, as depicted in Figure 4. For the years 2015–2020, the regions with a decreasing trend in the change in the value of cropland area were mainly located in Inner Mongolia East Four League, and Heihe, Harbin, Qiqihar, Daqing, Heilongjiang Province, Baicheng, Songyuan, Jilin Province, and Liaoning Province, as shown in Figure 4.

3.2 Spatiotemporal characteristics of cropland conversion

Table 3, covering the period from 1980 to 2020, provides insights into cropland transformations. During this period, cropland was primarily converted into woodland, built-up land, and grassland, spanning areas of 11,906.62 km^2, 10,809.33 km^2, and 6,406.81 km^2, respectively. The corresponding percentages were 35.13, 31.89, and 18.90%. Conversely, cropland was primarily derived from woodland, grassland, and unused land, with areas of 32,230.00 km^2, 31,945.30 km^2, and 15,421.20 km^2, representing proportions of 37.53, 37.19, and 17.96%. Within Table 3, specific periods reveal further details of cropland conversion and derivation. Cropland was converted into woodland, covering 20,495.97 km^2 (2005–2010), 15,146.69 km^2 (2015–2020), 9,833.13 km^2 (1990–1995), and 9,829.29 km^2 (1995–2000). Cropland was converted into grassland, spanning 17,304.61 km^2 (2015–2020), 16,381.82 km^2 (2005–2010), 11,026.61 km^2 (1990–1995), and 8,253.09 km^2 (1980–1990). Additionally, cropland was converted into built-up land, with areas of 9,652.68 km^2 (2005–2010),

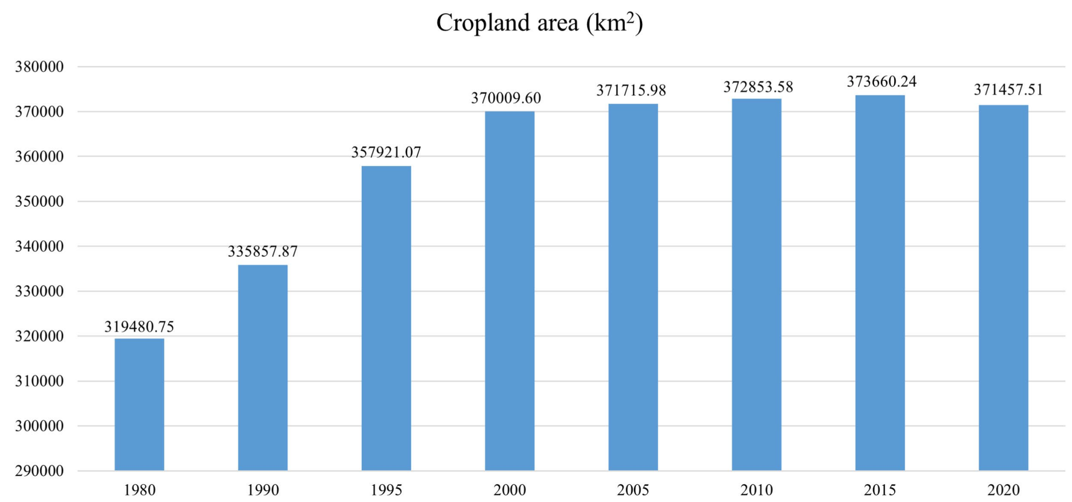

FIGURE 3
The trend of cropland area during 1980–2020.

6,017.78 km² (2015–2020), 1,787.50 km² (1990–1995), and 1,667.18 km² (1980–1990). Table 3 also illustrates that cropland was derived from woodland, covering 22,655.57 km² (2005–2010), 17,328.72 km² (1990–1995), 14,519.07 km² (1995–2000), and 13,772.18 km² (2015–2020). Similarly, cropland was derived from grassland, with areas of 21,850.91 km² (1990–1995), 19,691.74 km² (2005–2010), 15,649.51 km² (2015–2020), and 15,320.24 km² (1980–1990). Finally, cropland was derived from unused land, covering 8,395.56 km² (2015–2020), 7,776.65 km² (2005–2010), 6,651.40 km² (1990–1995), and 6,642.35 km² (1980–1990).

TABLE 2 Cropland change during 1980–2020.

Period	Change value (Km²)	Period	Change ratio (%)
1980–1990	16377.12	1980–1990	5.13%
1990–1995	22063.20	1990–1995	6.57%
1995–2000	12088.53	1995–2000	3.38%
2000–2005	1706.38	2000–2005	0.46%
2005–2010	1137.60	2005–2010	0.31%
2010–2015	806.66	2010–2015	0.22%
2015–2020	−2202.73	2015–2020	−0.59%
1980–2020	51976.76	1980–2020	16.27%

3.2.1 Spatiotemporal characteristics of cropland converted into woodland

Between 1980 and 2020, as shown in Figure 5 (1980–2020), the regions with cropland conversions into woodland (≥37.90 km²) were primarily located in Jilin Province, Liaoning Province. Figure 5 (2005–2010, 2015–2020, 1990–1995, 1995–2000) demonstrates significant changes in patch colors for regions (≥37.90 km²) of cropland converted into woodland. Conversely, Figure 5 (1980–1990, 2000–2005, 2010–2015) shows different patterns. Specifically, during 2005–2010, Figure 5 (2005–2010) reveals that regions (≤37.89 km²) of cropland converted into woodland were mainly located in Qiqihar, Daqing, Suihua, Yichun in Heilongjiang Province, Baicheng, Songyuan, and Changchun in Jilin Province, as well as Shenyang, Jinzhou, Panjin, and Liaoyang in Liaoning Province, and western Hulunbeier in Inner Mongolia. In the period of 2015–2020, Figure 5 (2015–2020) shows that regions (≤37.89 km²) of cropland converted into woodland were mainly located in Suihua, Qiqihar, Daqing, Yichun in Heilongjiang Province, Baishan, Tonghua, Baicheng, Changchun, and Yanbian Korean Autonomous Prefecture in Jilin Province, and most of Jilin Province. In the same period, regions (≥253.66 km²) of cropland converted into woodland were primarily found in Heihe in Heilongjiang Province and the eastern parts of Hulunbeier in Inner Mongolia.

For the years 1990–1995, Figure 5 (1990–1995) depicts regions (≥37.90 km²) of cropland converted into woodland mainly located in Harbin, Mudanjiang, Heihe in Heilongjiang Province, Baicheng, Songyuan, Jilin, Liaoyuan, Tonghua in Jilin Province, and Fuxin, Jinzhou, Huludao, Dalian, Dandong in Liaoning Province, along with eastern Hulunbeier, central Xing'an League, southwestern Tongliao, and southeastern Chifeng in Inner Mongolia. Lastly, during 1995–2000, Figure 5 (1995–2000) shows regions (≥37.90 km²) of cropland converted into woodland mainly located in Daqing, Harbin, Heihe in Heilongjiang Province, and Chaoyang, Huludao in Liaoning Province, and Baicheng, Songyuan, Jilin in Jilin Province.

3.2.2 Spatiotemporal characteristics of cropland converted into grassland

From 1980 to 2020, Figure 6 (1980–2020) shows that the regions (≥49.94 km²) of cropland converted into grassland were mainly located in Chifeng, Tongliao, Xing'an League, western Hulunbuir, Inner Mongolia, Chaoyang, Fuxin, and Liaoning Province. Additionally, the regions (≥178.68 km²) of cropland converted into grassland were primarily located in western Hulunbuir, Inner Mongolia. Figure 6 also reveals that in the time periods 2015–2020, 2005–2010, 1990–1995, and 1980–1990, the regions (≥49.93 km²) of cropland converted into grassland were predominantly situated in Inner Mongolia's East Four League. Furthermore, for the years 2015–2020 and 2005–2010, the regions (≥178.68 km²) of cropland converted into grassland were concentrated in Inner Mongolia's East Four

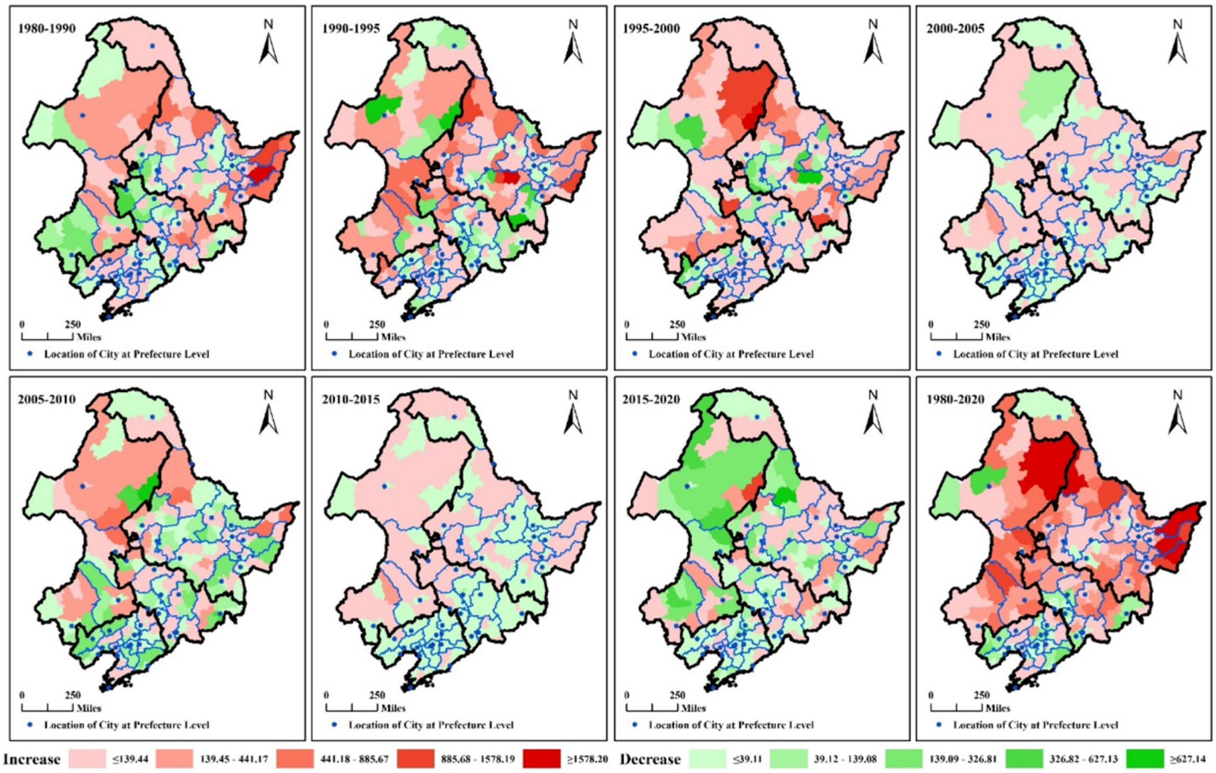

FIGURE 4
Spatial distribution of cropland area change values (Unit: km^2). Note: The thick black line is the provincial boundary (Including the four eastern leagues of Inner Mongolia) (The same as below), and the thin blue line is the prefecture-level city boundary (The same as below), red indicates an increase in the value of cropland change, and red indicates a decrease in the value of cropland change.

League. In the 2015–2020 period, the regions (≥398.62 km^2) of cropland converted into grassland were mainly located in Inner Mongolia's East Four League. Also, in 2005–2010, regions (≥49.93 km^2) of cropland converted into grassland were observed in various parts of Heilongjiang Province.

3.2.3 Spatiotemporal characteristics of cropland converted into built-up land

During 1980–2020, Figure 7 (1980–2020) shows that the regions (≥65.73 km^2) of cropland converted into built-up land were primarily located in Songyuan, Changchun, and Jilin in Jilin Province, as well as in Dalian, Fuxin, Shenyang, Chaoyang, Yingkou, and Dandong in Liaoning Province. Additionally, the regions (≥115.56 km^2) of cropland converted into built-up land were mainly situated in Jilin Province and Liaoning Province.

During 2005–2010, Figure 7 (2005–2010) reveals that the regions (≤10.86 km^2) of cropland converted into built-up land were primarily concentrated in the western parts of Hulunbeier, the northwestern parts of Tongliao in Inner Mongolia, and Yichun in Heilongjiang Province. In contrast, the regions (≥65.73 km^2) of cropland converted into built-up land were mainly found in Chaoyang, Fuxin, Shenyang, Anshan, Dalian, Dandong in Liaoning Province, as well as in Changchun, Siping, Jilin in Jilin Province, and Qiqihar, Suihua, Harbin in Heilongjiang Province.

During 2015–2020, Figure 7 (2015–2020) illustrates that the regions (≤10.86 km^2) of cropland converted into built-up land were predominantly situated in the west of central Hulunbeier in Inner Mongolia, and Tieling, Fushun, Benxi, Dandong, Huludao, Jinzhou in Liaoning Province. Also, these changes were notable in Baicheng, Songyuan, Tonghua, Baisan, and Yanbian Korean Autonomous Prefecture in Jilin Province, Yichun, Daxinganling in Heilongjiang Province. In contrast, the regions (≥10.87 km^2) of cropland converted into built-up land exhibited the opposite trend.

Additionally, Figure 7 shows that the regions (≥10.86 km^2) of cropland converted into built-up land during 1990–1995 were mainly concentrated in Qiqihar, Daqing, Mudanjiang in Heilongjiang Province, and Baicheng, Shenyang, Siping in Jilin Province, and Tongliao in Inner Mongolia, and Shenyang, Tieling, Anshan in Liaoning Province. The regions (≥10.86 km^2) of cropland converted into built-up land during 1980–1990 were mainly located in the Sanjian Plain, Heihe, Qiqihar, Harbin in Heilongjiang Province, and Songyuan, Changchun, Siping in Jilin Province.

3.2.4 Spatiotemporal characteristics of woodland converted into cropland

From 1980 to 2020, Figure 8 (1980–2020) reveals that the regions (≤60.77 km^2) of woodland converted into cropland were primarily concentrated in prefecture-level city locations and their surrounding areas. Notably, this transformation occurred in Qiqihar, Daqing, Suihua, Harbin, Yichun, Daxinganling in Heilongjiang Province, as well as in northwestern Hulunbeier, parts of Xing'an League, most of Chifeng, southeastern Tongliao in Inner Mongolia, and in Baicheng, Changchun, Songyuan in Jilin Province, Shenyang, Liaoyang, Panjin, Yingkou in Liaoning Province. The regions (≥196.29 km^2) of woodland

TABLE 3 The results of the land use transition matrix.

From class	To class	1980–1990		1990–1995		1995–2000		2000–2005	
		Area (km^2)	Ratio (%)	Area (km^2)	Ratio (%)	Area (km^2)	Ratio (%)	Area (km^2)	Ratio (%)
Cropland	Woodland	4193.84	25.17%	9833.13	36.72%	9829.29	45.88%	1251.28	36.19%
Cropland	Grassland	8253.09	49.54%	11026.61	41.17%	6419.01	29.96%	1314.28	38.01%
Cropland	Waterbody	613.39	3.68%	833.81	3.11%	1198.64	5.60%	148.92	4.31%
Cropland	Built-up land	1667.18	10.01%	1787.50	6.67%	1138.19	5.31%	532.17	15.39%
Cropland	Unused land	1932.01	11.60%	3299.11	12.32%	2837.15	13.24%	211.23	6.11%
Cropland	Total	16659.51	100.00%	26780.17	100.00%	21422.28	100.00%	3457.87	100.00%
Woodland	Cropland	10552.29	31.94%	17328.72	35.48%	14519.07	43.33%	1489.72	28.87%
Grassland	Cropland	15320.24	46.37%	21850.91	44.74%	12084.17	36.06%	1908.53	36.98%
Waterbody	Cropland	357.22	1.08%	1910.70	3.91%	808.34	2.41%	385.57	7.47%
Built-up land	Cropland	164.95	0.50%	1100.28	2.25%	1259.31	3.76%	204.03	3.95%
Unused land	Cropland	6642.35	20.11%	6651.40	13.62%	4839.73	14.44%	1172.80	22.73%
Total	Cropland	33037.04	100.00%	48842.00	100.00%	33510.62	100.00%	5160.64	100.00%

From class	To class	2005–2010		2010–2015		2015–2020		1980–2020	
		Area (km^2)	Ratio (%)	Area (km^2)	Ratio (%)	Area (km^2)	Ratio (%)	Area (km^2)	Ratio (%)
Cropland	Woodland	20495.97	35.21%	685.42	32.21%	15146.69	31.96%	11906.62	35.13%
Cropland	Grassland	16381.82	28.14%	279.33	13.13%	17304.61	36.51%	6406.81	18.90%
Cropland	Waterbody	4042.74	6.95%	84.09	3.95%	1447.63	3.05%	2449.07	7.23%
Cropland	Built-up land	9652.68	16.58%	911.98	42.86%	6017.78	12.70%	10809.33	31.89%
Cropland	Unused land	7634.81	13.12%	167.15	7.86%	7478.51	15.78%	2325.29	6.86%
Cropland	Total	58208.02	100.00%	2127.97	100.00%	47395.21	100.00%	33897.13	100.00%
Woodland	Cropland	22655.57	38.18%	728.35	24.50%	13772.18	30.48%	32230.00	37.53%
Grassland	Cropland	19691.74	33.19%	1284.80	43.21%	15649.51	34.64%	31945.30	37.19%
Waterbody	Cropland	2620.85	4.42%	106.23	3.57%	2360.26	5.22%	2437.95	2.84%
Built-up land	Cropland	6592.25	11.11%	306.16	10.30%	5002.85	11.07%	3852.29	4.49%
Unused land	Cropland	7776.65	13.11%	547.72	18.42%	8395.56	18.58%	15421.20	17.96%
Total	Cropland	59337.08	100.00%	2973.25	100.00%	45180.36	100.00%	85886.74	100.00%

converted into cropland were mainly concentrated in Heihe, Harbin, Mudanjiang, Shuangyashan, Qitaihe, Jixi, Jiamusi in Heilongjiang Province, Baicheng, Jilin, Tonghua, Baisan, Yanbian Korean Autonomous Prefecture in Jilin Province, Fuxin, Dalian, Dandong in Liaoning Province, and Eastern Hulunbeier in Inner Mongolia.

During 2005–2010, as shown in Figure 8 (2005–2010), regions with woodlands (≤60.77km²) that were converted into cropland were primarily distributed in prefecture-level city locations and their surrounding areas. This included Qiqihar, Daqing, Suihua, Yichun, Harbin, Daxinganling in Heilongjiang Province, and Baicheng, Songyuan, Changchun, Siping in Jilin Province, as well as Shenyang, Jinzhou, Fuxin in Liaoning Province, along with most of Chifeng, the southeast of Tongliao, and parts of Hulunbeier in Inner Mongolia. The regions with woodlands (≥196.29km²) converted into cropland were mainly concentrated in Heihe, Mudanjiang, Harbin, Jiamusi, Shuangyashan, and Jixi in Heilongjiang Province, as well as Jilin, Yanbian Korean Autonomous Prefecture in Jilin Province, and the eastern parts of Hulunbeier and portions of Xing'an League in Inner Mongolia.

Figure 8 shows that in the years 1990–1995, regions with woodlands (≥60.78km²) converted into cropland were primarily distributed in Heihe, Mudanjiang, Harbin, Shuangyashan, Jixi, and Yichun in Heilongjiang Province. They were also prominent in Songyuan, Changchun, and Jilin in Jilin Province, as well as Huludao, Chaoyang, Fuxin, and Dandong in Liaoning Province, and central Xin'an League, eastern Hulunbeier, and western Hulunbeier in Inner Mongolia.

In the period 1995–2000, the regions with woodlands (≥60.78km²) converted into cropland were mainly concentrated in Heihe, Daxinganling, Harbin, Mudanjiang, Qitaihe, Shuangyashan, Jiamusi, and other areas in Heilongjiang Province. They also extended to Baicheng, Songyuan, Jilin, and Yanbian Korean Autonomous Prefecture in Jilin Province, as well as Dandong, Dalian, Chaoyang in Liaoning Province, and eastern Hulunbeier, central Xing'an League, and southeastern Chifeng in Inner Mongolia.

Furthermore, from 2015 to 2020, regions with woodlands (≥60.78km²) converted into cropland were primarily seen in

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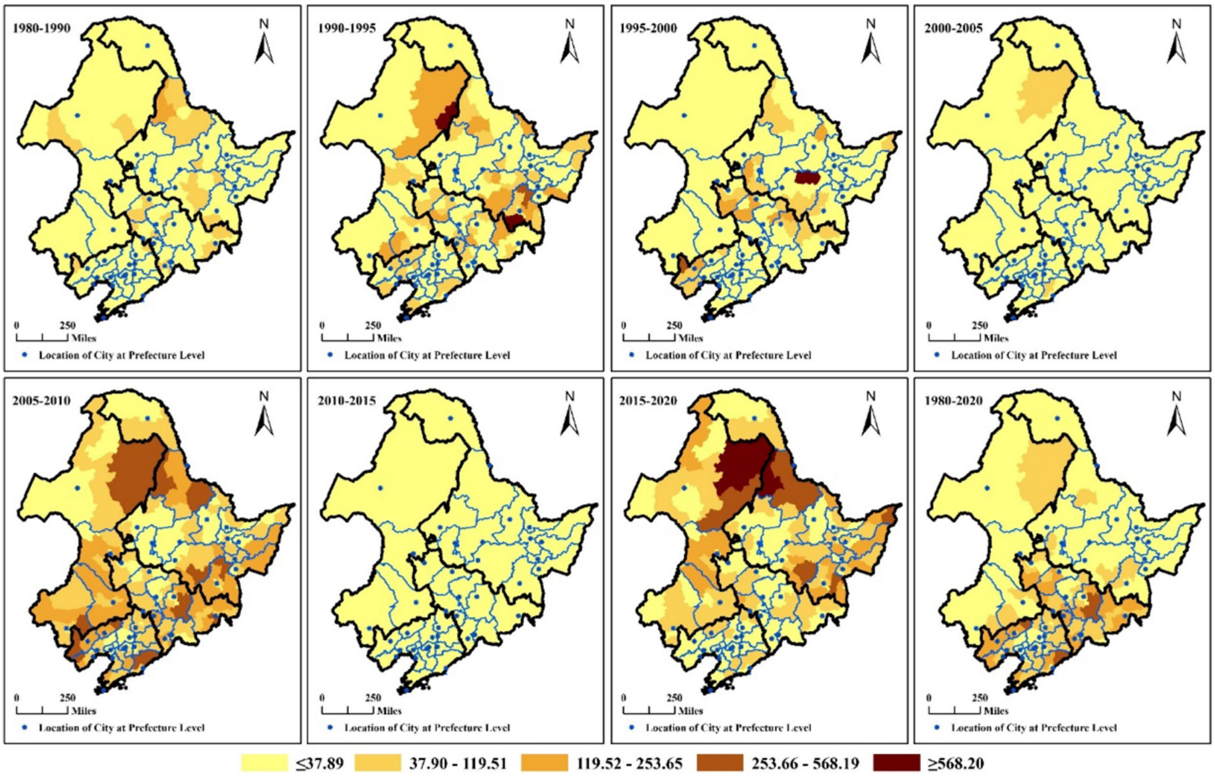

FIGURE 5
Spatial distribution of the areas of cropland converted into woodland (Unit: km^2). The areas of cropland converted into woodland of all periods were unified into five categories using the natural breakpoint method (The same as below).

Daxinganling, Hehe, Harbin, Mudanjiang, Jixi, Shuangyashan, Qitaihe, Jiamusi, and Hegang in Heilongjiang Province. They were also notable in Songyuan, Siping, Jilin, Yanbian Korean Autonomous Prefecture in Jilin Province, as well as Dandong in Liaoning, and the eastern and northern areas of Hulunbeier, Xing'an League, Tongliao, Chifeng, and other parts of Inner Mongolia.

3.2.5 Spatiotemporal characteristics of grassland converted into cropland

Between 1980 and 2020, as depicted in Figure 9 (1980–2020), the regions with grasslands (≥82.87km^2) converted into cropland were primarily concentrated in Hulunbeier, Xing'an League, Tongliao City, and parts of Chifeng in Inner Mongolia. Additionally, they were prominent in Baicheng and Songyuan in Jilin Province, and in Heihe, Qiqihar, Daqing, Hegang, Jiamusi, Shuangyashan, and Jixi in Heilongjiang Province. For regions with more significant conversions (≥517.32km^2) of grassland into cropland, the main areas included Hulunbeier, Xing'an League, Tongliao, Chifeng in Inner Mongolia, as well as Heihe, Jixi, Shuangyashan, and Jiamusi in Heilongjiang Province.

Figure 9 further highlights that regions with extensive conversions (≥82.87km^2) of grassland into cropland were primarily situated in the four eastern leagues of Inner Mongolia during various timeframes (1990–1995, 2005–2010, 2015–2020, 1980–1990, 1995–2000). These regions also encompass Heihe (1990–1995, 2005–2010, 2015–2020, 1980–1990), Jiamusi (1990–1995, 2015–2020, 1980–1990), Jixi (1990–1995, 2005–2010, 2015–2020, 1980–1990, 1995–2000), Shuangyashan (1990–1995, 2005–2010, 1980–1990, 1995–2000), Daxinganling (1980–1990) in Heilongjiang Province, as well as Baicheng (1990–1995, 2005–2010, 1980–1990) and Songyuan (1990–1995, 1980–1990) in Jilin Province.

3.3 Spatiotemporal characteristics of altitude and slope changes in cropland

Figure 10 shows the spatial distribution of average altitude and average slope in cropland. From the geographical distribution, Figure 10A shows the spatial distribution of average altitude in cropland was high in the west, north, and east, and low in the middle, and the regions of low average altitude in cropland were located in Sanjiang Plain, Songnen Plain, and Liaohe Plain. From the administrative distribution, Figure 10A shows the regions (2.09–95.76, 95.77–195.44) of average altitude in cropland were located in Hegang, Jiamusi, Shuangyashan, Jixi, Harbin, Suihua, Daqing, Qiqihaer, Heilongjiang Province, and Baicheng, Songyuan, Siping, Changchun, Jilin Province, Huludao, Jinzhou, Panjin, Shenyang, Anshan, Yingkou, Liaoyang, Tieling, Dandong, Liaoning Province, and southeast of Tongliao, Inner Mongolia, etc., and the regions (305.76–537.84, 537.85–1253.84) of average altitude in cropland were located in parts of Inner Mongolia East Four League, and Mudanjiang, Heihe, Daxinganling, Heilongjiang Province, and Jilin, Liaoyuan, Tonghua, Baishan, Yanbian Korean Autonomous Prefecture, Jilin Province, and Chaoyang, Benxi, Fushun, Liaoning Province, etc. from The administrative distribution, Figure 10B shows the regions (5.12–8.10,

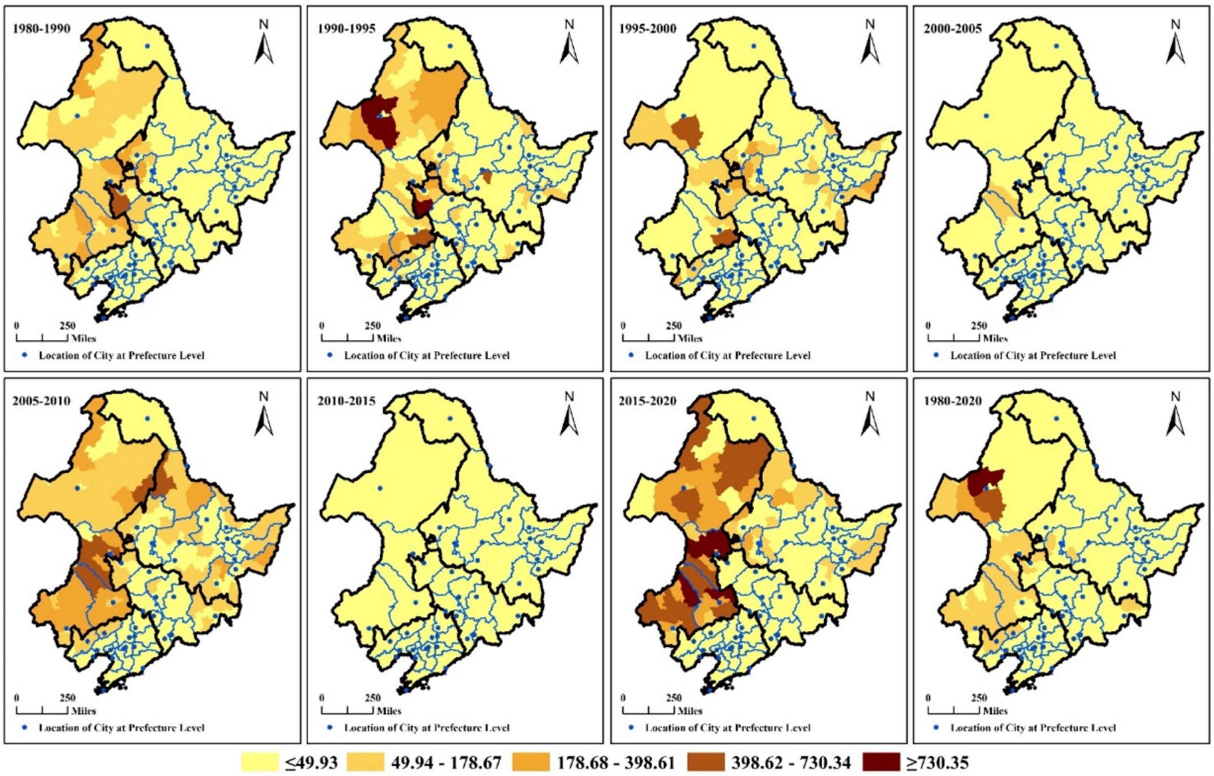

FIGURE 6
Spatial distribution of the areas of cropland converted into grassland (Unit: km^2).

8.11–12.30) of average slope in cropland were located in the areas around the Changbai Mountain Range from the geographical distribution, and in Mudanjiang, Heilongjiang Province, and Jilin, Baisan, Yanbian Korean Autonomous Prefecture, Jilin Province, and Fushun, Benxi, Dandong and Anshan, Liaoning Province, etc.

3.3.1 Spatiotemporal characteristics of altitude changes in cropland

Table 4 shows the average altitude change in cropland during 1980–2020. The average altitude of cropland in the black soil region of northeast China increased by 2.06 m, from 237.7656 m to 239.8277 m during 1980–2020. During the study period of 2015–2020, 1980–1990, and 2000–2005, the average altitude in cropland decreased, while in 1990–1995, 2005–2010, 1995–2000, and 2010–2015, the average altitude in cropland increased. The order of the change value of average altitude in cropland is as follows: 1990–1995 (3.21, 13.63‰), 2005–2010 (2.66, 11.10‰), 2015–2020 (−2.37, −9.80‰), 1980–1990 (−2.04, −8.60‰), 1995–2000 (0.67, 2.81‰), 2000–2005 (−0.09, −0.38‰), and 2010–2015 (0.03, 0.13‰).

Figure 11 displays the spatial distribution of average altitude changes in cropland, featuring three types of information: increase (red), decrease (green), and change value. The processing steps align with those used in Figure 4. During 1989–2020, as shown in Figure 11 (1980–2020), prefecture-level city locations and their surrounding areas exhibit a rising trend in the average altitude in cropland. Conversely, regions with a declining trend in the average altitude of cropland are predominantly found in Qiqihar, Suihua, and Jiamusi in Heilongjiang Province, as well as in Baisheng, Songyuan, Changchun, and the Yanbian Korean Autonomous Prefecture in Jilin Province. Additionally, some areas in Dandong, Liaoning Province, and eastern-central Chifeng, southwestern Tongliao, southwestern Xing'an League, and eastern and western Hulunbuir in Inner Mongolia demonstrate a decreasing trend. Furthermore, regions with an increasing trend (≥21.11) in the average altitude of cropland are located in parts of Heihe, Daxinganling, Yichun, and Mudanjiang in Heilongjiang Province, as well as portions of Baisan and the Yanbian Korean Autonomous Prefecture in Jilin Province. Additionally, central and western Hulunbeier, parts of Xing'an League in Inner Mongolia, and more areas show a rising trend. Conversely, areas with a decreasing trend (≥20.82) in the average altitude of cropland can be identified in parts of Chifeng and western Hulunbuir in Inner Mongolia, as well as parts of the Yanbian Korean Autonomous Prefecture in Jilin Province.

Figure 11 illustrates the numbers of regions with an increasing trend in the average altitude of cropland in Liaoning Province. These numbers exhibited a pattern of increase, followed by a decrease, then another increase. The spatial distribution demonstrated a trend of clustering with Shenyang at its center (1980–1990), expanding outward (1990–1995), followed by contraction (1990–2000 and 2000–2005), and later spreading to the southwest (2005–2010 and 2010–2015) and southeast (2015–2020).

In Jilin Province, Figure 11 reveals a similar pattern, with the numbers of regions showing an increasing trend in the average altitude of cropland following a sequence of increase, decrease, and another increase. These regions were predominantly located in most parts of Baicheng, Songyuan, Changchun, Siping, and Jilin (1980–1990), parts of each prefecture-level city (1990–2000), southwest parts

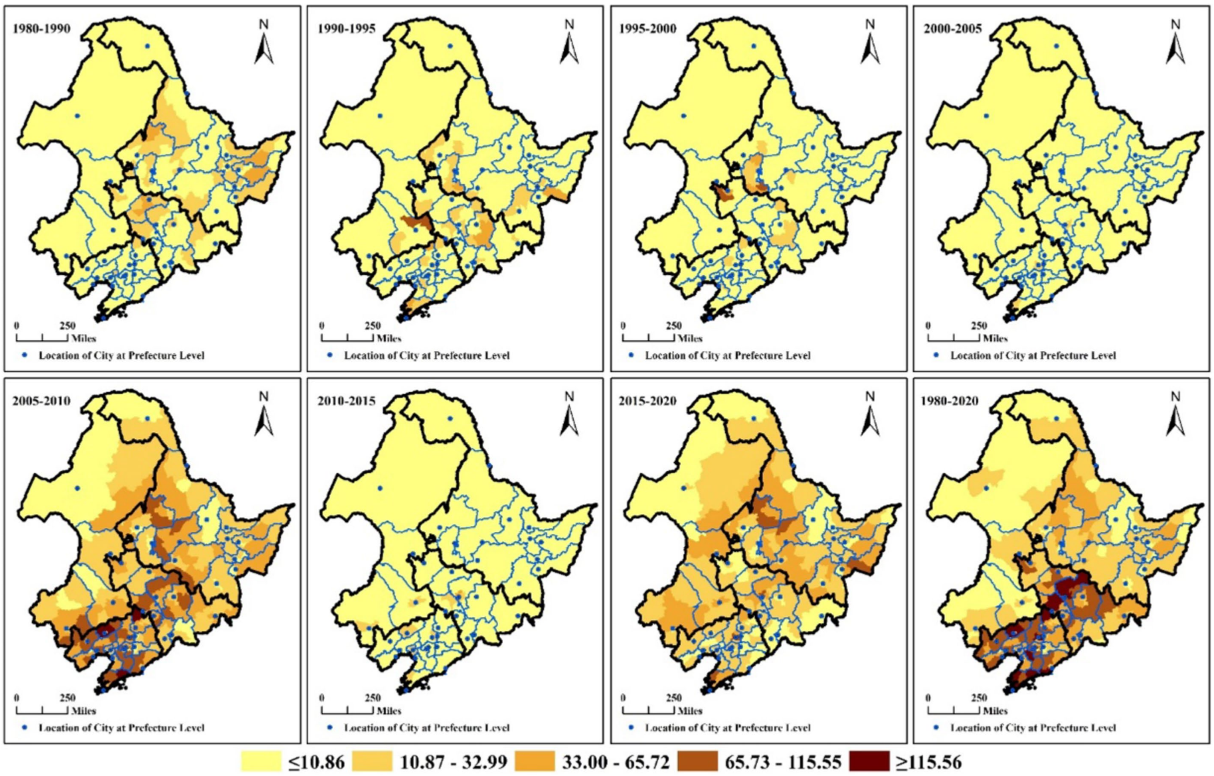

FIGURE 7
Spatial distribution of the areas of cropland converted into built-up land (Unit: km^2).

of Jilin Province (1995–2000), parts of Southeast Jilin Province (2000–2005), parts of Baicheng, Siping, Liaoyang, Tonghua, Baishan, the Yanbian Korean Autonomous Prefecture, and other regions (2005–2010), central Liaoning Province (2010–2015), and most of Jilin, Siping, and Liaoyuan (2015–2020).

In Heilongjiang Province, Figure 11 also displays a trend of increasing and decreasing in the numbers of regions with an increasing trend in the average altitude of cropland. These regions were primarily located in parts of southeastern Heilongjiang, Daxinganling, and Heihe (1980–1990), northwestern Heilongjiang, and parts of Daxinganling (1990–1995), parts of northwestern and eastern parts of Heilongjiang (1995–2000), parts of Heihe, Mudanjiang, Yichun, and Shuangyashan (2000–2005), Heihe and its surrounding regions, parts of Shuangyashan, Mudanjiang, and Jixi (2005–2010), Heihe and its surrounding areas, parts of Mudanjiang and Daxinganling (2010–2015), and parts of Daxinganling, Harbin, Mudanjiang, Yichun, and Hegang (2015–2020). In Inner Mongolia East Four Leagues, Figure 11 depicts a fluctuating pattern in the numbers of regions with an increasing trend in the average altitude of cropland, alternating between increase and decrease. These regions were primarily located in most of Hulunbeier (1990–1995, 2005–2010, 2010–2015), most of Xing'an League (1980–1990, 1995–2000, 2000–2005, 2005–2010), most of Tongliao (1995–2000, 2005–2010, 2010–2015), and most parts of Chifeng (1995–2000, 2010–2015, 2015–2020).

In each study period (Figure 11), the regions (≥21.11) exhibiting an increasing trend in the average altitude of cropland were located in various areas: parts of Heihe, Heilongjiang Province (1980–1990); parts of Daxinganling, Heihe, and Yichun, Heilongjiang Province, as well as parts of Hulunbeier and Chifeng, Inner Mongolia (1990–1995); parts of Hulunbeier, Inner Mongolia, parts of Daxinganling, Mudanjiang, Harbin, Heilongjiang Province (1995–2000); parts of Daxinganling, Heilongjiang Province, parts of Baishan, and the Yanbian Korean Autonomous Prefecture, Jilin Province, parts of Xing'an League and Chifeng, Inner Mongolia (2005–2010); and parts of Daxinganling and Yichun, Heilongjiang Province, parts of Chifeng, Inner Mongolia (2015–2020).

Additionally, the regions (≥20.81) displaying a decreasing trend in the average altitude of cropland were situated in the following areas: parts of Hulunbeier, Inner Mongolia (1980–1990); parts of Daxinganling, Heilongjiang Province, and parts of the Yanbian Korean Autonomous Prefecture, Jilin Province (1990–1995); parts of Hulunbeier, Inner Mongolia, parts of Yichun, and Harbin, Heilongjiang Province (1995–2000); parts of Daxinganling, Heilongjiang Province (2000–2005); part of Yichun, Heilongjiang Province, parts of Chifeng, Inner Mongolia, and parts of Huludao, Liaoning Province (2005–2010); and parts of Xing'an League and Chifeng, Inner Mongolia (2015–2020).

3.3.2 Spatiotemporal characteristics of slope changes in cropland

Table 5 shows the average slope change in cropland during 1980–2020. Over this period, the average slope of cropland in the black soil region of northeast China increased by 0.0369 degrees, from 2.4455 degrees to 2.4824 degrees. When categorized by study period, the average slope in cropland decreased during 1990–1995, 2015–2020, and 1980–1990, while it increased during 2005–2010, 1995–2000,

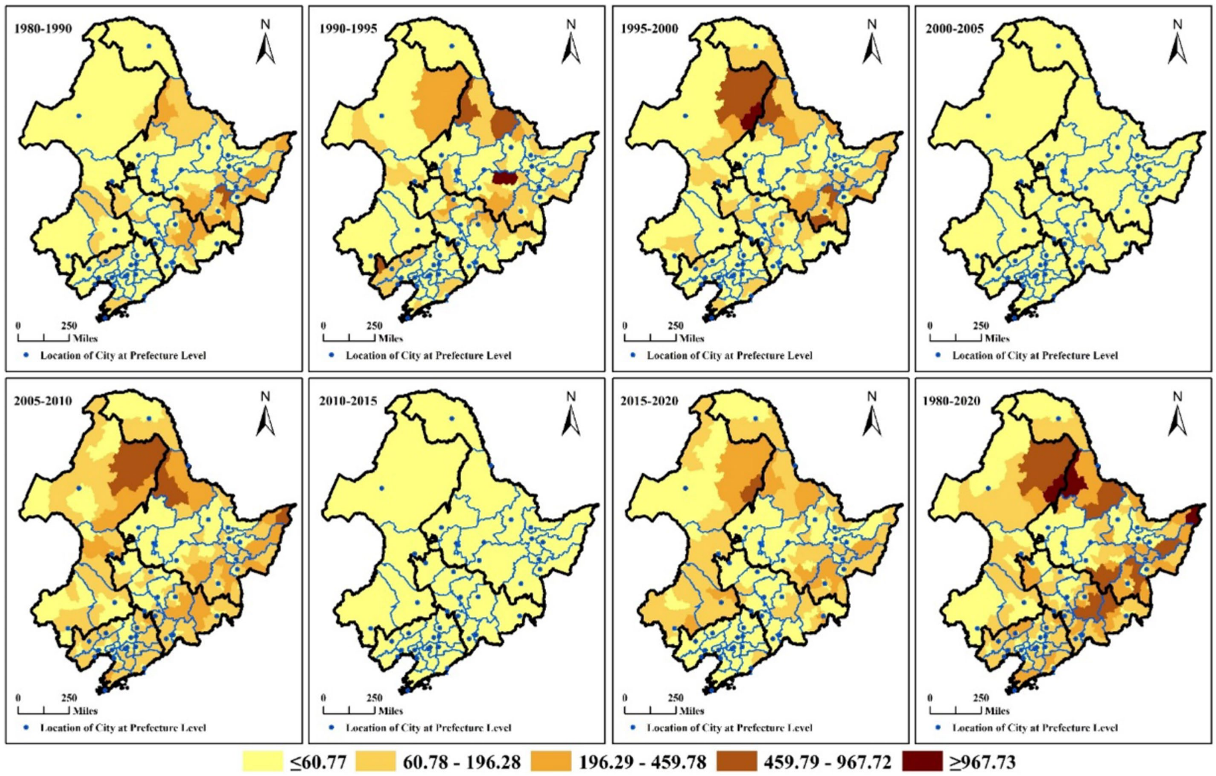

FIGURE 8
Spatial distribution of the areas of woodland converted into cropland (Unit: km^2).

2000–2005, and 2010–2015. The order of the change value in the average slope in cropland is as follows: 1990–1995 (0.1142, 46.53‰), 2005–2010 (0.0509, −20.26‰), 1995–2000 (0.0501, −19.52‰), 2015–2020 (0.0262, 10.67‰), 1980–1990 (0.0077, 3.15‰), 2000–2005 (0.0061, −2.43‰), and 2010–2015 (0.0041, −1.65‰).

Figure 12 illustrates the spatial distribution of average slope changes in cropland, incorporating three types of information: increase (in red), decrease (in green), and change value. The processing steps were consistent with those in Figure 4. During 1989–2020, as shown in Figure 12 (1980–2020), it highlights the locations of most prefecture-level city locations and their surrounding areas where the average slope in cropland exhibited an increasing trend. Conversely, regions with a decreasing trend in the average slope of cropland were identified in parts of Qiqihar, Daqing, Suihua, and Jiamusi in Heilongjiang Province, parts of Baishan, Songyuan, Changchun, Jilin, Baisan, and the Yanbian Korean Autonomous Prefecture in Jilin Province, parts of Chaoyang, Shenyang, Dandong, and Fushun in Liaoning Province, parts of Chifeng, Tongliao, Xing'an Meng, and Hulunbuir in Inner Mongolia. In addition, regions with an increasing trend (≥0.64) in the average slope of cropland were observed in parts of Yichun, Qitaihe, and Mudanjiang in Heilongjiang Province, parts of Hulunbeier in Inner Mongolia, and parts of Yingkou in Liaoning Province. Conversely, areas with a decreasing trend (≥0.53) in the average slope of cropland were situated in parts of Yanbian Korean Autonomous Prefecture, Baishan, and Tonghua in Jilin Province, parts of Chaoyang, Huludao, and Dandong in Liaoning Province, part of Yichun in Heilongjiang Province.

Figure 12 displays the numbers of regions with an increasing trend in the average slope of cropland in Liaoning Province. These numbers showed a pattern of increase, followed by a decrease, and then another increase. The regions were primarily located in most of Liaoning Province (1990–1995 and 2010–2015), the southeastern parts of central Liaoning Province (1995–2000), the central to northern and northwestern parts of Liaoning Province (2000–2005), Shenyang and its surrounding regions (1980–1990), Dalian (2005–2010), and the southwest of Liaoning Province (2010–2015).

In Jilin Province, Figure 12 reveals the numbers of regions with a decreasing trend in the average slope of cropland. These numbers followed a pattern of increase, then decrease, followed by another increase, and finally a decrease. These regions were predominantly located in most parts of Baishan, Tonghua, and the Yanbian Korean Autonomous Prefecture (1980–1990), parts of Baicheng, Songyuan, and Liaoyuan (1990–1995), most parts of Baicheng, Songyuan, Changchun, Jilin, Baishan, and Tonghua (1995–2000), most parts of Baicheng, and Siping (2000–2005), most parts of Siping, Changchun, Jilin, and the Yanbian Korean Autonomous Prefecture (2005–2010), most parts of Songyuan, Siping, Tonghua, Baisan, Jilin, and the Yanbian Korean Autonomous Prefecture (2010–2015), and parts of Changchun, Songyuan, and the Yanbian Korean Autonomous Prefecture (2015–2020).

In Heilongjiang Province Figure 12 depicts the numbers of regions with a decreasing trend in the average slope of cropland. This trend showed a pattern of decreasing, followed by an increase, and then another decrease. The regions were primarily located in parts of Qiqihar, Suihua, Daqing, Heyi, Yichun, Hegang, Daxinganling, and Jiamusi (1980–1990), parts of Daxinganling, Jiamusi, Shuangyashan, and Jixi, among others (1990–1995), parts

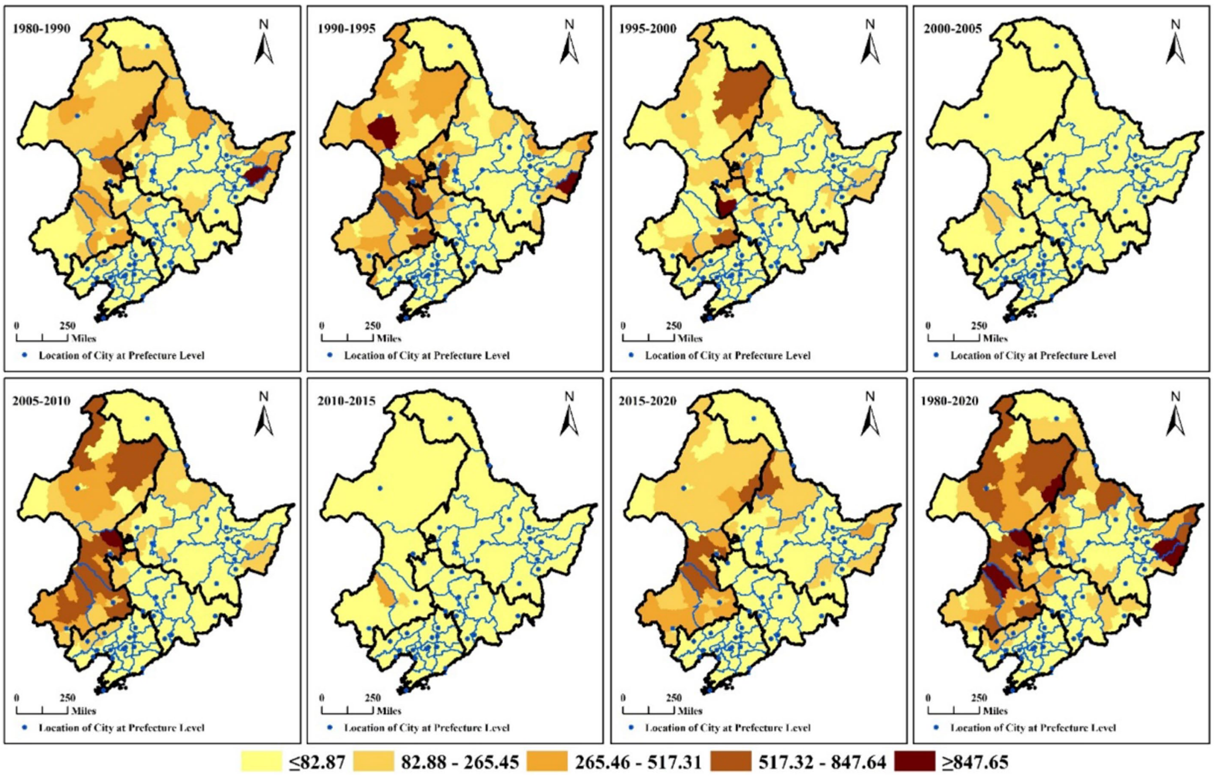

FIGURE 9
Spatial distribution of the areas of grassland converted into cropland (Unit: km²).

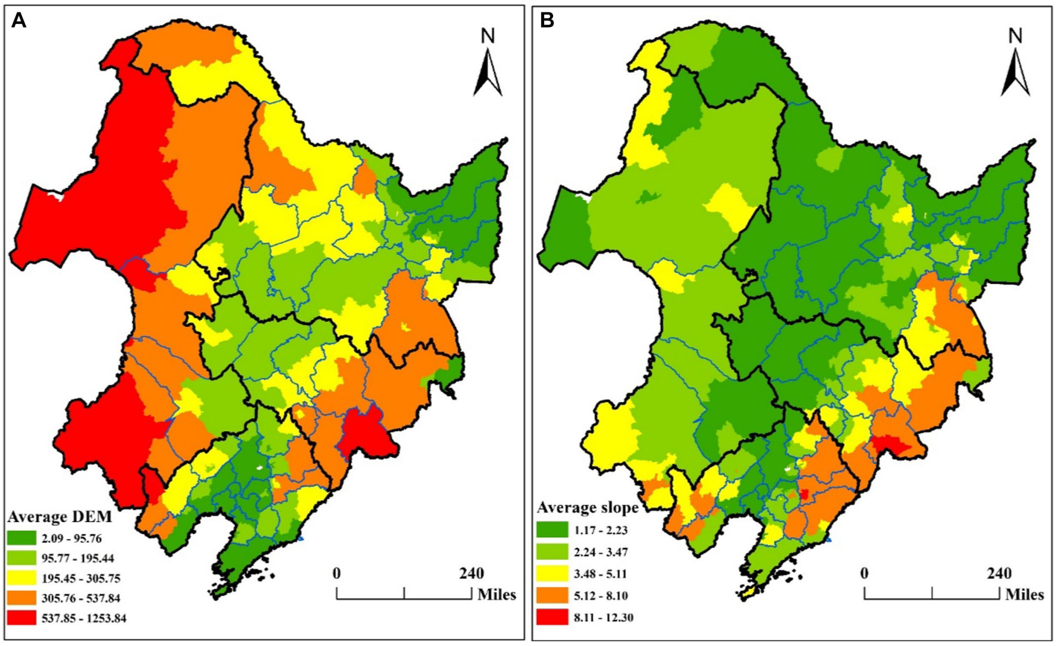

FIGURE 10
Spatial distribution of average altitude and average slope in cropland (Unit: m, degree). **(A)** shows the spatial distribution of mean elevation. **(B)** shows the spatial distribution of mean slope.

of Qiqihar, Daqing, Suihua, Jiamusi, Yichun, and Jixi (1995–2000), most parts of Harbin, Jiamusi, Qiqihar, and Suihua (2000–2005), Harbin and most of its surrounding regions (2005–2010), and most parts of Daxinganling, Heihe, Harbin, Mudanjiang, Jixi, and Shuangyashan (2010–2015), and most parts of Daxinganling, Heihe, Jixi, Shuangyashan, and Jiamusi (2015–2020).

TABLE 4 The average altitude change in cropland during 1980–2020.

Year	Average altitude(m)	Period	Change value (m)	Period	Change ratio (‰)
1980	237.7656	1980–1990	−2.04	1980–1990	−8.60‰
1990	235.7216	1990–1995	3.21	1990–1995	13.63‰
1995	238.9334	1995–2000	0.67	1995–2000	2.81‰
2000	239.6047	2000–2005	−0.09	2000–2005	−0.38‰
2005	239.5128	2005–2010	2.66	2005–2010	11.10‰
2010	242.1705	2010–2015	0.03	2010–2015	0.13‰
2015	242.2016	2015–2020	−2.37	2015–2020	−9.80‰
2020	239.8277	1980–2020	2.06	1980–2020	8.67‰

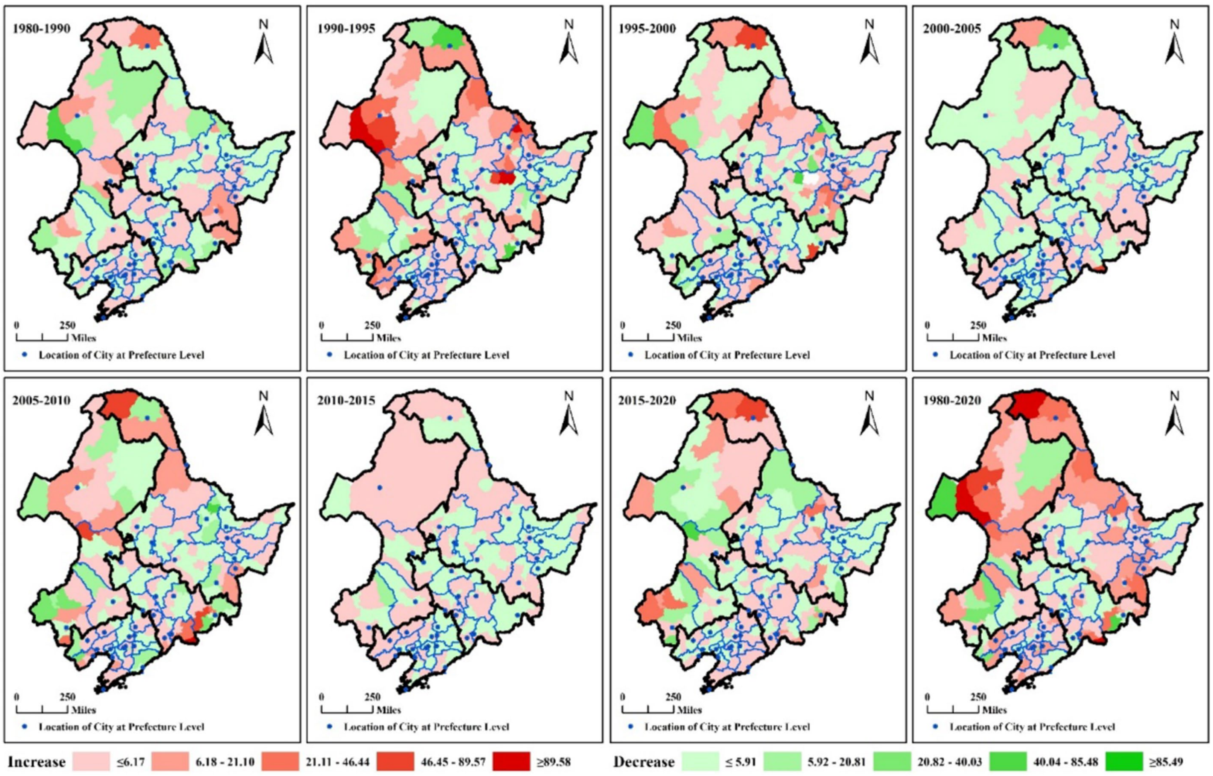

FIGURE 11
Spatial distribution of the average altitude changes in cropland (Unit: m). Red indicates an increase in the average altitude changes in cropland, and red indicates a decrease in the average altitude changes in cropland.

In Figure 12, the numbers of regions with an increasing trend in the average slope of cropland in Inner Mongolia East Four Leagues are presented. This trend displayed a pattern of both increasing and decreasing. The regions were primarily located in most parts of Hulunbuir (1990–1995 and 2005–2010), parts of Xing'an League (1990–1995, 1995–2000, and 2015–2020), parts of Tongliao (1990–1995 and 2015–2020), and parts of Chifeng (1995–2000, 2000–2005, and 2015–2020).

In each study period (Figure 12), the regions (≥0.64) with an increasing trend in the average slope of cropland were situated in various areas: parts of Mudanjiang in Heilongjiang Province (1980–1990), parts of Harbin and Yichun in Heilongjiang Province, parts of Hulunbeier in Inner Mongolia, parts of Chaoyang and Huludao in Liaoning Province (1990–1995), parts of Yichun and Mudanjiang in Heilongjiang Province (1995–2000), parts of Daxinganling in Heilongjiang Province, parts of Hulunbuir in Inner Mongolia (2005–2010), and parts of Daxinganling, Yichun, and Mudanjiang in Heilongjiang Province (2015–2020). Additionally, the regions (≥0.64) with a decreasing trend in the average slope of cropland were found in various areas: parts of Hulunbeier in Inner Mongolia (1980–1990), parts of Yichun and Mudanjiang in Heilongjiang Province (1990–1995), parts of Hulunbeier in Inner Mongolia, parts of Yichun and Harbin in Heilongjiang Province (1995–2000), parts of Yichun and Mudanjiang in Heilongjiang Province, parts of Baisan and the Yanbian Korean Autonomous Prefecture in Jilin Province, parts of Dandong, Chaoyang, and Huludao in Liaoning Province (2005–2010), and parts of Daxinganling in Heilongjiang Province, parts of Hulunbuir in Inner Mongolia (2015–2020).

TABLE 5 The average slope change in cropland during 1980–2020.

Year	Average slope (Degree)	Period	Change value (Degree)	Period	Change ratio (‰)
1980	2.4455	1980–1990	0.0077	1980–1990	3.15‰
1990	2.4532	1990–1995	0.1142	1990–1995	46.53‰
1995	2.5674	1995–2000	−0.0501	1995–2000	−19.52‰
2000	2.5172	2000–2005	−0.0061	2000–2005	−2.43‰
2005	2.5111	2005–2010	−0.0509	2005–2010	−20.26‰
2010	2.4602	2010–2015	−0.0041	2010–2015	−1.65‰
2015	2.4562	2015–2020	0.0262	2015–2020	10.67‰
2020	2.4824	1980–2020	0.0369	1980–2020	15.08‰

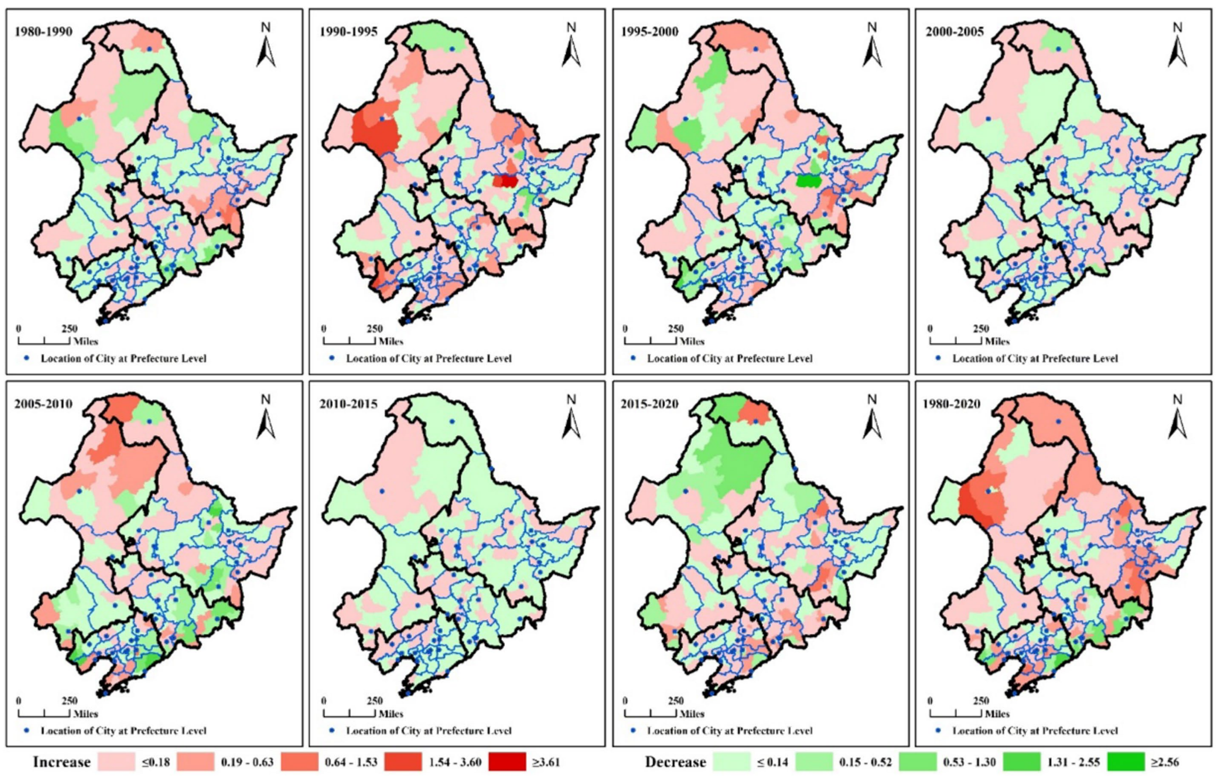

FIGURE 12
Spatial distribution of the average slope changes in cropland (Unit: degree). Red indicates an increase in the average slope changes in cropland, and red indicates a decrease in the average slope changes in cropland.

3.4 Spatiotemporal characteristics of landscape changes in cropland

Table 6 shows the results of the calculation of PLAND, LSI, LPI, DIVISION, and CLUMPY index, and Table 7 shows their change value. During 1980–2020, Tables 6, 7 show the PLAND, LSI, LPI, and CLUMPY index increased, the PLAND index from 25.70 to 29.87%, increased 4.17%, LSI index from 510.52 to 518.91, increased 8.39, LPI index from 5.84 to 6.78%, increased 0.94%, and CLUMPY index from 0.8908 to 0.8909, increased by 0.0001. The changes in the above four indexes indicated the cropland proportion, predominance, and aggregation increased, and the cropland shape became more irregular. The DIVISION index decreased (Tables 6, 7), from 0.9957 to 0.9938, and decreased by 0.0019, indicating the cropland subdivision decreased during 1980–2020.

As shown in Tables 6, 7. The cropland proportion in 2015 was the largest, with a proportion of 30.06, and changed significantly during 1990–1995, 1980–1990, and 1995–2000. The cropland shape in 2010 was the most irregular, with several 524.99, and became more irregular significantly during 2005–2010, and in 1990 was more regular than other years, with several 480.56, and became more irregular significantly during 1980–1990. The cropland predominance in 2005 was the largest, with a percentage of 7.81, and increased significantly during 1995–2000, and 2015–2020, and 1995 was the smallest, with a percentage of 5.63, and decreased significantly during 2005–2010. The DIVISION index was close to 1 each year, indicating the cropland

TABLE 6 The results of the calculation of landscape metrics in cropland during 1980–2020.

Year	PLAND (%)	LSI (None)	LPI (%)	DIVISION (Proportion)	CLUMPY (Proportion)
1980	25.70	510.52	5.84	0.9957	0.8908
1990	27.02	480.56	5.81	0.9956	0.8979
1995	28.79	481.60	5.63	0.9954	0.8985
2000	29.76	490.59	7.24	0.9935	0.8968
2005	29.90	498.57	7.81	0.9925	0.8952
2010	29.98	524.99	5.57	0.9957	0.8897
2015	30.06	522.06	5.58	0.9957	0.8903
2020	29.87	518.91	6.78	0.9938	0.8909

TABLE 7 The change value of the landscape metrics in cropland during 1980–2020.

Period	PLAND	LSI	LPI	DIVISION	CLUMPY
1980–1990	1.32	−29.97	−0.02	−0.0001	0.0071
1990–1995	1.78	1.04	−0.18	−0.0002	0.0006
1995–2000	0.97	8.99	1.61	−0.0019	−0.0017
2000–2005	0.14	7.99	0.57	−0.0010	−0.0016
2005–2010	0.08	26.42	−2.23	0.0032	−0.0055
2010–2015	0.08	−2.94	0.00	0.0000	0.0006
2015–2020	−0.19	−3.15	1.20	−0.0019	0.0006
1980–2020	4.17	8.39	0.94	−0.0019	0.0001

subdivision was obvious. The CLUMPY index was close to 1 each year, indicating the distribution of cropland was aggregated.

Figure 13 shows Spatial distribution of average PLAND, LSI, LPI, DIVISION, and CLUMPY index in cropland. As shown in Figure 13A, the regions (≥29.00) with a high proportion of cropland were located in Sanjiang Plain, Songnen Plain, and Liaohe Plain. Figure 13B shows the regions (≥31.15) with more irregular of cropland shape were located in Liaoning Province except for the central region, most parts of Jilin Province, most parts of the four eastern leagues of Inner Mongolia, and most parts of Daxinganling, Heihe, Harbin, Mudanjiang, Jixi, Shuangyashan, Jiamusi, Heilongjiang Province, etc. Figure 13C shows the regions (≥25.69) with a high predominance of cropland were located in parts of Qiqihar, Suihua, Harbin, Jiamusi, and Hegang, Heilongjiang Province, and parts of Songyuan, Changchun, and Siping, Jilin Province, and parts of Tieling, Fuxin, Shenyang, Jinzhou, and Liaoyang, Liaoning Province, etc. Figure 13D shows the regions (≤0.69) with a low subdivision of cropland were located in Suihua and its surrounding regions, Heilongjiang Province, and Changchun, Siping, Jilin Province, and parts of Tieling, Shenyang, and Jinzhou, Liaoning Province, etc. Figure 13E shows the regions (≤0.91) with a low subdivision of cropland were located in most parts of Siping and Liaoyuan, Jilin Province, and parts of Tieling, Fushun, Liaoning Province, etc.

3.4.1 Spatiotemporal characteristics of changes in PLAND, LSI, LPI, DIVISION, and CLUMPY index

During 1980–2020. As illustrated in Figure 14 (PLAND), spatial clusters representing an increased proportion (hot spots) of cropland were primarily located in the Sanjiang Plain, as well as in parts of Hulunbeier, Heihe, Qiqihar, and Baicheng. Conversely, spatial clusters indicating a decreased proportion (cold spots) of cropland were mainly found in Liaoning Province, and in parts of Siping, Liaoyuan, Changchun, and Songyuan in Jilin Province. As indicated in Figure 14 (LSI), spatial clusters of regions with irregular cropland shapes (hot spots) were identified in parts of Yichun, Daqing, and Harbin in Heilongjiang Province, as well as in parts of Songyuan in Jilin Province and most areas of Fuxin in Liaoning Province. Conversely, spatial clusters of regions with regular cropland shapes (cold spots) were found in parts of Harbin and Mudanjiang in Heilongjiang Province, as well as in parts of Jilin in Jilin Province. As illustrated in Figure 14 (LPI), the spatial clusters indicating the predominance (hot spots) of cropland increased and were primarily located in the Sanjiang Plain. Concurrently, spatial clusters indicating the predominance (cold spots) of cropland decreased and were found in Liaoning Province, along with parts of Siping in Jilin Province. As depicted in Figure 14 (DIVISION), the spatial clusters of increased cropland subdivision (hot spots) were primarily situated in most parts of Liaoning Province, along with parts of Songyuan and Siping in Jilin Province. Simultaneously, the spatial clusters indicating a decreased cropland subdivision (cold spots) were primarily located in the Sanjiang Plain. As shown in Figure 14 (CLUMPY), the spatial clusters of increased cropland aggregation (hot spots) were mainly located in parts of Changchun, Jilin, Jilin Province. Simultaneously, the spatial clusters indicating decreased cropland aggregation (cold spots) were primarily situated in most parts of Liaoning Province.

4 Discussion

4.1 Driving mechanisms

The black soil area of northeast China is the most fertile in China and important for China's food security. The Chinese government has

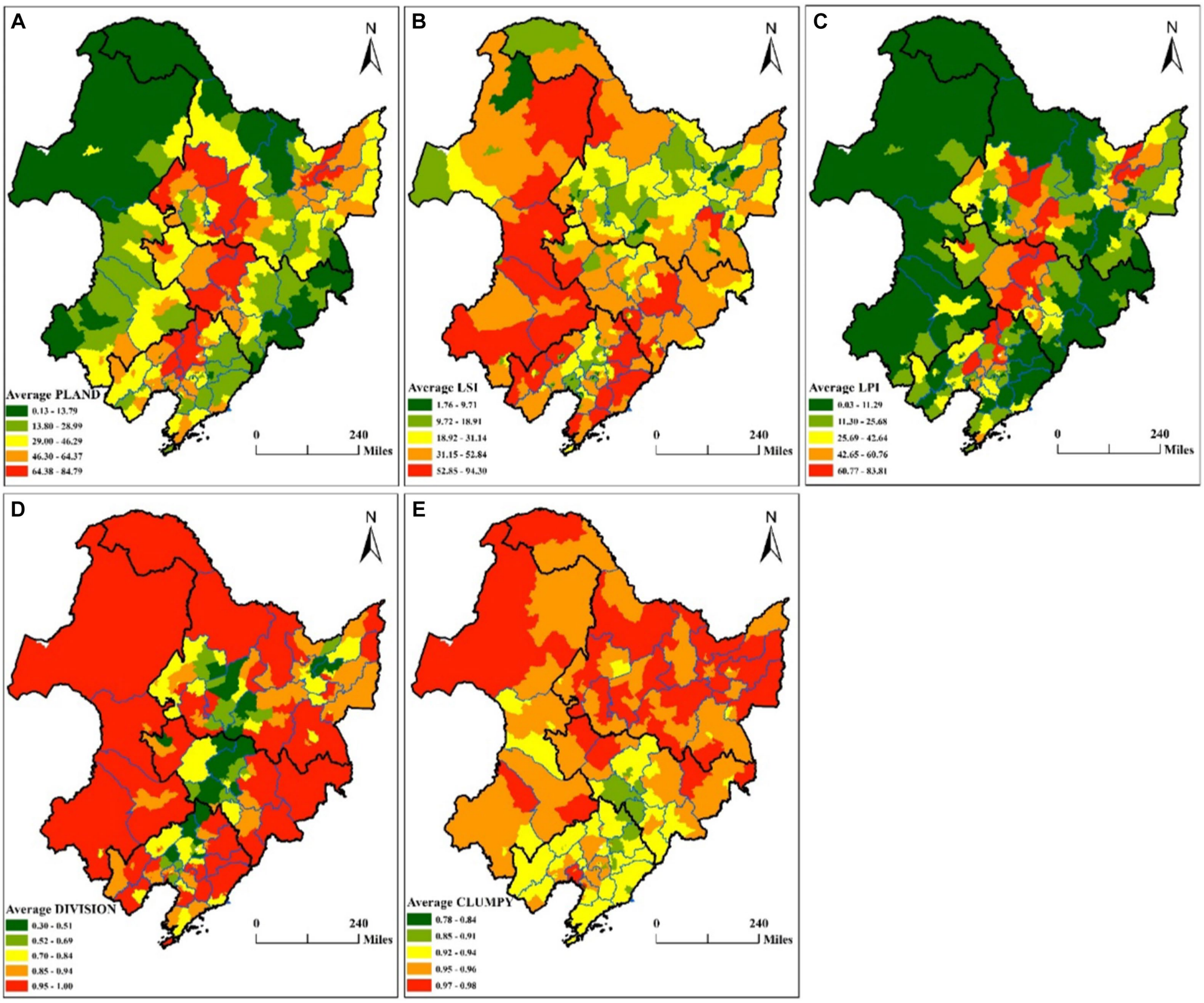

FIGURE 13
Spatial distribution of **(A–E)** denote average PLAND, LSI, LPI, DIVISION, and CLUMPY index (Unit: %, None, %, Proportion, Proportion).

enacted the Black Soil Protection Law of the People's Republic of China to protect the black soil in the black soil area of northeastern China. This paper uses remote sensing data to analyze the characteristics of cropland changes in the black soil area of northeast China more systematically and comprehensively.

Figure 3 and Table 2 present the cropland area in the black soil area of northeastern China, which increased from 319,480.75 km^2 in 1980 to 371,457.51 km^2 in 2020, marking a growth of 51,976.76 km^2. The regions that experienced cropland expansion were primarily the Sanjiang Plain in Heilongjiang Province and the Hulunbuir region in Inner Mongolia, bordering Heilongjiang Province. This cropland expansion occurred mainly during the periods of 1980–1990, 1990–1995, and 1995–2000. One of the significant factors driving this expansion was the increased demand for cropland resulting from population growth (Liu et al., 2017; You et al., 2021). According to population data from the statistical yearbook, the total population of Heilongjiang increased from 32.038 million in 1980 to 38.33 million in 2010, and then decreased to 31.71 million in 2020. The total population of Jilin increased from 22.107 million in 1980 to 27.238 million in 2010, and then decreased to 25.771 million in 2020. The total population of Liaoning increased from 34.869 million in 1980 to 42.517 million in 2010 and then decreased to 41.659 million in 2020. With the advancement of industrialization and urbanization, the Northeast no longer serves as the center of gravity for national economic development (Xiong, 2016; Tan et al., 2017). In response, the role of ensuring food security has become increasingly important, with policy factors playing a significant role, particularly after 2000. In September 2023, Chinese President Xi Jinping, during a speech in Harbin, put forth that ensuring stable grain production and supply is the primary task for the Northeast region.

This shift is exemplified by the Northeast Revitalization Plan, which, in 2007, designated Northeast China as a national important commodity grain and agricultural and livestock production base. Furthermore, the 14th Five-Year Plan for the Comprehensive Revitalization of Northeast China has underscored the importance of food security as one of the region's key goals. Figure 4 (1980–2020) illustrates a decrease in cropland in and around prefecture-level city locations, accompanied by an increase in areas far from prefecture-level city locations. This phenomenon arises from the inherent conflict between cropland protection and local interests. Land conversion from agriculture to construction is a key strategy employed by local governments to attract investment and boost fiscal revenue (Shen

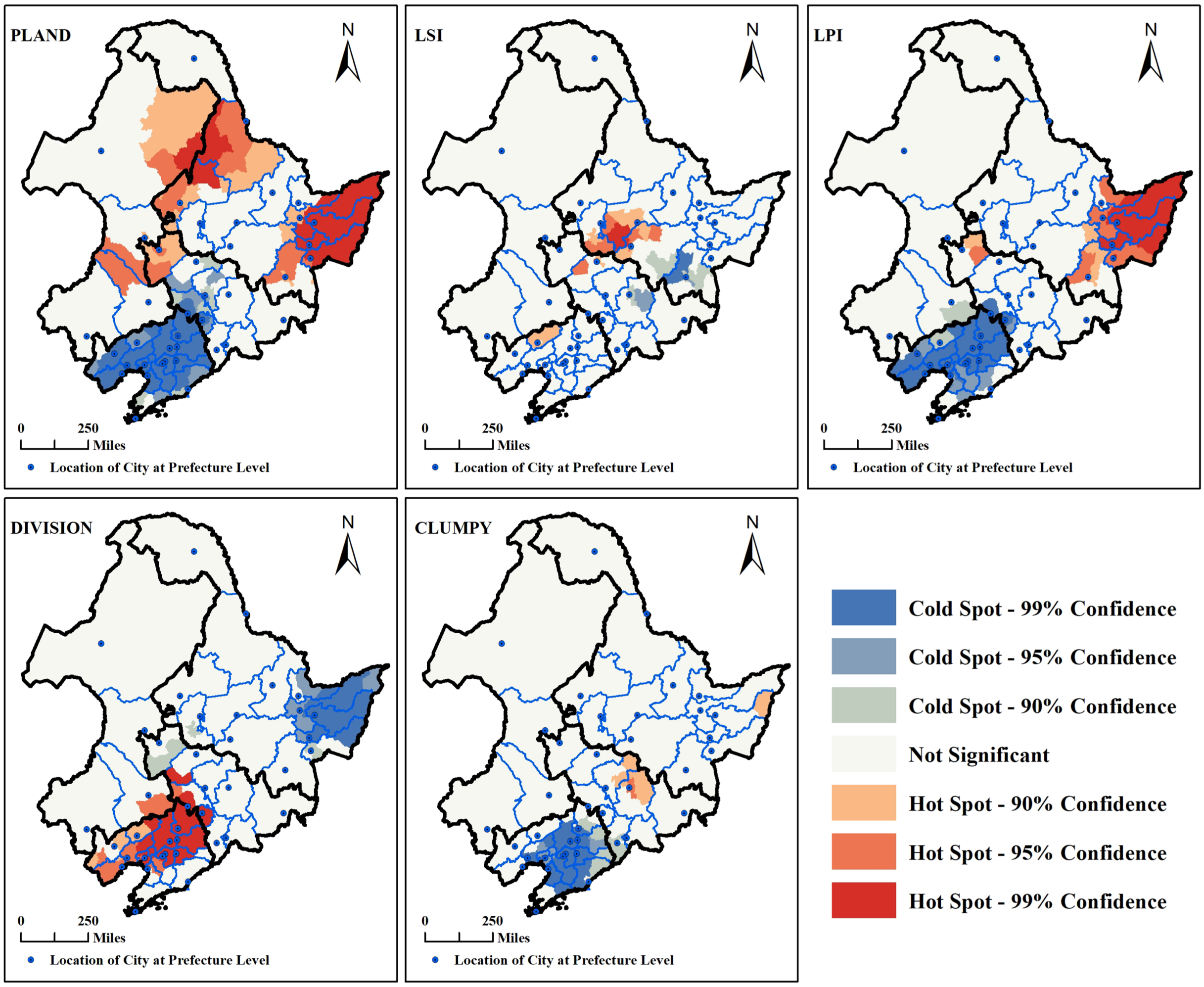

FIGURE 14
Hot spot analysis of changes in PLAND, LSI, LPI, DIVISION, and CLUMPY index during 1980–2020 (Unit: %, None, %, Proportion, Proportion).

et al., 2017). Figure 7 highlights a significant conflict between cropland protection and local interests, particularly in Liaoning and Jilin Province after 2005. One contributing factor to this conflict is the advantage offered by economic development opportunities (Chen et al., 2018).

During the period from 1980 to 2020, as shown in Table 3, cropland primarily resulted from the conversion of woodland and grassland, although there were instances of cropland being converted back to woodland and grassland. Regions where woodland was converted into cropland were mainly concentrated near the Changbai Mountain Range, the Sanjiang Plain, and areas bordering Heihe, Hulunbuir, and Qiqihar (see Figure 8). The conversion of grassland into cropland was primarily observed in Hulunbeier, Xing'an League, Tongliao City, parts of Chifeng in Inner Mongolia, and the Sanjiang Plain in Heilongjiang Province (see Figure 9). The substantial increase in cropland in Heilongjiang province contributes significantly to its status as the highest grain-producing province in China in recent years. After 2000, the implementation of policies promoting the return of cropland to grassland and woodland resulted in regions where cropland was converted into woodland (as shown in Figure 5) (Shen et al., 2021; Ma et al., 2022). Additionally, areas where cropland was converted into grassland were primarily situated in the East Four Leagues of Inner Mongolia (as depicted in Figure 6). The conversion of a significant amount of woodland and grassland to cropland has multifaceted implications for the environment, biodiversity, and sustainable land use. While expanding cropland can contribute to increased food production, it often comes at the expense of natural ecosystems. The loss of woodland and grassland can lead to habitat destruction, affecting various plant and animal species. Additionally, the conversion process may contribute to soil erosion, reduced water quality, and increased greenhouse gas emissions, further impacting the overall ecological balance. Moreover, the conversion of diverse ecosystems into monoculture cropland might result in decreased resilience to pests and diseases, potentially necessitating increased reliance on pesticides and fertilizers. Striking a harmonious balance between agricultural development and environmental preservation is essential for achieving long-term sustainability and securing food resources for growing populations.

As shown in Tables 4, 5, during the period from 1980 to 2020 in the black soil region of northeast China, the average altitude and slope of cropland increased by 2.06 m, from 237.7656 to 239.8277 m, and the average slope of cropland increased by 0.0369 degrees, from 2.4455 degrees to 2.4824 degrees. Notably, this trend was observed in provincial capitals and prefecture-level municipalities responsible for economic development. Urbanization in China has led to the relocation of farmland to higher elevations due to the constraints imposed by the requisition–compensation balance (Chen et al., 2022). In the implementation process, the dynamic balance system has replaced the basic farmland protection system. This shift has resulted in an increased conversion of high-quality cropland into industrial and residential uses, supplemented by low-quality cropland, consequently diminishing the quality of protected land Furthermore, under the policy of 'linking the increase in urban construction land with a decrease in rural construction land,' much of the compensatory farmland provided after land exploitation has been deemed inefficient, unreasonable, and unstable (Liu et al., 2019). The elevation and slope of cropland are pivotal factors shaping the agricultural landscape, and any increase in these elements inevitably has a substantial impact on cropland productivity. As cropland ascends to higher elevations or becomes steeper in slope, a myriad of challenges emerges, affecting agricultural practices and food production. Managing irrigation becomes more complex, soil erosion risk rises, and susceptibility to extreme weather events increases.

The evolving landscape patterns of cropland carry significant implications for the modernization and mechanization of agriculture. The shift toward mechanized and modernized agricultural production is a prominent trend, especially in the context of ongoing urbanization, industrialization, and the reduction of the agricultural population. Understanding these alterations in the cropland landscape is vital to facilitate a smooth transition toward efficient and sustainable agricultural practices. The PLAND, LSI, LPI, DIVISION, and CLUMPY landscape metrics were employed to analyze changes in landscape proportion, shape, predominance, subdivision, and aggregation in cropland. With the increasing influence of human activities in the black soil area of northeast China from 1980 to 2020, the landscape pattern of cultivated land underwent significant transformations. Cropland proportion, predominance, and aggregation increased, while the shape of cropland became more irregular. However, the subdivision of cropland decreased insignificantly (see Table 6). Given the changes in the landscape use of cropland discussed above, we observe a gradual strengthening of the food production function in the northeastern black soil area, signifying a critical contribution to China's food security. The cultivated land in this region is concentrated and continuous, facilitating mechanized operations. This concentration also accelerates the pace of modernization in agricultural production mechanization.

From 1980 to 2020, as depicted in Figure 14, it becomes evident that the changes in cropland proportion, predominance, subdivision, and aggregation were primarily concentrated in the Sanjiang Plain and Liaoning Province. These observations highlight the significant impact of human activities in these regions. Liaoning Province was the main region where cropland converted into built-up land, including urban development and industrial use. In contrast, the Sanjiang Plain experienced substantial growth in cropland. Cropland in Liaoning Province was repurposed for higher-yield uses, such as urban construction and industrial zones. Due to various factors, the Sanjiang Plain's economic development potential for higher yields is limited, and it primarily maintains a focus on agricultural development, establishing itself as a vital grain-producing region for the country.

In summary, the changes in China's cropland are primarily influenced by natural resource endowment, population growth, and food security policies. Firstly, the Northeast Black Soil Region is endowed with abundant land resources, fertile soil, ample water resources, and relatively flat terrain. The early growth of cropland in this region was driven by its strong land resource endowment and population growth. Due to the relatively low returns from agricultural production, particularly with the negative impact of urbanization and industrial development on agriculture, a majority of people are reluctant to engage in agricultural activities. The outflow of rural population and the conversion of substantial high-quality cropland into construction land have prompted the Chinese government to place greater emphasis on ensuring food security, leading to the successive implementation of cropland protection policies such as the Basic Farmland System and the balance of cropland occupation and compensation.

4.2 Recommendations

Based on these findings, the following are policy recommendations for the protection of cropland in the black soil region of northeast China. Scientific zoning of cropland for grain production. In particular, cropland is located in Sanjiang Plain, Songnen Plain, and Liaohe Plain, as it is flat and fertile and easy to realize mechanized farming, especially in the context of modern agricultural production. Naturally, cropland designated for food production should be located at appropriate altitudes and slopes, and any tendency to shift cropland to higher altitudes and steeper slopes should be controlled. In this paper, it was observed that the configuration of cropland is becoming increasingly complex, which hinders mechanization. Therefore, there is a need for careful consideration of land shape when delineating areas for grain production to facilitate mechanization. This is especially crucial given the growing scarcity of human resources in agriculture. The study also discovered that cultivated land is becoming fragmented, which somewhat hinders mechanized operations. Therefore, it is necessary to implement measures to prevent the fragmentation of cultivated land. The real-time monitoring of cropland changes (The violation of cropland protection) using remote sensing in cropland for grain production. With the advancement of remote sensing technology, high-resolution image capture becomes easy and provides an objective check of cropland changes. Changes in the regions of cropland for grain production need to be monitored in a focused manner.

5 Limitations and future work

We conducted an in-depth analysis of the spatiotemporal evolution characteristics of cropland in the Northeast Black Soil Region at the county level from 1980 to 2020. This analysis included the spatiotemporal evolution features of cropland's altitude and slope, as well as the spatiotemporal evolution features of the landscape pattern of cropland. This study provides a comprehensive understanding of the changes in cropland in the Northeast Black Soil Region under the influence of human activities, offering scientific references for land management and cropland protection in this region. However, this research has some limitations. Firstly, it is constrained by the accuracy of remote sensing data. Secondly, the methods employed may not fully capture the changing situation of cropland. Thirdly, there is a lack of quantitative analysis of driving mechanisms. Our future work will focus on constructing a theoretical framework for the changes in cropland in this region and quantitatively analyzing the driving mechanisms.

6 Conclusion

In this paper, we focus on Northeast China, which represents the world's third-largest black soil region. At the county scale, we analyzed nearly 40 years of land use/cover maps from 1980, 1990, 1995, 2000, 2005, 2010, 2015, and 2020, with a cell size of 30 m × 30 m. Our analysis employed mathematical statistics, GIS spatial analysis, land use transition matrix, landscape pattern analysis, and hot spot analysis methods to examine the spatiotemporal evolutionary characteristics of cropland quantity, spatial distribution, conversion patterns, altitude, slope, and landscape pattern within the Northeast China black soil region. The primary findings of this study are as follows:

1 During 1980–2020. The cropland area increased from 319,480.75 km^2 to 371,457.51 km^2, an increase by 51,976.76km^2. Within the prefecture-level city, the trend of decreasing the amount of cropland in and around the prefecture-level city locations, and the trend of increasing the amount of cropland was in regions far from the prefecture-level city locations.
2 During 1980–2020. Cropland was mainly derived from woodland, grassland, and unused land, with areas of 32230.00 km^2, 31945.30 km^2, and 15421.20 km^2, and cropland mainly converted into woodland, built-up land, and grassland, with areas of 11906.62 km^2, 10809.33 km^2, and 6406.81 km^2.
3 During 1980–2020. The average altitude of cropland in the black soil region of northeast China increased by 2.06 m, from 237.7656 m to 239.8277 m. The average slope of cropland in the black soil region of northeast China increased by 0.0369 degree, from 2.4455 degree to 2.4824 degree. The prefecture-level city locations and their surrounding areas where the average altitude and slope in cropland was an increasing trend.
4 During 1980–2020. Cropland in the black soil region of northeast China proportion, predominance, and aggregation increased, and the cropland shape became more irregular, and the cropland subdivision decreased.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

JH: Data curation, Formal analysis, Funding acquisition, Project administration, Supervision, Writing – review & editing. DR: Data curation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. DT: Data curation, Writing – review & editing. XL: Data curation, Writing – review & editing.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. This paper is supported by the Research Fund of Renmin University of China (Fundamental Research Funds of Central Universities) under the project "Research on the Construction of Urban–Rural Unified Construction Land Market and Benefit Distribution Relationship Based on Land Development Right" (Grant no. 20XNL005).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 02 February 2024
DOI 10.3389/fsufs.2024.1229381

OPEN ACCESS

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RECEIVED 26 May 2023
ACCEPTED 08 January 2024
PUBLISHED 02 February 2024

CITATION
Ding Z, Zhang Q and Tang Y (2024) Nexus between farmland transfer, agricultural loans, and grain production: empirical evidence from China.
Front. Sustain. Food Syst. 8:1229381.
doi: 10.3389/fsufs.2024.1229381

Nexus between farmland transfer, agricultural loans, and grain production: empirical evidence from China

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Introduction: Food production stands as a critical global concern necessitating comprehensive investigation. This study utilizes provincial-level data from China to explore the intricate relationships between farmland transfer, agricultural loans, and grain production, with the aim of shedding light on the complexities of these dynamics.

Methods: A two-way fixed effects model and instrumental variable approach are applied to assess the interplay between farmland transfer, agricultural loans, and grain production. These methods provide a robust framework for understanding the complex relationships among these variables.

Results and discussion: The study reveals a notable positive correlation between farmland transfer and grain production. Conversely, agricultural loans demonstrate a significantly negative impact on grain production. However, the positive interaction term between farmland transfer and agricultural loans suggests a nuanced relationship. While profit-driven financial activities may not inherently favor grain production, they contribute to more efficient utilization of farmland resources, ultimately promoting grain production. The findings underscore the significance of continued government support for rural land system reform and active guidance of farmland transfer. It is emphasized that a moderate-scale operation of farmland is crucial for finance to play a lubricating and catalytic role. Furthermore, there is a need to guide agricultural finance towards investing in medium and long-term projects of agricultural production. Attention is also directed to preventing potential food crises arising from the phenomenon of "non- farming" associated with agricultural loans.

KEYWORDS

farmland transfer, agricultural loans, grain production, non-farming, China

1 Introduction

The market-oriented economic reforms implemented in China have resulted in a significant increase in agricultural production and the income levels of rural residents. Indeed, over the period 1980 to 2020, China's total grain output and *per capita* income of farmers have risen from 320.56 million tons and 216 yuan to 669.49 million tons and 17,132 yuan, respectively.[1] The income and agricultural output of farmers are largely determined by the impact of their livelihood activities, in

1 Data was compiled from China Statistical Yearbook.

which farmland transfer and agricultural production are two critical activities.

Farmland is the primary input required for agriculture, playing a vital role in food security, ecosystems, and the living standards of farmers (Fei et al., 2021). To optimize farmland and other resources such as capital and labor, bounded rational farmers will allocate farmland and resources from production sectors with lower marginal productivity to sectors with higher marginal productivity through appropriate land transfers, thereby addressing inefficiencies arising from farmland fragmentation and enhancing farm productivity and income (Berry, 1972; Barrett, 1996). Factors such as industrialization and urbanization (Liu et al., 2018), land finance system (Sippel et al., 2017) and labor migration (Gao et al., 2020), may lead to land transfer out of agriculture. On the other hand, the development of "appropriate-scale" farming (Rogers et al., 2021), farmland protection system (Li et al., 2021), and agricultural incentive policies (Lin and Huang, 2021) tend to promote the transfer of land into agriculture or within the agricultural sector. A well-functioning land market is critical, not only for non-agricultural growth but also for efficiently reallocating idle land resources (Jin and Deininger, 2009; Leimer et al., 2022). In addition, clear farmland property rights secure farmers' ability to use the land for specific purposes, stabilize labor supply, increase investment, and promote economic growth (Luo and Fu, 2009; Hornbeck, 2010).

Farmland transfer, accompanied by improvements in property rights reform, has proven to be an effective approach in achieving agricultural modernization and large-scale operation, and has also become a prerequisite for harmonizing urban and rural land demands to realize industrialization and urbanization (Kan, 2021). An example of such progress is the Chinese government's "Separation of Three Rights" principle, proposed in 2011 and formally established in 2018. This principle separates ownership rights, contract rights, and management rights for contracted rural land, aligning with the development trend of modern society. It satisfies the requirements of agricultural industrialization, allowing farmers to retain contract rights while transferring management rights. However, some studies have found that allocating land for large-scale investment projects may reduce food security (Shete and Rutten, 2015). Additionally, promoting farmland transfer has not always been effective in improving agricultural economies of scale (Luo, 2018) and, in some instances, may even result in reduced crop yields (Zhang et al., 2021).

Exploring the linkages between farmland transfer and agricultural production is therefore crucial in shaping future agricultural policies, particularly in light of the growing significance of food-related concerns. Clearly, the impact of farmland transfer on agricultural production is closely tied to the role of agricultural loans, which have been demonstrated in studies highlighting their potential to enhance financial inclusion and stimulate increased investment in the agricultural sector (Yang et al., 2018). Several studies have found that increased uptake of agricultural loans can lead to higher average agricultural productivity and raise agricultural income (Emerick et al., 2016; Khandker and Koolwal, 2016; Fink et al., 2020). Equally important is the inherent uncertainty involved in the development of agricultural loan programs related to farmland markets. Despite the availability of farmland mortgage loans through these markets, farmers often do not seek to align their access to formal credit with land rental market (Kochar, 1997). In addition, access to credit can facilitate potential tenants in securing more efficient land rental contracts (Das et al., 2019), and specific forms of loans may play a particularly pivotal role in stimulating investment in off-farm production and operations (Peng et al., 2020).

In China, substantial structural transformations are currently unfolding within the agricultural and rural domains. These transformations encompass the orderly and efficient flow of resources, such as farmland, labor force, and capital, between urban and rural areas and between agricultural and non-agricultural sectors. This dynamic has given rise to the emergence of novel agricultural entities such as agricultural cooperatives, family farms and agricultural enterprises, thereby amplifying the specialization of agricultural production. As a result, the farmland transfer market has gained momentum, leading to an upsurge in agricultural loans and the advancement of agricultural production. This phenomenon has spurred out interest in delving into various facets of farmland, including the mechanisms through which it influences agricultural loans, and how to promote farmland transfers while maximizing the use of agricultural loans to increase agricultural production and ensure food security.

Understanding the nexus between farmland transfer, agricultural loans and agricultural production is important, given that investments in agriculture – which directly boost agricultural production – are driven by the financing of financial capital, which, among other factors, is profoundly influenced by the allocation of farmland resources. The primary contributions of this study to the literature are threefold. First, this paper presents a novel attempt to examine the effects of farmland transfer and agricultural loans on grain production in China. Although there are multiple factors that affect grain production, farmland is the most fundamental element in the entire agricultural industry chain, and finance serves as a lubricant and catalyst for the flow of other elements. Secondly, food security is of paramount importance, and it is essential to answer the important question of whether the free flow of farmland factors and the capitalization of agriculture will lead to the non-food issue of farmland, which will in turn affect food security. Third, we show that the inverse agricultural loan-grain production relationship persists across various types of farmland transfers, possibly due to loans being used for trade and other commercial purposes rather than investment in grain production, but it is also found that agricultural loans will enhance the positive effect of farmland transfer on grain production.

The rest of the paper is structured as follows. Section 2 presents a comprehensive literature review. Section 3 presents the data and the methodology used in the study. The empirical results are then reported in section 4. The final section presents concluding remarks and implications.

2 Literature review

2.1 The economic impact of farmland transfer

Farmland transfer can be categorized into two types: transfer outside and within the agricultural sector. The former entails converting land from agricultural to non-agricultural use, while the latter involves the transfer of farmland among agricultural operators without changing its agricultural use, which is the focus in this study. Studies have identified several economic benefits of farmland transfer, including enhanced land use efficiency, increased farmers' household income, and shifts in agricultural structure. In an investigation of rural land rental markets in Malawi and Zambia, Chamberlin and Ricker-Gilbert (2016) revealed efficiency gains from transferring land to more productive users. Recent studies in developing countries like Vietnam, Ethiopia, and China (Adamie, 2021; Fei et al., 2021; Nguyen et al., 2021) also found positive effects of farmland transfer on production efficiency. These findings underscore the role of farmland rental markets in improving resource allocation and driving economic transformation in rapidly growing rural economies.

Farmland transfer can be categorized into rented-in and rented-out land (Wang et al., 2019). Farmers with rented-in land tend to centralize and engage in large-scale farming, reaping economies of scale, optimizing input utilization, and improving efficiency and productivity (Huang and Ding, 2016; Cao et al., 2020). In contrast, land rental markets provide stable income to farmers with limited non-land resources, enabling them to rent out land management rights and freeing redundant rural workers for off-farm employment (Grimm and Klasen, 2015; Peng et al., 2020). The farmland rental market contributes to a more balanced farm size distribution by facilitating efficient transfers from less productive to more efficient operators (Deininger et al., 2012). Research also shows that farmers can mitigate disaster-related losses by optimizing their farm size through land transfers, enhancing both efficiency, and resilience in the agricultural sector (Eskander and Barbier, 2022).

However, alongside these positive effects, Jin and Jayne (2013) and Baumgartner et al. (2015) have highlighted potential downsides, including income inequality and power imbalances resulting from large-scale farmland operations. Moreover, farmers who lease rather than own land face greater risks, as land ownership offers better tenure security (Sommerville and Magnan, 2015). While scaled farms can drive agricultural transformation, it remains crucial to strengthen land tenure security for local rural communities to protect land rights and support productivity investments by smallholder farmers (Jayne et al., 2019). Consequently, the outcomes of farmland transfer are nuanced, and non-food and non-agricultural issues deserve attention.

2.2 The impact of agricultural loans on agricultural production

Finance is one of the main constraints that hinder agricultural modernization in developing countries. Access to finance has been confirmed effective in promoting technology adoption and inputs use, leading to heightened agricultural productivity, increased rural incomes, and improved food security (Abate et al., 2016; Balana et al., 2022). Without access to such loans, cash-constrained households are often unable to adopt new seed, fertilizer, or chemical technologies that would enable them to intensify production (Poulton et al., 2010; Fink et al., 2020). Developed countries like the United States, Canada, and Australia have extended great support to agriculture, including credit support, such as farm mortgages aimed at providing capital for purchasing inputs and equipment (Martin and Clapp, 2015). Recent global food economy trends, such as growing demand, rising commodity prices, and ongoing agricultural industrialization, have made agriculture increasingly attractive to financial stakeholders. These stakeholders have introduced new models and logics into farmland ownership and agricultural production (Magnan, 2015). Thus, in order to realize returns from agricultural production, finance pushes for the increased capitalization of agricultural production (Clapp et al., 2017).

However, some studies have argued against the efficacy of microfinance in enhancing agricultural productivity and income derived from agriculture (Phan et al., 2014; Khandker and Koolwal, 2016; Thanh et al., 2019; Nakano and Magezi, 2020). For example, in a recent study on Vietnam, Thanh et al. (2019) found that while microfinance significantly increased total income and output value from all earned sources, these gains were largely driven by self-employment rather than agricultural activities like crop cultivation, livestock rearing, or aquaculture. Similarly, using a randomized control trial of microfinance in Tanzania, Nakano and Magezi (2020) found that microfinance did not lead to greater technology adoption or rice productivity. This is partly attributed to loans being used for trading and other business purposes instead of on-farm investments (Ksoll et al., 2016), as the agricultural productivity benefits of agricultural loans hinge on their appropriate use for on-farm purposes (Elahi et al., 2018). Another reason to consider is that loans from microfinance institutions may not yield significant effects in the short term, for instance, one year (Hossain et al., 2019).

2.3 Research on the farmland finance

In recent years, research in the realm of farmland and agri-food has increasingly focused on the concept of financialization. Land, traditionally perceived for its "use value" in meeting human needs, is now being treated as a pure financial asset alongside its "exchange value" in the market (Harvey, 1982; Haila, 1988). However, Coakley (1994) and Ouma (2015) have highlighted the unique nature of agricultural land, which is intrinsically tied to factors such as weather dependence, geographical variability, socioecological embedment, and political significance, making it less amenable to transformation into a standard asset class. In an era of increasing resource scarcity, the financialization of farmland as a quasi-financial asset is becoming increasingly prominent (Fairbairn, 2014; Ashwood et al., 2022). The argument for considering farmland as an investment opportunity is rooted in the principles of contemporary portfolio management theory, which assert that diversification increases expected portfolio returns while minimizing volatility (Chen et al., 2015; Fairbairn et al., 2021). In particular, clear farmland property rights play a central role, not only as a crucial aspect of investor's economization strategy but also as a key driver of the "value creation" process (Ouma, 2016).

In China, as land cannot be privately owned, farmland finance relies on using land as collateral for financial services. This practice serves to enhance the economic value of farmland and attract funding for agriculture. Recent empirical studies have found that legal guarantees of land property rights and land transfer have a significant and positive impact on the demand for and likelihood of obtaining agricultural loans (Zhang et al., 2019; Gong and Elahi, 2022). This agricultural loans represent a crucial source of investment for farmers, and easier access to them can incentive farmers to invest more in their land (Peng et al., 2020; Wang et al., 2023). The combination of lengthening rental tenures, escalating land prices, and increased capitalization has emboldened farmland consolidation, augmenting both the financial and productive appeal of land (Rotz et al., 2019). While some farmers perceive this interest from financial actors as a means to increase the value of their assets, others view it as a threat to family farming and a contributor to further disparities in land resource distribution (Sippel et al., 2017).

Despite insights from previous literature on the economic impact of farmland transfers, the relationship between agricultural loans, farm production, and the financialization of farmland, the connections among farmland transfer, agricultural loans, and grain production in China remain intricate. Ongoing rural revitalization is altering how farmland transfers among agricultural operators. Farmland transfer promotes the shift from small-scale farmers to larger farms, encourages farm size and specialization, and effectively boosts food crop yields, a significant driver behind the growth of farmland transfers. However, the land rent cost associated with farmland transfer, along with the challenge of "limited profits from grain cultivation," may result in substantial farmland allocation to "non-grain" crops, reducing the area devoted to food crops and subsequently impacting grain production. In addition, previous studies have overlooked the influence of farmland transfers and agricultural loans on China's grain production. This study addresses this research gap by investigating the relationships among farmland transfer, agricultural loans, and grain production using a panel dataset from China.

3 Data and methodology

3.1 Data

The primary objective of this paper is to investigate the nexus between farmland transfer, agricultural loans and grain production in China. This study utilizes a panel dataset that covers 30 provinces and spans the years from 2009 to 2020. We employ two-way fixed effects and instrumental viable techniques to explore the interrelationship among the factors. The variable used in the study were compiled from diverse resources, including the China Statistical Yearbooks, China's Rural Operation and Management Statistics Annual Reports, Almanac of China's Finance and Banking, China Rural Statistical Yearbooks and China Population & Employment Statistical Yearbook. Table 1 presents a summary of the variables. In addition to the core variables, the study incorporates other variables closely related to grain production, such as labor force, fertilizer and pesticide consumption, plastic film usage, machinery, irrigated areas and crop damaged areas.

In particular, grain production is measured as the total output of grain crops, including cereals, beans and tubers. The mean of grain production is approximately 2035 (10,000 tons), but the standard deviation indicates that data of grain production is widely dispersed. As we can see from the Figure 1. The geographical distribution of grain production in 2009 and 2020 is evident. Farmland transfer refers to the transfer of farmland management rights from farmers who possess such rights to other farmers or economic organizations. This process encompasses sub-contracting, leasing, exchanging, and swapping land-use rights, as well as establishing joint share-holding entities with their farmland. Agricultural loans are loans issued by financial institutions to provide funds for agricultural production. These loans are extended to various entities involved in agricultural, forestry, animal husbandry, and fishery production. Figures 2, 3 reveal substantial variations in farmland transfer and agricultural loans across different provinces in 2009 and 2022, revealing apparent correlations with changes in grain production.

3.2 Methodology

The empirical approach applied in this study explores the relationship between farmland transfer, agricultural loans and grain production through an extension of the standard production function.

This framework is able to examine the impact of farmland transfer and agricultural loans in addition to the basic drivers of inputs.

The production function is assumed to be Cobb–Douglas form,

$$Y_{it} = A_{it} N_{it}^{\alpha_1} K_{it}^{\alpha_2} L_{it}^{\alpha_3} M_{it}^{4}, \quad (1)$$

where i denotes the province, t denotes time, Y represents grain production, A is the index of technological progress, N, K, L, M are farmland, capital, labor and intermediate inputs. $\alpha_1, \alpha_2, \alpha_3$, and α_4 are the output elasticity of each input.

In order to assess the nexus among the studied variables, we reinterpret the figures of the variables by taking their natural logarithm. When taking the logarithm of Equation (1), the following linear multivariate regression is produced,

$$LnY_{it} = \theta_0 + \theta_1 Ln\_Farmland_{it} + u_i + D_t + \varepsilon_{it} \quad (2)$$

TABLE 1 Definition of variables.

Variable	Definition	Mean	Std. Dev.	Min	Max
Grain Production	Grain crops production (10,000 tons)	2034.93	1693.63	28.70	7540.80
Farmland Transfer	Transferred farmland, including sub-contract, lease, exchange and swap their land-use rights, or joined share-holding entities with their farmland (1,000 hectare (ha.))	862.14	870.18	8.62	4600.51
Agricultural Loans	Loans issued by financial institutions to operators engaged in agricultural production (100 million yuan)	1080.37	750.90	36	4,397
Labor	Number of labor force living in rural areas, excluding migrant workers (10 thousand)	1044.53	748.68	32.5	2920.2
Fertilizer	Consumption of chemical fertilizers (10 thousand tons)	190.36	144.97	5.5	716.10
Pesticide	Consumption of pesticide (10 thousand tons)	5.57	4.20	0.12	16.90
Agrifilm	Consumption of agricultural film (10 thousand tons)	8.05	6.61	0.24	32.30
Mechan	Power of agricultural machinery (10 thousand kilowatts)	3341.30	2909.59	94	13,353
Irrigate	Effective irrigated area (1,000 ha.)	2156.24	1625.46	109.2	6117.6
Disaster	Area of crops damaged by disaster (1,000 hectares), including drought, flood, hailstorm, freezing, typhoon	423.03	456.13	0	3,130

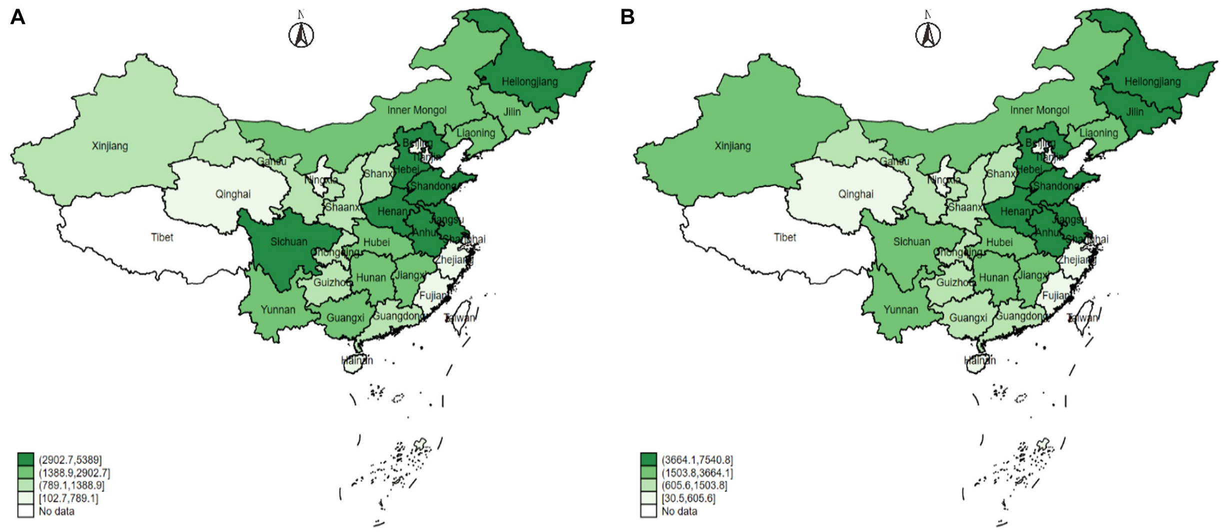

FIGURE 1
China's grain production in 2009 and 2020. **(A)** Grain production in 2009. **(B)** Grain production in 2020.

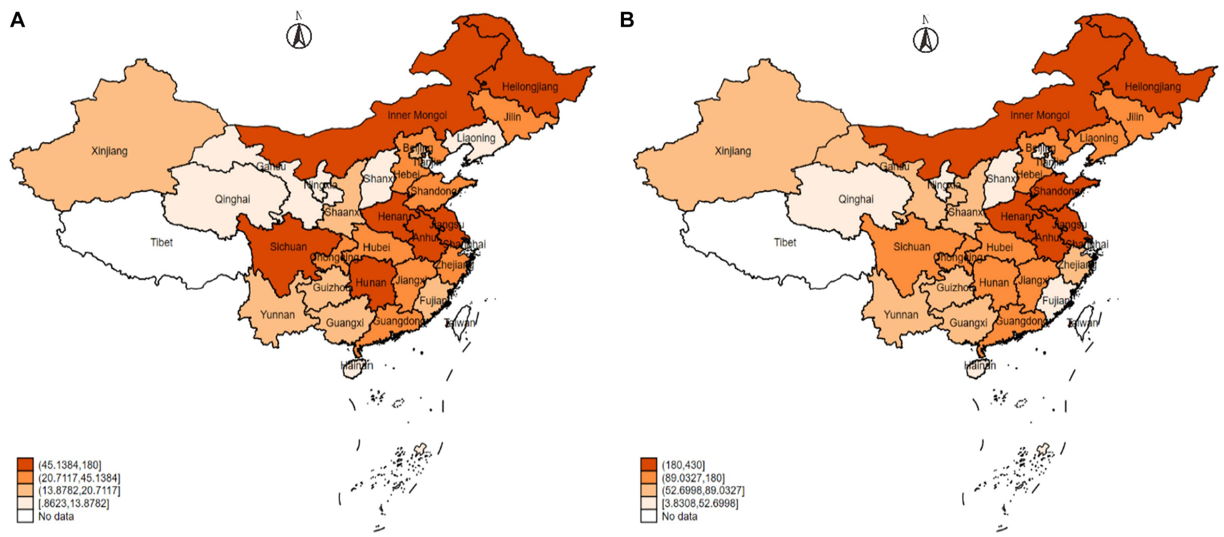

FIGURE 2
China's farmland transfer in 2009 and 2020. **(A)** Farmland transfer in 2009. **(B)** Farmland transfer in 2020.

where Y_{it} denotes grain yield, $Farmland_{it}$ denotes the transferred farmland, u_i represents regional fixed effects and is used to capture specific features averaged across provinces, such as topography, precipitation, temperature and other unobservable factors, and D_t is time-specific effects and captures seasonal or cyclical effects, and other changes over time.

The Equation (2) can be employed to examine the relationship between farmland transfer and grain production, while controlling for farm fixed effects that remain constant over time. However, other inputs such as capital usage, which is subject to change over time, may also influence the farmland – grain production relationship.

Therefore, we include agricultural loans as a moderating variable and incorporate labor, fertilizer usage, pesticide usage, agricultural film usage, total power of agricultural machinery, effective irrigation area, and crop disaster area to control for farm fixed effects. In theory, apart from the negative impact of disaster area on agricultural production, the input of other factors are supposed to increase grain yield. Based on this, the empirical model of this study is formulated as Equation (3):

$$\begin{aligned} LnY_{it} &= \theta_0 + \theta_1 Ln\_Farmland_{it} + \beta_1 Ln\_Labor_{it} + \\ &\beta_2 Ln\_Fertilizer_{it} + \beta_3 Ln\_Pesticide_{it} + \\ &\beta_4 Ln\_Agrifilm_{it} + \beta_5 Ln\_Mechan_{it} + \\ &\beta_6 Ln\_Irrigate_{it} + \beta_7 Ln\_Disaster_{it} + u_i + D_t + \varepsilon_{it}. \end{aligned} \tag{3}$$

The two-way fixed effects model with agricultural loans included as a moderating variable is then as Equation (4):

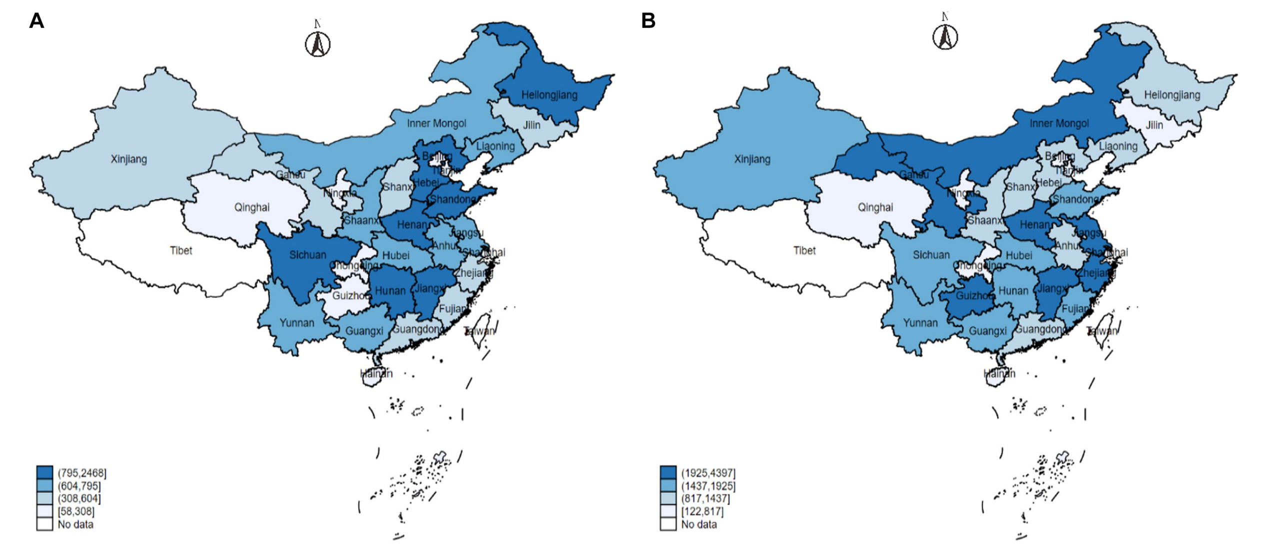

FIGURE 3
China's agricultural loans in 2009 and 2020. **(A)** Agricultural loans in 2009. **(B)** Agricultural loans in 2020.

$$\begin{aligned} LnY_{it} &= \theta_0 + \theta_1 Ln\_Farmland_{it} + \theta_2 Ln\_Loans_{it} + \\ &\theta_3 Ln\_Farmland_{it} Loans_{it} + \beta_1 Ln\_Labor_{it} + \\ &\beta_2 Ln\_Fertilizer_{it} + \beta_3 Ln\_Pesticide_{it} + \\ &\beta_4 Ln\_Agrifilm_{it} + \beta_5 Ln\_Mechan_{it} + \\ &\beta_6 Ln\_Irrigate_{it} + \beta_7 Ln\_Disaster_{it} + u_i + D_t + \varepsilon_{it}. \end{aligned} \tag{4}$$

In addition, in order to address potential endogeneity issues in the model, this study further employs the instrumental variable method.

4 Results and discussion

4.1 Results

This study employs a two-way fixed effects model to conduct regression analysis, and the results are presented in Table 2. Since farmland transfer involves three main directions – transfer to farmers, professional cooperatives, and enterprises – we not only examine the overall effect of farmland transfer on grain production but also separately analyze its impacts on grain production when transferred to each of these entities.

As can be seen from the columnI, after controlling for other variables, farmland transfer demonstrates a significant positive correlation with grain production at the 1% level. This indicates a strong positive relationship between farmland transfer and grain production. The results suggest that for every 1% increase in the quantity of farmland transfer, there is a corresponding 0.113% increase in grain yield. This finding is consistent with the results of Fei et al. (2021) and Rogers et al. (2021), that is, Land transfer can improve land use efficiency. In addition, the results further suggest that when farmland is transferred to farmers, cooperatives, and enterprises, a 1% increase in quantity results in grain yield increases of 0.085, 0.07, and 0.019%, respectively. This highlights the significant contributions of farmland transfer to both farmers and cooperatives in enhancing grain production. In addition, the coefficients of labor force, fertilizer usage, agricultural film, and irrigation exhibit significant effects at a level of 5% or higher. This indicates that these inputs noticeably impact grain production. Although the area affected by natural disasters shows a significant negative correlation with grain yield, the coefficient is relatively small. This suggests that agriculture possesses a strong capacity for resilience against disasters.

The results in column II incorporate agricultural loans and the interaction terms between agricultural loans and different types of farmland transfer. It is interesting to note that agricultural loans show a significant negative correlation with grain production, indicating that a 1% increase in agricultural loans leads to a 0.06% decrease in grain yield. However, the coefficient of the interaction term between farmland transfer and agricultural loans is significantly positive, indicating that agricultural loans act as a moderating effect that enhances the main effect. In other words, although agricultural loans alone do not lead to increased grain production, their combination with farmland transfer contributes to the improvement of grain yield. One possible reason might be that agricultural loans can provide farmers with additional resources and capital, and when combined with farmland transfers, can improve land use efficiency and productivity. This infusion of resources may produce benign interactive effects. In addition, agricultural loans often face increased uncertainties and challenges due to the inherently risky nature of agriculture. The property attributes of farmland can help reduce agricultural credit risks, thereby enhancing the overall effect in a positive direction.

Given the potential influence of endogeneity in the benchmark regression results due to omitted variables and reverse causality between farmland transfer and agricultural production, this paper employs an instrumental variable (IV) approach to address the endogeneity issue. The primary focus of this paper is to assess the impact of farmland transfer on grain production. Therefore, our main objective is to find instrumental variables for farmland transfer. In this study, wage income, financial expenditure, and *per capita* road area are selected as instrumental variables for farmland transfer.

The findings of Su et al. (2018) and Fan et al. (2021) have indicated that non-agricultural employment has a significantly positive impact

TABLE 2 **The estimation results on farmland transfer, agricultural loans, and grain production relationship.**

Variable	Farmland transfer	Transfer to farmers	Transfer to cooperatives	Transfer to enterprises	Variable	Farmland transfer	Transfer to farmers	Transfer to cooperatives
	I	II	I	II	I	II	I	II
Ln_Farmland Transfer	0.113*** (0.025)	0.104*** (0.025)	0.085*** (0.023)	0.077*** (0.022)	0.070*** (0.014)	0.075*** (0.014)	0.019 (0.018)	0.023 (0.017)
Ln_Agricultural Loans		−0.061*** (0.019)		−0.043** (0.020)		−0.062*** (0.019)		−0.060*** (0.020)
Ln_*Transfer* ×Loans		0.026*** (0.008)		0.002** (0.001)		0.002** (0.001)		0.003*** (0.001)
Ln_Labor	0.801*** (0.098)	0.810*** (0.096)	0.796*** (0.099)	0.796*** (0.098)	0.748*** (0.099)	0.749*** (0.096)	0.847*** (0.102)	0.862*** (0.099)
Ln_Fertilizer	0.227** (0.103)	0.147 (0.102)	0.209** (0.104)	0.143 (0.104)	0.198** (0.102)	0.108 (0.102)	0.238** (0.108)	0.136 (0.108)
Ln_Pesticide	0.031 (0.061)	−0.017 (0.062)	0.077 (0.062)	0.043 (0.063)	0.010 (0.061)	−0.014 (0.061)	0.048 (0.063)	0.016 (0.062)
Ln_Agrifilm	0.124** (0.049)	0.013 (0.054)	0.102** (0.050)	0.038 (0.052)	0.129*** (0.049)	0.046 (0.052)	0.131*** (0.051)	0.043 (0.054)
Ln_Mechan	0.014 (0.040)	0.015 (0.039)	0.027 (0.041)	0.021 (0.040)	0.016 (0.040)	0.016 (0.039)	0.010 (0.042)	0.007 (0.041)
Ln_Irrigate	0.533*** (0.079)	0.488*** (0.078)	0.513*** (0.080)	0.484*** (0.079)	0.523*** (0.078)	0.480*** (0.078)	0.551*** (0.081)	0.512*** (0.080)
Ln_Disaster	−0.016** (0.007)	−0.013* (0.007)	−0.015** (0.008)	−0.014* (0.007)	−0.016** (0.007)	−0.015** (0.007)	−0.016** (0.008)	0.015** (0.007)
Region fixed	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time fixed	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	−3.598*** (0.588)	−2.646*** (0.614)	−3.133*** (0.604)	−2.421 (0.627)	−2.570*** (0.615)	−1.581** (0.644)	−3.564*** (0.606)	−2.685*** (0.628)
N	360	360	360	360	360	360	360	360
R-sq: within	0.615	0.638	0.607	0.625	0.6207	0.642	0.591	0.616
F	26.09***	25.95***	25.33***	24.50***	26.78***	26.37***	23.68***	23.63***

The values in parentheses are standard errors.

10.3389/fsufs.2024.1229381

on farmland transfer, primarily due to the higher attractiveness of non-agricultural wages. Therefore, in this paper, we consider wage income as an instrumental variable for farmland transfer since it does not directly affect grain production but influences the decision to transfer farmland. Financial expenditure refers to government spending on agricultural and water affairs, encompassing investments and expenditures made by the government in the agricultural sector. These expenditures contribute to the improvement of rural infrastructure and agricultural production conditions, potentially exerting a significant impact on farmland transfer. While *per capita* road area may not directly influence agricultural production, accessible road transportation plays a vital role in facilitating the transportation of agricultural products. This, in turn, enhances market opportunities and serves as a motivating factor for farmland transfer.

The regression results using the instrumental variable (IV) approach are presented in Table 3. The validity test of instrumental variables shows that the regression coefficients of wage income, financial expenditure, and *per capita* road area in the first-stage regression are all statistically significant at a 5% level or higher, indicating a positive correlation with farmland transfer. In particular, the coefficient of financial expenditure is significantly negative, suggesting that increased government investment in the agricultural sector and improvements in agricultural production conditions lead farmers to be more inclined to cultivate the farmland themselves rather than transferring it. In addition, compared to the promoting effect of road on farmland transfer, the coefficient of wage income is relatively small, implying a limited role of wage income improvement in facilitating farmland transfer. The results of the under-identification test, Hansen J statistic, and Cragg-Donald Wald F statistic also indicate that the instrumental variables are appropriate. Consistent with the baseline regression results, different types of farmland transfer exhibit a significant positive effect on grain production, while agricultural

TABLE 3 Regression results using IV approach.

Variable	Farmland transfer	Transfer to farmers	Transfer to cooperatives	Transfer to enterprises
Ln_Farmland Transfer	0.259* (0.147)	0.365*** (0.135)	0.120** (0.056)	0.312*** (0.123)
Ln_Agricultural Loans	−0.377*** (0.122)	−0.401*** (0.100)	−0.196*** (0.058)	−0.285*** (0.076)
Ln_*Transfer* ×Loans	0.052*** (0.019)	0.067*** (0.018)	0.028** (0.012)	0.056*** (0.017)
Ln_Labor	0.813*** (0.134)	0.726*** (0.132)	0.780*** (0.127)	0.840*** (0.140)
Ln_Fertilizer	0.111 (0.103)	0.139 (0.111)	0.074 (0.100)	0.056 (0.115)
Ln_Pesticide	−0.089 (0.071)	−0.118 (0.075)	−0.057 (0.064)	−0.107 (0.072)
Ln_Agrifilm	0.056 (0.087)	0.064 (0.067)	0.008 (0.079)	0.103 (0.097)
Ln_Mechan	0.007 (0.030)	0.011 (0.033)	0.001 (0.029)	0.029 (0.031)
Ln_Irrigate	0.463*** (0.083)	0.452*** (0.080)	0.446*** (0.088)	0.499*** (0.084)
Ln_Disaster	−0.009 (0.010)	−0.006 (0.010)	−0.012 (0.009)	0.008 (0.011)
First-stage regression				
Wage income	0.00002*** (5.92e-06)	0.00002*** (5.92e-06)	0.00004*** (9.47e-06)	0.00003*** (6.84e-06)
Financial expenditure	−0.0004*** (0.0001)	−0.0004*** (0.0001)	−0.001*** (0.0001)	−0.001*** (0.0001)
Road	0.130** (0.055)	0.092** (0.040)	0.056** (0.019)	0.122** (0.057)
Underidentification test	35.441*** [0.000]	35.032*** [0.000]	39.757*** [0.000]	41.535*** [0.000]
Cragg-Donald Wald *F* statistic	25.435	28.420	40.329	34.513
Hansen J statistic	3.257 [0.196]	1.835 [0.399]	7.328 [0.256]	0.903 [0.545]

*, **, and *** represent significance level at 10, 5, and 1%, respectively. The value in brackets is the standard error, and the value in square brackets is *p*-value.

loans show a significant negative impact at the 1% level. However, the coefficient of the interaction term between farmland transfer and agricultural loans is significantly positive at the 1% level, suggesting that agricultural loans enhance the main effect, and the combination of agricultural loans and farmland transfer contributes to an increase in grain production.

According to various statistical criteria, apart from agricultural loans, there are different types of loans in the agricultural sector, including rural loans, rural household loans and agriculture-related loans. In particular, rural loans refer to loans provided to rural households, rural enterprises and various organizations, emphasizing loans within the administrative scope of counties and below. Rural household loans, on the other hand, are loans issued by commercial banks to eligible rural households for purposes such as production, operation, consumption, and other needs. Agricultural-related loans can be broadly classified into two main categories: loans for agriculture, forestry, animal husbandry, and fisheries (commonly known as "agricultural loans"), and other loans associated with agriculture. The latter category encompasses loans for agricultural materials and the circulation of agricultural products, loans for rural infrastructure construction, loans for agricultural product processing, loans for manufacturing agricultural production materials, loans for farmland construction, loans for agricultural technology, as well as loans for real estate, the construction industry, and rural individual businesses. Due to the different focuses of these various types of loans, their moderating effects on the relationship between farmland transfer and grain production may also differ.

Table 4 presents the role of loans in different agricultural sectors regarding the impact of farmland transfer on grain production. The results indicate that rural loans, rural household loans, and agriculture-related loans are significantly and negatively correlated with grain yield. However, their interaction terms with farmland transfer are all positive, indicating an enhancement of the main effects. Specifically, the findings in columns 1, 3, and 5 reveal that a 1% increase in rural loans, rural household loans, and agriculture-related loans results in a decrease in grain yield of 0.064, 0.058, and 0.048%, respectively. However, when effectively combined with farmland transfer, these loans contribute to an increase in grain yield by 0.119, 0.111, and 0.117%, respectively. Among the control variables, both the labor force and irrigated area remain significant at the 1% level, indicating their importance in grain production. In addition, the application of chemical fertilizers also has a significant positive impact on grain yield.

4.2 Discussion

As global policymakers increasingly focus on food security, food production has become a key area of academic attention. While existing research has explored the economic impacts of farmland transfer and the effects of farmland and finance on agricultural production, the connections among farmland transfer, agricultural loans, and grain production in China remain intricate. And in China, ongoing rural revitalization is altering the agricultural investment and financing model as well as changing how farmland transfers among agricultural operators. In contrast, this study utilizes provincial-level data from China spanning 2009–2020. Employing a two-way fixed effects model and an instrumental variable approach, we assess the impact of farmland transfer and agricultural loans on grain production.

Our findings reveal that farmland transfer contributes to an increase in grain production. The positive effects of farmland transfer to farmers, cooperatives, and enterprises differ, with the most significant effects observed when farmland is transferred to farmers and cooperatives. Therefore, this study argues that farmland transfer to farmers and cooperatives is most conducive to enhancing grain production. This finding aligns with recent studies focusing on farmland transfer and food production (Zang et al., 2021, 2023; Kuang et al., 2022), which highlight the optimization of arable land resource allocation, increased investment, and the promotion of agricultural economic growth through farmland transfer. Continuing to encourage farmland transfer is beneficial for promoting agricultural production and China's "rural revitalization" initiative.

Interestingly, agricultural loans show a significant negative correlation with grain production. This result is similar to the findings of Khandker and Koolwal (2016), who discovered that microcredit raises agricultural income from activities such as livestock rearing but does not affect crop production. Additionally, this finding aligns with research conducted by Ksoll et al. (2016) and Nakano and Magezi (2020), suggesting that agricultural loans are being utilized for trading and other business purposes rather than investments in grain production, thus not contributing to an increase in grain yield. Although agricultural loans alone do not lead to increased grain production, we find that the interaction between agricultural loans and farmland transfer contributes to the improvement of grain yield. This finding is consistent with Jiang et al. (2023), who recently found that farmland transfer improved credit demand and increased agricultural investment. Luo (2018) also suggests that using land contracting rights as a financing tool integrates the profit-seeking nature, liquidity, exclusivity, and profitability of capital, achieving the financialization of farmland and forming productive entities that provide "specialization production." Therefore, we argue that while finance serves as a lubricant and catalyst for the flow of other elements in the development of the agricultural industry, its profit-seeking nature may lead to non-agriculturalization. Hence, financial instruments in the agricultural sector should be more closely integrated with medium- to long-term agricultural industry projects. For example, governments should consider relaxing pilot programs for mortgage loans secured by farmland management rights.

Furthermore, we find that farmland transfer, especially when transferred to farmers with financial support, contributes more to grain production compared to transfers to cooperatives and enterprises. Thus, we argue that despite the growing importance of new agricultural operating entities, including cooperatives and family farms, in China's agricultural industry development, the participation of farmers with a certain scale of cultivation remains a crucial force for grain production.

5 Conclusions and policy implications

The current global food security faces multiple challenges, including dwindling land resources, water scarcity, and insufficient agricultural technology and infrastructure. This study, using provincial-level data from China spanning 2009–2020, employed a two-way fixed effects model and instrumental variable approach to assess the impact of farmland transfer and agricultural loans on grain production. Our findings indicate that farmland transfer has a

TABLE 4 Regression results of different types of agricultural loans.

Variable	Country loans	Country loans -IV	Farmer loans	Farmer loans -IV	Agricultural related loans	Agricultural related loans-IV
Ln_Farmland Transfer	0.119*** (0.025)	0.112* (0.078)	0.111*** (0.025)	0.168** (0.083)	0.117*** (0.025)	0.129** (0.047)
Ln_ Loans	−0.064* (0.036)	−0.194** (0.077)	−0.058** (0.026)	−0.161** (0.072)	−0.048** (0.021)	−0.169** (0.084)
Ln_Transfer × *Loans*	0.023*** (0.007)	0.026** (0.012)	0.016*** (0.005)	0.019* (0.010)	0.024*** (0.007)	0.026** (0.013)
Ln_Labor	0.815*** (0.097)	0.819*** (0.135)	0.898*** (0.104)	0.871*** (0.125)	0.813*** (0.097)	0.840*** (0.137)
Ln_Fertilizer	0.214** (0.101)	0.172* (0.103)	0.167 (0.104)	0.144 (0.100)	0.226** (0.101)	0.190* (0.104)
Ln_Pesticide	0.003 (0.061)	−0.027 (0.069)	−0.048 (0.064)	−0.076 (0.073)	−0.009 (0.061)	−0.017 (0.066)
Ln_Agrifilm	0.036 (0.054)	0.030 (0.077)	0.037 (0.055)	0.024 (0.086)	0.056 (0.052)	0.054 (0.080)
Ln_Mechan	0.002 (0.040)	0.020 (0.029)	0.002 (0.040)	0.021 (0.031)	0.022 (0.040)	0.007 (0.028)
Ln_Irrigate	0.480*** (0.079)	0.480*** (0.089)	0.502*** (0.078)	0.506*** (0.084)	0.476*** (0.079)	0.469*** (0.088)
Ln_Disaster	−0.015** (0.007)	−0 0.013 (0.010)	−0.012 (0.007)	−0.010 (0.010)	−0.012* (0.007)	0.011 (0.010)
Region fixed	Yes	Yes	Yes	Yes	Yes	Yes
Time fixed	Yes	Yes	Yes	Yes	Yes	Yes
Constant	−3.025*** (0.603)		−3.494*** (0.581)		−3.259*** (0.594)	
N	360		360		360	
R-sq: within	0.630		0.629		0.631	
F	25.06***		25.01***		25.12***	
First-stage regression						
Wage income		0.222*** (0.027)		0.413*** (0.035)		0.260*** (0.045)
Financial expenditure		−0.001*** (0.0001)		−0.001*** (0.0001)		−0.0005*** (0.0001)
Road		0.053** (0.020)		0.069*** (0.013)		0.016*** (0.004)
Underidentification test		49.670*** [0.000]		48.204*** [0.000]		38.791*** [0.000]
Cragg-Donald Wald *F* statistic		94.251		80.453		57.598
Hansen *J* statistic		0.713 [0.700]		1.218 [0.544]		2.268 [0.322]

*, **, and *** represent significance level at 10, 5, and 1%, respectively. The value in brackets is the standard error, and the value in square brackets is *p*-value.

significantly positive effect on grain production, particularly when farmland is transferred to farmers. In contrast, agricultural loans exhibit a notable negative influence on grain production. However, the interaction between farmland transfer and agricultural loans is positive, suggesting that while financial capital's profit-oriented nature may not favor low-profit grain crops, it contributes to increasing overall farmland productivity and, subsequently, grain yields. In addition, loans from different statistical categories within the agricultural sector demonstrate a significant negative impact on grain production, but their interaction effects with farmland transfer remain positive, reinforcing the robustness of our results.

These findings carry important policy implications for ensuring food security through the lenses of farmland and finance. Firstly, the government should continue promoting rural land system reforms and actively facilitate farmland transfer. A moderate-scale farmland operation is essential for finance to play a supportive role, and farmland transfer is crucial for promoting large-scale operations. Establishing standardized farmland transfer markets can incentivize agricultural entities to make long-term investments in farmland, thereby enhancing the efficient use of financial and other resources and ensuring the long-term sustainability of grain production. In addition, through the development of farmland finance that integrates farmland and finance, such as farmland mortgage loans, the property attributes of large-scale agricultural land can be leveraged, which will also help to further enhance agricultural productivity. Secondly, it is essential to remain cautious about non-grain challenges that may arise from financial development. While finance has been acknowledged for its positive impact on rural economies, including ours, inconsistent results regarding its influence on grain production suggest the need for careful guidance of agricultural finance. This guidance should direct investments toward medium and long-term agricultural production projects while preventing potential food crises resulting from "non-agricultural" agricultural loans. Thirdly, giving due importance to the rural labor force is significant. Our research reveals that the rural labor force consistently has a positive effect on grain production. Higher non-agricultural wages can drive farmland transfer, free up rural labor from farming, and attract rural labor to urban employment opportunities. Excessive rural-to-urban migration can be detrimental to grain production. Therefore, in addition to increasing grain subsidies for farmers, promoting market-oriented labor factor reforms and facilitating the two-way flow of urban and rural labor is essential.

Although this study has produced valuable findings, there are still areas requiring further exploration and enhancement. For instance, the reliance on macro-level data in this study poses challenges in integrating the individual characteristics, behaviors, and perspectives of farmers and agricultural operators into the analysis. Moreover, the relatively short timeframe of this study may limit its ability to capture long-term impacts and evolving dynamics. Future research endeavors could contemplate extending the observation period to encompass a more comprehensive view of trends. In addition, given the spatial mobility associated with farmland transfer and agricultural loans, future research may also benefit from exploring spatial measurements as a methodological approach.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

ZD contributed to conception and design of the study, and wrote the first draft of the manuscript. QZ organized the database. YT made significant contributions during the paper revision. He played a crucial role in enhancing the introduction and literature review sections in response to reviewers' feedback, addressing grammatical issues and ensuring overall improvement in the paper. ZD and QZ performed the statistical analysis. All authors contributed to the article and approved the submitted version.

Funding

This study is supported by the National Social Science Fund of China (21CGL026).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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TYPE Original Research
PUBLISHED 13 February 2024
DOI 10.3389/fsufs.2024.1270265

OPEN ACCESS

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RECEIVED 31 July 2023
ACCEPTED 02 January 2024
PUBLISHED 13 February 2024

CITATION
Tebeje AK, Abebe WB, Hussein MA, Mhiret DA, Zimale FA, Desta G, Assefa TT, Tilahun SA and Ahmed MA (2024) Dynamics of soil quality in a conserved landscape in the highland sub humid ecosystem, Northwestern Ethiopia. *Front. Sustain. Food Syst.* 8:1270265.
doi: 10.3389/fsufs.2024.1270265

Dynamics of soil quality in a conserved landscape in the highland sub humid ecosystem, Northwestern Ethiopia

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Several studies have assessed the dynamics of soil quality induced by soil and water conservation (SWC), but many showed disagreement over the efficacy of SWC interventions in the Ethiopian highlands. This study used a before and after soil and water conservation practices (SWCP) comparison approach to evaluate the effect of SWCP on soil quality dynamics. Fifty-four composite and 10 undisturbed soil samples were collected in 2012 (before SWCP) and 2022 (after SWCP). Statistical mean, analysis of variance, and principal component analysis were applied to test the significant differences among treatments. The findings demonstrated that SWCP has significantly improved most of the soil quality indicators such as soil organic matter, total nitrogen, available phosphorous, pH, total porosity, field capacity, and available water, and reduced the value of bulk density and coarse fragments. The interaction effect of landscape position and types of structures provided statistically significant results for soil organic matter, total nitrogen, magnesium, calcium, and base saturation. Soil and stone-faced soil bunds treated at lower landscapes were superior in improving soil quality attributes. The soil quality indexing showed, the overall soil quality improvement as a result of SWCP was about 32.15%. The level of improvement for different SWCPs was 32% for stone faced soil bunds and 33% for soil bunds. The findings revealed that SWCP implementation can improve soil quality. Soil organic matter is a key biological quality component that contributed 25% to the soil quality index and highly impacted soil physicochemical properties. We suggest additional assessment of best and integrated land management practices to ensure further improvement in soil quality, crop productivity, and ecosystem services in the subhumid ecosystems.

KEYWORDS

landscape, soil erosion, soil quality, sub-humid, watershed management

1 Introduction

In the last 50 years, about 2 billion hectares of land have been degraded, resulting in the loss of 11.9 to 13.4% of the world's agricultural supply (Tsymbarovich et al., 2020; Hussain et al., 2021). Land degradation is defined in this context as the loss of land quality and, as a result, land productivity (Rashid et al., 2016). Productivity in Africa has fallen by half, owing mostly to soil erosion and its consequences (Lal, 2015; Bekele et al., 2022). This results in a yield loss ranging from 2 to 40%, depending on local socio-environmental conditions (Eswaran et al., 2019).

As part of other agricultural lands of the world, soil erosion is widespread in the East African highlands, including in the Ethiopian highlands (Girmay et al., 2020). The problem of soil erosion in the Ethiopian highlands was felt some 4,000 years ago with the introduction of agriculture (Wassie, 2020). As studied, this has reduced soil fertility and land productivity (Meseret, 2016). The amount of soil lost in Ethiopia's highlands varied from 5 to 300 t ha^{-1} $yr.^{-1}$ depending on terrain, land use, and agro-ecological zones (Selassie and Amede, 2014; Meseret, 2016; Lemma et al., 2019; Adem et al., 2020). This estimate is equivalent to the loss of more than 3 mm of topsoil per year (Zegeye et al., 2010). On the other hand, it takes about 100 years to form 1 cm of soil (Chalise et al., 2019). As a result, the erosion rate in Ethiopia is higher than soil formation rates.

Laboratory and field experiments have been conducted to assess the effects of erosion on soil quality and productivity (Wang et al., 2020). In soil quality assessment studies, various types of soil quality indicators, also known as soil characteristics, were used. The choice of a relevant attribute was determined by the research purpose and the availability of data. For example, some studies use a combination of soil physicochemical properties (Rinot et al., 2019; Leul et al., 2023), whereas others consider selected variables to address specific soil quality (Alemayehu and Fisseha, 2018; Alewoye Getie et al., 2020). These studies have shown that soil erosion induced soil quality deterioration including nutrient availability, water-holding capacity, and soil response to fertilization (Nachimuthu and Hulugalle, 2016; Kebede et al., 2022).

Moreover, some studies have been conducted to measure soil quality changes as a result of SWC treatments. Amare et al. (2013), Belayneh et al. (2019), Mengistu et al. (2016), Siraw et al. (2020), and Tolesa et al. (2021) discovered a significant improvement in soil organic carbon, total nitrogen, available phosphorous, available potassium, pH, clay content, cation exchange capacity, and soil hydrology in Ethiopian highlands. Mengistu et al. (2016) found that conserved plots had higher magnesium and calcium content than non-conserved plots. All these studies have found that conserved plots improved several soil quality indicators than non-conserved plots.

In contrast, particular research works found an absence of substantial positive improvements in soil quality indicators after SWC treatments. For instance, although the contents of exchangeable potassium and magnesium in the conserved micro-watershed were slightly higher than that in the non-conserved plots, the differences were statistically non-significant (Du et al., 2022). Mengistu et al. (2016) reported a statistically non-significant difference in soil organic carbon content between soils treated with SWC measures and those without in the Bokole watershed, and a non-significant improvement in soil hydrology parameters at the Anjeni watershed after 25 years of conservation work. Similarly, Amare et al. (2013) found non-significant changes in pH, available phosphorous, available potassium, calcium, and magnesium between conserved and un-conserved sites.

Regardless of the disparities in research results, most prior studies made in Ethiopia were based on paired sites, i.e., a comparison of conserved and non-conserved sites due to a lack of historical data on soil qualities before SWCP was made. This method, on the other hand, was incapable of accounting for the intrinsic variability of soil chemical characteristics over a short distance. In general, there is disagreement on the efficacy of SWC interventions implemented in Ethiopia (Dagnew et al., 2015). As Tilahun and Belay (2019) suggested the response of land to SWC measures is the result of a complex interaction of several factors such as agroecology, age of treatments, and placement of structures. The present study hypothesized that soil and water conservation practices in sub-humid tropics will have a significant beneficial impact on soil quality.

Most previous research relied on the short-term effects of SWC using paired site comparison of conserved and unconserved adjacent sites due to a lack of historical data on soil quality indicators (Yu et al., 2018). Soil properties, on the other hand, changed dynamically throughout time and under any conditions. This study is uniquely designed to examine the true and long-term (2012–2022) soil quality improvement in subhumid ecosystems over space and time as a result of the implementation of SWCP in the area. Therefore, the objective of the present study is to (i) assess the dynamics of soil properties caused by SWCP and (ii) evaluate the effects of conservation practices and landscape on soil properties in the sub-humid highlands of Ethiopia.

2 Materials and methods

2.1 Area description

The study was conducted in the Debre Mawi watershed, located in the northwestern Ethiopian highlands (Figure 1). The watershed has an area of 97 ha and is located between 11°21′18″ to 11°22′1" North latitudes and 37°25′3″ to 37°25'l37"East longitudes. The elevation varies between 2,195 to 2,308 meters above the mean sea level. The slope gradient varies from plain (0–5%), gentle (5–8%), moderate (8–15%), steep (15–30%), to extremely steep (>30%) accounting for about 17.46, 22.72, 38.53, 21.18 and 0.14% of the area. The climate is sub-humid, with a mean annual total rainfall of 1,240 mm and a mean annual temperature of about 20°C (Dagnew et al., 2015). The rainfall pattern is mono-modal, largely concentrated between June and September. The major soils are Haplic Vertisols (32.33%), Luvic Nitisols (23.96%), Haplic Luvisols (21.58%), Vertic Cambisols (16.16%), and Haplic Leptsols (5.97%).

2.2 Soil and water conservation structures inventory

The soil and water conservation structures were extracted from Google Images, verified on the ground, and categorized into three management conditions: non-conserved, soil bund, and stone-faced soil bund areas. The stone-faced soil bunds and soil bunds covered about 51 and 32% of the watershed, respectively, leaving 17% to

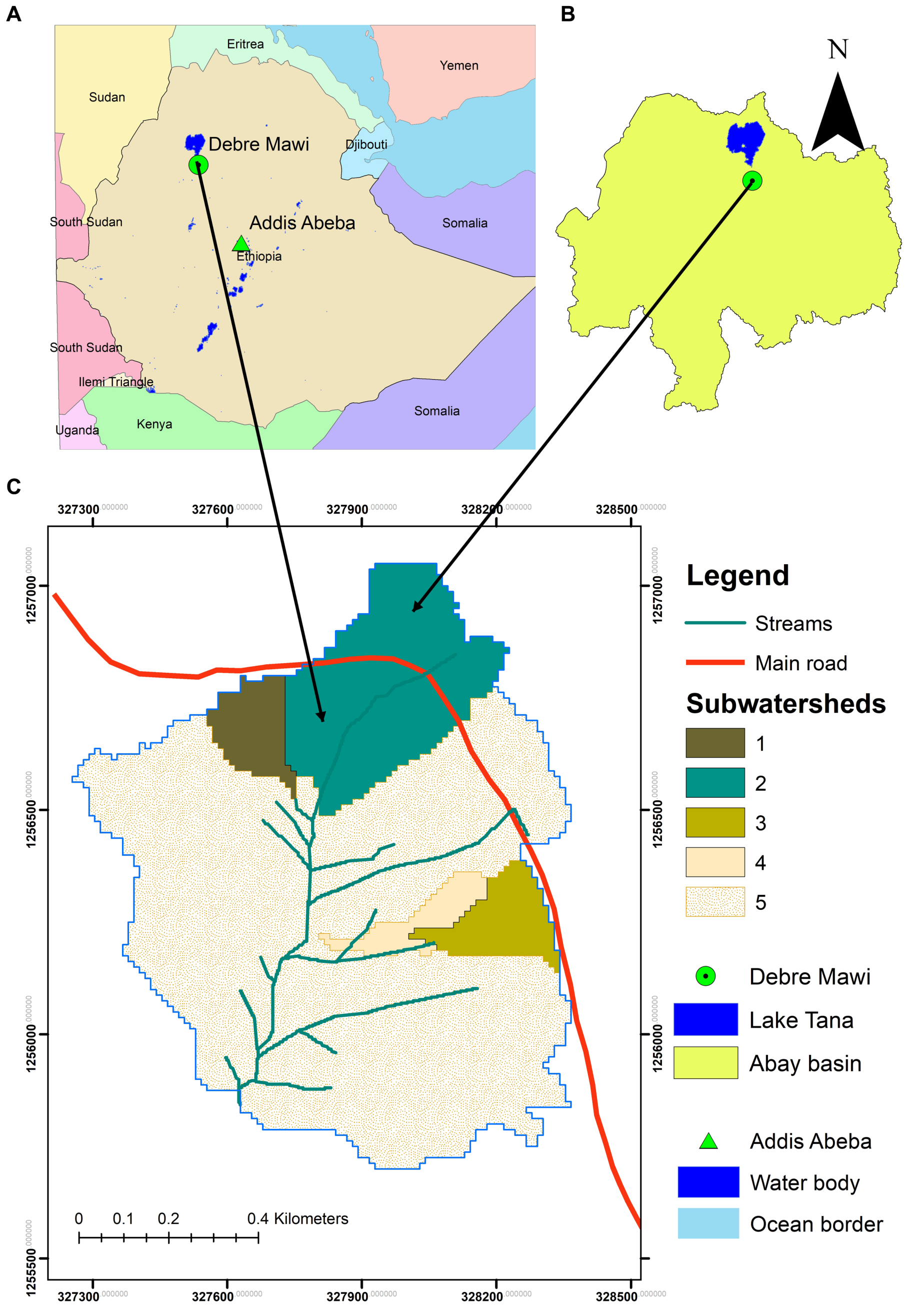

FIGURE 1
Location map of Debre Mawi over Ethiopia **(A)**, abbay basin and lake tana **(B)** and watershed features of Debre Mawi **(C)**.

be non-conserved. The SWCPs were made up of stone and soil with heights ranging from 0.3 to 0.6 meters. The horizontal distance between the bunds was 32 meters. On hilly terrain, the spacing was lowered so that the greatest height change between successive bunds was 1.5 meters (Mhiret et al., 2019).

2.3 Experimental setup and design

The research in general has a factorial experiment with three experimental variables, time (before and after), types of SWC structures (non-conserved, soil bund and stone bund) and landscape units (upper, middle and lower landscape positions) considered as depicted in Table 1. This study employed the before and after intervention comparison technique to compare soil quality before and after the implementation of soil and water conservation. Before the implementation of SWCP, a preliminary soil sampling was conducted in January 2012. Stone-faced soil bunds and soil bunds were the two main SWC structures, which were largely built from 2012 to 2014. Subsequently, soil samples were collected in 2022 at the same location sites as the ones taken before the implementation of SWCP and used to represent soil data after the implementation of SWCP. Samples were also collected in 2022 at non-conserved locations to verify the true changes in soil quality brought by SWCP.

TABLE 1 Number of selected plots, replications, and disturbed soil samples assigned before and after the implementation of SWCP based on landscape and types of SWCP.

Landscape position	Before SWCP (2012)			After SWCP (2022)				
	Selected plots	Replication	Samples	Selected plots			Replication	Samples
				Soil bund	Stone-faced soil bund	Non-conserved		
Upper	2	3	6	2	2	-	3	12
Middle	2	3	6	2	2	2	3	18
Lower	1	3	3	1	1	1	3	9
Total	5		15	13				39

SWCP, soil and water conservation practices.

Concomitantly, the study (i) assess changes in soil properties due to SWC treatments and (ii) evaluate the interaction effects of conservation practices and landscape position (Table 1). In 2012, 5 plots were established in the three landscapes for soil sampling before the implementation of SWCP. In 2022, the watershed area was divided into conserved and non-conserved areas, explicitly subdivided into soil bunds, stone-faced soil bunds, and non-conserved plots. The three landscape units intersected with the watershed categorization made in 2022 (stone-faced soil bund, soil bund, and non-conserved areas), yielding 8 combinations after the implementation of SWCP. The 13 representative plots were chosen as given in Table 1.

The primary study interest was to examine the impacts of SWCP on the dynamics of soil qualities after years of implementation. This temporal cluster analysis compares data collected from conserved plots in 2022 as one group to data obtained from non-conserved plots in 2012. The first group includes data from 10 conserved field plots with replications collected in 2022, whereas the second group includes data from 5 selected plots with replications gathered in 2012. This research design did not use data from non-conserved plots gathered in 2022.

Also, a comprehensive analysis was performed to analyze the interaction effect of landscape and conservation practices on soil properties. Landscape and types of conservation practices were experimental variables as indicated in Supplementary Table S1. The data collected before the implementation of SWCP in 2012 were labeled as "non-conserved 2012" for the interaction study. Some data was also collected from non-conserved plots found in the middle and lower landscape, and represented as "non-conserved 2022." The statistical comparison was made among 11 treatment combinations (Supplementary Table S1).

2.4 Soil sampling

Soil sampling was systematically designed to represent experimental variables before and after the implementation of SWCP, landscape units, and conserved and non-conserved units, with replications. Soil samples from the selected plots (Table 1) were collected by delineating 10 m x 10 m size plots of 0–20 cm depth. Composite and core soil samples were collected using Auger and core sampler. Core samples were taken at the center of each plot using a sharp-edged steel cylinder (core sampler). Before the implementation of SWCP, 5 core samples were collected at 5 sampling plots without replication. Similarly, 5 undisturbed core samples were collected after the implementation of SWCP at the same location as the samples taken before the implementation of SWCP. A total of 10 undisturbed soil samples were collected without replication.

About 5 soil samples were obtained before the implementation of SWCP in 2012, whereas 39 soil samples were collected after the implementation of SWCP in 2022. A total of 54 disturbed soil samples were collected from experimental treatments and replications (Table 1). For non-conserved plots, soil samples were collected at the edge of rectangular plots. For conserved areas, samples were excavated from the upper (0.5 m from the upper bund), middle (midpoint between two successive bunds), and lower (0.5 m from the lower bund) part of two successive bunds.

2.5 Laboratory analysis procedures

Soil samples were analyzed at Lihiket Design and Supervision Corporation Soil Laboratory, Bahir Dar (Ethiopia) where the analysis procedures were similar for soil samples collected both before and after soil and water conservation have been implemented. The samples were air-dried, crushed, and passed through a 2-mm sieve. The soil material that remained on the sieve was considered a percent coarse fragment, expressed by the mass of coarse material divided by the mass of the soil sample multiplied by 100. Soil pH was determined potentiometrically in the supernatant suspension of 1:2.5 soil-to-water suspensions using a pH meter as described by Van Reeuwijk (1986). The electrical conductivity of the saturated paste (ECe) was evaluated on the filtrate of saturated soil paste extract obtained by vacuum suction using an electrical conductivity meter and adjusted to ECe at 25°C. Particle size distribution was determined by the hydrometer method (Bouyoucos, 1962) using sodium hexametaphosphate as dispersing agent, and bulk density was determined from the undisturbed core samples (Hao et al., 2008). Total porosity was determined using the formula indicated in Equation 1:

$$P = 1 - \frac{\rho b}{\rho s} 100 \quad (1)$$

Where P is total porosity (%), ρb is the bulk density (g cm^{-3}) and ρs is the particle density equal to 2.65 g cm^{-3} (Landon, 2014).

Available phosphorous content was determined by 0.5 M sodium bicarbonate extraction solution (pH 8.5) by Olsen (1982) method. The Kjeldahl method was used for total nitrogen determination (Bremmer and Mulvaney, 1982). Soil organic carbon was measured by the wet combustion procedure of the Walkley-Black method, and the amount of soil organic matter was calculated by multiplying the percent of organic carbon by a factor of 1.724 (Landon, 2014). The exchangeable bases (Na^+, Ca^{2+}, Mg^{2+}, and K^+) were extracted by excess ammonium acetate solution (Van Reeuwijk, 1986). Following the extraction, exchangeable Ca and Mg were read using atomic absorption spectrophotometer (AAS), and exchangeable Na and K were read by a flame photometer (Black, 1965). Cation exchange capacity (CEC) was determined by the ammonium acetate method from the distillation of the ammonium-saturated samples (Chapman, 1965). The percentage base saturation was calculated by dividing the sum of the base-forming cations (K^+, Mg^{2+}, $Ca^{2+,}$ and Na^+) by the CEC of the soil and multiplying by 100 (Landon, 2014).

The pressure plate membrane at 0.33 and 15 bars was used to determine the soil moisture content at field capacity and permanent wilting point, respectively. Available water holding capacity was estimated from the difference between the water content at field capacity and the permanent wilting point.

2.6 Soil quality improvement analysis

Soil quality improvement was examined by calculating the soil quality index as described by Leul et al. (2023). Principal component analysis (PCA) was used as a factor extraction method to group measured soil properties into different principal components and select the minimum dataset (MDS) of soil quality indicators that best represent soil quality function (Leul et al., 2023). In this study, 18 measured and derived soil quality indicators were subjected to correlation and PCA. The PCA helps to reduce the dimension of the dataset without losing any information and select the most important indicators of the soil quality while correlation was useful to understand the relationships among soil properties. In each PC, the indicator with the highest factor loading (greater than or equal to 0.7) absolute value is selected for further scoring. Multivariate correlation was used to reduce the redundancy of the data when more than one factor was retained under one PC (Gelaw et al., 2015; Guteta and Abegaz, 2017). One or more soil quality indicators that best represent soil quality function were nominated in each PCs considering the highest factor loading and bivariate correlation analysis results.

The scores of MDS indicators were determined using a linear function as a function of their performance of soil function using Equation 2 and Equation 3 for "less is better" and "more is better" correspondingly (Tesfahunegn, 2016; Yu et al., 2018).

$$S = \frac{Xmin}{X} \quad (2)$$

$$S = \frac{X}{Xmax} \quad (3)$$

Where S is the linear score varying from 0 to 1, Xmax and Xmin are the maximum and minimum values of each observed soil property and x is the value of the soil property. The soil quality indicators were scored as "more is better" for those properties that have a positive effect on the soil quality for example organic matter. "Less is better" for the soil properties with a negative effect on soil quality, for example, bulk density and "optimum" for one which can have a positive and negative effect when increasing or decreasing (Yu et al., 2018).

Accordingly, selected soil quality indicators were combined into a single index, and the soil quality index was calculated using Equation 4 as described by Leul et al. (2023).

$$SQI = \sum_{i=0}^{n} Wi\ x\ Si \quad (4)$$

Where Wi is the weighting factor of each indicator derived by PCA, Si is the linear score for the selected MDS and n is the number of soil parameters selected in the MDS. Finally, the soil of the study area was classified based on the weighted addictive soil quality index as low soil quality SQI (0.38–0.44), moderate soil quality (SQI, 0.45–0.54), and high soil quality (SQI, 0.55–0.6) and very high for SQI >0.6 (Li et al., 2004).

2.7 Statistical analysis

A normality test was performed to determine whether the data were normally distributed, using the Shapiro–Wilk normality test (Hanusz and Tarasińska, 2015) with a significance level greater than 0.05. Thus, non-normally distributed parameters were transformed using logarithmic transformation (Sedgwick, 2012).

Descriptive and inferential statistics such as mean, analysis of variance (ANOVA), and multivariate analysis were applied to data from disturbed and undisturbed soil samples. The relevant test statistics were applied to different soil quality indicators, and it was determined whether there was a significant difference before and after the implementation of SWCP, as well as the interaction effect of landscape and types of structures. Due to a lack of replicated data, paired samples T-tests were performed to compare bulk density, soil moisture, and then available water content and total porosity data of correlated samples.

Soil data from disturbed samples were analyzed using one-way ANOVA to test the overall effects of SWCP on soil quality indicators (SQI), before and after the implementation of SWCP. Concomitantly, two-way ANOVA was made to test the interaction effects of landscape and conservation practices on soil physicochemical properties as indicated in Supplementary Table S1. Tukey (HSD) multiple comparisons test was used to distinguish differences among treatment means.

All significant tests were carried out at a significance level of $p < 0.05$ unless specified. The statistical analysis was manipulated using Statistical Package for Social Scientists (SPSS) V 26.0 (IBM Corporation, United States).

3 Results

3.1 Effects of SWC interventions on soil physical quality

3.1.1 Soil bulk density and total porosity

There was a significant ($p < 0.05$) difference in soil bulk densities before and after the implementation of SWCP (Table 2). As shown in Supplementary Table S2, the mean bulk density value before the

TABLE 2 Statistical significance level of main effects and their interactions.

No	Soil properties	Before and after SWCP		Among landscape units		Among types of management practices		Landscape and management practices interaction	
		T-value	*p*-value	*F*-value	*p*-value	*F*-value	*p*-value	*F*-value	*p*-value
1	Bulk Density	3.164	0.034	–	–	–	–	–	–
2	Total Porosity	3.164	0.034	–	–	–	–	–	–
3	FC	4.225	0.01	–	–	–	–	–	–
4	PWP	0.99	0.37	–	–	–	–	–	–
5	AWC	3.10	0.04	–	–	–	–	–	–
6	Coarse fragment (%)	8.088	0.007	208.33	0.00	167.61	0.00	57.33	0.00
7	Sand (%)	0.056	0.814	15.46	0.00	0.31	0.82	1.05	0.40
8	Silt (%)	1.099	0.300	4.40	0.02	0.66	0.58	0.18	0.97
9	Clay (%)	0.235	0.630	8.39	0.001	0.34	0.79	0.38	0.86
10	pH	11.046	0.002	5.11	0.01	4.26	0.01	0.86	0.52
11	EC	0.865	0.357	0.89	0.42	0.97	0.42	1.57	0.19
12	OM	71.667	0.000	15.75	0.00	71.38	0.00	3.23	0.01
13	TN	28.032	0.000	31.23	0.00	76.07	0.00	14.47	0.00
14	C: N	23.797	0.000	1.06	0.36	5.05	0.004	1.59	0.18
15	P	21.961	0.000	13.16	0.00	15.32	0.00	1.09	0.38
16	Ca	2.254	0.14	19.76	0.00	8.74	0.00	2.44	0.05
17	Mg	1.178	0.28	56.60	0.00	19.46	0.00	9.88	0.00
18	Na	3.871	0.056	3.33	0.05	7.43	0.00	0.83	0.54
19	K	0.817	0.371	46.09	0.00	3.92	0.01	0.38	0.86
20	CEC	3.254	0.078	71.84	0.00	4.57	0.00	1.02	0.42
21	BS	0.001	0.971	21.29	0.00	6.87	0.00	6.86	0.00

FC, field capacity; PWP, permanent wilting point; AWC, available water content; pH, $-\log[H^+]$; EC, electric conductivity; OM, organic matter; TN, total nitrogen; C:N, carbon nitrogen ratio; P, available phosphorous; Ca: calcium; Mg: magnesium; K, potassium; CEC, cation exchange capacity; and BS, base saturation.

implementation of SWCP (1.44 g cm^{-3}) was greater than after the implementation of SWCP (1.28 g cm^{-3}). The study found that SWCP reduces bulk density by 11% on average, but the magnitude varies by landscape unit (Supplementary Table S2).

Soil total porosity ranged from 42.45 ± 10.38% before the implementation of SWCP and changed to 53.20 ± 0.00% after the implementation of SWCP. The mean total porosity after SWCP implementation was significantly higher (51.7%) than before SWCP implementation (45.7%) and the difference was significant at $p < 0.05$ (Table 2). The implementation of SWCP resulted in an average 13% improvement in total porosity (Supplementary Table S2; Figure 2).

3.1.2 Soil moisture content

The moisture contents of soils improved significantly following the implementation of SWCP as indicated in Supplementary Table S3, and the difference was significant for field capacity (FC) ($p = 0.01$) and available moisture content ($p = 0.04$; Table 2). In contrast, there was a non-significant difference for permanent wilting point (PWP) ($p = 0.37$). The volumetric moisture content after the implementation of SWCP (14.14%) was higher than before SWCP implementation (10.31%) (Supplementary Table S3). Similarly, soil FC after the implementation of SWCP (38.27%) was considerably greater than before SWCP implementation (33.59%).

The AWC was significantly higher in treated soils than in untreated soils, but it varied both in space and time (Figure 2). The highest mean AWC recorded after SWCP implementation was 14.14 ± 0.88%, whereas the mean AWC before the SWCP was 10.31 ± 1.17% as presented in Supplementary Table S3.

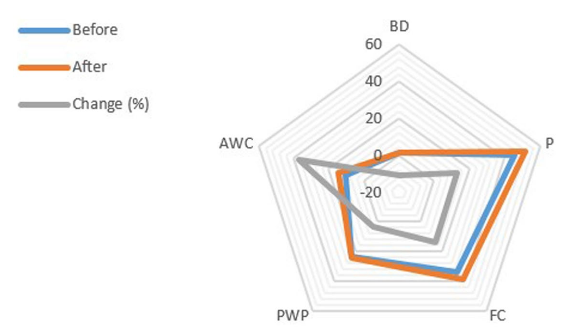

FIGURE 2
Soil physical and hydrological properties before and after the implementation of SWCP and percent changes due to SWCP (BD-bulk density; P-total porosity, FC-field capacity; PWP-permanent wilting point and AWC-available water content).

3.1.3 Coarse fragment

There was a significant ($p < 0.01$) difference in the proportion of coarse fragments before and after the implementation of SWCP

TABLE 3 Effects of landscape units and types of SWCP on coarse fragments (CF), organic matter (OM), total nitrogen (TN), calcium (Ca^{2+}), magnesium (Mg^{2+}), and base saturation (BS).

Landscape unit	Type of SWCP	CF	OM	TN	Ca2+	Mg2+	BS
Upper slope	Non-conserved 2012	2.80^{a}	1.35^{a}	0.13^{ab}	10.77^{a}	2.77^{a}	33.64^{a}
	Soil bund	2.62^{a}	3.00^{de}	0.41^{c}	12.70^{abc}	3.74^{abc}	37.00^{a}
	Stone-faced soil bund	2.75^{a}	3.10^{de}	0.44^{c}	13.65^{abcd}	4.02^{abc}	40.22^{ab}
Middle slope	Non-conserved 2012	10.82^{d}	2.07^{abc}	0.14^{ab}	13.54^{abcd}	4.63^{bcd}	52.99^{bc}
	Non-conserved 2022	13.73^{e}	1.79^{ab}	0.06^{a}	11.85^{ab}	3.99^{abc}	44.76^{abc}
	Soil bund	8.52^{c}	3.34^{ef}	0.33^{bc}	16.81^{bcde}	5.10^{cde}	59.46^{c}
	Stone-faced soil bund	2.35^{a}	2.85^{cde}	0.41^{c}	12.34^{abc}	4.02^{abc}	36.19^{a}
Lower slope	Non-conserved 2012	6.60^{b}	2.35^{bcd}	0.06^{ab}	17.60^{cde}	5.88^{def}	43.40^{ab}
	Non-conserved 2022	9.70^{cd}	1.94^{ab}	0.09^{ab}	12.60^{abc}	3.40^{ab}	30.73^{a}
	Soil bund	3.50^{a}	4.10^{f}	1.10^{d}	19.60^{e}	6.80^{f}	45.55^{abc}
	Stone-faced soil bund	5.20^{b}	3.4^{ef}	0.90^{d}	18.20^{de}	6.20^{ef}	43.26^{ab}

Means in the same column represented by the same letter are not statistically significant.

(Table 2). The mean percentage of coarse fragments before the implementation of the SWCP was 6.8% which changed to 4.1% after the implementation of the SWCP.

The interaction of landscape and conservation practices had a significant effect on the percentage of coarse fragments, at $p<0.01$. The highest mean coarse fragments, 13.73% were observed in soil samples taken from non-conserved plots in the middle landscape in 2022 (Table 3).

3.1.4 Particle size distribution

There was no significant difference in sand, silt, and clay content before and after the implementation of SWCP (Table 2). However, the proportion of sand and clay was slightly reduced while the percentage of silt was slightly higher after the implementation of SWCP as compared to before the implementation of SWCP (Figure 3).

The interaction effect of landscape and conservation practices on sand ($p=0.4$), silt ($p=0.97$), and clay ($p=0.86$) content were statistically non-significant. Similarly, the effect of conservation practices had no significant effect on sand, silt, and clay content (Table 2). Landscape, on the other hand, had a significant effect on sand and clay content at $p<0.01$ and silt content at $p<0.05$. The lower landscape had the highest clay content (58.19%) as indicated in Supplementary Table S5.

3.2 Effects of SWC interventions on soil biochemical properties

3.2.1 Soil organic matter

The organic matter content of the soil demonstrated a significant variation between before and after the implementation of SWCP at $p<0.01$ (Table 2). The mean organic matter content of soils was 1.84% before the implementation of SWCP and increased to 3.21% after the implementation of SWCP.

The landscape and conservation practices interaction had a significant ($p=0.015$; Table 2) effect on soil organic matter content. Soil bund (4.10%) and stone-faced soil bund (3.41%), accounted for the highest mean organic matter content (Table 3; Figure 4). When compared to other treatment combinations, the plots without conservation structures accounted for the least amount of organic matter content. Overall, when compared to 2012 measurements, both soil and stone-faced soil bunds increase soil organic matter content across all landscapes, but the magnitude was greater in the lower landscape than in the middle and upper landscape positions (Figure 4).

3.2.2 Soil pH and ECe

There was a significant difference in pH value ($p<0.01$) before and after the implementation of SWCP but exhibited a non-significant difference in electric conductivity ($p=0.36$). The mean pH value was 5.69 before the implementation of SWCP and drastically lowered to 5.25 after the implementation of SWCP.

The interaction effects of landscape and conservation practices did not affect soil pH and ECe. Unlike ECe, soil pH was significantly affected by both the main effects of landscape and conservation practices (Table 2). The mean soil pH value in the lower landscape (5.74) was substantially higher than the upper and middle landscape's (5.33) as presented in Supplementary Table S5. The mean soil pH value of non-conserved plots sampled in 2012 (5.69) and in 2022 (5.55) was significantly higher when compared with farm plots treated with both stone-faced soil bunds and soil bunds (Supplementary Table S4).

3.2.3 Soil total nitrogen

The analysis of variance performed before and after the implementation of the SWCP revealed a significant variation ($p<0.01$) in the total nitrogen content (Table 2). The mean total nitrogen was 0.12% before the implementation of the SWCP and increased to 0.58% following the implementation of the SWCP.

The interaction effect of landscape and conservation practices on the mean total nitrogen content was significant ($p\leq0.01$; Table 2). When compared to other interactions, lower landscape soil bunds (1.10%) and stone-faced soil bunds (0.90%) had the highest mean TN (Table 3). Farm plots without conservation structures (from 0.06–0.14%; Table 3) at three landscape positions accounted for the least nitrogen content. Overall, both soil and stone-faced soil bunds increase

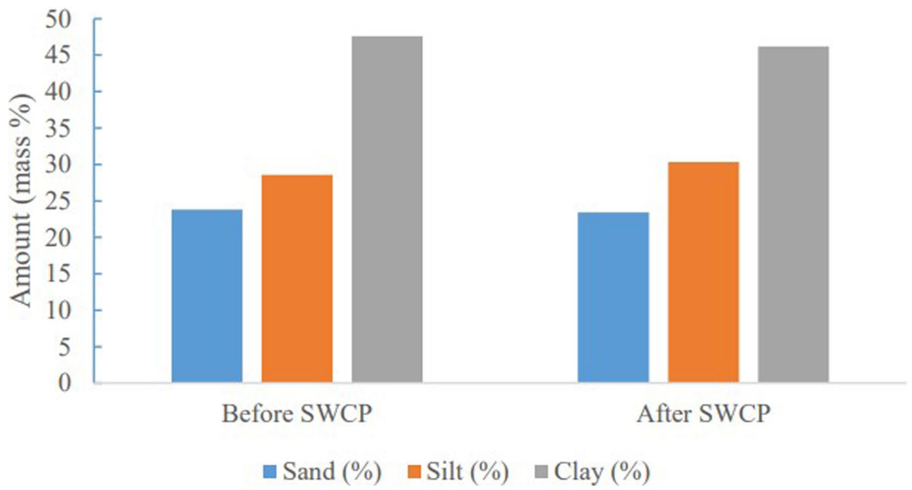

FIGURE 3
Effects of SWCP on sand, silt, and clay content of soils.

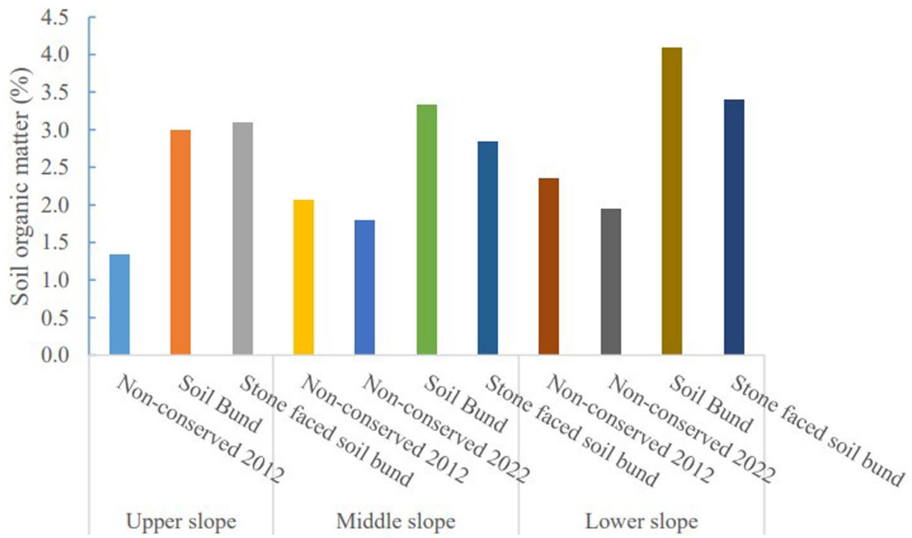

FIGURE 4
Representation of the effect of landscape and conservation practices on soil organic matter content.

nitrogen content, but the magnitude was greater at lower than middle and upper landscapes. The lower landscapes had very low nitrogen content as compared to other landscape units in 2012 but improved faster than the middle and upper landscapes after SWCP treatment.

3.2.4 Available phosphorous

There was a significant ($p < 0.01$) difference in available phosphorous content (Table 2) between before and after the implementation of SWCP. The mean available phosphorous content was 5.54 ppm before SWCP and significantly increased to 10.19 ppm after the implementation of SWCP.

Available phosphorous was non-significantly affected by the interaction effects of landscape and conservation practices, but significantly affected by the main effects of conservation practices and landscape positions (Table 2). Results from plots with stone-faced soil bunds (10.48 ppm) and soil bunds (9.91 ppm) had a significantly higher mean available phosphorous (Supplementary Tables S4, S5). Furthermore, the mean available phosphorous was significantly higher at the upper landscape (10.54 ppm), followed by the middle (7.17 ppm) and lower landscape (4.81 ppm).

3.2.5 Exchangeable bases

The statistical analysis result showed non-significant differences for calcium ($p = 0.14$), magnesium ($p = 0.28$), sodium ($p = 0.05$), and potassium ($p = 0.37$) content between before and after the implementation of SWCP. However, as presented in Table 3, unlike potassium and sodium, the interaction effect of landscape and conservation practices was significant for magnesium ($p < 0.01$) and calcium ($p < 0.05$) content.

Landscape had a significant effect on potassium content ($p < 0.01$) and sodium content ($p < 0.05$; Table 2). The highest mean sodium

TABLE 4 Results of PCA for soil attributes from different types of conservation practices and landscape positions based on the minimum data set (MDS) method.

Principal component	PCA1	PCA2	PCA3	Communality
Coarse fragments (%)	−0.49	−0.14	**0.71**	0.90
pH H_2O	0.50	**−0.91**	0.00	0.85
Sand (%)	0.40	−0.78	0.44	0.95
Silt (%)	0.61	−0.72	−0.14	0.90
Clay (%)	−0.53	0.81	−0.21	0.97
OM (%)	**0.81**	0.48	0.01	0.88
TN (%)	**0.71**	0.57	−0.12	0.84
P (ppm)	**0.71**	−0.43	−0.51	0.95
Ca (Cmolc kg^{-1})	0.37	0.84	0.35	0.97
Mg (Cmolc kg^{-1})	0.38	0.77	0.48	0.98
Na (Cmolc kg^{-1})	0.51	0.76	0.32	0.95
K (Cmolc kg^{-1})	0.02	**0.92**	−0.09	0.99
CEC (Cmolc kg^{-1})	−0.01	**0.94**	−0.31	0.98
BS (%)	0.37	**0.91**	−0.07	0.97
Bulk density (g cm^{-3})	−0.18	−0.07	**−0.86**	0.89
FC (% vol)	0.44	0.19	0.66	0.72
PWP (% vol)	0.38	0.21	0.62	0.69
AWC (% vol)	0.46	0.52	**0.74**	0.75
Eigenvalue	6.22	4.51	2.93	
% Variance	41.47	30.03	19.50	
% Cumulative variance	41.47	71.50	91.00	
Weightage factor	0.46	0.33	0.21	

FC, field capacity; PWP, permanent wilting point; AWC, available water content; pH, −log[H^+]; EC, electric conductivity; OM, organic matter; TN, total nitrogen; C:N, carbon nitrogen ratio; P, available phosphorous; Ca, calcium; Mg, magnesium; K, potassium; CEC, cation exchange capacity; and BS, base saturation. The soil parameters in bold are the ones with high load and those in bold and underlined are selected as soil quality indicators (retained in the MDS).

(0.16 Cmolc kg^{-1}) and potassium (1.04 Cmolc kg^{-1} soil) content were observed in the lower landscape as indicated in Supplementary Table S5. Moreover, conservation practices have a significant effect on sodium ($p \le 0.01$), and potassium ($p \le 0.01$) content. Plots with soil bunds (0.18 Cmolc kg^{-1} soil) had the highest sodium content as compared with other treatments (Supplementary Table S4).

3.2.6 Cation exchange capacity and base saturation

There was a non-significant difference in CEC ($p = 0.08$) and percent BS ($p = 0.97$) before and after the implementation of SWCP. Similarly, CEC was non-significantly affected by the interaction effects of landscape and conservation practices. But, the interaction effect of landscape and conservation practices on BS was significant ($p < 0.01$). Soil bunds in the middle (59.46%) and lower landscape (45.55%) showed the highest mean base saturation (Table 3).

Conservation practice, both in space and time has a significant effect on CEC ($p \le 0.01$). The highest significant mean CEC was observed on soil bunds (46.28 Cmolc kg^{-1}) and stone-faced soil bunds (48.17 Cmolc kg^{-1} soil) treated farm fields (Supplementary Table S4). Similarly, the landscape had a significant effect on CEC ($p < 0.05$). The highest CEC (58.05 Cmolc kg^{-1} soil) was observed on the lower landscape (Supplementary Table S5).

3.3 Soil quality indicators

To effectively describe the soil quality dynamics in the research area, about 18 soil parameters were used for principal component analysis. Principal component analysis (PCA) extracted three components that have eigenvalue greater than one and explained 91% of the total variability. PCA1, PCA2, and PCA3 accounted for 41.47, 30.03, and 19.50% of the variability in the same order (Table 4). Major indications under each principal component were attributed to a significant weight loading and variance. As shown in Table 4, PCA1 accounts for 41.47% of the variance in soil quality and is regarded as the best soil quality indicator in this study. In PCA1, the highly loaded variables are organic matter (OM), total nitrogen (TN), and available phosphorous accounted for 0.81, 0.71, and 0.71, respectively. Organic matter has the highest load and hence retained and the correlation of the other variables was checked. The correlation between organic matter with total nitrogen was significant (Supplementary Table S6). Hence, total nitrogen was not retained in PCA1. The correlation between organic matter and available phosphorous was not strong, therefore it was retained in the first PCA. Thus, based on their larger weight loading, soil organic matter, and available phosphorous content were the two most heavily weighted variables under PCA1 and considered soil biological quality components.

In the second factor (PCA2), the high load variables are cation exchange capacity, exchangeable potassium, soil pH and base saturation with high weighted variables of 0.94, 0.92, 0.91, and 0.91, respectively (Table 4). Due to a significant correlation between cation exchange capacity and exchangeable potassium (Supplementary Table S6), exchangeable potassium was not retained. As a result, the CEC, pH, and BS were kept for the minimum data set (MDS) requirement in PCA2. This PCA2 is renamed as "chemical quality component."

Soil bulk density, available water holding capacity (AWC), and percent coarse fragment had a high load in the third component that accounted for 19.5% of the variability (Table 4) and found no strong correlation between variables. The minimum data set in PCA3 includes bulk density, available water capacity, and coarse fragment. This component represented the "soil physical quality component".

3.4 Soil quality improvements in conserved landscape

To further understand the impacts of soil and water conservation on soil quality, a weighted additive soil quality index (SQI) generated from the PCA was developed. According to the PCA and correlation, the contents of soil organic matter, available phosphorous, pH, cation exchange capacity, bulk density, available water holding capacity, and contents of coarse fragments were selected as the primary indicators of the soil quality index, as shown in Table 4.

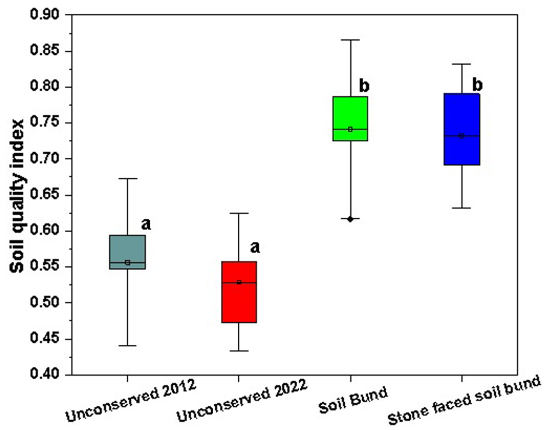

FIGURE 5
SQI for the different soil and water conservation practices (SWCP), unconserved fields before SWCP (2012) and unconserved fields after SWCP (2022) (means represented by the same letter are not significant at $p < 0.05$ level).

The difference in SQI between treatments was statistically highly significant ($p = 0.00$). The difference in treatment means is also statistically significant. However, no significant differences were observed between untreated fields in 2012 and 2022, or between soil bunds and stone-faced soil bunds (Figure 5). Based on the weighted additive soil quality index and the limited data set, the soil quality index in this study varied from 0.53 to 0.74. The mean soil quality index for soil samples obtained in 2012 (before SWCP) was 0.56, but it declined to 0.53 for non-conserved agricultural plots assessed in 2022, suggesting a 5.26% fall in overall soil quality, as indicated in Figure 5, Table 5, and Supplementary Table S7. For conserved plots, stone-faced soil bund has the lowest soil quality index (0.73), while soil bund has a soil quality rating of 0.74 (Table 5). The study area's soils were originally classified as high soil quality (0.56), but soil bunds and stone-faced soil bunds improved to very high soil quality indexes of 0.74 and 0.73, respectively. Soil and water conservation practices improved soil quality by 32% for stone-faced soil bunds, 33% for soil bunds, and declined by 5.26% for areas without soil and water conservation practices. However, soil quality index was non-significantly affected by landscape units ($p = 0.14$) and the interaction effects of landscape and conservation practices ($p = 0.6$).

Table 6 and Supplementary Figure S1 show the observed association between soil quality indicators and soil quality index. The soil quality index and available phosphorous ($R^2 = 0.70$) and organic matter ($R^2 = 0.68$) had a significant and positive correlation. There was a modest correlation with percent coarse fragment ($R^2 = 0.41$), bulk density ($R^2 = 0.3$), and cation exchange capacity ($R^2 = 0.23$), as well as extremely low associations with percent base saturation and available water holding capacity (Table 6; Supplementary Figure S1).

4 Discussion

4.1 Effects of SWC interventions on soil physical quality

Following the implementation of the SWCP, there was a considerable improvement in total porosity (13%), available soil moisture, and FC soil moisture, as well as a decrease in bulk density

TABLE 5 Soil quality index computations.

Conservation practices	Summation of Scoring (Si) and weighting (Wi) of soil quality indicators								SQI
	OM, %	*P*, ppm	pH H_2O	CEC, Cmolc/kg	BS, %	BD (g/cm3)	AWC, %	Coarse fragments (%)	
2012 W/O SWCP	0.11	0.08	0.10	0.08	0.06	0.06	0.04	0.03	0.56
2022 W/O SWCP	0.11	0.05	0.10	0.08	0.06	0.07	0.06	0.01	0.53
Soil bund	0.20	0.14	0.09	0.08	0.07	0.07	0.06	0.03	0.74
Soil and stone bund	0.18	0.15	0.09	0.09	0.06	0.07	0.05	0.05	0.73

SQI, Soil Quality Index. 2012 W/O SWCP refer to analysis results from unconserved fields in 2012, 2022 W/O SWCP refer to analysis results from unconserved fields in 2022. Si is the score of each parameter in the MDS, and Wi is the weighting of soil indicators. OM, organic matter; P, available phosphorous; CEC, cation exchange capacity; BS, base saturation; BD, bulk density; AWC, available water content.

TABLE 6 Relationships between soil quality index (SQI) and soil quality indicators expressed using R^2.

	OM (%)	*P* (ppm)	pH H_2O	CEC (Cmolc/kg)	BS (%)	BD (g/cm^3)	AWC (%)	Coarse fragments (%)
SQI	0.68	0.70	0.08	0.23	0.01	0.30	0.17	0.41

SQI, soil quality index; OM, organic matter; P, available phosphorous; CEC, cation exchange capacity; BS, base saturation; BD, bulk density; AWC, available water content.

(10%) and coarse fragments. The lower mean bulk density and higher total porosity implied from higher improvement in soil organic matter after the implementation of SWCP. Siraw et al. (2020) and Taye et al. (2022) revealed parallel findings in conserved watersheds in Ethiopia, which were generally ascribed to reduced slope gradients, slower runoff, and improved sediment and soil organic matter settlement. These innovations have an agreement with the present study described that SWCP accumulates soil organic matter and lower bulk density.

In the present study, SWCP improved FC, and available water holding capacity as a result of organic matter improvement and reduced soil erosion rates due to decreased runoff, enhanced infiltration, and thereof soil moisture content. This is because of the shorter slope length that created a runoff barrier and enhanced soil water-holding capacity, thereby filling soil pores with moisture within the conserved areas. This pattern corresponds to the findings of Tolesa et al. (2021), Tiki et al. (2015), Pramanick et al. (2022), and Siraw et al. (2020). This is owing to the improvement of organic matter and retention of soil particles due to the implementation of SWCP. The observed differences indicated the potential of SWCP to improve key soil biological and hydrological properties.

The percent of coarse fragments decreased significantly after the implementation of SWCP. This means that non-conserved soils are more prone to erosion and contain a higher percentage of coarse fragments than conserved soils. This is because bund reduced the loss of soil particles (Amare et al., 2013; Belayneh et al., 2019) and lowered the percentage of coarse fragments indirectly. When compared to the respective data from non-conserved plots in 2012, there was a substantial increase in coarse fragments on non-conserved plots sampled in 2022. Welemariam et al. (2018), reported comparatively greater percentages of coarse fragments on non-conserved grazing pastures, while terraces had significantly lower percentages of coarse fragments in Ethiopia highlands.

Significant changes in soil texture were not anticipated within the study time frame because the process of soil formation takes several years to alter soil texture. The modest change in the percent sand, silt, and clay in this study could be attributed to the process of particle removal from one portion of the watershed and deposition in another location within the study area. This is consistent with the findings of Tolesa et al. (2021) and Siraw et al. (2020), who found no significant differences in sand, silt, and clay content following the implementation of SWCP, due to the short duration of the watershed practice, which was 8 years, which cannot make a significant difference in weathering of materials. Demelash and Stahr (2010), on the other hand, found a substantial difference in soil texture after 10 years of conservation. The disparities in percent sand, silt, and clay in the upper, middle, and lower slopes were attributable to clay migration downward at any condition including conserved fields. Because of the increased deposition of enormous masses of clay down the slope, the clay content of the soil increases from the upper to the lower landscape. This conclusion is similar to the findings of Hishe et al. (2017) and Tamene et al. (2017), who found substantial changes in soil particles with landscape position. This means that SWCPs are ineffective at retaining clay materials in high rainfall sub-humid ecosystems when fine clay materials are prone to moving with the removal of surplus water.

4.2 Effects of SWC interventions on soil biochemical properties

A 75% increase in soil organic matter content could be attributed to increased root and above-ground biomass and deposition and retention of organic matter due to the implementation of SWCP. This difference was caused by increased deposition and biomass cover as a result of SWCP implementation. Several researchers reported similar findings (Hishe et al., 2017; Alewoye Getie et al., 2020; Guadie et al., 2020; Laik et al., 2021). Furthermore, increased soil organic matter content has a positive impact on soil quality indicators such as water holding capacity, total porosity, bulk density, pH, and total nitrogen which improves water availability, aeration, rooting condition, and fertility quality components in conserved plots.

The considerable decrease in soil pH could be caused by an increase in soil organic matter, increased infiltration, and leaching of soluble ions in subhumid areas following the implementation of SWCP. The leaching of cations from upper and middle landscapes and deposition in the lower landscapes could be a major reason for the differentiation of soil pH across landscapes. This result is consistent with the findings of Erkossa et al. (2018) and Pham et al. (2018). In all the cases, SWCP significantly lowerd soil pH value. This implies, soil pH slightly decreased with time without the implementation of SWCP mainly due to continuous leaching of basic cations and pH significantly decreases with the implementation of SWCP mainly due to improvement in soil organic matter content. Similar results were reported by Belayneh et al. (2019) and Demelash and Stahr (2010) in the highlands of Ethiopia.

The effect of SWCP on total nitrogen was significant and this coincides with Yifru and Miheretu (2022), Yaekob et al. (2022), Tolesa et al. (2021), Siraw et al. (2020), Mengistu et al. (2016), Dagnew et al. (2015), and Demelash and Stahr (2010) reported higher nitrogen content in terraced landscapes. Without SWCP, nitrogen content declined by 57% on the middle landscape and increased by 50% on the lower landscape. This discrepancy was attributed to nitrogen removal from upper and middle landscapes and its deposition to lower landscapes and the retention capacity of bunds. Studies confirmed the existence of the highest total nitrogen in lower landscapes and conserved farm fields (Assefa et al., 2020).

The increase in phosphorous content was mainly due to the overtime accumulation of phosphorous fertilizer application and less soil erosion and less removal of available and applied phosphorous because of SWCP. Similar implications have been reported by Tanto-Doko (2022). Overall, there was a slight decrease in mean available phosphorous from non-conserved farm plots sampled in 2022 as compared to 2012 due to continuous soil erosion. However, there was a significant increase in mean available phosphorous content due to SWCP as compared to non-conserved plots sampled in both 2012 and 2022. Phosphorous was higher in upper than lower lopes. This assessment result was attributed to the high rates of application of phosphorous fertilizers at the upper landscape dominated by Nitisols and Luvisols along with being less liable to leaching, unlike other nutrient elements. The lower landscape is dominated by Vertisols, which are clayey and have a high organic matter content, and where the soil phosphorous content is prone to fixation problems due to a clayey organic matter complex.

Exchangeable bases (Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}) are weathering derived. Therefore, no significant changes are envisaged within the years of SWCP implementation. However, there were significant differences in the interaction effect of landscape and management practices on Ca and Mg. In each instance, the maximum calcium and magnesium content was observed in soil bunds constructed at the lower landscape, where exchangeable bases are soluble with runoff water and liable to drain downslope and excellently retained by soil bunds of lower landscapes. On the other hand, the main effects of landscape and management practices on Na and K content are significant due to the effect of conservation structures on the erosion processes, which affect the distribution of basic cations over upper, middle, and lower landscapes. This could also be related to their removal from the upper slopes and depositions in the lower slopes. The findings of Noorbakhsh et al. (2008) also reported significant differences in available K among landscapes which increased downslope. The significantly higher K and Na were observed on plots with soil and stone-faced soil bunds and this result is consistent with the reports of Amare et al. (2013) and Taye et al. (2022), which clarified the accumulation of soluble bases in conserved fields.

Lower and middle landscapes received bases from upper landscapes and conserved the existing ones due to SWCP, hence a high percent is expected. However, the larger CEC at lower landscapes may result in a low percent base saturation. Nonetheless, due to SWCP, which lowers cation removal and favors cation deposition in the upper landscape, the percent base saturation stays high in the lower landscape but slightly lower than in the middle landscape. This conclusion was related to increased clay and organic matter content at lower landscape positions. Cation exchange capacity varies with clay content, type, and soil organic matter. Vertisols in lower landscapes typically have high CEC values due to smectitic clay mineralogy and increased clay content. However, Nitisols with kaolinitic mineralogy in the upper landscape tend to have low CEC.

4.3 Soil quality improvement

Soil and water management-induced soil dynamics were assessed using the soil quality index. The assessment was based on 8 selected soil quality indicators which were systematically regrouped into biological, chemical, and physical soil quality components. The highest contribution for the SQI was found for soil biological properties (organic matter content and available phosphorous) weighted about 46%, followed by chemical properties (soil pH, cation exchange capacity, and percent base saturation) weighted 33%, and physical properties (bulk density, available water holding capacity) which have 21% contribution. In this study, organic matter content contributed 25% of the soil quality index. Soil biology is an excellent indication of soil quality and health since soil organic matter content impacts nutrient reserve, soil structure, infiltration rate, water retention capacity, and numerous soil ecological functions (Ngangom et al., 2020; Cai et al., 2022; Hassan et al., 2022). In tropical ecosystems, soil fertility is also an important quality component that impacts soil productivity as well as controlling soil biological, chemical, and physical features (Schiefer et al., 2015; Erkossa et al., 2018). Furthermore, soil pH influences nutrient availability and toxicity, which influences soil health and crop yield (Khelil et al., 2020; Kebede et al., 2022). Soil moisture impacts crop production in any ecosystem (Uwizeyimana et al., 2018; Wen et al., 2021). Bulk density is a basic quality indicator that affects soil strength and stability (Koudahe et al., 2022). As a result, the three soil quality components explain soil quality dynamics in the study area and, most likely, in other sub-humid tropical ecosystems.

The overall soil quality improvement due to the implementation of SWCP was 32% for stone-faced soil bunds and 33% for soil bunds mainly from the complimentary effects of three soil quality components. However, soil quality decreased by 5.26% from 2012 to 2022 on farm plots without the implementation of soil and water conservation structures. This conclusion implies landscape-conservation practices were the best implementation strategy in sub-humid highland ecosystems to improve soil quality. This suggests that non-conserved soils are more prone to soil quality deterioration. This is why soil and stone-faced soil bunds reduce the deterioration of certain soil quality indicators (Amare et al., 2013; Belayneh et al., 2019).

The effect of SWCP on soil quality indicators shows considerable results in reversing soil quality degradation and improving soil biology, fertility, and hydrology. This can help to enhance land rehabilitation and increase land productivity. In addition to land rehabilitation, soil quality improvement at the landscape scale could enhance hydrological services, carbon sequestration, and crop productivity. However, there are wide variations among research reports, which may be related to differences in the level of efficiency of SWC measures due to differences in age and type of SWCP, quality of construction, scale of maintenance, and agroecology. The majority of soil quality indicators yielded meaningful findings in this investigation.

5 Conclusion

The study looked into the effects of SWCP on soil physicochemical properties and soil quality in a sub-humid ecosystem. SWC practices have been critical in reversing land degradation and limiting additional harm to land resources. According to the study results, soil and water conservation measures demonstrated a statistically significant difference in most soil quality indicators when compared to conventional farmlands. Organic matter, available phosphorous, cation exchange capacity, soil pH, percent base saturation, bulk density, available water holding capacity and percent coarse fragments could be most relevant indicators of changes in soil quality induced by soil and water conservation practices. The soil quality indexing showed that SWCPs improved soil quality by 32.15% overall. The level of improvement was 32% for stone bunds and 33% for soil bunds, in contrast to a 5.26% decrease in soil quality on farm fields without soil and water conservation practices from 2012 to 2022. As a result, the null hypothesis is invalid, and the study accepts the alternative once demonstrating that the highlighted soil and water conservation practices significantly improve soil physicochemical properties, soil quality, and crop productivity in Ethiopia's subhumid environments. However, in terms of the present food insecurity and sustainability problem, overall improvement in soil quality remains lower. This might be attributed to inadequate farm management and maintenance, as well as a failure to prioritize the integration of various forms of SWC and agronomic practices capable of sustaining long-term advantages in soil quality, land productivity and ecosystem services. This implies that SCWP, which was limited to soil and stone-faced soil bunds like the majority of Ethiopian community watersheds, significantly affected the rate of improvement and shown the potential to improve even more than this value. Thus, in the future, integration of additional SWCP (agronomic and biological practices) would be the most likely alternative option for full-fledged soil quality enhancement.

We propose an additional soil quality study on best and integrated land management and its improvements in soil quality attributes, crop productivity and ecosystem services in the highlands of Ethiopia.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

AT: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Writing – original draft. WA: Methodology, Writing – review & editing. MH: Writing – review & editing, Formal analysis, Software. DM: Writing – review & editing, Conceptualization, Investigation. FZ: Formal analysis, Writing – review & editing, Supervision. GD: Data curation, Formal analysis, Methodology, Supervision, Writing – review & editing. TA: Formal analysis, Methodology, Supervision, Writing – review & editing. ST: Writing – review & editing. MA: Conceptualization, Investigation, Writing – review & editing, Supervision.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. International Crops Research Institute for Semi-Arid Tropics provides financial support for publication of this article.

Acknowledgments

We are thankful to Ghent University for the support during a short research stay. The sustainable water management under pressure in Ethiopia project was providing a short research stay at Kiel University, Germany.

Conflict of interest

AT and WA were employed by Lihiket Design and Supervision Corporation.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2024.1270265/full#supplementary-material

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frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 06 March 2024
DOI 10.3389/fsufs.2024.1348094

OPEN ACCESS

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RECEIVED 01 December 2023
ACCEPTED 23 February 2024
PUBLISHED 06 March 2024

CITATION
Desta G, Legesse G, Ahmed MI, Muluneh A and Birhanu B (2024) Assessing flood risks and exploring opportunities for flood-based farming in the dry lowlands of Ethiopia.
Front. Sustain. Food Syst. 8:1348094.
doi: 10.3389/fsufs.2024.1348094

Assessing flood risks and exploring opportunities for flood-based farming in the dry lowlands of Ethiopia

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Food grown in the rainfed system in Ethiopia is frequently insufficient to meet household food needs due to recurrent drought, which causes severe food insecurity. Ethiopia's drylands have also been hit by an increase in torrential floods. As a result, the ability to adapt to shocks and risks decreases. Despite the opportunity of highland-to-lowland to lowland connectivity, the opportunities for flood-recession farming are poorly understood. This study maps flood recession opportunities incorporating national flood occurrence information, flood images, and SMAP surface soil moisture from Soil Moisture Active Passive (SMAP) images in Omo Gibe basin and Mile sub-basin. The analysis demonstrates that during the past three decades, there have been substantial flood incidents in the country's eastern, south-eastern, and southern regions. Notably, floods that happened in 1996, 2005, 2006, 2013, and 2018 affected 90, 91, 74, 74, and 69 locations, respectively. In 2020, flooding affected a considerable area (274 locations), which demonstrates the rise in flood hazards. Based on multi-criteria suitability analysis, about 32 million hectares of lowlands are highly suitable (61%) and moderately suitable (39%) for flood-based farming. In the Omo-Gibe and the Mile sub-basin, flood-recession zone mapping using a change detection approach revealed that Omo-Gibe basin has 107,359 ha and 29,550 ha of flood zones suitable for flood recession farming and Mile sub-basin of 8,048 ha and 88 ha, during the major and short rainy seasons, respectively. Our results highlight the extent of flood-prone areas and their suitability for flood farming and provide evidence of alternative strategies for managing flood risks. Consequently, identifying potential flood-prone areas using remote sensing technology aids decision-makers and subject-matter experts in introducing and demonstrating various types of flood-based farming. Further research is recommended to identify and validate appropriate flood farming practices under different biophysical and socio-economic contexts and explore complementary opportunities as well as support informed decision-making on flood risk management and recession flood strategies in the dry lowlands of Ethiopia.

KEYWORDS

flood occurrence, multi-criteria analysis, landscape segments, recession farming, Ethiopia

1 Introduction

Drylands are challenging environments where human ingenuity, knowledge systems, and the careful use of natural resources are essential for survival. Globally, drylands represent 45.4% (66.7 mill km2) of the Earth's total terrestrial area, significantly more than the previous statistical estimations (41%, ~ 60 mil km2) (MEA, 2005). Drylands cover 47 percent of the land in Eastern Africa or 328 million hectares; and the lowland dryland areas in Ethiopia, which are the focus of this study, cover about 55 percent of the landmass of the country (FAO, 2010). The drylands of Ethiopia have been faced with an increasing number of recurrent droughts and floods, leading to a decline in the potential for adaptation to shocks and risks (Davies and Bennett, 2007; OCHA, 2007). Due to the regular occurrence and cyclic nature of drought and flood in the lowlands, increasing disasters have become characteristics of large parts of the dryland pastoral and agro-pastoral populations (Müller-Mahn et al., 2010). Flooding is recognized as one of the major environmental hazards and catastrophic natural disasters in Ethiopia, and its physical manifestation has increased over the years (OCHA, 2007; Amede et al., 2022). The northeastern, eastern, southeastern, and southern lowlands of Ethiopia have experienced flash floods emerging from degraded highland mountain areas caused due to land use conversion, overgrazing, erosion, and soil depletion, which are also related to high intensities of rainfall in the highlands (Getnet et al., 2022; Gumma et al., 2022). Over the last decade, flood incidents have been significant across the country, and the events have become increasingly pronounced with the increase in the extent of land degradation in upstream areas (Barvels and Fensholt, 2021). The frequency and risks of large-scale river floods increase when heavy rainfall occurs on degraded mountainous areas in the highlands.

Managing flood water for productive use is one of the flood mitigation strategies that reduce flood hazards and simultaneously addresses food security issues in dry lowland environments (Gain et al., 2017; Amede et al., 2022; Zenebe et al., 2022). Many research findings stated that flood-based farming is an entry point to efficiently utilizing hazardous floods for productive use through various forms of engineering measures and agricultural practices (Mekdaschi Studer and Liniger, 2013; Tamagnone et al., 2020). For example, the potential suitability of spate irrigation was assessed and reported in Ethiopia (Hagos et al., 2014) and specifically in Logiya watershed in Afar (Bushira and Abudle, 2020) and Western Arsi (Chukalla et al., 2013). Flood-based farming, according to Steenbergen et al. (2011), contributes to food security and provides numerous environmental benefits across a wide range of geographies by making flood water available for agricultural use. Flood-based farming is important for nutritional security and household coping mechanisms during the dry season when other food sources are depleted (Singh et al., 2021). Annual flood regimes of rivers are important in flood-affected areas, where flood-based farming could be an effective solution to meet food security and sustain livelihoods (Motsumi et al., 2012; Balana et al., 2019; Tariq et al., 2020).

Flood-based farming is a rainfed farming system that occurs in dryland areas and relies on supplementary water derived from various types of floods (Liman Harou et al., 2020). It is a practice that depends on the residual soil moisture and soil nutrient deposits remains after flood recedes (Nederveen et al., 2011; Balana et al., 2019). Flood-based farming usually occurs in relatively low-lying areas with gentle topography. Various forms of flood-based farming are found across the world's drylands (Varisco, 1983; Steenbergen et al., 2011; Liman Harou et al., 2020). However, to determine the extent and duration of flood-based farming, the flood water supply is often difficult to predict due to uncertainties in the timing, duration, size, and frequency of floods from ephemeral and perennial streams (Steenbergen et al., 2011). Furthermore, to utilize riverine floods, the river courses are changing from season to season leading to changes in riverbed levels and sediment accumulations.

Flood-based farming has been inadequately studied and understood under the context of Ethiopian highland and lowland geographical configuration (Castelli and Bresci, 2017; Meaza et al., 2017). Alemayehu (2014) has made detailed assessments of the status of existing spate practices, challenges and potentials. He emphasized huge potential and the possibility of transforming the high spate potential to drought-prone lowland parts of the country. Meaza et al. (2017) studied the potentials of marginal grabens in their water resources and fertile soils in the Rift Valley of Ethiopia. Despite the information on the current status of spate practices and the availability of information on historical flash floods and disasters, a comprehensive locally and temporally disaggregated magnitude of flood events, as well as associated flood farming opportunities, is rarely available in Ethiopia. Nowadays, remotely sensed multi-temporal satellite imagery (Pacetti et al., 2017) significantly overcomes the limitations associated with measured data on flood incidents and moisture data at landscape scale; remote sensing and geospatial technologies and models, such as Google Earth Engine (GEE), remote sensing (RS) and GIS techniques, bivariate models, and machine learning tools, are frequently used to assess flood-prone areas and their potential for flood-based farming (Pandey et al., 2022; Priyatna et al., 2023). Flood risk analysis and mapping are the primary products used in flood risk management systems to visualize and represent information for decision-making processes. In this context, assessing and improving understanding of the spatial extent of flooding and the spatial dynamics of soil moisture is critical for land use planning and assessing the potential impact of flood-based farming on agricultural production in Ethiopia's dry and drought-affected lowlands. The objectives of this research are: (1) To identify the national flood risk areas through reviewing data and information from historical flood incidents, (2) to demarcate potential flood-prone areas optimally suitable for flood-based farming using experts' knowledge, and (3) to delineate flood recession zones and analyze the trends of seasonal soil moisture regimes of case study landscapes using remote sensing techniques for assessing the potential flood recession farming.

2 Materials and methods

2.1 Description of the study area

The Omo Gibe and Awash basins are the largest river basins in the southwestern and northeastern parts of Ethiopia, respectively. The study was conducted in two contrasting basin systems in the highland-lowland configuration: Mile Sub-basin which is one of the terminal sub-basin of Awash basin and Omo Gibe basin (Figure 1 and Table 1). Both sites also represent the landscape of hydrologically interconnected upstream highlands and downstream lowlands. Omo Gibe River Basin drains the heavy rainfall from the west, central, and

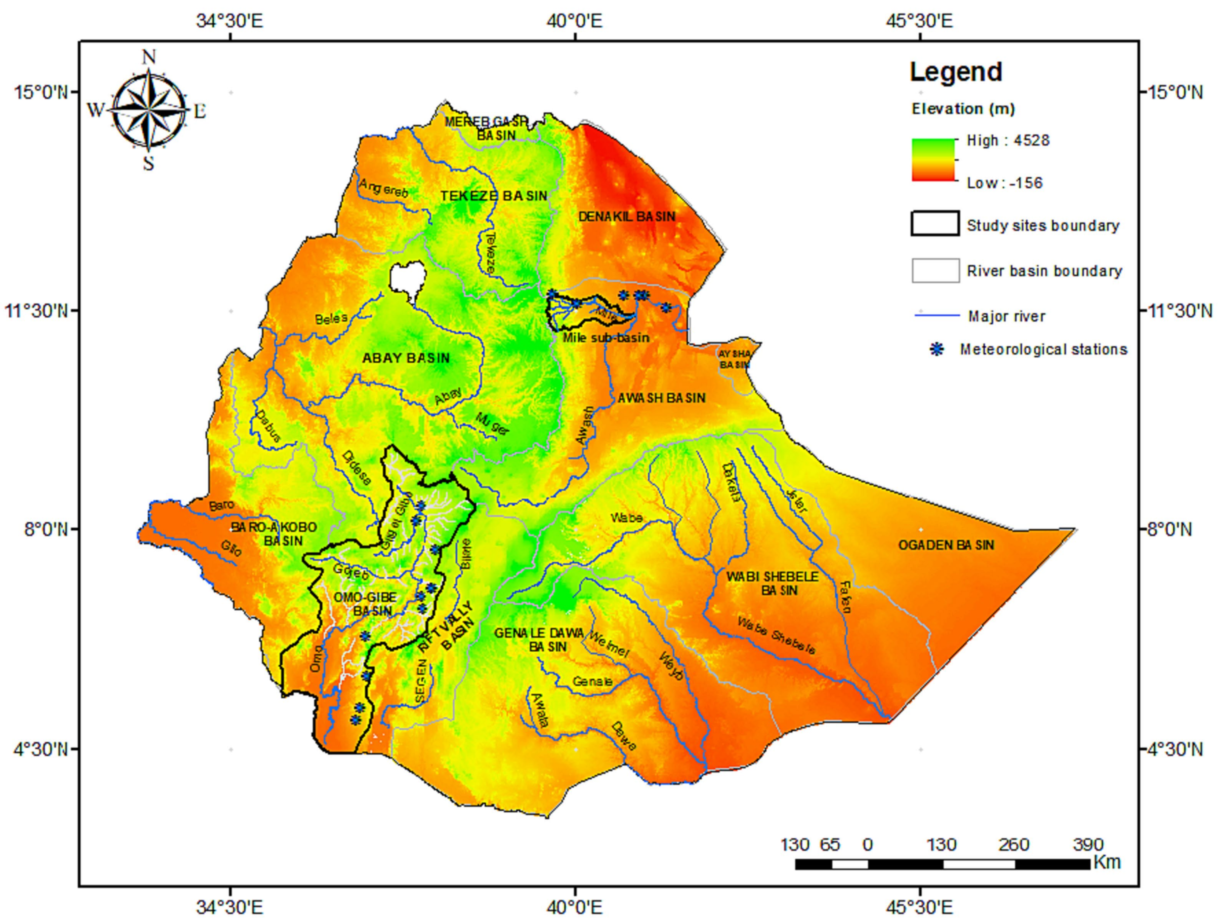

FIGURE 1
Location map of the case study landscapes (Omo Gibe Basin and Mile sub-basin in Awash Basin), names of basins and rivers, rainfall stations in the study landscapes and the mountain chains with high elevation ranges that are sources of flash floods. Readers refer to the names of rivers and basins and their locations in this map for the discussions about flood prone areas and flood suitability in the body of the text.

TABLE 1 Characteristics of the three landscape segments in Omo Gibe and Mile sub-basin river basins.

Landscapes	Landscape segment	Annual average rainfall range (mm) (mean)	Drought frequency range (*mean*)	Elevation range (m)	Average temperature range (°C) (*mean*)	Average slope gradient (%)	Dominant soil type
Omo Gibe	Upper landscape	908–2,262 (1654)	5–9 (7)	904–3,576	17–19 (18.2)	15.2	Pellic vertisols
	Mid landscape	956–2,507 (1773)	5–9 (7)	499–3,440	19–21 (19.5)	24.7	Dystric nitisols
	Lower landscape	455–1,590 (907)	5–10 (8)	336–3,396	24–27 (26.2)	11.5	Eutric fluvisols
Mile sub-basin	Upper landscape	532–1,408 (980)	7–8 (7)	952–3,654	15–17 (16.1)	27.6	Eutric regosols
	Mid landscape	451–1,293 (903)	7–8 (8)	647–2,226	22–24 (23)	12.3	Calcaric fluvisols
	Lower landscape	207–726 (468)	8–9 (8)	396–1,275	28–30 (29)	4.8	Orthic solonchaks

southern parts, flooding the Southern Omo Lowlands. It has a remarkable range of altitude, temperature, rainfall, and farming systems. The basin is characterized by diverse topographic features with the elevation ranges from 336 masl in the southern part to 3,576 masl in the northern highlands. Rainfall is characterized by a unimodal pattern from June to October (in the central and northern parts) and a bimodal pattern (southern parts) (Dagnachew et al., 2020; Orkodjo et al., 2022). The highest peak happens from July to August due to the largest part of the basin receiving rainfall from an unimodal monsoon pattern. On the other hand, significant flood peaks occur during March to May due to rainfall in the lower parts of the basin. Annual rainfall ranges from 318 mm in the southern lowlands to 2,228 mm in the highlands. The mean annual maximum temperature in the basin ranges from 16.6°C in the highlands to 34.8°C in the southern lowlands. The mean annual minimum temperature shows similar trends. The high minimum temperature (23.2°C) is observed in the south lowlands, whereas the lowest temperature (3.9°C) is observed in the west highlands (Anose et al., 2021). Mixed farming is the dominant livelihood in the Omo basin, in which the agropastoral system where local cattle, sheep, goat, and camel breeds are dominant in the south lowlands and the cereal-pulse and coffee cropping system (cereals such as wheat, maize, sorghum, teff, finger millet; beans; taro, potato, coffee, and enset) is dominant in the western, central, northern, and eastern highland parts of the basin.

The Mile sub-basin drains the highlands of the northeastern escarpment and flows towards the extremely dry and fragile lowlands of the Afar regional state. The elevation ranges from 406 to 3,654 m asl. The upper part of the landscape is experiencing bimodal rainfall, while the lower part characterized by erratic and unreliable rainfall, is often plagued by drought and excessive flood risks (Gumma et al., 2022). Annual rainfall varies from 232 mm in the western lowlands to 1,144 mm in the eastern highlands of the Mile sub-basin. The higher mean annual maximum and minimum temperatures (34.2 and 21.6°C) are observed in the eastern highlands, whereas the corresponding lower mean temperatures (17.1 and 2.1°C) are observed in the western lowlands. The upstream parts are dominated by sorghum-based production mixed with livestock farming, particularly cattle production. Whereas, pastoral and agropastoral livelihood systems in the form of a combination of maize-based production and cattle and goat-based livestock farming are the dominant production systems in the downstream parts.

2.2 Stratified sampling of landscape segments

Omo Gibe and Mile sub-basins were divided into three landscape segments or zones (upper, middle, and lower) based on geomorphologic features, which vary in rainfall amount, soil types, elevation, slope characteristics, and frequency of drought occurrence (Table 1). The segmentation aids in characterizing flood sources, flood recession areas, and various flood zone classes. The watershed of the Omo Gibe basin area lies at elevations of 336–3,576 m, and it descends rapidly into depressions. The upper and middle Omo drainage systems show striking geometric arrangements of their streams. The lower third of the basin defines a complex tectonic depression. The upper middle zone in the western part and the upper north zone are characterized by high and moderate rainfall. The upper Gibe is covered with dense drainage, while the lower Omo Gibe basin is plain and dominated by slopes less than 5%, which are commonly flooded during the short and long rainy seasons. Mile Sub-basin is one of the Awash terminal sub-basins located in the Amhara and Afar regions at elevations ranging from 406 to 3,654 m. It has a high flood water potential draining the western highlands of the basin and varies temporally and spatially across the basin. The Mile sub-basin has a rugged topography with steep slopes in the upper and middle portions of the basin adjacent to the Amhara highlands and a relatively flat landscape in the lower portion.

2.3 Data sources and analysis

In this study, the data we dealt with is mainly data on flash flood occurrence and remotely sensed data. Since the study is focused on flash floods that exceed the stream size and spread over the river courses, measured discharge or flow data was not used. Instead, historical records of flash flood occurrence during the major (*Meher*) and short (*Belg*) rainy seasons (i.e., flood incidents and their date of occurrence and level of damage) were used as input to do remote sensing analysis of flood and soil moisture images. The historical flood events were also used to validate the spatial and temporal distribution of floods estimated from remote sensing. The extent of the spatial distribution of potential of recession flood farming was delineated using combined analysis of temporal flood events (images identified based on rainfall events) and soil moisture (i.e., SMAP image). The study made use of a variety of data sources, both primary and secondary. The study dataset primarily consists of spatial and non-spatial data, such as historical flood records, satellite imagery, and GIS-based raster and vector data, which were integrated and analyzed for assessing flood risk locations and potential areas for flood-based recession farming (Table 2).

2.3.1 Historical flash flood records

In Ethiopia, to develop natural hazard emergency response plans for humanitarian assistance, the National Flood Task Force hosted by the National Disaster Risk Management Commission (NDRMC) is in charge of recording seasonal flash flood events. Flash floods are caused by heavy rainfall in a short period and are usually reported with damages and fatalities. Flash floods often lead to issue early warning and emergency response alerts. Sixty years (1960–2020) seasonal flash floods, compiled from the United Nations Office for the Coordination of Humanitarian Affairs (UN-OCHA) flash flood snapshot reports and infographics (OCHA, 2007), as well as additional flash flood records compiled from literature (Desta et al., 2021) and the global flood dataset,[1] were synthesized for assessing historical flood occurrence and associated flood risks. The database on flash floods records the duration of flood incidents in a locality, the extent of damage, and the overall situation of the incident. The historical data was also converted into spatial maps that show flood hotspot locations and district scale frequency of flood occurrence, which were used as base maps for the delineation of potential flood- based farming zones.

2.3.2 Multi-criteria analysis for delineating suitable flood-based farming zones

Expert knowledge was used to assess the socio-ecological suitability of flood-prone areas for targeting flood-based farming. Senior experts in the fields of hydrology and agriculture, who have practical knowledge of flood occurrence and flood farming and conducted their field research in the case study basins, were brought together to conduct a multi-criteria suitability analysis. During a week-long workshop, we brought together eight senior researchers and experts to identify important factors influencing flood-based farming and assist in the execution of GIS-based multi-criteria suitability analyses. First, the experts brainstormed the context of flood risks in the basins as well as flood farming principles and techniques and agreed to the context using Google Earth images. They identified the criteria and established a common understanding of the description of each of the criteria factors. Once they had reached an

1 https://public.emdat.be/data

TABLE 2 Multi-criteria applied for the socio-ecological suitability of flood farming.

Decision criteria	Source	Resolution	Suitability class		
			High suitable	Moderate suitable	Unsuitable
Historical flood occurrences	UN-OCHA flood reports and https://public.emdat.be/data		Base map	Base map	Base map
Land use/Land cover	ESA (2016)	20 m	• Cultivated land • Grassland	• Bushland and shrubland • Barren land	• Woodland (Restricted) • Forest (Restricted) • Waterbody & wetland areas (Restricted), • Alpine vegetation (Restricted)
Annual mean rainfall (mm)	CHIRPS	5.5 Km	• <500	• <500	• >500 (Restricted)
Slope (%)	SRTM DEM	30 m	• <= 5%	• 5–8%	• > = 8%
Geomorphology (landscape, slope, shape)	ISRIC (Ethiopia)	50 m	• 100–1,005 = all Bottom landscape • 2,100–2,230 = part of Flat landscape	• 2,230–3,121 = Part of Flat landscape	• >3,121 including all Slope and Summit landscapes
Soil texture (considering water holding and permeability)	Harmonized World Soil Database	1 Km	• Silty clay • Sandy clay • Silty clay loam • Clay loam • Sandy clay loam • Loam • Light clay (<55%)	• Sandy loam • Silt loam	• Sand • Loamy sand • Silt • Heavy clay (>55% clay)
Soil depth	AAIT SWAT database	250 m	• 0–10 cm	• 10–30 cm	• >30 cm
Farming system/livelihood zones	FEWS-NET		• Cropping zone with dryland food crops • Agropastoral zones with mixed dryland food crops and livestock • Pastoral area		• Cropping zone with highland food crops • Agropastoral zones with highland food crops and livestock

agreement on the subject of flood-based farming and criteria, each expert was asked to identify the criteria/ factors that influence flood-based farming and to set the threshold for each criterion by visualizing the spatial distribution of each factor in flood-prone areas. Criteria indicators included climate, soil, farming systems, land use and land cover, topography, and socioeconomic factors. To determine suitable potential flood-prone areas for flood-based farming, the weight of each decision criterion was estimated using the Analytical Hierarchical Process (AHP) in GIS, with experts' pairwise ranking of factors as input.

Two classes were determined, highly suitable (SC1) and moderately suitable (SC2), as described in Table 2. The suitability analysis provided a contextualized and firsthand estimate of potential suitable areas for flood-based farming out of flood-prone areas. Because of the limitation of detailed information about flood farming analysis at the basin scale from past research, we established assumptions for the suitability analysis. Thus, the suitability analysis was carried out taking into account the following assumptions: (1) The current level of suitability analysis aims to assess and delineate potential flood-prone areas to be targeted for alternative flood-based farming strategies and interventions. (2) The suitability mapping did not consider the amount of flooding and duration of flooding, as this information is scarce in every river system. (3) The suitability does not differentiate between hazardous and useful floods, with the assumption that floodplain areas that received hazardous flash floods can be utilized either to improve the productivity of extensive pasture or rangeland or used to grow crops through a recessionary farming practice during the post-flood. (4) The suitability mapping broadly targets the arid and semi-arid lowland areas as well as drought-affected areas and pastoral, agropastoral, and sedimentary dryland farming systems. (5) Flood farming areas should exclude water bodies, wetlands, biodiversity reserve areas, forest areas, built-up areas, parks, and protected areas. Flood-prone areas that receive annual rainfall >500 mm was excluded, assuming the amount of rainfall is sufficient for rainfed farming.

2.3.3 Remotely sensed image analysis

Besides the historical flood information and experts' knowledge, cloud-based remotely sensed satellite imageries in the Google Earth Engine (GEE) platform were used to detect and further verify the flooded areas suitable for flood-recession farming. GEE, which is a cloud-based platform for geospatial data analysis, was used for image processing and analysis using Application Programming Interface (API) code written in JavaScript. A change detection approach using a combination of multi-temporal Synthetic Aperture Radar (SAR) and other satellite imageries (Table 3) was applied for flood recession mapping through a comparison of backscattering signals between the flood image (events during post-flood period) and a reference image (events during pre-flood period) in GEE platform. The historical flash flood event records at each locality which were documented by UN-OCHA and (see footnote 1) were used as input to define periods of pre- and post-images and at the same time used to validate results of remote sensing analysis in the season. The years 1988, 1996, 1998, 2006, 2010, 2012, 2016, 2018, and 2020 were significant historical flood occurrences in Ethiopia. Historically, a total of 123 (in 58 districts) and 19 (in 7 districts) flash flood events were recorded in Omo and Mile study landscapes, respectively. The most recent years, 2016, 2018, and 2020, were chosen as input to analyze change in flood incidents that occurred during the short rainy season (*Belg*) and major rainy season (*Meher*). *Most flood events were recorded in 2020.* Using the records of the flood events from the 3 years, the seasonal flood occurrence periods were identified. After defining a separate flood window period for the short (*Belg*) and major (*Meher*) seasons by using meteorological rainfall data, the extent of flood-prone areas at the two study locations was determined by analyzing 234 [85 for the short (*Belg*) season and 149 for the major (*Meher*) season] Sentinel SAR images. To determine the extent of suitable areas (out of flood prone areas) for flood recession farming, the amount and duration of soil moisture needs to be examined if it meets the crop water requirement during the growth period. For this purpose, remote sensing products of soil moisture (SMAP) and CHRIPS rainfall data were also used to define soil moisture ranges during the pre and post flood periods. Radar satellite images from Synthetic Aperture Radar (SAR) sensors which have all weather day-night image acquisition capability are the most suitable for flood mapping (Hostache et al., 2012; Priyatna et al., 2023). According to the predefined parameters, the entire Sentinel-1 GRD filtered by the instrument mode [Interferometric (IW)], polarization (VV), pass direction (descending), spatial resolution (10 m) was clipped to the boundaries of study area and the selected time periods using API codes in GEE (see Supplementary materials). ArcGIS was used for map generation (Table 4).

3 Results

3.1 Flood occurrence and associated risks in Ethiopia

Flash floods occur in Ethiopia every year during the major rainy season (June to September) and the short rainy season (March to May) due to heavy rainfall or excessive river flow. Almost 90% of flood events in the country occur as a result of heavy rain, which causes rivers to overflow and inundate areas along riverbanks in lowland plains. Based on historical flash flood data compiled from various sources, the spatial extent of historical flood events in Ethiopia in the period from 1960 to 2020 was analyzed and depicted (Figure 2). The analysis of flood occurrence and associated risks revealed that the number of flood-prone areas had increased since the 1990s, with a significant change occurring after the 2010s. Before the 1990s, the number of flood-prone locations was between 6 and 23. However, the flood-affected areas steadily increased to 247, 306, and 540 in the 1990s, 2000s, and 2010s, respectively (Figure 3). Excessive floods occurred in 1996, 2005, 2006, 2013 and 2018 affected 90, 91, 74, 74, and 69 locations in the country. Exceptionally, flood events in 2020 have affected large areas (274 locations) of the country, indicating an increase in flood risks in recent years. The 2020 climate bulletin of the National Meteorology Agency indicated that the total rainfall amount of the year 2020 exceeded 1,250 mm over western and the highland of Amhara, Benishangul-Gumuz, Eastern Oromia, and most of SNNPR and the central and western Oromia. In association with this, for example, the annual total rainfall amount reported over Nekemte was as high as 2243.7 mm, and in general 2020 is wetter than 2019. Previous studies also

TABLE 3 Description of image data used to detect flood recession areas.

Data	Data format	Use	Reference year	Resolution	Source
Sentinel 1- C-band Synthetic Aperture Radar (SAR)- Ground Range Detected (GRD) imagery	Raster	Satellite image for producing initial flood extent map	2020	10 m	ESA
Soil Moisture Active Passive (SMAP)	Raster	Soil moisture data for defining pre- and post-flood time periods	2020	10 km	NASA GSFC
Climate Hazards Group InfraRed Precipitation with Station (CHIRPS)	Raster	Rainfall data for defining pre- and post-flood time periods	2010–2021	5.5 km	UCSB/CHG
WorldClim	Raster	Characterizing climate condition and drought frequency	Long term	1 km	
JRC Global Surface Water dataset	Raster	Refining the flood extent map based on duration of water on the earth surface (>10 months per year)	2020	30 m	EC JRC
Hydrologically Conditioned DEM (HydroSHEDS)	Raster	Digital Elevation Model for refining the flood extent map based on slope class (<5%)		90 m	World Wildlife Fund (WWF)

TABLE 4 Area coverage (ha) and percentage of flood prone areas suitable for flood-based farming.

Basin name	Highly Suitable (SC1)	Moderately suitable (SC2)	Total	Percentage
Abbay	–	–	–	–
Awash	2,631,907	2,287,870	4,919,776	15.1
Aysha	129,051	255,569	384,620	1.2
Baro Akobo	–	–	–	–
Denakil	736,353	2,400,820	3,137,173	9.6
Genale Dawa	5,391,356	2,779,105	8,170,460	25.1
Mereb Gash	1,062	21,617	22,678	0.1
Ogaden	2,129,652	82,069	2,211,721	6.8
Omo Gibe	684,340	302,697	987,036	3.0
Rift Valley	575,158	881,046	1,456,205	4.5
Tekeze	41,224	300,757	341,981	1.0
Wabi Shebele	7,572,167	3,411,512	10,983,679	33.6
Total	19,892,269	12,723,061	32,615,330	

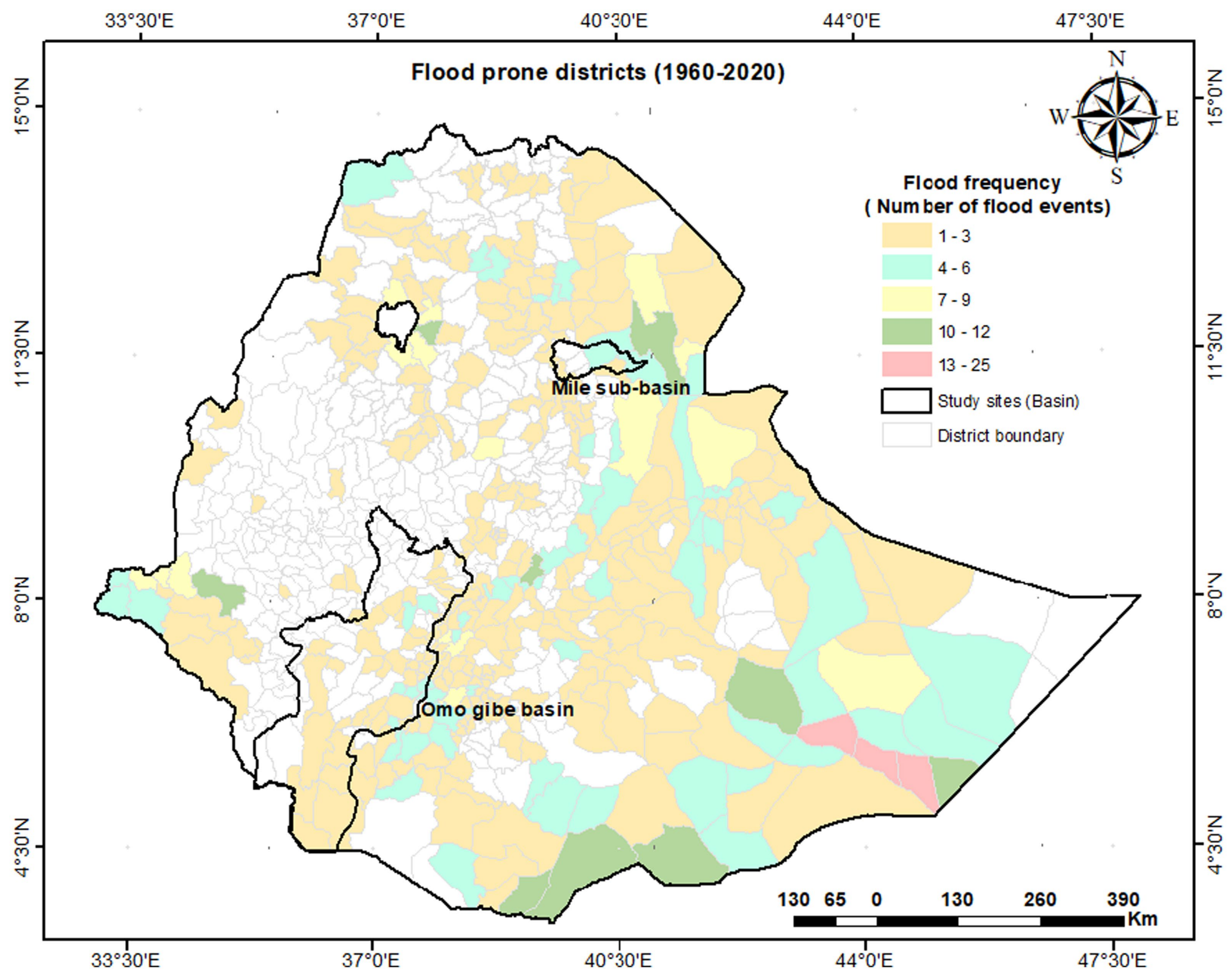

FIGURE 2
Flood-prone areas (shaded areas) in Ethiopia and displaying frequency of flood occurrence (1–25 times) per location (Source: remapped from historical data records of UN-OCHA seasonal flood snapshots, https://public.emdat.be/data, and Mamo et al., 2019) [adapted from Desta et al. (2021)].

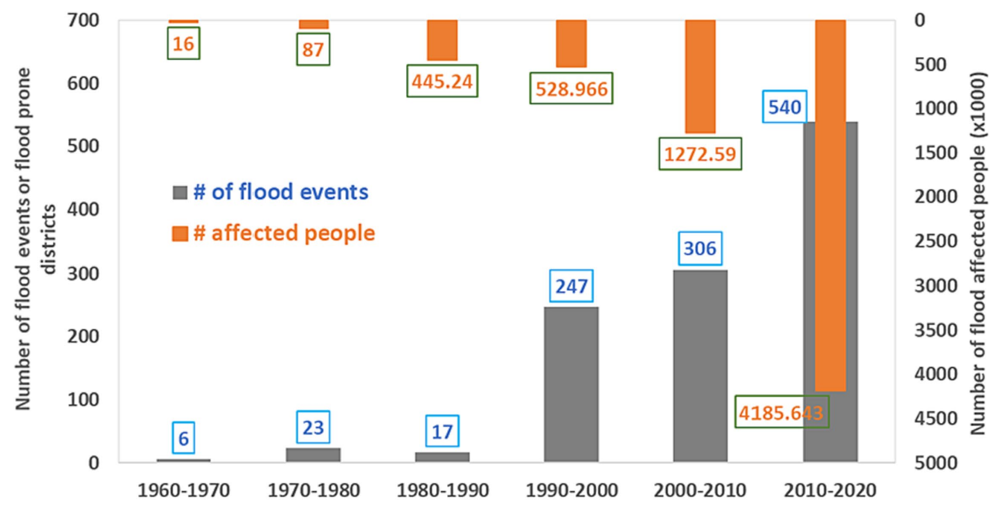

FIGURE 3
Trends of flood incidents (number of flood-prone locations) and total affected people over decades (1960–2020) (own analysis and https://public.emdat.be/data) [adapted from Desta et al. (2021)].

reaffirm the increased frequency of flood incidents over the last 20 years (Mamo et al., 2019; Demissie et al., 2021; Wudineh et al., 2022). The studies identified land use change, vegetation degradation, and climate change and variability as the main driving factors for the increased incidents of flooding. These highlights that beyond the heavy rainfall events, the change in land uses and deforestation in the upstream mountain areas specifically in the south, southeast, eastern, and Rift Valley areas have a major influence for increased occurrence and frequency of flooding. These areas are also facing cyclic risks of droughts. This section presents the spatial distribution and frequency of flood prone areas (Figure 2)- and the suitability of the flood prone areas for flood farming (Figure 4). The names of basins, rivers and local names presented in this section are illustrated in Figure 1. As depicted in Figure 2 and the suitability map in Figure 4, during July to September, heavy rains in neighboring highland areas of Oromia (the southeast mountain chains in Bale and Harargie zones) and partly in the southern region cause flooding along the Wabishebele, Genale, and Dawa rivers (refer river names in Figure 1). Flood occurs every year in areas along the lower Wabishebele river. Flooding occurs at least once every 3 years in the upper, middle, and lower Awash River, Baro and Gilo Rivers in Gambella, flood plain areas around Lake Tana in the upper Abay Basin, lower Omo river in South Omo, and along the Genale and Weyb rivers (see Figure 1 and Figure 2). Heavy rainfall in the highlands of northeastern mountain chains of Amhara and Tigray and the central highlands often caused an overflow of Awash River and its tributaries in Afar. In the southern part of the country, floods occurred in the Konso area (Segen river) and along the Omo River during March to May and July to November. In the Rift Valley, floods occurred in the floodplain areas along the Bilatie River and around Lake Abaya (for example Humbo and Offa districts). During heavy rains, Flooding in the Fogera and Dembia floodplains is caused by Lake Tana's backflow and the overflow of the Gumara, Rib, and Megech rivers that drain to Lake Tana. As a result, Awash, Wabishebele, Genale, Dawa, Omo Gibe, Baro, and Akobo Rivers, as well as the floodplains surrounding Lake Tana and the Rift Valley Lakes occupied large flood-prone areas (Figure 2). This shows the occurrence of extensive flood incidents in the south, southeast, eastern, central and Rift Valley parts whereas the north and northwest (like Abay and Tekeze basins) have no frequent records of floods except the Lake Tana flood plains. This is likely partly attributed to the large coverage of the soil and water conservation practices. These practices could reduce the occurrence of flash floods. Under increased spatial coverage of flood-prone areas and growing flood frequency over years, the associated humanitarian risks and damages on economic activities have been increased (OCHA, 2007) as indicated in Figure 3. For instance, the number of people affected by floods (both displaced and deaths) increased over decades, from 16 thousand in the 1960s to 4.2 million in the 2010s (Figure 3).

In recent years, the cyclicity of drought and flood events in the Horn of Africa is more frequent, where the occurrence of multi-hazard events is likely to amplify disaster impacts (IPCC, 2022). These cyclic disaster risks are the results of complex spatiotemporal interactions between risk components, impacts, and societal response (Matanó et al., 2022). The EM-DAT international disaster database indicates that over the last 20 years (2002–2021) floods (n = 793) and droughts (n = 137) represented 55% of natural hazards in Africa (n = 1,693), with 14,053 and 20,821 deaths, respectively. As also observed by Di Baldassarre et al. (2017), there is a fluctuating trend of annual drought-flood recurrences, indicating that the interplay of droughts with floods.

Floods occur more frequently than droughts, with annually an average of 40 flood events and seven drought events. When we see floods in otherwise dry areas, it is important to be aware and spread awareness that when a lot of rain falls in a very short period after longer periods of drought this leads to a shallow absorbance of the rain. For instance, drought hazards lead to soil degradation, reduced sub-surface water storage, and a lower capacity for soil infiltration, which increases runoff and proneness to flood risk. Unfortunately, the short and heavy rainfalls in the dry areas is a disaster as it came in big volume and became a flood. The recent drought that occurred in Borena Ethiopia is associated with flash floods.

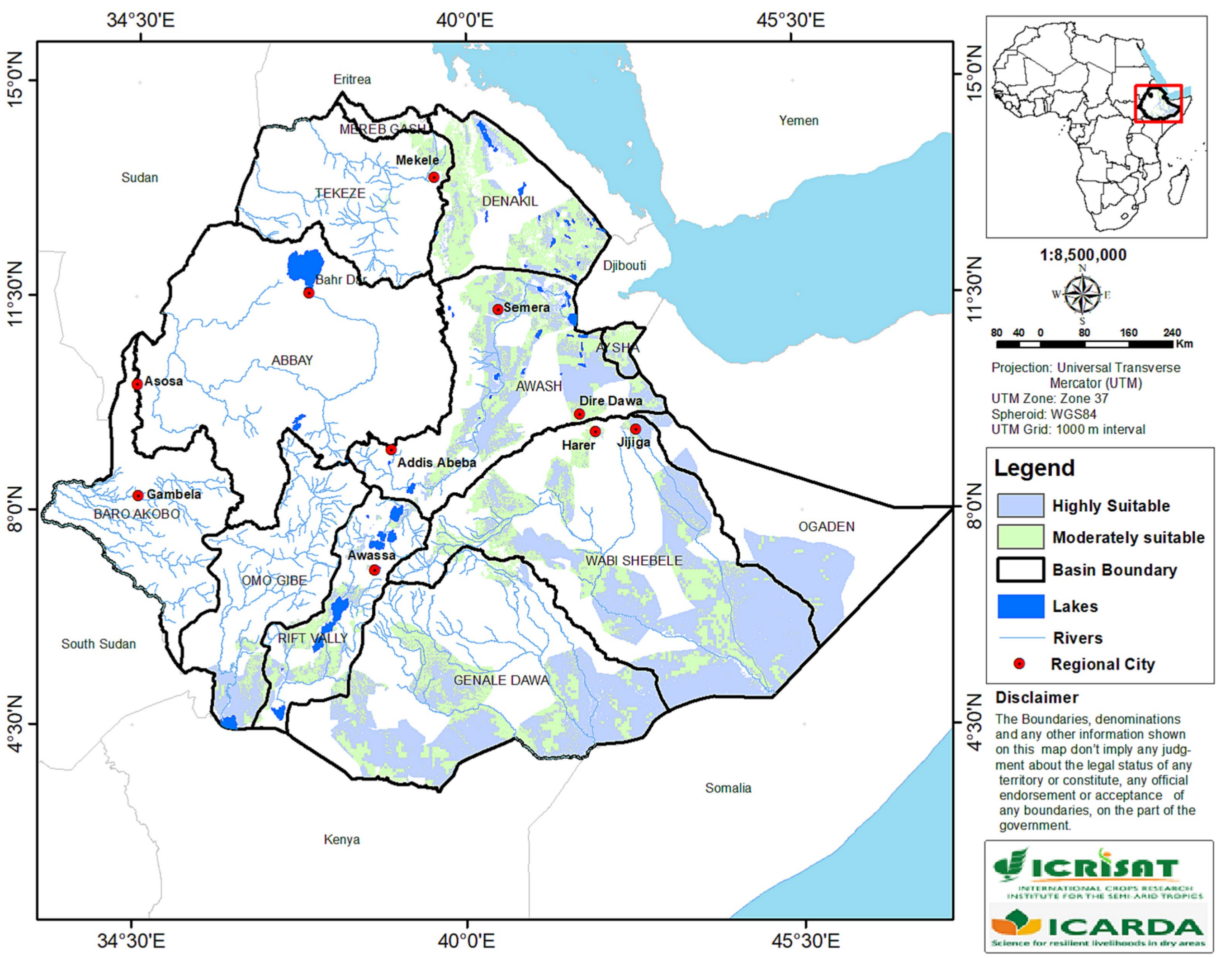

FIGURE 4
Map of socio-ecological suitability of flood prone areas for flood-based farming in Ethiopia using multi-criteria methods by expert knowledge. The suitability map was prepared for CGIAR WLE deliverable (source: Desta et al., 2021).

3.2 Suitability of flood-prone areas for flood-based farming in Ethiopia

Considering the historical flood-prone areas (section 3.1) as a base map, GIS-based multi-criteria suitability analysis using an expert-based AHP technique was used to delineate flood-prone areas potentially suitable for flood-based farming. The multi-criteria suitability mapping resulted in 32.6 million ha of land in the country which is estimated to be suitable and moderately suitable for various types of flood-based farming. Sixty-one percent of the total suitable flood recession areas (20 million ha) were classified as highly suitable (SC1), while 39 percent (12.6 million ha) were classified as moderately suitable (SC2) (Figure 4).

Table 4 presents basin scale area coverage of suitable areas for flood based farming. Basin-wise analysis showed that the lower part of the Wabi Shebele basin has the largest area coverage which accounts for 10.9 million ha (33.6%) of the total land area classified as SC1 and SC2. It is followed by Genale Dawa with 8.17 million ha (25.1%) and Awash 4.92 million ha (15.1%). Considering highly suitable classes alone (SC1), Wabi Shebele has the largest area coverage (7.57 million ha, 38.1%) followed by Genale Dawa (5.39 million ha, 27.1%), and Awash (2.63 million ha, 13.2%). Basins such as Ogaden, Omo Gibe, and Rift Valley have 2.13 million, 0.68 million, and 0.57 million hectares of highly suitable areas. Although basins like Abbay and Baro Akobo have flood-prone areas, they are excluded from the suitability analysis as most of the flooded areas receive more than 500 mm of seasonal rainfall. Thus, identification and delineation of flood areas using a hybrid of expert knowledge and geospatial analysis supports informed decision-making on the flood risk and flood farming strategies using best agricultural technologies and practices. The magnitude of suitable flood areas revealed that flood-based farming could be an entry point for boosting agricultural production in the drought-affected and food-insecure areas of the lowlands.

3.3 Soil moisture during pre- and post-flood events

Figure 5 shows the soil moisture trend in April before and after events of extreme rainfall at the different meteorological stations located in the Awash Mile-Asaita flood landscape. To detect flooded areas in the lower landscape, we took SAR images on 10 April 2020 as pre-flood image and 28 April 2020 as post-flood image. In the Mile-Asaita flood zone, there were no extreme rainfall events during early

April. It is observed that soil moisture from 1 to 10 April is low (Figure 5) extracted from the before extreme image. Similarly, the rainfall chart shows very little rainfall from 1 to 10 April except for small rainfall in the lower part of the flood landscape at Chifra station. After 11 April, sudden increments in soil moisture were observed and steadily attained peak soil moisture (10 mm) on 20 April. The soil moisture was strongly matched with the rainfall trend (Figure 5) occurring at the upstream meteorology station (Sirinka). The increase in soil moisture in the lower flood areas after the occurrence of rainfall in the upstream highlands shows that there is a strong correlation between upstream rainfall source areas and downstream flood recession areas.

Figure 6 shows the trends of soil moisture and rainfall events in the Omo Gibe river basin. The soil moisture pattern is drawn for relevant rainfall months at three landscape zones that demonstrate the occurrence of flood recession areas. For instance, in the 2020 rainy season, the moisture trends indicate four distinct moisture retention periods, February to Mid-May, Mid-May to September, October to November, and December to January. Two seasons, February to May and October to November provided adequate soil moisture content between 10 and 20 mm while the remaining months had an average 10 mm of soil moisture (Figure 6, bottom). The soil moisture trends are very much associated with the spatial and temporal distribution of rainfall events in the landscape (Figure 6, top). Disaggregating the low and high soil moisture patterns in relation to upstream, middle, and lower zones of the landscape can provide information about where the flood recession becomes an opportunity for agricultural production.

3.4 Soil moisture characteristics over landscapes

Soil moisture patterns were assessed for case study landscapes during the *Belg* (March to May) and *Meher* (June to September) rainfall seasons, taking into account intense flooding years (2016, 2018, and 2020) (Figures 7, 8). In the Omo Gibe basin, there was steadily increasing soil moisture during the short season. The increase in soil moisture is highly associated with the rainfall occurring in each landscape segment. The occurrence of sufficient soil moisture at lower landscapes is attributed due to the rainfall amount in the season and subsequent flood events from upstream landscapes. However the daily rainfall amount is small during major (*Meher*) season compared to the short (*Belg*) season, except slight increase after mid-September. The soil moisture recorded an average value of 10 mm and above. The soil moisture trends in the two seasons indicate that there is readily available soil moisture to enhance the recession farming. For instance, from March to May, the areas can receive sufficient soil moisture for crop recession farming lasting at least two and half months. Similarly, between June and December, the soil moisture in the lower landscapes was sufficient enough to sustain crop and pasture production.

In the Mile sub-basin, very distinct soil moisture trends were observed between the three landscape positions that imply strong interconnectivity of the landscapes. Although there is a considerable and consistent availability of soil moisture in lower landscapes between July and mid-October over several years, the occurrence of sufficient soil moisture from March to May is season-dependent. As a result, the Mile sub-basin landscape experiences more consistent soil moisture availability during the main rainy season, which could potentially support lowland agro-pastoral production systems and regreen the fragile and dry rangeland environment. This result is well supported by Gumma et al. (2022) who have reported and delineated potential flood farming opportunities in Afar.

In contrast, flood-based farming in the Omo Gibe basin can be more beneficial during the short rainy season and slightly extended between September and November whereas, there is a potential flood farming opportunity for dryland crops in the Mile sub-basin during the major rainy season, June to September. Since there are peak soil moisture weeks, caution has to be taken in the choice of crops that

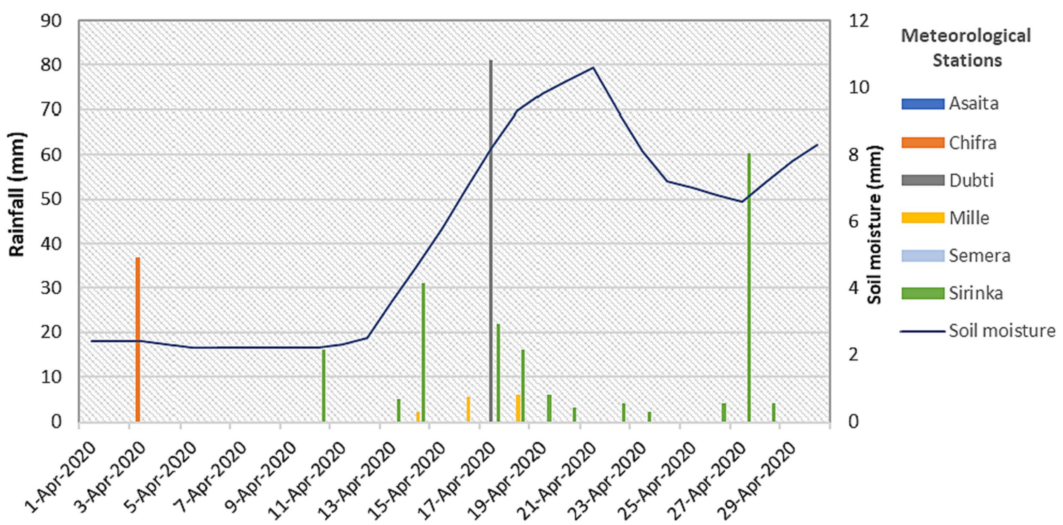

FIGURE 5
Distribution of rainfall events (bars) occurred at different meteorological stations in the Mile sub-basin and trends of surface soil moisture (SMAP) (line graph) extracted from before and after flood events in the selected Mile-Asaita flood landscape. Meteorological stations at Dubti, Asaita, and Semera did not record any rainfall during the month of April.

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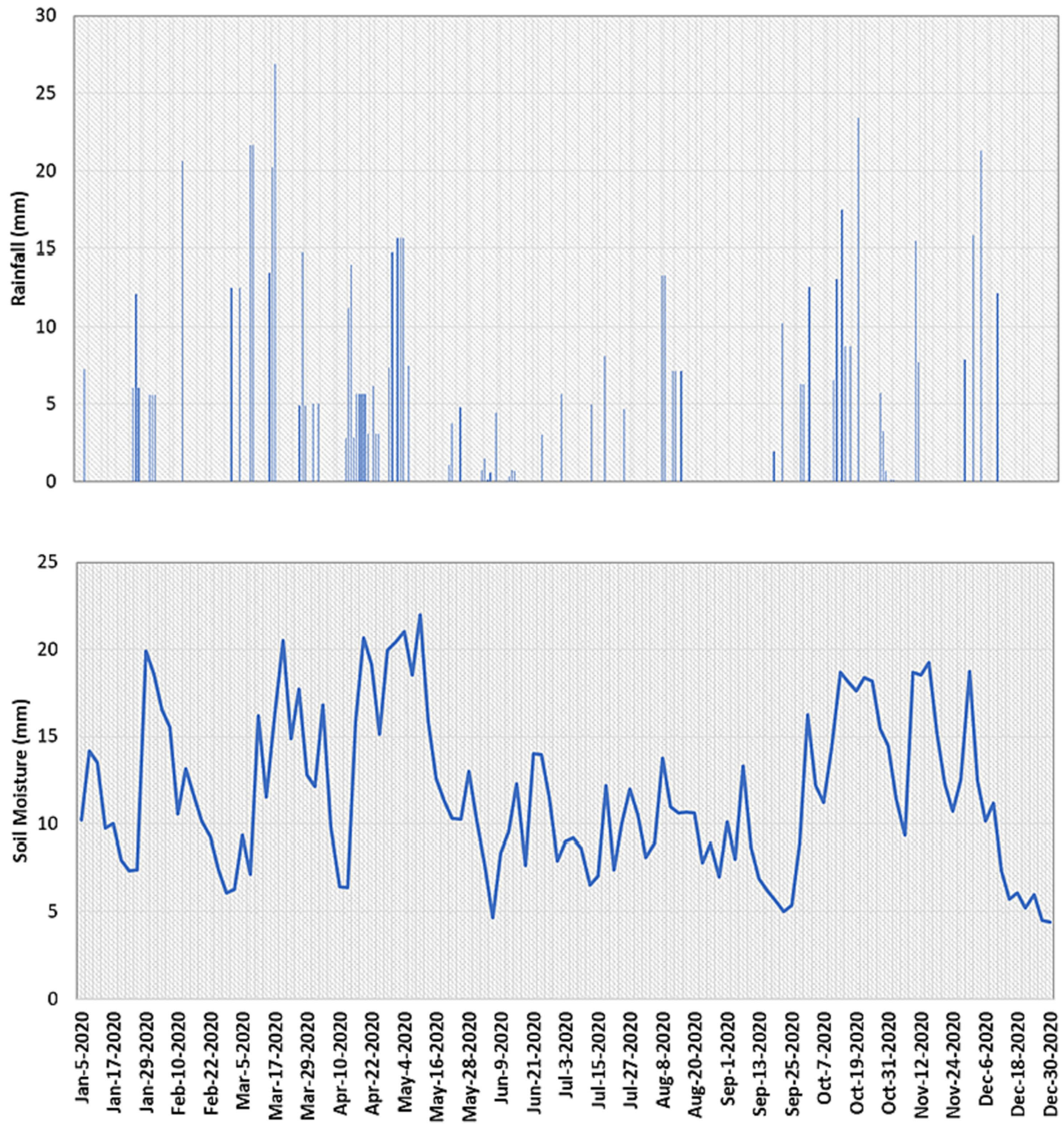

FIGURE 6
Rainfall events **(top)** and the corresponding trends of seasonal soil moisture pattern **(bottom)** in 2020 at Omo Gibe basin. The rainfall and soil moisture amount is the weighted average of the spatial distributed rainfall and soil moisture in the basin.

tolerate excess soil moisture conditions. Apart from its crop and livestock feed production opportunities, this seasonal soil moisture availability could help to improve ecosystem services such as mitigating the degraded environment and replenishing the subsurface water (Getnet et al., 2022).

3.5 Delineation of flood recession zones

Floods resulting from heavy rainfall and artificial drainage obstructions between upstream and downstream areas are regularly experienced in dry lowland areas. Rainfall and topographic conditions are key indicators of flood potential in geographically interconnected landscapes. In line with this, the two case study landscapes were initially characterized in terms of rainfall, elevation, and slope (Figure 9). The results revealed that the Omo Gibe basin experiences a high mean annual rainfall of 1,237 mm (318–2,228 mm) compared to the Mile sub-basin's 686 mm (232–1,144 mm). Topographically, more flat land, which has less than 5% slope and is geographically interconnected to the adjacent highlands, exists in the Mile sub-basin than in the Omo Gibe sub-basin.

Considering seasonal rainfall and soil moisture conditions before and after the flood events, slope and land cover of the two basins, flood analysis using remotely sensed derived data in the GEE platform was carried out to delineate potential flood zones for flood recession farming during major (*Meher*) and short (*Belg*) seasons. The results of flood and moisture trend analysis revealed that Omo Gibe basin has larger area coverage of flood zones for conducting recession farming

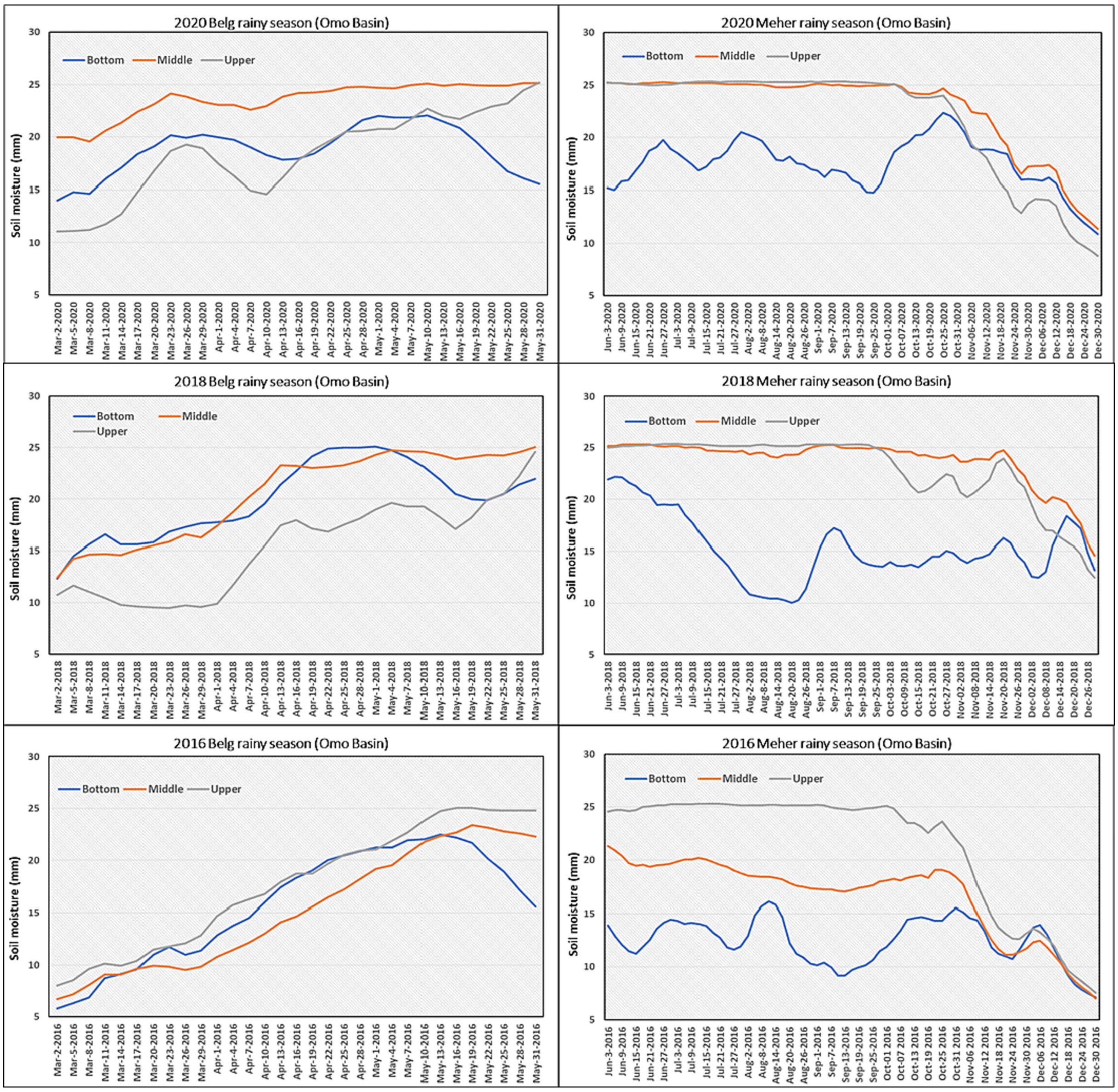

FIGURE 7
Soil moisture pattern of Omo Gibe river basin along three landscape zones during short (*Belg*) and major (*Meher*) rainy seasons.

in both *Meher* and *Belg* seasons than Mile sub-basin (Figure 10). Omo Gibe basin has 107,359 ha (1.4%) and 29,550 ha (0.4%) of land suited for flood recession farming during major (*Meher*) and short (*Belg*) rainy seasons, respectively. Whereas, 8,048 ha (1.44%) and 88 ha (0.02%) of suitable land for recession farming were obtained in the Mile sub-basin during *Meher* and *Belg* seasons, respectively.

4 Discussions

4.1 Flood trends and drivers

The increase in the occurrence and frequency is evident from the historical flood records. These changes are also in line with changes in the stream channel forms (width, length, depth) and community perceived claims in the increase in flood discharge and frequency (Demissie et al., 2021). Demissie et al. (2021) indicated a sudden increase in discharge characterizes flash floods of small rivers, with high flow velocities in the range of 2–3 m s-1 with Froude numbers greater than 1. Furthermore, Meaza et al. (2018) reported increased flows (up to 732 m^3 s-1) recorded in the largest rivers during the rainy seasons. Regarding the driving factors for increased flooding, high rainfall events, and variability is probably responsible for triggering flash floods (Borga et al., 2014; Douinot et al., 2016). Degefu and Bewket (2017) also reported the strong association of large scale climate signals like El Nino-Southern Oscillation (ENSO) with peak flood frequency. However, in the study landscape catchment degradation including land use conversion from forest, woodlands and shrublands to croplands and overgrazing of the landscapes are the most important causes (Demissie et al., 2021). The ecology in many parts of the highlands is considerably damaged. This damage is mainly attributable to the increasing human and livestock populations,

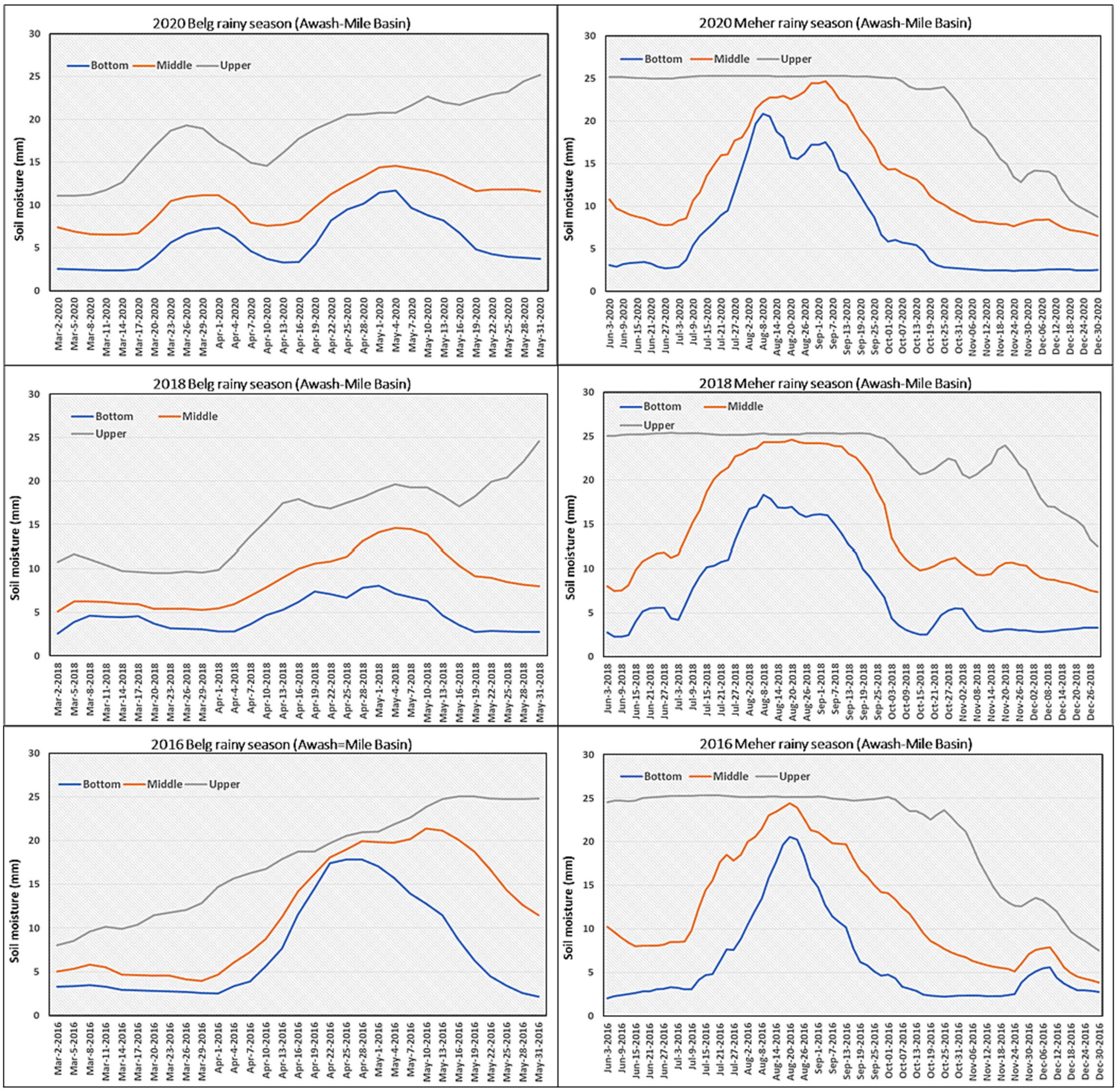

FIGURE 8
Soil moisture pattern of Mile sub-basin river basin along the three landscape zones during short [Belg (short)] and major [Meher (main)] rainy seasons.

cultivation on steep slopes, and deforestation (Kassawmar et al., 2018; Berihun et al., 2019).

4.2 Change detection approach for delineating flood recession zones

Flood-recession farming in the Omo and Mile case study landscapes is conditioned by the flood that is caused by heavy rainfall events associated with degraded upstream areas and replenishes the soil's water reserve. But, due to many constraints, the occurrence of this flood is increasingly uncertain. However, a remotely sensed approach was adopted in the Google Earth Engine (GEE) platform using Sentinel-1A SAR technology integrated with multiple image processing functions to differentiate the inundated pixels from other pixels. A combination of change detection and the application of the GEE algorithm was used to detect floodplains (Bhatt and Rao, 2014; Pandey et al., 2022; Priyatna et al., 2023). The approach is capable of analyzing the spatio-temporal dynamics in floods and seasonal soil moisture and informing the practice of recession farming. The case study in this paper illustrates the potential of the landscape segments in the upstream and downstream configuration of the study landscapes to generate floods and provide opportunities of flood recession farming. The results underline the relevance of remotely sensed approaches (Pacetti et al., 2017) together with expert knowledge in assessing flood occurrence along the landscapes and delineating flood recession zones. The period of recession farming is dependent on the duration and level of soil moisture content needed and the type of crop. Overall, more than 10 mm soil moisture content was measured in the recession period which is adequate for the maturity of many crops. Pertaub and Stevenson (2019) reported the farming of a variety of crops under recession farming in Omo Valley and its potential to

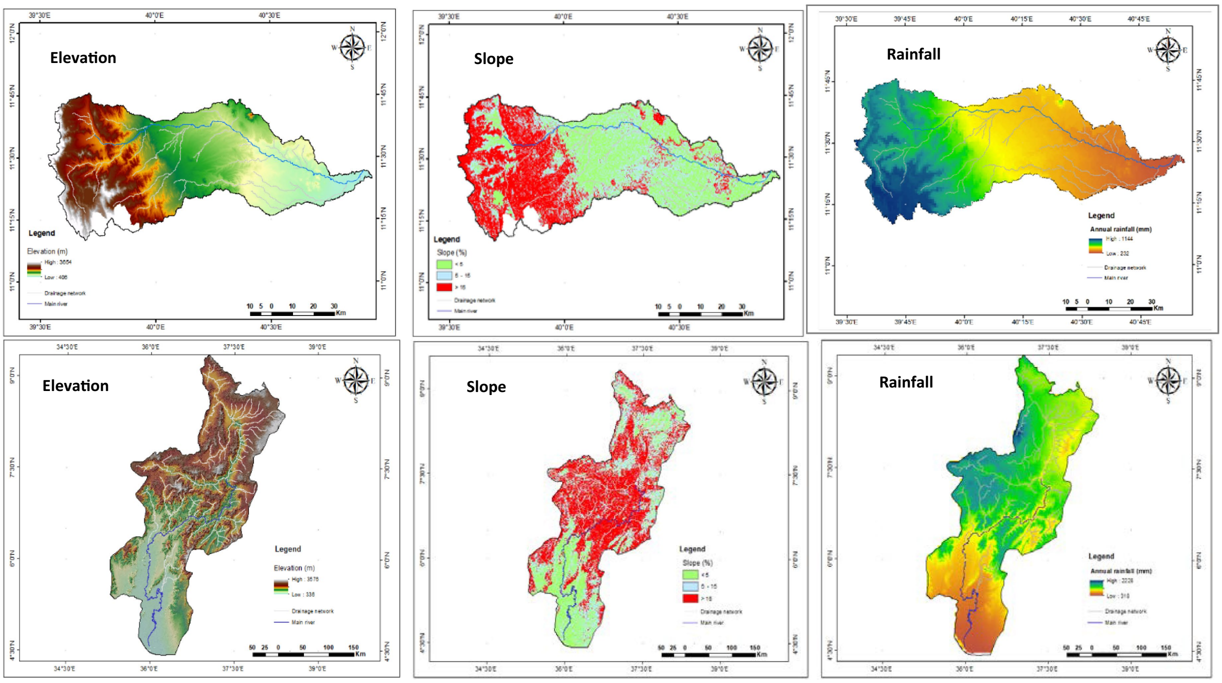

FIGURE 9
Elevation, slope, and rainfall characteristics of Mile sub-basin **(upper lane)** and Omo Gibe basin **(lower lane)**.

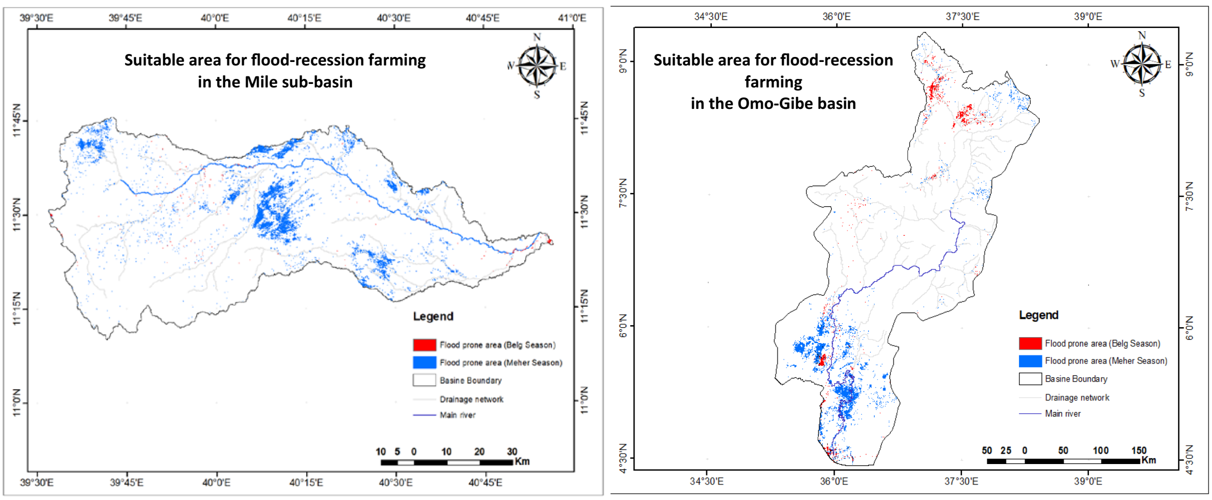

FIGURE 10
Maps show suitable areas for flood recession farming (out of the flood prone areas presented in Figure 2) using pre- and post flood change detection methods from satellite images in Mile sub-basin **(Left)** and Omo Gibe basin **(Right)**. Blue and red colors represent areas suitable for flood based farming during major (Meher) and short (Belg) rainy seasons.

produce food that would last for much of the year. The sorghum yields under recession farming range from 0.5–0.8 tons ha-1 in Nyangatom, 1–2 tons ha-1 in Dassanech and 3.0 tons ha-1 in Kara (Pertaub and Stevenson, 2019). The annual flooding in the case study landscapes enhances the fertility of the soil by deposition of alluvials which favors the cultivation of several grain and fodder crops such as maize, sorghum, pearl millet, cowpea, mung bean, haricot bean and grass forages (Getnet et al., 2022) and increases the productivity of the natural pasture (Atanga and Tankpa, 2021; Atubiga and Atubiga, 2022). Based on that it is recommended that more attention should be given to flood recession farming to ensure all year-round farming in the areas as a measure of ensuring food security.

4.3 Implications of flood-based farming on integrated approach and current flood risk emergency responses

Natural flood risk reduction and utilizing flash floods to boost agricultural production requires more than just designing and financing the construction of engineering measures. It requires a concerted effort and dedicated finances to support coordinated efforts of stakeholders and communities at local and higher levels. Regarding planning and implementation of flood farming practices, lack of spatial and temporal flood occurrence information, lack of integrated and cross-sectoral participation across upstream and downstream landscape actors (Alemayehu, 2014; Castelli and Bresci, 2017), and lack of sustainable financing might be among the challenges of flood management. We learned from our study that there remains a need for advocacy and awareness that increases the implementation of flood farming practices to reduce the risk of flash floods and mitigate droughts. A proper understanding of flood occurrence and adaptability of the locations for flood farming will give ample opportunity in drought-prone areas to create resilient livestock and crop production systems. To this end, it is important to develop integrated floodwater governance with a clear flood management plan that involves the community at upper and lower landscapes (Castelli and Bresci, 2017; Demissie et al., 2021). The integrated flood management plan could have a range of purposes including interventions on agricultural production under dryland situations, rangeland management, livestock water supply, and restoring the soil and water resources. More importantly, economically flood farming is one of the potential entry points for creating an agricultural production value chain in the drought-affected drylands and upstream highlands. Thus, flood farming practices have the potential to influence local livelihoods, economies, and biophysical systems as it is the only source of water in arid and semi-arid environments (Alemayehu, 2014; Meaza et al., 2017; Desta et al., 2021). Thus, addressing the knowledge and evidence gap on the potentials of flood farming contributes to an informed decision toward unlocking the opportunities of flood farming to support livelihoods and economic development in the drought-prone areas, specifically in the Rift Valley areas, the Afar lowlands, South Omo valleys and the lowlands of Awash and Wabishebelle rivers.

Realizing the potential of flood farming implies a shift from a project-oriented approach to a process-oriented holistic approach based on the inclusion of stakeholders and communities in the process (Castelli and Bresci, 2017). Flood risk management should be responded to by formulating an integrated approach embedded in the context of integrated water resources management and land use planning. The uncertainty of the flood incidents or sudden nature of occurrence, the local scale of the event, and the very short flood concentration time should be taken into consideration when developing a risk mitigation and agronomic management strategy. Due to these special characteristics, flash floods are best managed by the local authorities with active and effective involvement of the people at risk who have experienced the local trends and nature of flood occurrence over the years. Thus, flood management measures and intensification practices should be encouraged and supported with regular communication and technical backup on the rainfall forecasts, flash flood inventories, and flood frequency information, and coordinated land management and land use plans which will enable it to scale up. Flood databases and decision support tools can further facilitate the decision-making and implementation of flood risk management as well as flood farming.

The current policy response to manage flood risks is through the preparation of an emergency response plan. Beyond the emergency flood response plan that aims to provide preparedness and emergency precautionary measures and develop an emergency response to flood-affected people, there is a need for an investment strategy to deal with flood farming opportunities within the overall integrated basin water management strategy that aims to unlock potentials of floodwater management and facilitate and coordinate the actions of different actors. The strategy to manage floods should be focused on providing the necessary technical, financial and legal framework for the competent authorities to play their legitimate role.

5 Conclusion

Assessing flood-induced risks and understanding flood-causing factors are the first steps in exploring adaptation alternatives in flood-prone locations so that flash floods can be turned into productive use using appropriate flood management strategies. In Ethiopia's dry lowlands, floods are among the most frequent natural disasters. Since the 1990s, Ethiopia has experienced an incremental rise in the number of flood incidents and associated risks. The investigation of the frequency and geographic range of flood occurrences showed a dramatic increase in flood events over decades along with increased drought incidents. This is predominantly attributed to the interaction of various factors, including heavy rainfall, topography, land degradation – conversion of natural ecosystems to agricultural land uses, and changes in land use and geomorphologic conditions.

Remote sensing technologies using pre and post-flood detection approaches assist in quickly identifying areas for landscape flood occurrence. Combined application of GIS-based multi-criteria suitability analysis and remotely sensed satellite imageries were used for delineation of potential flood zones for flood recession farming. Specifically, the flood change detection approach for a predefined window period in the season proved to provide reliable flood recession distribution in a situation where there are scarce and uncertain flood records. Consequently, using a combination of remote sensing images and expert knowledge aids decision-makers, particularly subject-matter experts and irrigation planners, in introducing and demonstrating various types of flood-based farming as well as supporting informed decision-making on flood risk management strategies. The results insight into the access and availability of flood recession farming in the dry lowlands and smallholder farmers can take advantage of the fertile nature of the soil by engaging in the production of different types of food crops. It has the potential to ensure food security and livelihoods of the drought-affected communities. The study concludes that the full potential of flood recession farming and specific technological options can be assessed through comprehensive research about the different aspects of flood recession farming. Given the unpredictability of rainfed farming in the dry lowlands, there is a clear need for investment and adaptation of flood-based livelihood strategies and mainstreaming this practice in policy-making for drought management and sustainable food production in the dry lowlands.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found at: https://public.emdat.be/data.

Author contributions

GD: Conceptualization, Investigation, Methodology, Writing – original draft. GL: Data curation, Formal analysis, Methodology, Software, Writing – review & editing. MA: Data curation, Formal analysis, Methodology, Writing – review & editing. AM: Data curation, Investigation, Methodology, Writing – review & editing. BB: Data curation, Investigation, Methodology, Writing – review & editing.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. This work was partly financed under the CGIAR Research Program on Water, Land and Ecosystems (WLE) supported by Funders contributing to the CGIAR Trust Fund. For details visit https://wle.cgiar.org/donors. We also recognize the support of the EU RESET Plus Innovation Fund funded ELSAT project (Project Number: 11.0363/019) which cover staff time of lead and second authors.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2024.1348094/full#supplementary-material

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frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 12 March 2024
DOI 10.3389/fsufs.2024.1307781

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OPEN ACCESS

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RECEIVED 05 October 2023
ACCEPTED 28 February 2024
PUBLISHED 12 March 2024

CITATION
Wang X and Wang YN (2024) Farmer differentiation and cultivated use system resilience from a perceptive behavioral perspective: influencing mechanisms and governance strategies.
Front. Sustain. Food Syst. 8:1307781.
doi: 10.3389/fsufs.2024.1307781

Farmer differentiation and cultivated use system resilience from a perceptive behavioral perspective: influencing mechanisms and governance strategies

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Introduction: The adaptive management strategy of the cultivated land use system is crucial for achieving sustainable development, particularly when viewed from the perspective of perceptual behavior. This study integrated farmers' behavior, perceptions, and willingness into the resilience evaluation index system of the cultivated land use system.

Methods: By resilience calculation method of cultivated land use system and linear regression method, it also explored the effect of farmer differentiation on the resilience of cultivated land use systems under the influence of socioeconomic systems, thereby providing a scientific reference for the adaptive management of cultivated land use systems.

Results: The key findings are as follows: First, in general, the production resilience of the peasant household cultivated land use system was low, with significant resilience differentiation of resource elements and stratification of ecological and scale structures. However, the total resilience remained relatively stable. Second, farmers' cultivated land use systems exhibit uneven resilience, with a lack of production and ecological protection, indicating low efficiency and weak functioning of the cultivated land use system. Third, farmers' differentiation into non-agricultural employment is high, with low dependence on land. The resilience of the cultivated land use system varies significantly among different types of farmers, with imbalance and production deficiency being the main types of resilience in the farmland use system. Fourth, the economic differentiation of farmers and the differentiation of cultivated land use negatively affected the resilience of the cultivated land use system; the more pronounced the differentiation, the lower the resilience.

Discussion: Based on these findings, the primary management strategies to enhance the resilience and adaptability of the cultivated land use system include improving the production resilience of the system, increasing the enthusiasm of different types of farmers to invest in the resource elements of the cultivated land use system, promoting the transformation of ecological protection consciousness and behavior among various types of farmers, and improving the willingness for cultivated land transfer.

KEYWORDS

scale of farmers, cultivated land use system resilience, farmer differentiation, adaptive governance, cultivated land use system

1 Introduction

Cultivated land serves as a fundamental resource for maintaining global ecological and food security and promoting human survival and sustainable development (Ares et al., 2001). With the impact of climate change, the economic crisis and the increasingly severe form of international trade, protecting cultivated land and ensuring food security have become key tasks for all countries (Tilman et al., 2002). However, the contradictions between people and land, such as the solidification of cultivated land property rights, the weak systematic management of cultivated land, the abandonment of farmland by farmers, and the extensive use of cultivated land, hinder the implementation of the cultivated land protection system, affect the production, life and ecological functions of cultivated land, and become the root challenges for the effective use and protection of cultivated land (Bahar and Kirmikil, 2021). From the perspective of the production function of cultivated land, the non-grain, non-agricultural, fragmentation and fertility degradation of cultivated land make the ability of cultivated land to supply food weaker and weaker, and affect the stability of grain production (Mander et al., 2007). From the perspective of the living function of cultivated land, less cultivated land management income can not guarantee the basic living needs of farmers, reduce the willingness of farmers to engage in agricultural production, and further lead to the loss of rural labor force. From the perspective of ecological function of cultivated land, the blind pursuit of extensive use of grain yield causes irreversible quality loss of cultivated land fertility, and further damages the balance of the ecosystem in the process of ecosystem circulation (Costanza et al., 1997). It can be seen that the balance and coordination of production, life and ecological functions of cultivated land are the key and difficult points in the process of utilization and protection of cultivated land. In the face of the complexity and uncertainty of cultivated land protection, how to coordinate the relationship between human activities and cultivated land use, and improve the social security and ecological protection functions of cultivated land while ensuring the production function of cultivated land is a hot topic of academic attention.

Modern research prioritizes enhancing the productivity of cultivated land, while ensuring its sustainable use and maintaining the quantity, quality, and ecology of the land. Numerous studies have examined the current state and dynamic changes in global cultivated land use, focusing on aspects such as characteristics of the cultivated land use system, quality evaluation, ecosystem service value, production efficiency, and carbon emissions. These studies suggest that the production and ecological potential of cultivated land can be improved through various methods (Amichi et al., 2012; Liang and Li, 2020; Niu et al., 2021). Consequently, scholars have proposed the protection of cultivated land through the construction of a "quantity–quality–ecology" evaluation system, comprehensive land improvement, and a balance between occupation and compensation, among other control measures and policies. These strategies aim to enhance the sustainable development capacity of cultivated land use system (Song et al., 2015; Lyu et al., 2022). However, because the cultivated land use system is one of the most complex subsystems in the socio-ecological system and is in a state of dynamic balance, it is insufficient to evaluate its quality solely using static methods. Resilience thinking, which refers to a system's ability to withstand disturbances in a changing environment and reorganize its elements to achieve a new balance and sustainable development, offers a fresh perspective. Therefore, this study explored how to maintain the stability of a cultivated land use system under internal and external forces, using resilience thinking and a dynamic balance perspective. This approach provides new theoretical support for understanding the operational laws of cultivated land use systems.

Resilience is a complexity, intersections and multi-disciplinary concept, which has undergone a transition from engineering resilience to ecological resilience and then to evolutionary resilience (Gunderson, 2000; Volkov et al., 2021). At present, many scholars have applied the resilience theory to the cultivated land use system, studying how cropland use systems adapt to stress, and its connotation has changed from expressing the state and adaptability of cultivated land to emphasizing the transformation ability of cultivated land to respond to pressure based on the existing state (Lyu et al., 2022). In terms of the resilience evaluation of cultivated land use system, scholars mostly set up a multi-dimensional evaluation model from the perspective of national, provincial and municipal scales, cultivated land natural resources, farming conditions, ecological services, production capacity, social security and other attributes and functions of cultivated land, and adopted multi-source spatial data and socio-economic data to carry out comprehensive evaluation (Ares et al., 2001; Nguyen et al., 2019; Léger-Bosch et al., 2020; Shonhe and Scoones, 2022). In terms of driving mechanism, many scholars have shown that the resilience of cultivated land use system is mainly influenced by climate, terrain, soil, farmers' agricultural production technology, farming methods, input and utilization and other natural environment and human factors. At the same time, rural labor transfer, location factors, urbanization level, "non-food," farmers' livelihood conditions, agricultural development policies, also affect the play of resilience (Sutcliffe et al., 2015; Maltou and Bahta, 2019; Calo, 2020). In summary, the study on the comprehensive evaluation and driving mechanism of large-scale cultivated land use system resilience has been perfected (Özerol and Bressers, 2017). However, there are few studies on the resilience of cultivated land use system based on rural and subject small-scale perspectives, and the driving mechanism of the resilience of cultivated land use system is not only the direct influence of a single factor, but also the correlation influence of multiple factors inside and outside the system is the key reason for the change of the resilience of cultivated land use system, and the correlation logic is also crucial to study.

Farmers' attitudes and behaviors toward agricultural development policies and farmland protection significantly influence the resilience of cultivated land. As key components of the cultivated land use system, farmers possess a strong sense of initiative and maintain extensive social networks, both of which significantly affect the system's resilience (Baird et al., 2020). The behavior, understanding, and willingness of farmers can influence the composition, structure, and morphological changes in the cultivated land use system (Bahar and Kirmikil, 2021). However, many studies treat farmers as separate entities from the cultivated land use system, rather than as integral parts of the system's resilience (Meng et al., 2019; Hossard et al., 2021; Rachunok et al., 2021). These studies were limited to evaluating the current situation of the inherent resources of the cultivated land use system, ignoring the resistance of farmers to the external pressures of the cultivated land use system and the use of internal resources. The mechanism of the resilience of the cultivated land use system and the reorganization of the elemental resources of the cultivated land use system have not been reflected. Therefore, based on the current situation of resource elements of the cultivated land utilization system, the perception, behavior, and coping measures of farmers to the pressure are reflected, which is a deep analysis of the operation law of the cultivated land utilization system and further sublimation of the concept and evaluation of the resilience of the cultivated land utilization system; therefore, it is crucial to incorporate farmers' perceptions, behaviors, understanding, and willingness within the cultivated land use system into the evaluation of cultivated land resilience. This involves constructing an evaluation framework for the resilience of a cultivated land use system, based on perceived behavior.

As the social ecosystem continually evolves and globalization progresses rapidly, farmers' perceived behaviors shift, leading to their gradual detachment from the cultivated land use system (Zamchiya, 2013; Nyantakyi-Frimpong and Kerr, 2017). This detachment has resulted in changes in the intensity, scale, environment, and internal components of the cultivated land use system, thereby affecting its resilience efficiency (Olofsson, 2020; Yin et al., 2020). The most evident manifestation of the social and economic system's influence on farmers' behavioral perceptions is their differentiation (Shonhe and Scoones, 2022). Investigating the resilience characteristics, influence mechanisms, and adaptive governance strategies of cultivated land use systems among farmers with varying types of differentiation is crucial for enhancing the theoretical framework of sustainable cultivated land use and identifying adaptive transformation strategies for cultivated land (Angeler et al., 2015).

Based on this, on the basis of the previous comprehensive evaluation of the natural and functional attributes of the cultivated land use system, this study integrated the perceived behavior of farmers into the resilience assessment index system of the cultivated land use system, and highlighted human perception and subjective initiative more than previous studies. In addition, farmer differentiation, as the most intuitive manifestation of farmers' resistance to adaptation pressure, on the one hand, accepts the influence of social ecosystem, on the other hand, plays a role in the cultivated land utilization system. Therefore, combined with the existing research on the driving mechanism of cultivated land use system, analyze the impact of the differentiation of farmers' occupation and economy on the resilience of cultivated land use system under the background of globalization, its beneficial to better understand the mechanism of farmland use system resilience under internal and external pressure and environment, and then put forward targeted management strategies of farmland use system.

2 Theoretical framework

2.1 Connotation of cultivated land use system resilience

Resilience is the capacity of a system to respond to unexpected disturbances. This concept includes three aspects: the system's resilience in withstanding shocks, while preserving its existing structure and function; the system's adaptability in managing shocks through experiential learning, self-reorganization, and adjustment; and the system's ability to form a new developmental trajectory and achieve transformation and upgrading (Léger-Bosch et al., 2020). Cultivated land use systems are a combination of natural ecosystems, such as cultivated land, climate, hydrology, and biodiversity, and social and economic systems, such as human development, protection, and utilization (Calo, 2020). The resilience of the cultivated land use system refers to the ability of arable land systems to resist and adapt to disturbances using resource factors and to restore stable sustainable development. Resilience reflects the extent to which an arable land system can withstand external disturbances. The creation of a new development path to realize system renewal and transformation, while maintaining the basic structure and function of the cultivated land use system, is a further refinement of the concept of resilience of the cultivated land use system (Sundstrom et al., 2023). The development of the resilience function is closely tied to factors within the cultivated land use system, such as resource endowment, material economy, cultural customs, ecological environment, population, industry, and social networks. The connectivity and cooperation of these factors form the foundation for resistance to interference (Meng et al., 2019; Lyu et al., 2022). Therefore, the resilience of cultivated land-use systems refers to their capacity to adapt to external disruptions and achieve transformation and upgrading through internal factor reorganization and morphological-structural changes in response to the challenges posed by the external social environment. Resilience is crucial for maintaining the system's sustainable development (Bahta and Lombard, 2023). The resilience of cultivated land use systems can be divided into the following four components: resource element resilience, production resilience, ecological resilience, and scale structure resilience (Lyu et al., 2022). These components refer to the input and richness of various resource elements of cultivated land use systems, the strength of the production function and social security function, habitat quality and ecosystem service function, and the production form and spatial structure of cultivated land (Gunderson and Holling, 2002; Faria and Morales, 2020).

2.2 Farmers' behavior and cultivated land resilience

As primary stakeholders and actors in cultivated land use systems, farmers use these resources to withstand disturbances. Their decision making and resource access collectively determine the system's response to shocks and pressures (Legesse and Drake, 2005). Drawing from behavioral theory, it is evident that the system environment influences farmers' subjective initiative. Their perception of this environment dictates their livelihood behavior, which in turn shapes the composition and structure of the cultivated land use system. This forms a system's method of responding to pressure and reflects its resilience (Özerol and Bressers, 2017). Governance, defined as the maintenance of organizational order, promotion of development, and progress control by an independent collective within or outside the organization, relies on systems, methods, or means to maintain order. As the primary participants in governance activities, farmers' perceived behavior reflects the governance effectiveness (Muller et al., 2016). Consequently, evaluation of the resilience of the farmland use system should be grounded in the interaction between farmers and the system environment, focusing on farmers' environmental perceptions and resource use. In other words, the assessment of the resilience of the cultivated land use system should be approached from the perspective of farmers' perceptions and behaviors.

Agricultural land systems must possess adequate food and economic production capabilities to withstand the food crisis and the strain of agricultural labor shortages brought on by global population growth and rapid urbanization (Human and Soleimanian, 2018). Within this system, elements such as people, land, finance, technology, and machinery form an integrated entity, with changes in any element affecting the entire system (Hu et al., 2021). Farmer differentiation refers to the transfer and change of farmers' employment, identity and quality improvement, which is the final choice result of farmers' behavior perception (Yin et al., 2020). Driven by the external social environment, the choices made by farmers in terms of livelihood, residential area and future development will eventually lead to the differentiation of farmers in different directions of employment and identity, which will further affect the input of farmers to the elements of the cultivated land utilization system and the intensive management behavior of cultivated land scale (Adger, 2000; Zamchiya, 2013). Specifically, the differentiation of farmers can be divided into two categories: economic differentiation and farming utilization differentiation. The economic differentiation of farmers is mainly manifested in the diversified choices of farmers' livelihood and professional and part-time farmers' professional identity, while the differentiation of cultivated land utilization is mainly manifested in the differences of farmers' cultivated land utilization behaviors (Nyantakyi-Frimpong and Kerr, 2017). The more farmers tend to divide into non-agricultural and smallholder farming, the lower the resilience of cultivated land use system (Shonhe and Scoones, 2022). As the development gap between urban and rural areas widens, cities and towns are becoming increasingly attractive to farmers, placing the agricultural land system under the pressure of gradual labor force loss (Blesh and Wittman, 2015). Owing to their part-time employment, many farmers are unable to commit fully to agricultural production. This results in a decrease in farmers' investment in agricultural land, a lack of agricultural mechanization, and in some cases, even the abandonment of arable land (Baysse-Lainé and Perrin, 2018; Keleg et al., 2021).

Therefore, the decision of farmers to continue cultivation and the extent of their investment in the cultivated land system can influence the basic composition of the system. If the cultivated land system fails to maintain appropriate grain yield and economic benefits, it can affect its production function, which in turn can influence its resource elements and production resilience (Bertoni et al., 2018; Darnhofer, 2021). As a crucial component of the ecological environment, cultivated land systems offer a range of ecological service functions. This is fundamental for ensuring food production and agricultural development and demonstrates the ecological resilience of cultivated land systems (Ares et al., 2001). Moreover, the size of the cultivated land system, intensity of its contiguity, and structure of its planting can all affect the efficiency of land use, which can further limit the grain yield and economic output of cultivated land. The larger and more concentrated the cultivated land system and the higher the proportion of food crops, the stronger the functions and scale structure resilience of the cultivated land system.

However, the weaker the ecological protection consciousness of farmers, the more likely it is to damage the ecological environment of cultivated land because of the pursuit of cultivated land production efficiency, and then reduce the ecological toughness of cultivated land (Graeme, 2011; Gong et al., 2019). Concurrently, the unique household contract responsibility system in China, coupled with the characteristics of the natural geographical environment, has resulted in fragmented cultivated land in many regions, thereby reducing the prevalence of large-scale intensive production (Léger-Bosch et al., 2020). Under these circumstances, factors such as whether farmers possess stable property rights over cultivated land, their decision to transfer land, and their choice of management scale significantly affect the efficiency of cultivated land use. These decisions can further influence the resilience of the scale structure of cultivated land systems (Gong et al., 2019; Gyapong, 2020).

In summary, the economic differentiation of farmers and the differentiation of cultivated land use affect the intensity and mode of cultivated land use, and then affect the resource elements, production, ecology and scale structure toughness of cultivated land use system. Therefore, this study assumes that the economic differentiation of farmers and the differentiation of cultivated land use will have an impact on the resilience of resource elements, production resilience, ecological resilience, and the scale and structure toughness of cultivated land use systems and then drive changes in the resilience of cultivated land use systems (Figure 1).

3 Research methods and data sources

3.1 Description of study area

To examine the current state of regional agricultural development, this study focused on 12 villages in Xiqiao Town, Shimenshan Town, and Wucun Town, all within Qufu City, Shandong Province, China. Qufu spans 815 square kilometres, has jurisdiction over eight towns and four villages. In 2020, agricultural land constituted over 70% of the city's total land area, marking it as one of China's highly urbanized regions with intensive agricultural land use. The selected rural areas have cultivated land accounting for 81% of their total land area, and half of their population engages in agricultural work.[1] The degree of rural agricultural mechanization is steadily increasing, and agricultural entities such as family farms, agricultural cooperatives, and leading agricultural enterprises are thriving, leading to a progressively diversified agricultural economy. However, rural cultivated land use systems face numerous challenges and disruptions owing to climate disasters such as droughts and floods, as well as external effects such as an unstable agricultural market and rapid urbanization. These factors affect farmers' perceptions of and the functionality of cultivated land during its use.

The three towns selected in this study represent different stages of rural development. Shimenshan Town, the most remote city center, is a traditional village with a focus on forestry and animal husbandry. Adjacent to Shimenshan is Wucun Town, a village undergoing agricultural modernization. It is characterized by a southern plain and a significant number of large grain producers, family farms, and agricultural cooperatives. Finally, Xizhou Town, located near the city center and primarily composed of plains, has a high *per capita* disposable income but lags in agricultural development. This is a typical characteristic of villages heavily influenced by urbanization. In summary, these three towns collectively represent a spectrum of rural development types (Figure 2).

1 http://www.qufu.gov.cn/

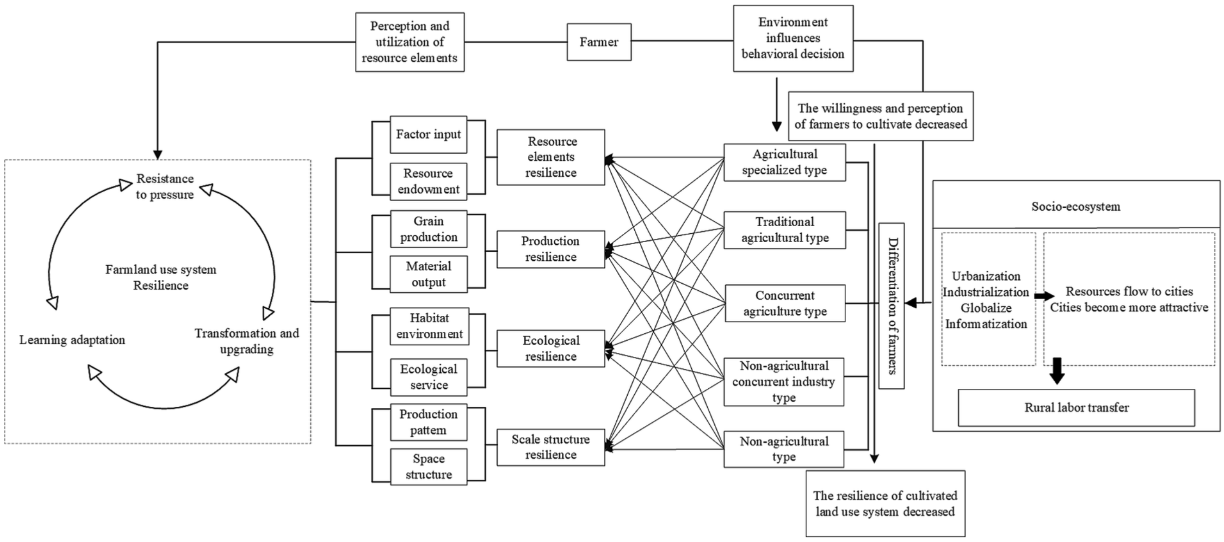

FIGURE 1
Theoretical framework.

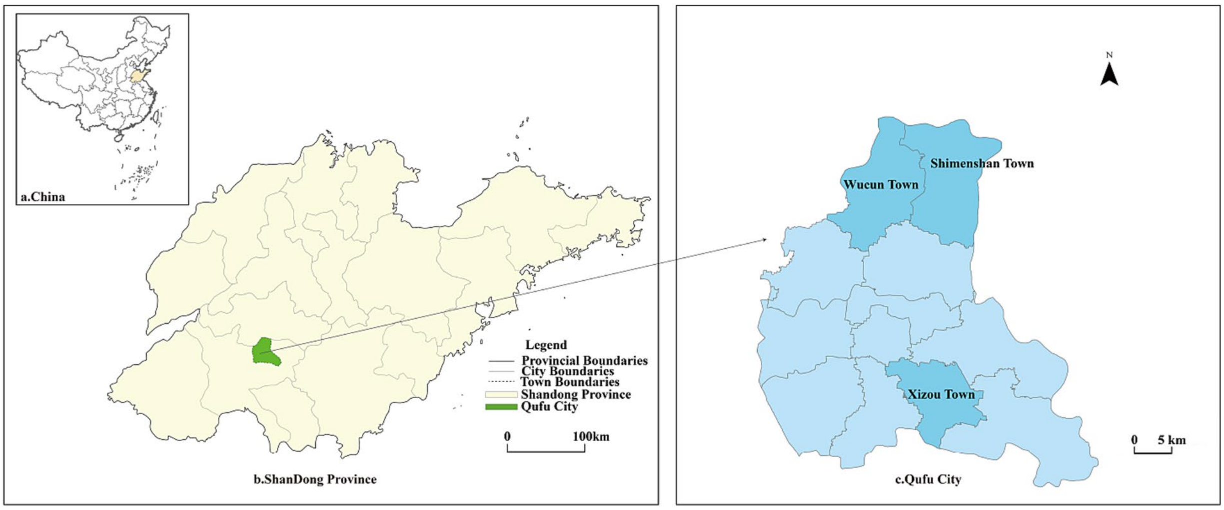

FIGURE 2
Study area map.

3.2 Research design

Data for this study were gathered from a survey conducted among farmers in Qufu City in 2020. First, the purpose of the study was clarified and a survey questionnaire was designed in accordance with the natural and social conditions of Shandong Province. This included questionnaires for both farmers and villages and three rounds of discussions were held. Subsequently, a few villages in Qufu City were chosen for a preliminary investigation, and the questionnaire was revised based on the findings of this pre-investigation. Finally, the towns of Shimenshan, Wucun, and Xizou were selected, each with distinct characteristics. In each town, four natural villages were chosen randomly, and approximately 30 farmers from each village were randomly selected for household surveys and face-to-face interviews. Each household questionnaire took between one and a half hours to complete and each village questionnaire took between half an hour and one hour.

3.3 Study population, sampling procedure, and sample size

The research population for this study primarily comprised a permanent rural population and village officials selected predominantly through random interviews conducted in rural areas. The farmers' questionnaire captured a wide range of information, including details about the farmers' family size, behavior related to cultivated land use, production, and management, and perceived behavior. The data used in this study included farmers' human, social, and material capital statuses and their perceptions of the ecological environment and policies, all of which were used to measure farmers' decision-making behavior. Additionally, it included the fundamental characteristics of the cultivated land use system, farmers' inputs and outputs related to cultivated land use, and changes over the past 5 years to assess the resilience of the cultivated land use system. The village questionnaire primarily investigated the overall natural and economic conditions of the rural areas, providing an understanding of the resilience of the cultivated land use system. Respondents were village officials. Shimenshan Town, Wucun Town, and Xiqiao Town in Qufu City were selected for the survey through random sampling. Subsequently, four natural villages were randomly selected in each town, and approximately 30 households were randomly chosen in each village for household surveys and in-person interviews. A total of 380 questionnaires were distributed to farmers and 12 to villages. After excluding invalid questionnaires, 324 valid farmers and 12 valid village questionnaires were obtained.

4 Method of data analysis

4.1 Construction of index system

This study aimed to assess the resilience of cultivated land use systems at the farmer level. The evaluation begins with an examination of farmers' perceptions, behaviors, understanding, and willingness to use cultivated land. Relevant indicators were selected to establish an evaluation system centered on the resilience of resource elements, production resilience, ecological resilience, and the scale structure of the cultivated land use system. The resilience of resource elements within the cultivated land use system primarily stems from farmers' contributions to labor, technology, machinery, capital, and other elements of the system. The average labor input, average economic input, degree of agricultural technology training, and irrigation methods chosen by farmers were used as indicators for the measurement. The resilience of the cultivated land use system is reflected in its ability to ensure food security and satisfy farmers' economic output requirements. Therefore, it is measured by economic income per land unit, grain output per land unit, and *per capita* planting income. The ecological resilience of a cultivated land use system signifies the robustness of the system's ecological service functions and habitat quality (Drever et al., 2006).

The overuse of chemicals and environmental degradation can result in decreased ecological resilience. As such, the extent of farmers' fertilizer use, their readiness to reduce this use, and their methods of agricultural waste management are employed as indicators of ecological resilience (Bertoni et al., 2018; Feofilovs and Romagnoli, 2021). The resilience of the scale structure of a cultivated land use system embodies the characteristics and spatial structure of an area. A superior scale structure indicates more stable property rights over cultivated land, enhanced functions of the land use system, and increased resilience of the scale structure. Consequently, this is assessed by the fragmentation level of cultivated land, farmers' willingness to operate on a larger scale, and the stability of their property rights over cultivated land (He et al., 2011; see Table 1).

Differentiation among farmers can, to some extent, mirror their perceptions and behaviors within the cultivated land use system. Consequently, farmers were categorized into five types based on their economic income: the scale of cultivated land management (with scale management defined as more than 30 mu), labor input, and land dependence: agricultural professional, traditional agricultural, agricultural concurrent, non-agricultural concurrent, and non-agricultural (see Table 2).

4.2 Model specification

Drawing on the resilience theory, we developed a cognitive framework for the resilience of cultivated land use systems. This framework begins with the multidimensional aspects of cultivated land, including resource elements, production, and ecological and scale structure resilience. Using an index model, we constructed a resilience evaluation equation to assess the resilience of a cultivated land use system. On this basis, a linear regression model was used to calculate the regression coefficient of peasant household differentiation on the toughness of cultivated land use systems, and the relationship between the two was clarified.

4.3 Normalization of index data

To eliminate the dimensional influence among the indices, we used the deviation standardization method to normalize the indices as follows:

$$\text{Positive index}: \text{Ui} = (\text{Xi} - \min \text{Xi}) / (\max \text{Xi} - \min \text{Xi}), \quad (1)$$

$$\text{Reverse index}: \text{Ui} = (\max \text{Xi} - \text{Xi}) / (\max \text{Xi} - \min \text{Xi}), \quad (2)$$

Equations 1 and 2, where Ui is the standardized index variable value, Xi is the original value of the index variable, and minXi and maxXi are the minimum and maximum values of the original value Xi of the index variable, respectively.

4.4 Entropy weighting method

The index system is weighted, and given by the following equation:

$$W_j = \frac{(1 - e_j)}{\sum_{j=1}^{n}(1 - e_j)}, \quad (3)$$

Equation 3 where e_j is the index information entropy and W_j entropy is the index entropy weight of item j in the evaluation index system of cultivated land resilience.

4.5 Resilience evaluation equation

System resilience is the weighted sum of various resiliences within the system, and is given by

TABLE 1 Resilience index system of cultivated land use system at the scale of farmers.

Resilience type	Indicators	Indicator meaning	Direction	Unit	Weight
Resource elements resilience	Average labour input	Agricultural labour force/cultivated land area	+	People/hm^2	0.245
	Economic input per land	Economic input of planting industry/cultivated land area	+	Yuan/hm^2	0.252
	Agricultural technical training level	Have farmers received technical training (No = 1; Yes = 2)	+		0.252
	Irrigation mode	Indicates the construction degree of farmland water conservancy facilities (rainwater = 1; Flood irrigation = 2; Furrow irrigation = 3; Border irrigation = 4; Sprinkler irrigation = 5)	+		0.251
Production resilience	Average planting income	Planting income/cultivated land area	+	Yuan/hm^2	0.344
	Average grain yield	Grain output/cultivated land area	+	kg/hm^2	0.345
	Per capita planting income	Economic income of planting industry/agricultural working population	+	Yuan/person	0.311
Ecological resilience	Excessive application of chemical fertilizer	Fertilizer application rate/cultivated land area-225 kg/hm^2	–	kg/hm^2	0.333
	Willingness to reduce chemical fertilizer application	Willingness of farmers to reduce fertilizer consumption (No = 1; Yes = 2)	+		0.334
	Treatment methods of agricultural garbage	Garbage disposal methods such as pesticide bottles and agricultural films (Throw away the edge of the field at hand = 1; Take home and concentrate on the way out = 2; Recycling in garbage recycling station = 3)	+		0.333
Scale structure resilience	Degree of farmland fragmentation	Number of cultivated land plots/cultivated land area	–		0.330
	Farmers' willingness to operate on a large scale	Farmers' willingness to operate on a large scale (No = 1; Yes = 2)	+		0.335
	Stability of farmers' cultivated land property rights	Whether farmers' cultivated land is confirmed and certified (No = 1; Yes = 2)	+		0.335

$$R_j = \sum_{i=1}^{m} W_j \times U_{ij} \quad R = \sum_{j=1}^{n} R_j, \tag{4}$$

Equation 4, where R_j is the resilience of the resource elements, production, ecology, and scale structure of the cultivated land system, which are components of the resilience of the system. The variable m denotes the number of indicators and n signifies the component fraction of cultivated land resilience, which, in this case, was four. Finally, R denotes the total resilience of the system and is expressed as the sum of the normalized index variables.

4.6 Linear regression model

Resource element, production, ecological, scale structure, and total resilience of the cultivated land use system were used as dependent variables, and the economic differentiation of farmers and the differentiation degree of cultivated land use were used as independent variables to verify the impact of farmer differentiation on the resilience of the cultivated land use system:

$$y = ax_1 + bx_2 + c \tag{5}$$

Equation 5 where y is the dependent variable, x is the independent variable, a and b are regression coefficients representing the relationship between the independent and dependent variables, and c is a constant.

5 Results

5.1 Resilience measurement of cultivated land use system at the farmers' scale

The resilience of the farmers' cultivated land use system overall is relatively stable, but the resilience of production is generally low. There is significant differentiation in the resilience of resource elements and notable stratification in the resilience of ecological and scale structures. By applying the resilience evaluation equation to the cultivated land use system, the resilience of the resource elements, production, ecology, and scale structure were weighted and summed. This process resulted in 324 samples of resilient farmers' cultivated land use systems (see Figure 3). Figure 3A shows that the resilience value of the cultivated land use system at the farmers' scale was primarily concentrated between 1.20 and 2.00, demonstrating a strong characteristic of agglomeration. The sample of farmers exhibits a range of high and low values, with the highest being 2.59 and the lowest being 0.71, indicating a significant difference. This suggests that the resilience of the cultivated land-use system at the farmer level is relatively stable, although some farmers exhibit low resilience. Examining the resilience of resource elements, production, ecological

TABLE 2 Differentiation types of farmers.

Types of farmers' differentiation	Proportion of agricultural income	Farmland management scale	Labour input	Land dependence
Agricultural specialty type	Over 80%	Scale operation	Agriculture	Strong
Traditional agricultural type	Over 80%	Small-scale peasant management	Agriculture	Strong
Concurrent agriculture type	50–80%	Small farmers and scale management	Agriculture	Stronger
Non-agricultural concurrent industry type	10–50%	Small farmers and scale management	Non-agricultural	General
Non-agricultural type	Below 10%	Small farmers and scale management	Non-agricultural	Weak

aspects, and scale structure of the farmers' cultivated land use system (Figures 3B–E, respectively), it is evident that the production resilience value of the system is the lowest, primarily ranging between 0.10 and 0.20, with only a few farmers achieving higher values. The resilience value of the system's resource elements was mostly below 0.30, with a few exceeding 0.3, and the values for the sample farmers' resource elements were dispersed. Furthermore, the ecological and scale structure resilience values of the system displayed clear stratification. The ecological resilience value is mainly concentrated between 0.3 and 0.9, with dense stratification, while the scale structure resilience exhibits a distinct three-tier stratification, approximately at 0.20, 0.60, and 1.00, with most farmers around 0.60. This analysis revealed that the resilience of the cultivated land use system varies among farmers, but all share the issue of low production resilience. Combined with other international research results, the perceived behavior of farmers does not significantly improve the resource factors, production, ecology, and scale structure toughness of the cultivated land use system but will affect the differentiation characteristics of the various types of toughness of the cultivated land use system.

5.2 Proportion of cultivated land use system resilience at the farmers' scale

Examination of the resilience of farmers' land use systems showed that resource element and production resilience are relatively low, whereas ecological and scale structure resilience are comparatively high (Figure 4). Specifically, the resource element resilience in these systems constituted less than 25% of the total resilience, with a noticeable disparity between the high-value and low-value samples. This significant polarization suggests that farmers' investment in resource elements of land use systems is low and that investment behaviors vary among different farmers. The proportion of production resilience to total resilience is also low, typically below 15%, indicating a weak production function within the land-use system, which fails to ensure food security and farmers' economic income effectively. Conversely, ecological and scale structure resilience accounted for a substantial portion of the total resilience, mostly ranging between 20 and 60%. This suggests that farmers' awareness, behavior, and willingness to manage the scale of ecological protection, concentration and contiguity of cultivated land, and stability of property rights are the primary contributors to the resilience of their land use systems. Considering the background of international food security, it is necessary to learn from the practices of countries with high food output to improve the productivity of the cultivated land use system by ensuring the scale and structure of the cultivated land use system and promoting the input of resource elements such as technology and machinery to ensure the production demand of the cultivated land use system.

Based on the proportion of each cultivated land use system's resilience to the total resilience, we categorized the resilience of farmers' cultivated land use systems into seven types: resource factor scarcity, production scarcity, ecological scarcity, ecological protection, high-scale structure resilience, unbalanced, and balanced. Among these resilience types, the unbalanced and production shortage types were more prevalent, whereas the balanced and ecological protection types were less common (Table 3).

Specifically, the category with the highest proportion was production shortages, which accounted for 45.68% of the total. The defining characteristic of farmers within this category is extremely low resilience in their cultivated land use system, whereas other types of resilience are either high or moderate. This suggests that these farmers have a higher level of input factors, stronger ecological protection awareness, greater willingness to manage on a larger scale, a more robust integrity of cultivated land, and stronger stability of property rights during land use. However, the cultivated land use system has not achieved effective input–output transformation, and the efficiency of resource factor use is low. This may be due to farmers balancing the production and ecological functions of the cultivated land use system.

In addition to production deficiencies, imbalanced resilience constituted a significant proportion (38.27%). This is characterized by low resilience in resource element production and high resilience in scale structure ecology, indicating that these farmers invest less in resource elements and exhibit low intensity in the use of cultivated land systems. However, their ecological protection, scale management behaviors, and cognitions are relatively strong, which could further decrease the resilience of resource elements and production in cultivated land use systems. Moreover, several categories such as resource element deficiency, ecological deficiency, ecological protection, high-scale structural resilience, and imbalance account for a smaller proportion. Nevertheless, they highlight the variations in farmers' behaviors regarding cultivated land use and the imbalance among the various functions of the cultivated land use system.

5.3 Farmers' differentiation and cultivated land use system resilience

5.3.1 Resilience structure of cultivated land use system under the background of farmer differentiation

Farmers in the research area exhibited a significant shift toward non-agricultural employment, reducing their reliance on land. Traditional, professional, and concurrent agriculture account for only 12.65% of

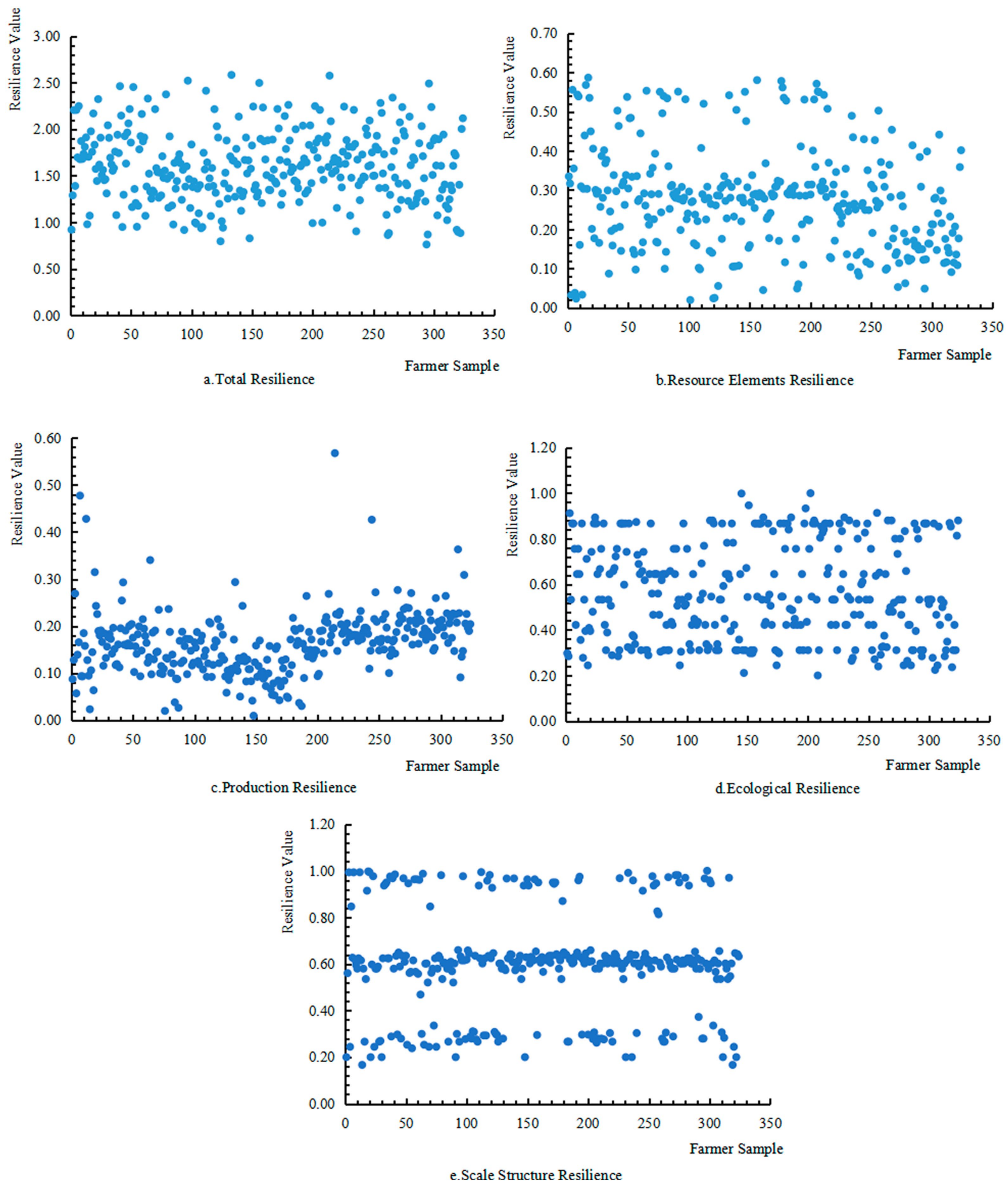

FIGURE 3
Evaluation results of cultivated land use system resilience at the scale of farmers. **(A-E)** represents the total resilience, resource elements resilience, production resilience, ecological resilience and scale structure resilience of cultivated land use system, respectively.

farmers whose primary source of income is agriculture. A substantial majority (87.35%) were non-agricultural farmers who relied primarily on non-agricultural activities for their livelihoods. These findings indicate a severe loss of agricultural labor in the area, with agricultural production income constituting a minor portion of farmers' total income. Although most farmers possess the right to use their homesteads and manage contracted farmland, they often opt to transfer or use cultivated land extensively. By calculating the average resilience of the cultivated land use systems among different types of farmers, significant disparities were apparent. Professional and concurrent agricultural farmers exhibited higher average resilience (1.78 and 1.68, respectively), while non-agricultural farmers had the lowest average resilience (1.56). The data suggest that professional farmers who rely primarily on agriculture for their livelihood employ scientific agricultural technology and machinery,

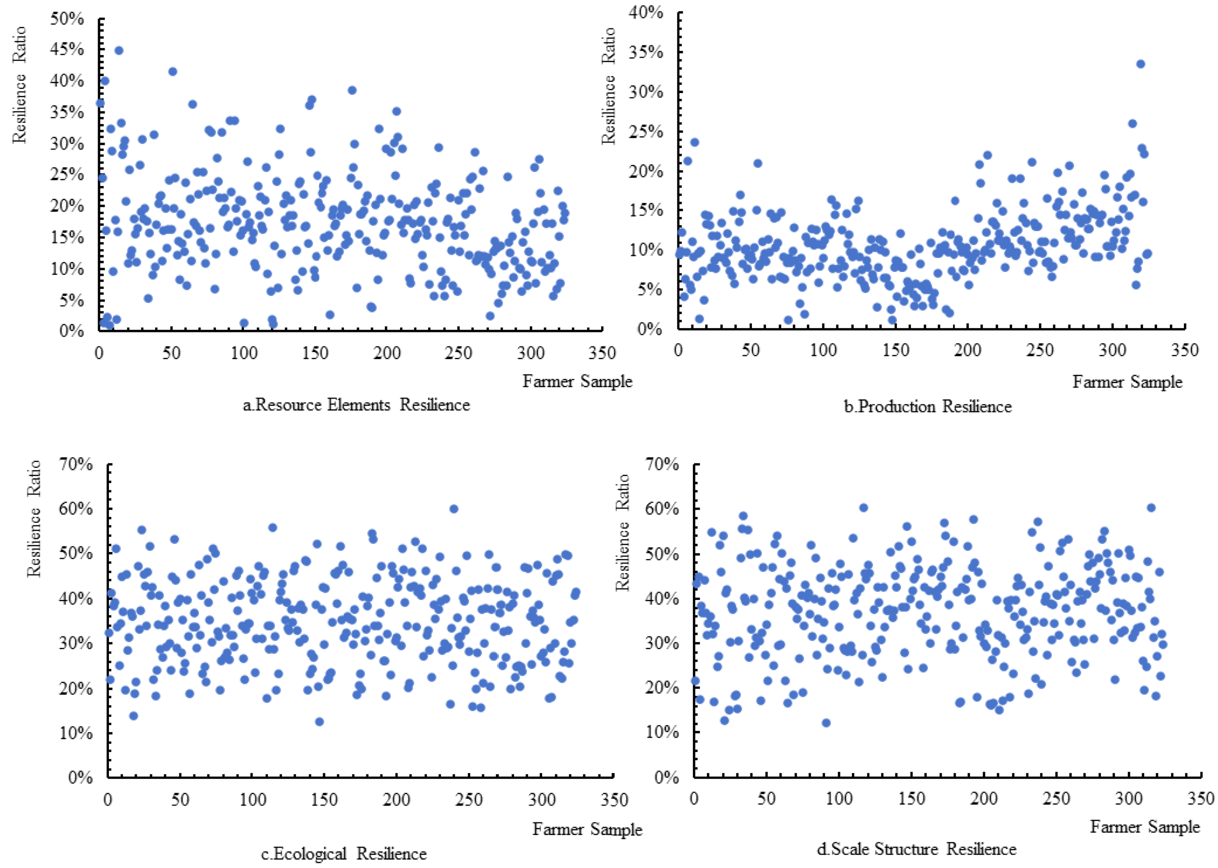

FIGURE 4
Proportion of various cultivated land use system resilience at the scale of farmers. **(A-D)** represents the resource elements resilience, production resilience, ecological resilience and scale structure resilience of cultivated land use system, respectively.

TABLE 3 Resilience classification of farmers' cultivated land use system.

Resilience types of cultivated land use system	Number of samples (pieces)	Percentage
Lack of resource elements	23	7.10
Production shortage type	148	45.68
Ecological deficiency type	11	3.40
Ecological protection type	2	0.62
High resilience type of scale structure	10	3.09
Unbalanced type	124	38.27
Balanced type	6	1.85

invest more in capital, labor, and land, and consequently reap better benefits. Cultivated land-use systems are intensive. Concurrent agricultural farmers, on the other hand, invest capital and technology acquired through non-agricultural labour into the cultivated land use system, thereby enhancing its resilience to some extent. In contrast, non-agricultural farmers who invest most of their production factors in non-agricultural activities demonstrate low efficiency and resilience in their cultivated land use systems (Table 4).

The resilience of farmers' cultivated land use systems can be classified into two main types: unbalanced and production-deficient. Traditional and professional agricultural farmers predominantly exhibit an unbalanced type, suggesting deficiencies in their production, ecology, scale structure, and resilience of resource elements within their cultivated land use systems. Conversely, farmers involved in concurrent agricultural and non-agricultural industries, as well as non-agricultural farmers, tend to display a high proportion of resilience and production deficiencies in their cultivated land use systems. This indicates that these farmers' resource elements are not being used efficiently and that the production function of their cultivated land systems is weak (Figure 5). Considering the proportion of differentiated farmers with various types of cultivated land use system resilience, traditional agricultural farmers have lower production resilience than other types, leading to an imbalance in their cultivated land use system resilience. For professional agricultural farmers, the imbalance in their cultivated land use system resilience was primarily the result of their higher-scale structural resilience. However, the resilience of the scale structure of the cultivated land-use system was the main factor limiting the resilience of the cultivated land use systems of traditional agricultural, agricultural, non-agricultural, and non-agricultural farmers (Figure 6). Therefore, the resilience of farmers' cultivated land use systems can be enhanced by improving the input and use efficiency of resource elements, increasing the resilience of resource elements and production, stabilizing farmers' cultivated land use property rights, and promoting scale operations.

5.3.2 Influence mechanism of farmer differentiation on cultivated land use system resilience

To investigate the effect of farmer differentiation on the use of cultivated land, the proportion of agricultural income was used to denote the extent of economic differentiation among farmers. A higher proportion of agricultural income indicated a lower level of economic differentiation. The scale of cultivated land use by farmers was used to represent the degree of differentiation in land use, with a cultivated land management area over 30 mu assigned a value of zero and all other values assigned a value of one. A larger scale of cultivated land management suggests that farmers rely primarily on agriculture for their livelihood, indicating a lower degree of differentiation. These two indicators serve as independent variables representing farmer differentiation, whereas the resource element resilience, production resilience, ecological resilience, scale structure resilience, and total resilience of the cultivated land use system are dependent variables. A linear regression model was used to assess the effects of farmer differentiation on the resilience of cultivated land use systems.

The findings indicate that economic differentiation among farmers negatively affects the resilience of resource elements, ecological resilience, and the overall resilience of the cultivated land use system. In other words, the lower the proportion of a farmer's income derived from agriculture, the less resilient the cultivated land use system becomes. This can be attributed to the rapid urbanization and industrialization that has spurred the growth of non-agricultural industries in rural areas, leading to rural labor outflows. Consequently, farmers are more inclined toward non-agricultural development, resulting in less investment in the resource elements of the cultivated land use system. Coupled with the indiscriminate use of chemical fertilizers and pesticides to boost productivity and the lack of clean, environmentally friendly technologies, this leads to low ecological and overall resilience of the cultivated land use system. Furthermore, differentiation in farmers' cultivated land use has a significant negative effect on the production, scale structure, and overall resilience of the cultivated land use system. That is, the smaller the scale of a farmer's cultivated land use, the greater the differentiation and the less resilient the cultivated land use system becomes. Farmers who cultivate a certain amount of land tend to rely on agriculture as their primary livelihood, resulting in a strong degree of sustainable and intensive land use. However, when the scale of cultivated land use is small, farmers are more likely to seek non-agricultural livelihoods, and their willingness to intensively manage cultivated land diminishes. This leads to the serious issue of abandoned, idle, and offset use of cultivated land, which in turn reduces the production resilience, scale structure resilience, and overall resilience of the cultivated land use system (see Table 5). In summary, the economic differentiation of farmers and the differentiation of cultivated land use impact the resilience of resource elements, production resilience, ecological resilience, and the scale and structure resilience of cultivated land use systems. The hypothesis is not completely valid that the economic differentiation of farmers has a negative impact on the resilience of resource elements and ecological resilience, and the total resilience of cultivated land use systems. However, the differentiation in farmers' cultivated land use has a significant negative effect on the production toughness, scale structure toughness, and total toughness of cultivated land use systems.

6 Adaptive management of cultivated land use systems at the farmer scale

6.1 Measures to improve the cultivated land use system production resilience of various types of farmers

Production resilience is a critical factor that limits the enhancement of overall resilience in cultivated land use systems. Therefore, it is crucial to implement various strategies to improve the resilience of these systems. First, efforts should be made to enhance the level of mechanization, technical sophistication, and modernization of land use by farmers. This can be achieved by accelerating the rate of innovation and popularization of agricultural science and technology. Regardless of whether the farmers are traditional, professional, concurrently agricultural, concurrently non-agricultural, or non-agricultural, it is essential to address deficiencies in agricultural mechanization and achieve unified social services in this area. Second, comprehensive improvement of cultivated land should be promoted. This involves integrating the abandonment of cultivated land with the advancement of agricultural mechanization, effectively consolidating resources, reducing farming costs, and encouraging the development of high-standard farmland and infrastructure. This includes transforming fragmented and inefficient farmlands into a more productive system through slope-to-ladder, scale, ditch-to-ditch, road-to-road, dry-energy irrigation, and waterlogged energy drainage. Finally, the marketization, branding, and industrialization of agricultural products should be strengthened. This can be achieved by extending the agricultural industrial chain, selling agricultural products directly to the market, establishing unique agricultural brands, expanding agricultural sales channels, and integrating the production, processing, transportation, and sales of agricultural

TABLE 4 Differentiation degree of farmers and resilience structure of cultivated land use system.

	Traditional agricultural type (TA)	Specialized agricultural type (SA)	Concurrent agricultural type (CA)	Non-agricultural concurrent industry type (NACI)	Non-agricultural type (NA)
Mean value of resilience	1.61	1.78	1.68	1.61	1.56
Number of households	5	12	24	158	125
Proportion (%)	1.54	3.70	7.41	48.77	38.58

TA, SA, CA, NACI, and NA are the short forms of traditional agricultural type, specialized agricultural type, concurrent agriculture type, concurrent agriculture type, non-agricultural concurrent industry type, and non-agricultural concurrent industry type, respectively.

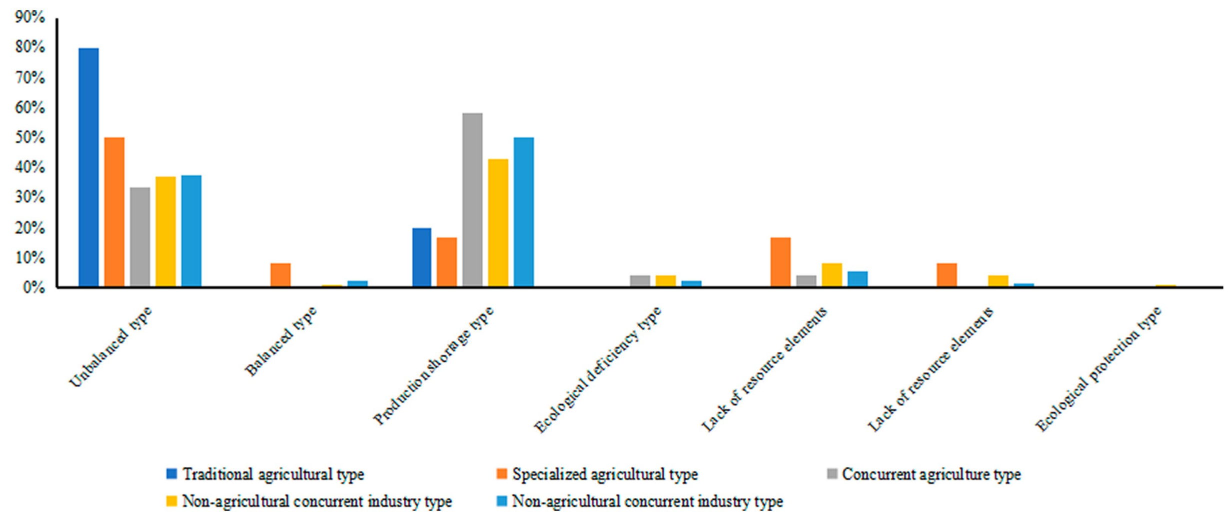

FIGURE 5
Resource resilience types of the cultivated land use system of differentiated farmers.

products into agricultural production. These measures can increase farmers' income and, in turn, enhance the production resilience of the cultivated land use system (Quendler and Morkūnas, 2020).

6.2 Enhance the enthusiasm of various types of farmers to invest in the resource elements of a cultivated land use system

The evaluation results of the resilience of the cultivated land use system at the farmer scale revealed that the primary reason for the system's low input was the farmer's minimal contribution to the system's resource elements. Therefore, to increase the resilience of cultivated land use systems, it is crucial to boost farmers' willingness to invest in the system's resources. First, the government should enhance its support for agriculture and rural areas, refine relevant laws and regulations, lessen the burden on farmers, and improve the corresponding social security systems and infrastructure. This will increase the appeal of agriculture and rural areas to farmers, encourage them to return to the countryside and invest in agriculture, and mitigate the negative effects of the dual urban–rural development structure on rural labor loss. Second, the training of agricultural science and technology talent should be strengthened, along with technical training for small farmers, agricultural cooperative members, and new professional farmers. This will enhance the role of talent and scientific and technological elements in increasing the resilience of the cultivated land use system and improve farmers' precise understanding and control of the demand for system elements. Finally, financing channels for farmers' agricultural production should be expanded, offering diverse preferential financing policies, relaxing financing conditions, and encouraging social capital to invest in agriculture and rural areas. This will alleviate financing difficulties in agriculture and rural areas and promote the inflow of funds into the cultivated land use system (Perrin et al., 2018; Kuang et al., 2020).

6.3 Promote the transformation of farmers' awareness and behavior of ecological protection and improve their willingness to transfer cultivated land

According to the research results, all types of farmers have a high awareness of ecological environmental protection, but due to the impact of farmer differentiation, farmers' ecological protection behaviors are less, and the phenomenon of cultivated land fragmentation is serious. Therefore, it is necessary to further improve the toughness of cultivated land use system, promote the transformation of farmers' awareness and behaviors of cultivated land protection, and enhance farmers' willingness to transfer cultivated land and improve the scale utilization efficiency of cultivated land. First, while farmers demonstrate a strong understanding of the ecological protection of the cultivated land use system, this has not yet translated into their behavior toward ecological protection, necessitating governmental intervention to mobilize the necessary resources, provide farmers with the requisite support for ecological agriculture, decrease the production cost of ecological agriculture, and incentivize farmers to protect the ecological environment of cultivated land through economic means. Second, advancement of ecological agriculture requires the development and implementation of new scientific and technological methods. These include the promotion of water-saving irrigation technology, development of circular agriculture, and use of biological pesticides and organic fertilizers. Coupled with increased publicity and mobilization, these measures can facilitate harmonious development of the ecological and production functions of cultivated land. Finally, it is important to stabilize the contracting and management rights of cultivated land, encourage the equitable distribution of cultivated land rights and interests, and reinforce the guidance and standardization provided by village collective organizations on cultivated land circulation. This can enhance farmers' willingness to transfer cultivated land; promote the diversification of cultivated land circulation subjects; achieve large-scale, intensive, and specialized management of cultivated land; and

FIGURE 6
Resilience structure of the cultivated land use system of various farmers. TA, SA, CA, NACI, and NA are respectively short form of traditional agricultural type, specialized agricultural type, concurrent agriculture type, concurrent agriculture type, non-agricultural concurrent industry type, non-agricultural concurrent industry type.

TABLE 5 Effect of farmer differentiation on cultivated land use system resilience.

	Resource elements resilience	Production resilience	Ecological resilience	Scale structure resilience	Total resilience
Economic differentiation	−0.117*	0.076	−0.104*	0.018	−0.022*
Cultivated land use differentiation	0.013	−0.193***	0.083	−0.137**	−0.165**

*, ** and *** indicate that the results are significant at the level of 10%, 5%, and 1%, respectively.

strengthen the resilience of the cultivated land use system (Urruty et al., 2016).

6.4 Improve the farmland property rights system and the farmland management system

As China's policy for protecting cultivated land has become increasingly extensive, there has been a certain level of protection or improvement in the quality, quantity, and ecological environment of cultivated land. However, the social issues prevalent in China's rural areas, such as uneven land rights, a wide income gap, difficulties in distributing collective rights and interests, subpar facility construction, and low land use efficiency, disrupt the internal operational order of the cultivated land system and diminish its state and ability to withstand interference pressure. Therefore, the Chinese government should give priority to the rural perspective and consider solving the internal problems of the cultivated land use system. First of all, it is necessary to further improve the system of three rights separation of agricultural land, improve the distribution mechanism of cultivated land income and transfer transaction mechanism, and promote the sharing of cultivated land property income and intensive use of scale. Secondly, ensure its internal stability by devising comprehensive policy actions that benefit farmers, bolster the sustainable intensification of cultivated land, and enhance the standards of rural infrastructure construction and public services. Finally, it is necessary to comprehensively evaluate the various factors affecting policy formulation and implementation in different rural areas, establish a governance organization of the cultivated land use system according to the actual situation in different regions, clarify the main body and object of governance, and adopt diversified and targeted governance means, so as to improve the governance capacity of the cultivated land use system and enhance the resilience of the cultivated land use system (Lyu et al., 2020).

This study integrated farmers' behavior, cognition, and willingness into the evaluation index system of cultivated land use system resilience. Evaluating the resilience of the cultivated land use system at the micro-scale emphasizes the importance of individual initiatives, thereby providing a more accurate reflection of the system's adaptive cycle. This study considers differentiation among farmers as a representation of their influence on the socioeconomic system and discusses its effect on the resilience of the cultivated land use system. Based on this understanding, the proposed countermeasures are practical and relevant to the real world. We conclude that the resilience of the cultivated land use system is primarily constrained by farmers' resource input and the productive capacity of cultivated land (Allison and Hobbs, 2004). From a long-term perspective, enhancing the resilience of the cultivated land use system requires a decrease in the trend of agricultural differentiation among farmers, an improvement in farmers' perception of agriculture and rural areas, an increase in resource input, and the transformation of behavioral consciousness regarding system resilience. This necessitates that farmers, under various incentives, balance the ecological functions of the cultivated land use system with their livelihood choices, thereby promoting the sustainable use of the system. The methods for achieving these goals are left for future research.

7 Conclusion

This study focused on typical villages in Qufu, Shandong, China, where a questionnaire survey was conducted with a random selection of 324 households. The resilience of the cultivated land use system as determined by farmers was evaluated from the following four perspectives: resource elements, production, ecology, and scale structure. This study also investigated how peasant household differentiation affects the resilience of farmland use systems. Based on these findings, adaptive governance strategies for cultivated land use systems have been proposed. The primary conclusions drawn from this study are as follows.

First, the proactive engagement of primary land users is crucial for determining whether an agricultural land-use system can undergo transformation and development. As the principal actors in this system, farmers' behaviors, understanding, and willingness influence the system's resilience. This influence is primarily evident in how farmers' behavioral choices and cognitive willingness affect the resource elements, production, ecology, and scale structure of the agricultural land-use system, particularly under the pressures of dual urban–rural development, globalization, and urbanization.

Second, the overall resilience of the farming system related to cultivated land use remained relatively stable, but the resilience of production was generally low. The resilience of resource elements varied greatly, and there was a noticeable stratification in the resilience of ecological and scale structures. When examining the various types of resilience within the farmers' cultivated land use system, the resilience of resource elements and production was relatively low, whereas ecological resilience and scale structure resilience were comparatively high. Among all the resilience types within the cultivated land use system, the unbalanced and production-deficient types were more prevalent, whereas the balanced and ecological protection types were less common. This suggests a disparity between farmers' cultivated land use behaviors and an imbalance between the various functions of the cultivated land use system.

Third, farmers in the study area exhibit a high degree of diversification into non-agricultural employment, which reduces their reliance on land. The resilience of the cultivated land use system varied significantly among farmers with different types of diversification. The primary types of resilience in the cultivated land use system among farmers are the unbalanced and production shortage types. The assumptions set forth in this study are not entirely valid; economic diversification among farmers negatively affects the resilience of resource elements, ecological resilience, and overall resilience of the cultivated land use system. In other words, the lower the proportion of farmers' income derived from agriculture, the lower the resilience of the cultivated land use system. The differentiation of a farmer's cultivated land use also has a clear negative effect on the production resilience, scale structure resilience, and overall resilience of the cultivated land use system. This implies that the smaller the scale of a farmer's cultivated land use and the greater the differentiation, the lower the resilience of the cultivated land use system.

Fourth, the evaluation results of the resilience of the cultivated land use system, viewed from the perspective of farmers' behavioral perceptions and the effect mechanism of farmers' households on this resilience, suggest that multiple strategies are needed. These include enhancing the production resilience of the cultivated land use system, increasing the eagerness of various farmers to invest in the resource elements of this system, encouraging a shift in farmers' understanding and behavior toward ecological protection, and improving their willingness to circulate cultivated land. These governance measures can strengthen the resilience of cultivated land use systems and boost their adaptability.

The world continues to face challenges on how to address the key issues that contribute to the food crisis, which has been exacerbated by conflict and climate change (Liang and Li, 2020). In both developed and developing countries, enhancing the ability of the cultivated land use system to resist external pressure and interference, and improving the resilience of the transformation and upgrading of the cultivated land use system are the basic and key tasks for maintaining social stability and ensuring people's livelihoods at this stage (Niu et al., 2021). However, in the face of the ever-changing international situation and agricultural development status, the perception and behavioral decision of farmers have become the key factors to improve the resilience of cultivated land use system. Therefore, in-depth understanding of the diversified decisions of different farmers in different environments and exploring their differentiated impact on the resilience of cultivated land use systems are conducive to countries around the world to go deep into local realities and accurately find differentiated strategies for improving the resilience of cultivated land use systems. The limitation of this study is that the perspective is only focused on China. How to explore the relationship between farmers' perception, behavior, differentiation and the resilience of cultivated land use system from a global perspective is the direction of future research expansion. At the same time, this study integrates farmers' perception into the cultivated land use system to explore the impact of farmers' differentiated behaviors on the resilience of the cultivated land use system. However, the interaction mechanism between people and land determines that not only farmers' behavioral perception will have an impact on the cultivated land use system, but also the cultivated land use system will in turn affect farmers' behavioral decisions. In this interactive mechanism, how to improve the resilience of cultivated land use system and promote sustainable development is the focus of future research.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the [patients/ participants OR patients/participants legal guardian/next of kin] was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

XW: Writing – original draft, Writing – review & editing. YNW: Writing – original draft, Writing – review & editing.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 02 April 2024
DOI 10.3389/fsufs.2024.1326581

OPEN ACCESS

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RECEIVED 23 October 2023
ACCEPTED 29 February 2024
PUBLISHED 02 April 2024

CITATION
Wang W, Gu Z, Han Z and Li Z (2024) Optimization of land use to accommodate nutritional transformation of food systems: a case study from the Beijing–Tianjin–Hebei region.
Front. Sustain. Food Syst. 8:1326581.
doi: 10.3389/fsufs.2024.1326581

Optimization of land use to accommodate nutritional transformation of food systems: a case study from the Beijing–Tianjin–Hebei region

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The transformation and reconstruction of China's food system not only faces many risks, such as the unceasing growth of food consumption on the demand side and the structural imbalance of dietary nutrition, but also must address serious challenges, such as constraints of resources, environment, and production capacity on the supply side. The optimal allocation of land use structure is an important method to realizing a transformation of sustainable food systems, achieving the goal of nutrition security, and guiding coordinated spatial development. This study takes the Beijing–Tianjin–Hebei region as an example, analyzing the development trends of the region's dietary nutrition structure clarifies the objectives for improving dietary nutrition. This study uses comprehensive optimization model and dynamic land system model, exploring land use optimization schemes under different nutritional goals and development scenarios. The result show that the dietary structure in the Beijing–Tianjin–Hebei region is transitioning from "food based" to "intake balance" and gradually evolved to "intake diversity," with the main objectives being to maintain stable calorie intake while moderately increasing protein intake and reducing fat intake. Achieving this goal will gradually increase demand for cultivated land and intensify spatial competition for land use. However, by optimizing land use allocation, it is possible to free up more spatial resources to balance economic development and ecological protection and reduce land use fragmentation, thereby significantly enhancing regional economic benefits and the value of ecosystem services based on improvements in dietary nutrition.

KEYWORDS

nutrition targets, comprehensive optimization model, land use dynamic simulation, food security, Beijing–Tianjin–Hebei region

1 Introduction

Agriculture is the foundation of country. Food and nutrition security is related to the national movement and people's livelihood. It is an important cornerstone for maintaining national security and promoting social development. The Chinese government has always regarded solving the problem of peoples' food as the top priority in governing the country.

After more than 70 years of efforts, the food security concept of "Grain is basically self-sufficient and cereals are absolutely safe" has been basically realized, the nutritional level of residents has been significantly improved, and a high-level, high-quality, efficient and sustainable food security system is being preliminarily established (Fan and Brzeska, 2014). With the accelerating process of urbanization, Chinese residents' dietary structure and consumption concepts have also undergone historic changes (Tian and Yu, 2015). According to the National Bureau of Statistics in 2019, the consumption of livestock and poultry meat, egg products, aquatic products, vegetables and fruits increased by 28.66, 47.99, 123.86, and 18.06%, respectively, compared with 2000, and grain consumption decreased by 31.14%. The decrease in rations and the rapid increase in the consumption of non-grain crops such as meats, vegetables, and fruits reflects the strong demands of Chinese residents for food diversity, nutrition, and health.

With the change in the global food supply and demand and society's attention to individual rights, the concept of nutritional safety has attracted extensive attention. The food security concept emphasizing national or regional food production and supply capacity is changing to focus on the level of access to food and nutrients by families or individuals (Xie et al., 2021). China has conducted six national surveys on residents' nutrition and health to understand changes in residents' dietary structure and nutritional health. The latest monitoring results show that, although the dietary nutrition and health status of residents have been greatly improved, the intake of beans, eggs, dairy, aquatic products, vegetables and fruits is low, but the intake of meat, oil, and salt is too high. Energy acquisition decreased gradually, the fat energy supply ratio remained high, and trace elements such as calcium and selenium were deficient and decreased year by year. Obesity and overweight rates reached 5.2 and 30.1%, respectively, and the incidence of hypertension and diabetes related to diet among adults over 18 increased to 25.2 and 9.7%, respectively. The unreasonable dietary structure and nutrient intake are further aggravated, and the health risk of residents' food consumption is continuously expanding (Zhao et al., 2023).

The transformation and reconstruction of China's food system not only faces many risks, such as the rigid growth of food consumption on the demand side and the structural imbalance of dietary nutrition, but also needs to address a series of challenges, such as the constraints of resources, environment, and production space on the supply side (Shi et al., 2013; Song et al., 2019). The realization of the goal of nutrition security increasingly depends on the optimal allocation of land resources, water resources, labor resources, technical resources, climate resources and other elements in the food system (Song et al., 2016; Imoro et al., 2021; Kang et al., 2023). Among them, land resources are the most important and basic resource guarantee related to the construction of a sustainable food system and the realization of national nutrition goals. However, the environmental cost of high investment in agricultural production has begun to appear, which has become a limiting factor restricting the further improvement of crop yield. It will be more difficult to achieve sufficient and diversified nutrition supply by relying only on growth in crop yield (Xu et al., 2017). Meanwhile, in the future, residents' nutrition-oriented food consumption will rely more on biogenetics and modern precision agricultural technology, and the technological progress of land promotion will also effectively improve the supply of nutritional elements *per capita* (Smith, 2013). This emergence and progress of innovative technologies will require optimal allocation of land resources.

The optimal allocation of land resources is to achieve various objectives and improve spatial benefits under different constraints through the adjustment of land use structure and spatial layout. The early optimal allocation of land use was mainly based on quantitative calculation, in which the goal was to achieve a high grain self-sufficiency rate. Land resources with the same structure will produce different benefits under different spatial layouts, and the adjustment of quantity is due to the lack of explicit characteristics of space, which has no strong practical significance for the realization of optimization objectives (Deng et al., 2008). The emergence of the land use dynamic simulation method provides a new theory and method for research on the spatial layout of land use optimization structures (Li et al., 2013).

At present, research on the optimal allocation of land use mostly takes the regional ecological and economic balance as the main goal (Yang et al., 2020; Ma and Wen, 2021) takes cultivated land protection as a subgoal under the multi-situation weight balance or simply takes the grain yield as the constraint condition (Wang et al., 2021). It lacks reflection on the new situation of food security and generally an insufficient description of the changes in agricultural supply structure and land demand affected by the improvement needs of residents' dietary nutrition in the future. At the same time, the optimization of land resources mostly focuses on the distribution among departments, and the consideration of interregional overall planning and coordination is relatively less. Food and nutrition supply is the most direct ecosystem service function of land. The necessary development space and good environmental experience are the benefits that today's society is more eager to obtain from land. Balancing the relationship between nutrition improvement, economic development and ecological protection and coordinating land use allocation based on this relationship can make the research more reasonable.

The Beijing, Tianjin and Hebei region (BTH) is one of the world-class urban agglomerations that China focuses on building. Its positioning is to build a "leading area for regional overall coordinated development and reform, a new engine of national innovation driven economic growth, and a demonstration area for ecological restoration and environmental improvement." However, at present, there is a large internal development gap in BTH, and there are obvious differences in industrial structure and population structure (Tian et al., 2019). In addition, income levels and market development levels will make the dietary structure and nutritional level of residents in the region at different development stages (Rischke et al., 2015). Food availability and nutritional security also face different challenges (Li et al., 2023). Taking BTH as an example, based on the analysis of residents' dietary structure and main nutrient intake since the 21st century, this paper establishes the regional nutrition improvement goal, constructs a comprehensive decision-making model, and discusses the optimal allocation scheme of land use under the balance of nutrition targets, economic targets, and ecological targets in the study area in 2030 (Figure 1). The research results have theoretical and practical significance for expanding the research on the coupling relationship between man and land under the change of food system and promoting the improvement of dietary nutrition level of regional residents, the improvement of labor quality and the coordinated and sustainable development of society, economy and ecology.

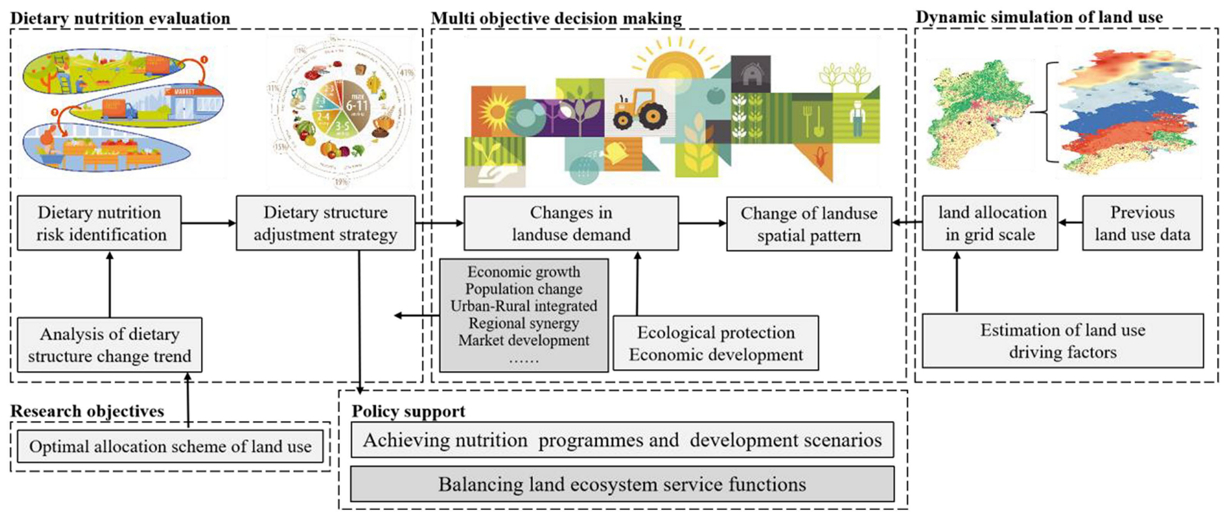

FIGURE 1
Optimal allocation of land use in BTH for serving dietary nutrition improvement.

2 Materials and methods

2.1 Study area

The Beijing-Tianjin-Hebei region (113°27′E ~ 119°53′E、36°03′N ~ 42°37′N) is located in the heart of the Bohai Sea Rim and has a temperate continental climate, including two municipalities directly under the central government of Beijing and Tianjin and 11 prefecture-level cities in Hebei Province, and is one of the three major urban agglomerations in China. It has a total population of about 110 million and covers a land area of about 215,000 km^2, accounting for 8.28 and 2.26% of the country's population and land area, respectively. The region has the most completed topography in China, with the Bashang Plateau in the north, the North China Plain in the south, and the Taihang Mountains in the west. The region has a variety of ecosystem types and functions and it's also a major source of food production and consumption. The net contribution rate of regional agricultural products to the national food production in 2018 reached 4.23, 5.70, 7.38 and 10.35% for cereals, vegetables, eggs, and dairy products, respectively (Figure 2).

2.2 Data sources

The spatial data used in this paper include the 30 m resolution grid data of land use in BTH in 2018, 2015 and 2010 from the resource and environment data center of the Chinese Academy of Sciences.[1] The land use types are reclassified to cultivated land, woodland, grassland, water body, construction land and unused land and then resampled to a 1 km grid. The data of land use driving factors include the kilometer grid dataset of GDP and population spatial distribution of the resource and environment data center of the Chinese Academy of Sciences and the 30 m dataset of China's altitude spatial distribution. Spatial distribution data of soil organic carbon content of Nanjing Institute of soil research, Chinese Academy of Sciences,[2] and spatial distribution data of precipitation of national meteorological science data center.[3] The socioeconomic data are derived from the *China Food Composition* and the statistical yearbooks of Beijing, Tianjin and Hebei Province from 2000 to 2018. Due to the lack of food consumption data of urban residents in Beijing from 2000 to 2015, the CPI index method is used for iterative calculation and mutual correction based on the food consumption and expenditure in 2000 and 2016, respectively. The specific equation is Eq. (1):

$$Q_{i,n+1} = \frac{Q_{i,n} \times C_{i,n+1}}{C_{i,n} \times CPI_{n+1}} \tag{1}$$

where $Q_{i,n}$ is the consumption of Class i food in year n and $C_{i,n}$ is the consumption expenditure of Class i food in year n.

2.3 Dynamics of land systems

Previous research has developed frameworks for studying land use patterns, integrating theoretical and empirical analyses of land use structures with models of land use change and interactions with environmental factors (Kauffman and Hayes, 2013). Studies often focus on the attributes of land units, examining their relationships with nearby or external environmental influences, using tools like Cellular Automata (CA), the Conversion of Land Use and its Effects (CLUE), and its variant for smaller areas (CLUE-S) to model spatial changes (Lambin et al., 2003; Veldkamp and Verburg, 2004). While

1 https://www.resdc.cn/

2 http://soil.geodata.cn

3 http://data.cma.cn/

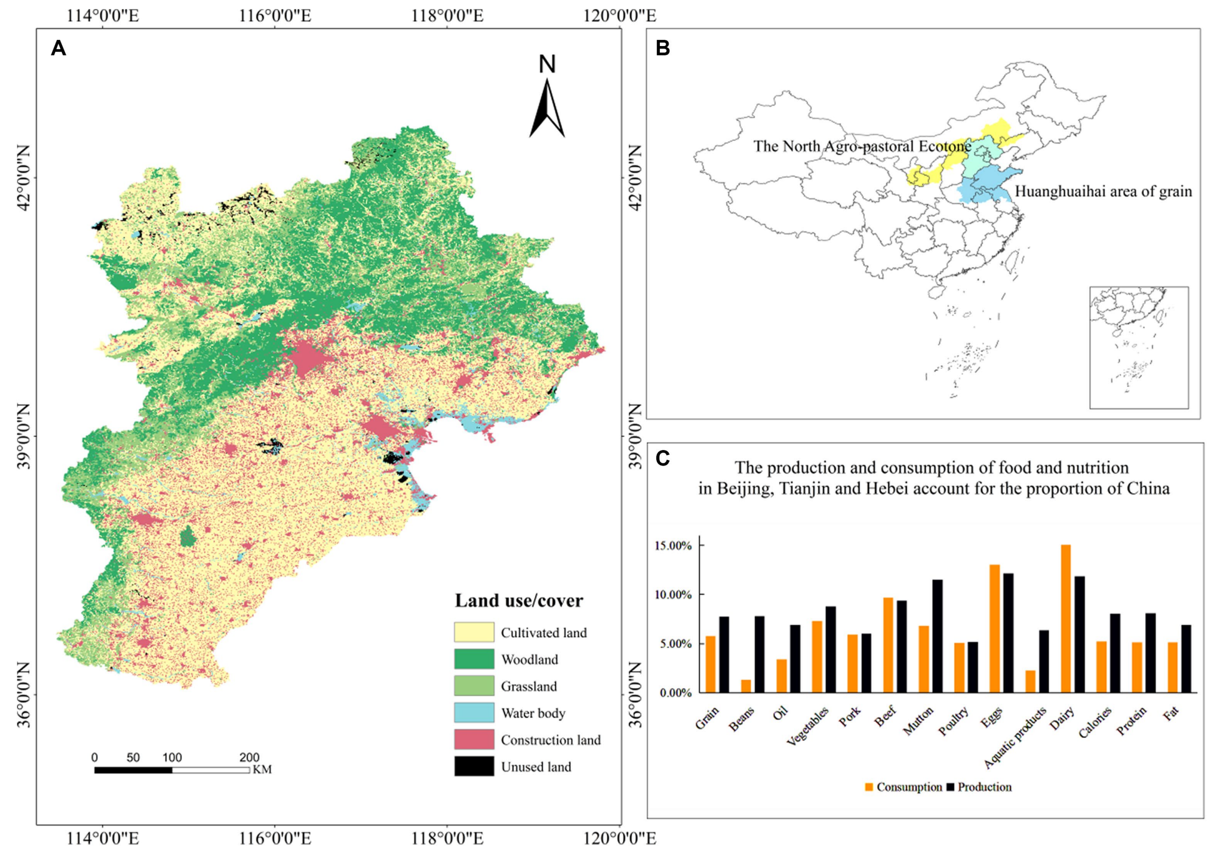

FIGURE 2
Basic information of the study area. **(A)** The type of regional ecosystem, **(B)** the spatial location of the area, **(C)** the contribution of regional food production to national food consumption and nutrition supply.

these models offer operational and scale advantages, they also need to be improved, such as the CA model's subjectivity in land use predictions and the CLUE models' inadequate consideration of land self-organization processes.

The Dynamic Land System (DLS) model is specifically developed to simulate dynamic land use/cover pattern changes. It represents a collection of applications for simulating changes in terrestrial ecosystem structures and succession models (Deng, 2011). Based on spatial analysis, the DLS model classifies and quantifies the impacts of driving factors to predict the probability of occurrence of different land use types. It simulates the macro patterns of land system succession and integrates the distribution probability of different land use types at the pixel level to achieve a spatial distribution of land area changes. The DLS model employs nonlinear models to simulate land use succession patterns. It assumes that the probability of grid i belonging to the kth land use type is $p_i^k = P\left(y_i^k = 1 \mid X_i, \hat{y}_i^k\right)$. Eq. (2) expresses this conditional probability in the form of a logistic function (Jin et al., 2019).

$$
\begin{aligned}
p_i^k &= \frac{1}{1+\exp\left[-\left(\alpha_0^k+\alpha_1^k x_{i1}+\alpha_2^k x_{i2}+\cdots+\alpha_l^k x_{il}+\cdots+\alpha_L^k x_{iL}+r\hat{y}_i^k\right)\right]} \\
&= \frac{1}{1+\exp\left[-\left(\alpha_0^k+\alpha^k X_i+r\hat{y}_i^k\right)\right]}
\end{aligned} \quad (2)
$$

where, p_i^k represents the likelihood of encountering the *k-th* land-use type in grid *i*, where x_{iL} encapsulates both natural and socioeconomic influences. The term α_i^k denotes the impact coefficient of these drivers, with $\alpha^k = \left(\alpha_1{}^k, \alpha_2{}^k, \cdots, \alpha_i{}^k, \cdots, \alpha_L{}^k\right)$ forming a coefficient vector. The spatial autocorrelation factor is signified by $\hat{y}_i^k$ and r stands for a specific coefficient. By applying a logarithmic transformation, we calculate the logit function, *logit(t)*, representing the grid i's logarithmic likelihood ratio for the *k*-th land use, leading to a nonlinear model for predicting land-use distribution as depicted in Eq. (3).

$$
\begin{aligned}
\text{logit}(t) &= \ln\left(p_i^k / \left(1-p_i^k\right)\right) \\
&= \ln\left(\exp\left(\alpha_0^k+\alpha_1^k x_{i1}+\alpha_2^k x_{i2}+\cdots+\alpha_l^k x_{il}+\cdots+\alpha_L^k x_{iL}+r\hat{y}_i^k\right)\right) \\
&= \alpha_0^k+\alpha^k X_i+r\hat{y}_i^k
\end{aligned} \quad (3)
$$

The concept of grid-scale land supply and demand balance highlights a state where the supply and demand for various land types are equalized at the grid level. A self-organizing simulation incorporating the neighborhood effect was employed to enhance model precision during the land-use competition and trade-offs simulation. This approach involves two key factors. One is the neighborhood enrichment factor, which quantifies the relative abundance of a specific land-use type within adjacent grids. This factor is determined by Eq. (4):

$$F_{i,k,d} = \frac{n_{i,k,d} / n_{i,d}}{N_k / N} = \frac{P_{i,k,d}}{P_k} \quad (4)$$

where, i represents the grid count; k denotes the land use type; d is the model's neighborhood radius. The neighborhood enrichment factor, $F_{i,k,d}$, calculates the relative concentration of a land use type k within a neighbourhood based on the ratio $P_{i,k,d}$ of the count of grids of type k to the total number of grids in the neighborhood centered on grid I . P_k indicates the ratio of the count of grids of type k to the total number of grids in the study area. An equation results greater (or lesser) than 1 suggests that the concentration of land use type k within a radius of i is higher (or lower) than its concentration across the entire study area.

The neighborhood interaction factor quantitatively measures the impact of different land use types across various neighborhoods, calculated using Eq. (5):

$$G_{l,k,d} = \frac{1}{N} \sum_{i \in l} F_{i,k,d} \quad (5)$$

where G_{idk} is the factor of neighborhood interaction for land-use types l and k; N_l denotes the total number of grids of the i-th land-use type in he study area; $i \in l$ denotes the grid of the l-th land-use type; and $£_{i \in l} F_i, d$ denotes the sum of the neighborhood enrichment of the k-th landise type within the neighborhood of the l-th land-use type. When the equation's solution is greater than (less than) 1, there may be a spatial, nutually promoting (suppressing) effect between land-use types, l and c, in the range of radius d that is statistically significant. Thus, the landuse factors relating to neighborhood interactions in different neighborhoods can be calculated within a quantitative analysis of the interactions of different land-use types in different neighborhoods by adjusting the neighborhood radius d.

2.4 Comprehensive optimization model

Through the comprehensive optimization model, solving the land use structure under different scenarios and objectives as input parameters for the DLS model. Firstly, the cultivated land area required by consumers to achieve the improvement goal by minimizing the existing dietary change is calculated. Then, under different nutrition improvement objectives, the economic and ecological benefits of land use were weighed, and the land use needs were obtained under different development scenarios. The comprehensive programming function is as follows, where Eq. (6) is the maximum target value, Eq. (7) is the minimum change in dietary structure when the goal is achieved, Eqs. (8) and (9) are the dietary nutrition goal constraints, Eq. (10) is the value constraint, and Eqs. (11), (12), and (13) are the land use area constraints.

$$V^* = \max \sum_{i}^{n} v_i S_i^* \quad (6)$$

$$\min\left[x_i^*\right] = \sum_{i=1}^{n} \alpha_i \left(\frac{x_i^* - x_i}{x_i}\right)^2, \ \alpha_i = \frac{e_i x_i}{\sum_{i=1}^{n} e_i x_i} \quad (7)$$

$$\text{s.t:} \quad \beta_p^1 \sum_{i=1}^{n} C_i^p x_i \le \sum_{i=1}^{n} C_i^p x^* \le \beta_p^2 \sum_{i=1}^{n} C_i^p x_i \quad (8)$$

$$x_{i,\min} \le x_i^* \le x_{i,\max} \quad (9)$$

$$S_1^* = \sum_{i=1}^{n} \frac{x_i^* p_i g_i}{f_i n_i} \times 365 \quad (10)$$

$$\sum_{i=1}^{6} q_i S_i^* \ge Q \quad (11)$$

$$S_i^{\min} \le S_i^* \le S_i^{\max} \quad (12)$$

$$\sum_{i=1}^{6} S_i^* = S \quad (13)$$

where V^* is the total target value, v_i is the target value per unit area of Class i land use type (Appendix Table A1), and S_i^* is the area of Class i land use type in 2030. x_i^* is the consumption of Class i food after achieving the nutrition improvement goal, and x_i it is the current consumption of Class i food. α_i is the proportion of energy intake of Class i food in total food intake. Refer to the China Food Composition and calculate the main nutritional components of food according to the nutritional content of food and the food structure of residents, as shown in Appendix Table A2. β_p^1 and β_p^2 represent the upper and lower limit coefficients of nutrition improvement objectives. C_i^p represents the content of P nutrients in Class i food. $x_{i,\min}$ and $x_{i,\max}$ represent the minimum and maximum recommended intake of Class i food. S_i^* is the cultivated land area required to meet the nutrition improvement goal, p_i is the population available for food production calculated by calories in 2030, and the land carrying capacity from 2000 to 2018 is converted by using food production data and nutrition data and extrapolated into GM (1,1). f_i represents yield of Class i food in 2030, and the yield of plant food is extrapolated by the GM (1,1) model using the yield data from 2000 to 2018. Animal food is converted by introducing the feed to meat ratio g_i. The feed to meat ratios of pork, beef and mutton, poultry, aquatic products, poultry eggs and milk are 3.3, 2.6, 2.1, 1.9, 2.5 and 0.3, respectively. n_i is the multiple cropping index of various foods in BTH. Referring to the results of remote sensing data monitoring and farmer interviews, the multiple cropping indices of grain crops in Beijing, Tianjin and Hebei were 1.05, 1.1 and 1.35, respectively, and those of vegetables were 2.8. q_i is the constrained value per unit area of Class i land use type, and Q is the present value of the constrained value. $S_i^{\min}, S_i^{\max}$ is the

TABLE 1 Connotation of development scenario.

Development scenario	Goal orientation	Value constraint	Land type constraints
Business as usual	Refer to the current development scenario	According to the current economic growth rate	The area of woodland, grassland, water body and unused land shall not be less than the current area.
Priority of economic development	Principle of maximizing economic benefits	Value of ecosystem services increased by 5%	The area of woodland, grassland, water body and unused land shall not be less than the current area.
Priority of ecological protection	Principle of maximizing ecological benefits	The economic value of land use increased by 5%	The area of construction land and unused land shall not be less than the present value, and the total area of woodland, grassland, water body shall not be less than 40% of the regional area.

minimum and maximum area limit of Class *i* land use type, and S is the total area of regional land.

2.5 Scenario design

This paper sets up three development scenarios of "Business as usual," "Priority of economic development" and "Priority of ecological protection" under different nutrition improvement objectives. The goal orientations of the three development scenarios are different, and the meanings of the constraint value and target value are also different (Table 1). The "Business as usual" emphasizes the future land use scenario under the mutual game between economic value and ecological value according to the current land use decision and land type transformation preference. The "Priority of economic development" relaxes the demand restrictions on construction land, takes the pursuit of maximizing the benefits of economic development as the value target, considers the protection of ecological land to a certain extent, and takes the low-speed growth of ecosystem service value as the value constraint. The "Priority of ecological protection" emphasizes the preference of ecological land such as woodland and grassland, limits the use conversion of ecological land, takes the maximization of ecosystem service value as the value target, and takes the low economic growth rate as the value constraint. It should be noted that, due to the concern that COVID-19 may cause disturbance to the normal food structure and dietary level, the goals and scenarios we designed are based on 2018 before the start of the COVID-19 pandemic.

3 Results

3.1 Dietary nutrition evaluation of residents in BTH from 2000 to 2018

The food consumption of residents in BTH from 2000 to 2018 can be divided into two periods prior to and after 2009. In the first period, the food consumption structure upgraded rapidly, from "grain based" to "intake balance." "grain base" refers to the large proportion of grains in the structure of food consumption and the single nutrient structure, with the main source of nutrients being grains for energy. "intake balance" refers to the increase in animal food consumption, the consumption of animal and plant food tends to be reasonable, and the dietary structure can reflect the nutrition mix. The rate of grain consumption decreased, and the proportion of grain in the dietary structure decreased from 47.74% in 2000 to 31.14% in 2009. During this period, the consumption of animal food increased rapidly. Driven by meat and milk, the consumption proportion of animal food increased from less than 9 to 13.89%, of which the consumption of dairy products reached 13.14 kg, 2.7 times that of 2000. The second period is from 2009 to 2018, from "intake balance" to "intake diversity," "Intake diversity" refers to a richer variety of food consumption, with the proportion of meat, eggs, milk, fruits, and vegetables increasing further in the dietary structure. Which is specifically reflected in the dynamic stability of the consumption of plant food represented by grain. The consumption of grain and vegetables fluctuated approximately 120 kg and 105 kg, and the consumption of fruits maintained a slight increase. The consumption of animal food increased faster than that in the previous period, and its proportion in the dietary structure further expanded (Figure 3).

Geographically, the dietary structure in BTH is similar, but they are in different adjustment periods. Beijing residents' dietary consumption is more balanced in structure, the change in dietary structure is relatively stable, the consumption level of grain is low, and the proportion of animal food is relatively high. Its evolution law is objectively in line with the dietary structure of residents in economically developed areas in pursuit of reasonable nutrition intake (Figure 4B). The main trend of dietary structure change of residents in Tianjin is diversification, the proportion of animal and plant foods is basically stable, the internal changes of animal and plant foods are more obvious, the consumption of aquatic products has an obvious geographical environment impact, and the consumption is higher than that of Beijing and Hebei (Figure 4C). The succession of residents' dietary structure in Hebei Province (Figure 4D) reflects the general law of BTH (Figure 4A) to a certain extent. The trend of consumption upgrading is obvious, which is specifically reflected in the reduction of plant food consumption dominated by grain and the expansion of animal food consumption represented by meat and milk, and the trend of consumption upgrading will continue.

The changes in the main nutrient intake of residents in BTH from 2000 to 2018 are shown in Table 2. The calorie intake of residents in the three places showed a downward trend from 2000 to 2009, which is related to the rapid reduction in food consumption, such as grain, during this period. After 2009, with the slight increase in grain consumption of urban residents and the stabilization of grain consumption of rural residents, the caloric intake of residents also gradually increased, and all exceeded the recommended minimum intake of 1648.95 kcal/day. Protein intake is generally low, and due to

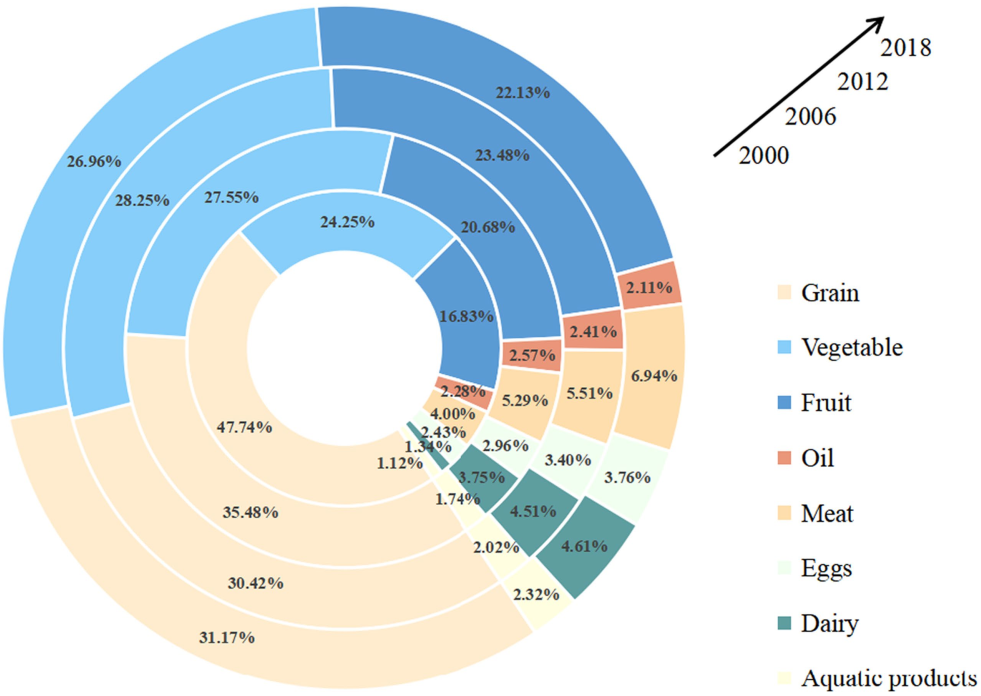

FIGURE 3
Changes in the dietary structure of residents in BTH,2000, 2006, 2012 and 2018.

the change in residents' dietary structure, the substitution of animal food for grain is insufficient; the protein intake in Hebei and Tianjin decreased year by year before 2012. Among the food sources of protein, the proportion of high-quality protein (the proportion of protein provided by animal food and beans in the total protein intake) of residents in Beijing, Tianjin and Hebei region increased to 50.86, 44.25 and 37.93%, respectively. There are regional differences in fat intake, and the fat intake of residents in the Tianjin and Hebei regions is generally at a low level.

3.2 Land use change in BTH from 2000 to 2018

The land utilization landscape in BTH changed significantly from 2000 to 2018, with the area of construction land and forest land increasing by 9,947 km^2 and 949 km^2, respectively, while the area of cultivated land, grassland, water, and non-utilized land decreased to a certain extent. It is mainly due to the increase in demand for construction land from major cities in the region such as Beijing, Tianjin, Shijiazhuang, and Tangshan caused by rapid economic development and the implementation of the policy of "returning farmland to the forest." The proportion of cultivated land decreased from 50.80% in 2000 to 46.13% in 2018, the proportion of construction land increased from 8.21% in 2000 to 12.81% in 2018, and the proportion of other land types decreased slightly but was relatively stable in the land utilization structure. In terms of land-use dynamics, the rate of change of various land utilization types in different periods showed inconsistency, and the rate of land utilization change gradually accelerated. The rate of decrease of cultivated land is −1.35, −0.55%, and −7.45% in 2000–2010, 2010–2015, and 2015–2018, respectively, and the rate of increase of construction land is 11.85, 3.65, and 34.54%, respectively, and the decrease of cultivated land and increase of construction land is significantly accelerated since 2015. The characteristics of land utilization structure and land utilization change rate reflected that the competition intensity of land utilization in the region gradually increased, the land utilization demand for economic development and ecological protection formed a greater threat to the land utilization for food production, and the function of food production and nutrition supply undertaken by the region was under greater pressure.

3.3 Nutrition objectives and dietary structure

According to the recommendations of the Chinese Dietary Guidelines, the daily energy requirement provided by the diets of Chinese residents should be maintained at 1600 ~ 2,400 kcal, and 120 ~ 200 g of meats intake should be maintained to ensure sufficient protein sources. At the same time, the fat intake is controlled at 80 g or less. When setting the nutrition improvement target, based on the multi-period Chinese residents' nutrition and health monitoring data, the energy intake of Chinese residents declined from excessive intake to insufficient. This is evidenced by the residents of Beijing, Tianjin, and Hebei, especially urban residents, whose caloric intake in recent years has been in the lower range of recommended values. Meanwhile, the protein intake of residents in the Beijing-Tianjin-Hebei region is on the low side, and there is still much room for improvement. As requested by the Chinese Dietary Guidelines for Residents and the reality of fat intake of residents in Beijing, Tianjin, and Hebei, fat

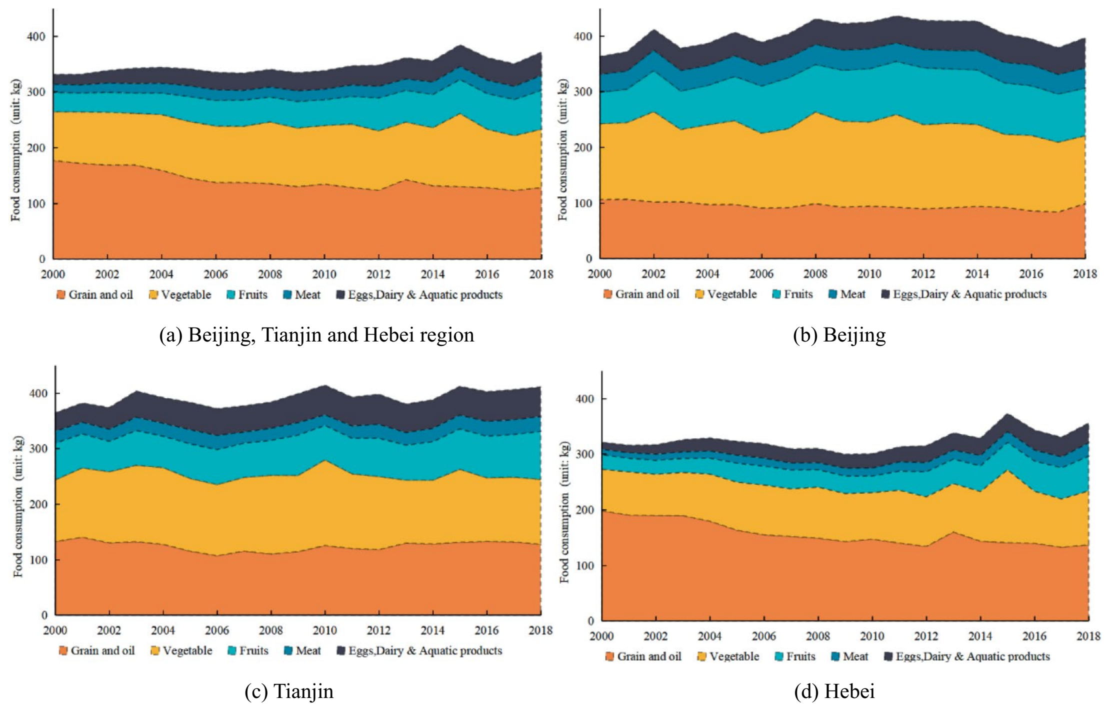

FIGURE 4
Comparison of dietary structure changes among residents in BTH from 2000 to 2018. **(A)** Beijing, Tianjin, and Hebei region, **(B)** Beijing, **(C)** Tianjin, **(D)** Hebei.

TABLE 2 Nutrient intake of residents in Beijing, Tianjin and Hebei from 2000 to 2018.

		2000	2003	2006	2009	2012	2015	2018
Calorie(KJ)	Beijing	1694.99	1796.00	1645.45	1747.36	1708.25	1763.49	1799.77
	Tianjin	2047.03	2069.28	1938.56	1859.62	1786.19	1996.73	1875.92
	Hebei	2282.02	2257.60	2000.99	1880.42	1850.92	1981.86	2011.46
	Recommended value	1648.95 ~ 2454.35						
Protein(g)	Beijing	50.36	52.49	51.02	54.57	53.33	54.54	58.38
	Tianjin	63.10	61.43	58.89	57.63	54.16	59.72	57.24
	Hebei	60.50	60.93	55.47	52.32	51.34	54.91	59.87
	Recommended value	56.69 ~ 82.97						
Fat(g)	Beijing	70.31	78.29	77.28	72.79	70.86	77.13	72.06
	Tianjin	74.72	78.70	75.62	69.54	70.91	69.11	62.22
	Hebei	47.07	52.45	55.79	55.65	58.60	67.48	65.29
	Recommended value	68.49 ~ 99.71						

intake should be reduced. However, the improvement of protein and calorie intake through the adjustment of dietary structure will inevitably lead to an increase in fat intake. Therefore, fat intake is set as a constraint indicator to keep the increase as low as possible. Therefore, taking the dietary structure of Beijing, Tianjin and Hebei residents in 2018 as the benchmark scheme and referring to the index requirements of the *Healthy China Initiative (2019–2030)*, the proposed three nutrition improvement targets and the dietary structure of Beijing, Tianjin and Hebei residents in 2030 that can achieve the three targets according to the principle of minimum change are shown in Table 3.

3.4 Land use demand under different nutrition targets and development scenarios

The calculated land use demand of the three nutrition objectives under the three development scenarios is shown in Figure 5. The cultivated land areas required for the three objectives are 83,777 km^2, 86,838 km^2 and 93,301 km^2, respectively, which are less than the current cultivated land area of 99,808 km^2. However, with the improvement of nutritional objectives, the demand for protein intake increases, the proportion of animal food in the dietary structure increases, the required cultivated land area will gradually expand, and the spatial competition of land use will become fierce. For different development scenarios, the reduced and vacated land space of cultivated land will be further balanced and distributed in production space and ecological space. Specifically, it mainly occurs in the land competition between construction land and woodland. Under the low nutrition target, the demand for construction land in the "Priority of economic development" is the largest, reaching 42,674 km^2, and the area for woodland is the smallest (45,770 km^2). The demand for woodland in "Priority of ecological protection" is the largest, reaching 59,090 km^2, and the area for construction land is the smallest (29,165 km^2). The land demand of grassland under different nutrition objectives and development scenarios changes little, which reflects that grassland plays a more balanced role in ecological protection, economic development and nutrition improvement. The demand for water in "Priority of ecological protection" is greater than that in "Priority of economic development," and profound changes have taken place in "Business as usual," indicating that water plays a key balance effect in the competition for ecological protection and economic development.

3.5 Comparison of land spatial patterns and land use benefits under different nutrition targets and development scenarios

Compared with "Business as usual" (Figure 6C), in "Priority of economic development" (Figure 6A), the spatial expansion effect of construction land is obvious, and most of them expand radially outward with the existing construction land as the center. Geographically, the conversion of cultivated land to construction land is more prominent in the northwest and southwest of Beijing, the north of Shijiazhuang, the south of Tangshan and the coastal areas of Tianjin. The scattered cultivated land in the woodlands of Chengde and Zhangjiakou in northern Hebei Province will be converted to construction land, and the forest areas in eastern Shijiazhuang will form new construction land. The dominant growth of ecological land in space occurred in the Bashang Plateau, with the transformation from cultivated land to forestland as the main type.

In "Priority of ecological protection" (Figure 6B), the distribution of forestland is more concentrated. The transfer effect of cultivated land to forestland is obvious in southwestern Beijing, the Middle East of Zhangjiakou, Chengde, Tangshan and northern Qinhuangdao. Along the Taihang Yanshan Mountains, an ecological corridor with forest and grassland as the main land type can be formed in Handan, Shijiazhuang, Baoding, west of Beijing, Zhangjiakou and Qinhuangdao, and the regional ecological space is more reasonable. The growth of construction land is mainly around the regional twin cities, and the outer ring of Beijing and the coastal area of Tianjin are the main growth points of construction land.

Under the same nutrition goal, the realization of spatial ecological benefits after land use optimization is more difficult than that of economic benefits. Under the low nutrition target, the spatial economic and ecological benefits of "Priority of economic development" and "Priority of ecological protection" are the largest, reaching 10309.08 billion yuan and 49.634 billion yuan, respectively, higher than 8771.48 billion yuan and 488.53 billion yuan in "Business as usual." In "Priority of economic development," the economic benefits of land use to achieve the three nutritional goals increased by 34.35, 27.80 and 13.98%, respectively. In "Priority of ecological protection," the ecological benefits of land use to achieve the three nutrition goals are increased by 16.08, 14.12 and 9.99%, respectively, compared with the current situation. Although higher levels of nutrition improvement solutions would trend toward more cultivated land utilization demands, they are all lower than the existing cultivated land area. The land utilization structure of service dietary nutrition improvement can release more spatial resources, the reduction of cultivated land area required for food generation can ease the current land constraint, and the cultivated land can be converted into construction

TABLE 3 Nutrition targets and corresponding dietary structure of residents in BTH in 2030 (kg/year).

	Region	Grain	Beans	Vegetable	Pork	Beef	Mutton	Poultry	Eggs	Dairy	Aquatic products	Oil
Current	Beijing	91.96	7.64	121.88	20.38	4.50	3.10	8.26	14.57	26.04	13.58	7.05
	Tianjin	117.96	7.15	116.85	16.79	2.95	1.58	5.78	17.71	18.65	16.73	9.86
	Hebei	129.78	8.27	97.13	16.06	1.58	1.55	5.03	13.94	15.39	6.11	7.33
Increase calorie intake by 10%, protein intake by 15% and fat intake no more than 5%												
Low nutrition target	Beijing	103.08	9.01	142.82	20.81	5.41	3.27	10.91	16.72	28.82	17.49	6.99
	Tianjin	131.71	8.48	136.85	17.20	3.58	1.68	7.71	20.44	20.69	21.72	9.79
	Hebei	144.13	10.11	115.49	16.35	2.00	1.66	7.18	16.59	17.25	8.43	7.16
Increase calorie intake by 15%, protein intake by 25% and fat intake no more than 10%												
Medium nutrition target	Beijing	105.63	10.14	154.16	21.55	6.31	3.49	13.43	18.84	30.92	21.12	7.06
	Tianjin	123.69	9.54	147.99	17.90	4.17	1.80	9.44	23.05	22.25	26.14	9.95
	Hebei	135.43	11.63	126.79	16.96	2.39	1.78	9.12	19.10	18.76	10.50	7.19
Increase calorie intake by 20%, protein intake by 35% and fat intake no more than 15%												
High nutrition target	Beijing	108.19	11.27	165.50	22.30	7.21	3.70	15.94	20.97	33.03	24.75	7.13
	Tianjin	126.97	10.63	159.30	18.57	4.77	1.91	11.24	25.72	23.84	30.72	10.08
	Hebei	139.14	13.21	138.40	17.55	2.80	1.91	11.15	21.70	20.29	12.66	7.19

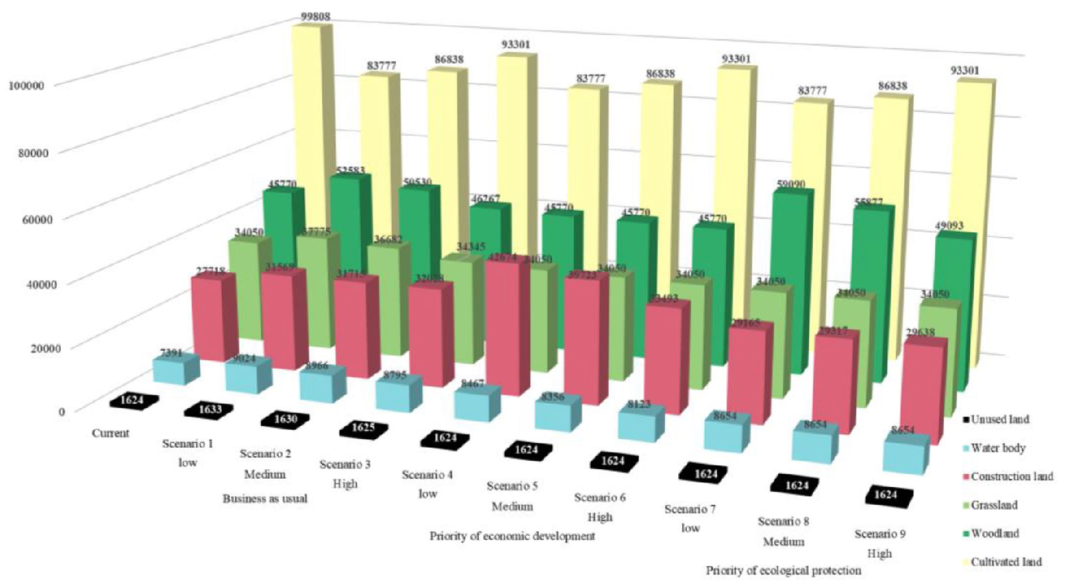

FIGURE 5
Land use demand under different nutrition targets and development scenarios.

land or ecological land. Thus, the economic benefits and ecological value of the region can be improved. Under the condition that the value of ecosystem services and economic benefits per unit area remains unchanged, the optimized spatial economic benefits and ecological benefits will increase by 4.99% ~ 10.01 and 2.22% ~ 7.09%, respectively.

4 Discussion

Adequate food guarantees and adequate nutrition access are the key material basis for global sustainable development. Establishing a sustainable food production system and eliminating all forms of nutrition problems on a global scale plays an irreplaceable supporting role in the realization of other sustainable goals. As the fundamental source of nutrients and energy required by human beings, land is the basic channel for the food system to realize material exchange and value exchange (Lambin and Meyfroidt, 2011). Therefore, integrating the food system with the regional system of human-land relationships and discussing the transformation and reconstruction of the food system (and the construction of a sustainable model from the perspective of the interactive relationship and driving factors between humans and the environment) can provide a scientific research paradigm for the goal of sustainable development (Zhuang et al., 2022). Starting from the changes in residents' food consumption structure and the diversified, hierarchical and differentiated characteristics of dietary nutrition needs, this study focuses on the optimal allocation scheme of resource elements under the balance of social value, economic value and ecological value in the socioeconomic-ecological composite system formed by the food life cycle. It has certain value for the theoretical expansion and practical innovation of the research on the coupling relationship between man and land under the change of food system.

As the country with the widest range, fastest speed and largest scale of urbanization in the world, China's land use structure has undergone great changes in the past 20 years. Different development needs shape the form of land use and promote the change of land use types. On the one hand, the rapid expansion of construction land has led to the occupation of a large number of high-quality ecological land, and the continuous reduction of grassland, forest land, water area and farmland (Wu et al., 2013) On the other hand, with China's emphasis on ecological and environmental protection, the construction of ecological projects has also affected the land use pattern. Some cultivated land has been returned to forests, grasslands and lakes (Zheng et al., 2018; Kong et al., 2022). Drastic land use change has put great pressure on the achievement of sustainable development goals at the regional and national levels. It is more urgent to balance the functions of land use, such as food production, economic development and ecological protection, and realize the optimal allocation of land use to meet the needs of different social development. From the perspective of future food consumption demand, we examined the land use optimization scheme under the priority of economic development and ecological protection according to the nutrition objectives determined by the healthy China strategy and the dietary guidelines for Chinese residents.

The results show that on the one hand, the adjustment of dietary structure can realize the reasonable nutritional intake of residents, on the other hand, it can also reduce the demand for cultivated land and release more space to meet the needs of other development. In the current context of rapid population growth, rapid changes in food consumption patterns, and surging demand for bioenergy production, competition for agricultural land has been tense for a long time. More and more suggestions point out that the intensive use of animal husbandry, the optimization of diet structure, the reduction of animal product consumption, and the substitution of food types can form the diet optimization path with the least impact on the environment to achieve the consumption of water and soil resources and the reduction of global greenhouse gas emissions (Shaikh et al., 2020; Mazac et al., 2022). Our research on the basis of further provide evidence and, in respect of dietary structure on the basis of existing in accordance with

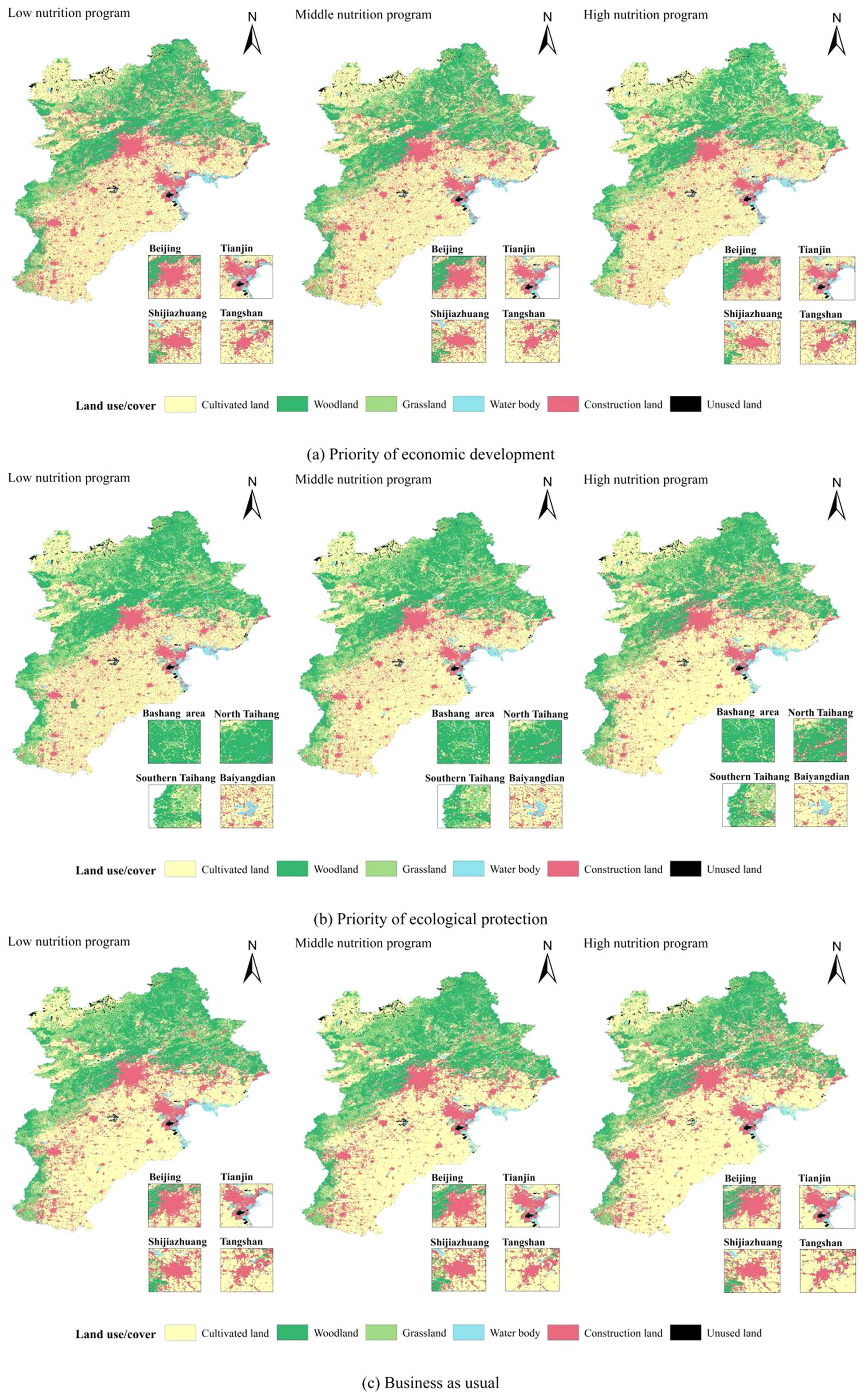

FIGURE 6
Land spatial pattern under different nutrition objectives and development scenarios. **(A)** Priority of economic development. **(B)** Priority of ecological protection. **(C)** Business as usual.

the principle of minimal changes to the pursuit of reasonable nutrition improvement targets, in the future under the condition of regional land capacity to maintain reasonable growth, changes in diet can alleviate the pressure of the current global land, and at the regional level to control the food consumption within the planet boundary.

In previous studies, there are few tools to solve the uncertainty between land use and natural and social system benefits. Even if the land use structure under the target benefit is determined, it is often unable to allocate the land demand to the most appropriate position. This study uses comprehensive optimization model and the DLS model to better solve this problem. At the same time, previous studies on optimizing the allocation of land resources have paid less attention to micro objectives. Some studies have incorporated residents' happiness, environmental satisfaction, and other factors into the objective functions of regional resource optimization, but these indicators are difficult to quantify. We also compared the results of this study with other studies on land use optimization in the Beijing-Tianjin-Hebei region (Bao et al., 2021; Meng et al., 2023), where the land use change trends showed spatial consistency under the same context, and the scale of the transformation of land classes into each other was roughly the same, but due to the differences in benefit coefficients selection, the economic value of the optimized and the ecosystem service values may be measured differently due to differences in the selection of benefit coefficients. However, compared with the traditional multi-objective optimization, this study based on nutritional goals and taking into account other development scenarios, achieving a combination of micro and macro levels. At the same time, the original intention of nutritional improvement is to enhance human capital, which is also an important way to achieve weak sustainability, land use optimization solutions from this perspective are more conducive to the achievement of regional sustainable development goals.

Indeed, there is still room for improvement in this study. For example, the BTH we studied is not a closed food system, and the nutritional goals include all residents involved in the production and consumption of BTH foods. The scenario selected and set based on statistical data and empirical parameters may make the accuracy of optimization results different from the real value. In the design of the nutrition improvement scheme, representative macronutrients are mainly selected, and less consideration is given to nutritional problems such as the lack of trace element intake common to residents in China's developed urban agglomerations. These problems can be solved by refining parameters and using more complex models in the future.

5 Conclusion

China's socio-economic development and people's growing demands for a better life pose new challenges and requirements for the transformation of land and food systems. Systematic research on the coupling relationship of the land system and the food system, and proposing the optimization scheme of land use are crucial for guaranteeing the nutritional supply demand and sustainable transformation of the food system. Based on the dietary structure and main nutrient intake of residents in the Beijing, Tianjin, and Hebei regions since the 21st century, this paper constructs a comprehensive land use structure optimization model based on serving dietary nutrition improvement and weighing socioeconomic development and regional ecological protection and uses the DLS model to simulate the allocation scheme of land use space optimization in Beijing, Tianjin, and Hebei in 2030. The main conclusions are as follows:

From 2000 to 2018, the dietary structure in BTH experienced a transformation from "focusing on grain" to "balanced intake" and then to "diversified intake," and the proportion of animal food consumption in the dietary structure further expanded. Maintaining a stable calorie intake, appropriately increasing protein intake and decreasing fat intake are the main objectives of future dietary restructuring in this region. The improved land use structure for nutritional transformation can release more space resources, better realize the balance between economic development and ecological protection and reduce the fragmentation of land use. On the basis of realizing the dietary nutrition improvement scheme, the regional economic benefits and ecosystem service value are greatly improved compared with the planned scenario.

Comparing the land use optimization scheme for serving dietary nutrition improvement with the planning scenario, the layout of the same land type in the spatial layout is more concentrated, which is more conducive to the exertion of land use function. In the scenario of "Priority of economic development," the construction land in the optimized scenario tends to be distributed in the regional dual core and the existing construction land concentration area. In the scenario of "Priority of ecological protection," more cultivated land in the north of the region is transferred to forestland, the policy space for returning farmland to forest is strengthened, the ecological corridor with forestland as the main land use type formed along the Taihang-Yanshan Mountains is further strengthened, and the role of the BTH ecological environment support area is more significant.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

WW: Conceptualization, Data curation, Formal analysis, Writing – original draft, Writing – review & editing. ZG: Conceptualization, Data curation, Writing – review & editing. ZH: Project administration, Writing – review & editing. ZL: Investigation, Software, Writing – review & editing.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. This research is supported by the National Natural Science Foundation of China (Grant No.72304263) and Innovation Centre for Digital Business and Capital Development of Beijing Technology and Business University (Grant No. SZSK202206).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Appendix

TABLE A1 Economic and ecological benefit coefficient per unit area of various land types.

	Cultivated land	Woodland	Grassland	Water body	Construction Land	Unused land
Economic value per unit area	10.915	19.148	17.122	40.264	184.994	0
Ecosystem service value per unit area	0.706	3.269	2.130	19.584	0	0.164

TABLE A2 Nutrients of main foods (Edible part of per kilogram food).

	Grain	Beans	Pork	Beef	Mutton	Poultry
Calorie (KJ)	3,553	3,900	5,278	1,496	2,670	627
Protein (g)	93	350	86.5	174.9	96.5	113.8
Fat (g)	25.7	160	544.2	88.7	250.6	176

	Oil	Vegetable	Fruits	Aquatic products	Eggs	Dairy
Calorie (KJ)	9,000	180	436	782	1,468	690
Protein (g)	0	11.4	6.2	125	123.8	33.6
Fat (g)	1,000	1.6	2.4	24.2	101.4	40.2

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TYPE Original Research
PUBLISHED 30 April 2024
DOI 10.3389/fsufs.2024.1359012

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RECEIVED 20 December 2023
ACCEPTED 16 April 2024
PUBLISHED 30 April 2024

CITATION
Hu S, Fu Z, Chen Z and Xue Q (2024) Heterogeneity measurement of the impact of the rural land three rights separation policy on farmers' income based on DID model. *Front. Sustain. Food Syst.* 8:1359012. doi: 10.3389/fsufs.2024.1359012

Heterogeneity measurement of the impact of the rural land three rights separation policy on farmers' income based on DID model

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Introduction: As is well known, the policy of separating three rights is another important milestone in China's land system reform. This policy has been in effect for 10 years and is of great significance to the livelihoods of rural families. In the implementation of policies, some farmers have obtained more land management rights, but some farmers have temporarily lost their land management rights. Existing research has shown that there is no consensus on the effect rural land three rights separation on increasing farmers' income, especially in terms of heterogeneity research, which is more scattered.

Methods: We will use the latest national fixed observation point data from the Ministry of Agriculture and Rural Affairs from 2011 to 2020, as well as data from Peking University Treasure Database, West Lake Law Library Database, China Statistical Yearbook, and China Rural Statistical Yearbook. This paper matched the unbalanced panel data of 9,846 rural household samples from 30 provinces except Hong Kong, Macao, Taiwan and Xizang, and conducted an empirical study using the multi time point DID method.

Result: The overall result shows that the policy of three rights separation of rural land can improve the income of farmers, and the impact is more obvious after the promulgation of relevant laws. From the perspective of farmers' heterogeneity, farmers with more training, food crop planting farmers, and farmers with relatively large land scales are more significantly affected by the policy's income increase effect.

Discussion: Scholars have yet to find a good explanation for how the rural land three rights separation affects farmers' income. In this article, it appears that the three rights separation policy has promoted the increase of farmers' income through intermediary mechanisms such as investment level, credit level, and non-agricultural employment level.

KEYWORDS

three rights separation, mortgage of agricultural land management rights, difference-in-difference model, income increasing effect, heterogeneity measure

1 Introduction

The report of the 20th National Congress of the Communist Party of China proposes to comprehensively promote rural revitalization and accelerate the realization of an agricultural power. Promoting rural revitalization in an all-round way is an important task for building an agricultural power in the new era. We should adhere to increasing farmers' income as the central task and make every effort to broaden the channels for farmers to increase their income and become rich. Income always depends on means of production, and farmers are more dependent on land resources than urban residents. For thousands of years, land has carried multiple functions such as the survival, management, and old-age security of farmers, and is therefore regarded as an important support for farmers to increase their income. China's reform originated in rural areas, with rural reform starting from land. The rural land property rights policy of separating rural land ownership, contracting rights, and management rights established in 2014 aims to continuously promote farmers' income through property rights reform.

There are three main types of research related to the topic of this article. The first is the study of the land property rights system and the land three rights separation. Research on land property rights systems in foreign countries has been relatively early, focusing on the relationship between transaction costs (Galiani and Schargrodsky, 2010) and agricultural land transfer rates (Holden et al., 2011). Security and stability of land property rights, reducing land disputes caused by unclear boundaries (Deininger et al., 2011). The study of land property rights system in China originated after the founding of the People's Republic of China, especially with the emergence of the household contract responsibility system, and more and more related research has been conducted (Bu and Liao, 2022). Until 2014, a large number of studies on the rural land three rights separation began to emerge, believing that property rights confirmation is beneficial for increasing the value of property rights and facilitating the identification of legitimate rights and interests by all parties involved in transactions, which helps to improve (Fang et al., 2022; Shi et al., 2023).

The second is the study of the impact of land property rights system on farmers' income. This type of research has a large scope, a large number of domestic and foreign research achievements, and a more solid foundation. The stability of land rights can reduce investment risks and promote the increase of long-term investment returns in agriculture (Besley, 1995; Huang et al., 2017; Li et al., 2019). Improving the stability of land property rights can reduce the corresponding protection costs, enhance the uniqueness of land, and reduce the corresponding protection costs through the exclusivity of land use (Azzam et al., 2021). Unstable land property rights are like stable taxes that are levied at any time. Uncertainty can affect farmers' production and operation expectations and frequently trigger land disputes. The rural land three rights separation in China is a continuation of its land system reform, and the separation of three circles has also had a certain impact on the income of farmers (Aldieri et al., 2021). Applying the theoretical model of land leasing market and introducing farmers' variables, a study was conducted in some provinces of China. The separation of land rights means that agricultural land rights can be mortgaged, which can improve agricultural production performance (Deiningerk and Jin, 2004). Zhang et al. (2021) found that the separation of land rights and rural land mortgage promoted the possibility of farmers living abroad. The length of time spent living outside the country is an important influencing factor for farmers' income level (Visser et al., 2020). Families' risk financial investment and participation in the risk financial market have both increased with the length of time spent living outside the country (Matita et al., 2022). The impact of mortgage of management rights on farmers' income in land system reform is uncertain (Kondolf et al., 2022). Some scholars believe that mortgage of agricultural land management rights is not conducive to income distribution (Luo et al., 2020; Peng et al., 2022). Radel et al. (2018) through reviewing the history of land evolution in Europe and the United States, found that mortgage of agricultural land can induce the concentration of land resources to a few farmers, which is more conducive to the investment of pesticides, fertilizers, and mechanized means, increasing the income of a small number of farmers, and harming the interests of the vast majority of farmers. Some scholars hold the opposite view, believing that the mortgage of agricultural land management rights promotes fair income distribution (Abdo, 2013; Myint et al., 2021). Tri et al. (2019) established a quantile regression model to analyze the income distribution effect of rural land transfer, and found that only the income increase effect of rural land transfer was significant, and it was more significant for farmers in economically developed eastern provinces.

The third is the study of the impact of the separation of land rights on resource allocation. The rural land three rights separation can promote the transfer of land management rights and facilitate the transfer of agricultural population to non-agricultural areas (Li L. et al., 2023). The new agricultural production methods such as agricultural trusteeship under the separation of three rights in rural land can promote the optimal allocation of production factors such as farmers and farmland, and also promote the transfer of rural labor to non-agricultural fields (Zhao et al., 2021). The rural population in China is increasingly shifting to urban areas, but currently the rural population base is still relatively large, and small farmers are still the main form of rural population in China (Yang and Qian, 2021). Through the reform of the separation of three rights in rural land, the land management rights can be revitalized, promoting the flow of modern production factors to agriculture and rural areas, and driving the modernization of small farmers (Peng and Zhou, 2021). But some scholars express concerns about the rural land three rights separation. The policy of separating three rights promotes the transfer of agricultural labor to cities, while also leading to further flow of agricultural production factors to cities, increasing the severity of imbalance (Li J. et al., 2023). The policy of rural land three rights separation has not fully respected the wishes and rights of farmers in its implementation, which has damaged fairness and sustainability, resulting in a lack of effectiveness in resource allocation (Xie et al., 2021).

There are many studies on the impact of rural land system on farmers' income in existing literature, and research on the impact of the separation of land rights on agricultural production efficiency, land scale management, and rural population urbanization has also formed a certain scale. However, there is relatively little research on the relationship between the rural land three rights separation policy and farmers' income, and there is also controversy over its positive and negative effects, and the research conclusions are not yet clear. At present, there is a lack of research analyzing the impact of the rural land three rights separation policy on household income effects from the perspectives of family heterogeneity and intermediary mechanisms. This article uses data from 2011 to 2020 to analyze 30 provinces in China, which helps to explore the deep relationship between the rural land three rights separation policy and farmers' income increase, clarify the mediating effect between these two variables, and provide ideas for accurately implementing policies to achieve common prosperity in agriculture and rural areas.

2 Research hypothesis

For a long time, Chinese farmers have been unable to obtain production funds by using land as an effective asset as collateral, which has seriously restricted their enthusiasm for production and management. In order to enable farmers to obtain more property rights and financial support, in 2014, China officially proposed a pilot policy of three rights separation, separating the management rights of land from the contractual management rights. Theoretically, farmers' production and operation require financial resources and financial support, and mortgage loans for agricultural land management rights increase their likelihood of obtaining corresponding support. In particular, after the promulgation of *The Rural Land Contract Law of the People's Republic of China* (hereinafter referred to as the "*Rural Land Contract Law*") in 2019, it was endorsed in legal form. The policy has improved the allocation efficiency of land resources for rural households, allowing family labor to choose industries based on needs, with a strong family income effect. As the main economic person, farmers will coordinate mortgage loans in accordance with the optimal principle. Clear property rights will enable farmers to make rational decisions, reduce friction in the land mortgage process, and reduce the transaction cost of land mortgage. Farmers obtain dividends by mortgaging their land management rights to the collective and participating in the collective purchase of shares. This is also an important way for the three rights separation to increase farmers' property income (Holden and Yohannes, 2002). When members of a collective economic organization have the right to contract, quantifying the land contractual management right into shares accelerates the process of land ownership confirmation and ensures the property rights of farmers. Based on this, the following hypothesis are proposed.

The principles of industrial economy are also applicable in agricultural economy. As the actual scale of farmers' land management continues to expand, the cost allocated to unit land or unit agricultural products will become lower and lower. Even if the technical conditions remain unchanged, the internal economies of scale effects will become particularly evident, leading to an increase in agricultural profits and an increase in farmers' income. Farmers obtain dividends by mortgaging their land management rights to the collective and participating in collective investment, which is also an important way for the three rights separation policy of land to increase their property income (Long and Tang, 2021). When members of collective economic organizations have the right to contract, quantifying the land contract management right into shares accelerates the process of land ownership confirmation and safeguards the property rights of farmers. Based on this, hypothesis 1 was proposed.

> *Hypothesis* 1: The policy of rural land three rights separation can improve the income of farmers, and the impact is more obvious after the law is promulgated.

Based on the assumption of economic man, on the one hand, training have a positive impact on the policy of rural land three rights separation. Farmers who have received more training are more rational in calculating the costs and benefits of agricultural production and non-agricultural operations, especially in analyzing the potential risks and comparative benefits brought by rural land three rights separation. After fully weighing the risks and benefits, make a decision on whether to mortgage a loan based on one's own situation, rather than blindly rejecting it. On the other hand, training and education have an indirect impact on the incentive for farmers to increase their income in the policy of three rights separation in rural land. Farmers with more training and education have a strong ability to engage in large-scale agricultural production and operation, and their liquidity asset allocation, production fund acquisition, and income and expenditure management level are high (Cui et al., 2021). Based on this, hypothesis 2 was proposed.

> *Hypothesis* 2: Farmers with more training are more significantly affected by the income increase effect brought by the policy of rural land three rights separation.

Mortgage loans for agricultural land management rights can effectively stimulate the expansion of the planting scale of economic crop farmers, while achieving the effective transfer of surplus household labor and expanding the multi-channel income sources of farmers (Ege, 2017; Fu and Hu, 2022). The benefits of developing food crops are relatively low, and farmers who grow food crops are more numb and slow in implementing the policy of dividing agricultural land ownership into three categories compared to those who grow economic crops. Economic crop planting farmers have achieved a transformation from traditional small-scale farmers to professional farmers through mortgage loans. The agricultural production mode is efficient and intensive, achieving connotative income growth for farmers, improving the level of agricultural production and operation, and optimizing the total factor productivity of agriculture. Economic crop farmers have higher resource allocation efficiency, and production factors such as land, capital, technology, and labor can complement each other, resulting in better income growth effects. Based on this, hypothesis 3 was proposed.

> *Hypothesis* 3: Compared with food crop farmers, the policy of rural land three rights separation has a more significant impact on economic crop farmers' income.

Small scale farmers tend to flow out of the land, while large scale farmers tend to flow into the land in order to achieve scale management (Ye et al., 2023). Therefore, the absolute scale of land will have an impact on the mortgage of agricultural land management rights. Due to the immovable nature of land, land mortgage and transfer are unlikely to occur in distant areas. Therefore, the relative size of land (the relative ranking of farmers' land size in their respective villages, as discussed later) will also have an impact on the mortgage of agricultural land management rights. Farmers with relatively large land scale are more inclined to use mortgage loans for agricultural land management rights to obtain funds, further expand production and operation scale, pay attention to relevant policy changes, and improve the level of scale income. Based on this, hypothesis 4 was proposed.

Hypothesis 4: The policy of rural land three rights separation has a more significant effect on the income of farmers with relatively large land scales.

The theoretical causal relationship between the rural land three rights separation and the assumed conditions and the increase in farmers' income can be seen in Figure 1.

3 Data and methods

3.1 Data source and processing

The data source includes the latest national rural fixed observation point data from the Ministry of Agriculture and Rural Affairs from 2011 to 2020, covering 23,000 farmers in 360 administrative villages in China. Due to special reasons, no statistical surveys were conducted in 1992 and 1994, and 33 statistical surveys had been completed by 2020. Data sources also include the Peking University Magic Treasure Database and the West Lake Law Library database, which are used to collect statistics on local regulations related to the separation of land rights, land tenure, and land tenure. Query the data from the *"China Statistical Yearbook"* and *"China Rural Statistical Yearbook"* to supplement it to meet the needs of the relationship between the separation of land rights, land tenure, and rural household income increase. Due to the lack of data in Xizang, this article finally matched the unbalanced panel data of 9,846 rural household samples from 30 provinces except Hong Kong, Macao, Taiwan, and Xizang. We acknowledge that excluding Hong Kong, Macao, Taiwan, and Xizang may raise concerns about data representativeness, which is an important limitation. Given that rural land in China is collectively owned, whereas in Hong Kong, Macao, and Taiwan, it is privately owned, it is challenging to include them in our study. In addition, since Xizang is located in a plateau area with a large area and a small population, the policy of rural land three rights separation has not been implemented. Although our research did not cover these regions, the unique characteristics of these individual areas do not hinder our in-depth analysis and exploration of mainstream rural family issues in China.

In terms of data processing: (1) Land area is an important variable in the rural land three rights separation, and the *per capita* land resource endowment varies greatly among provinces. Farmers with an operating area of 30 mu or more are considered as large-scale farmers; (2) Winsorize the variables at a level of 1% to reduce the adverse effects of extreme values; (3) The data processing software uses Stata16, and the core explanatory variables come from the Peking University Magic Treasure Database and the West Lake Law Library database. The control variable data comes from the national rural fixed observation point data and statistical yearbook.

3.2 Methods

Differences-in-Differences method (DID) is an effective economic policy evaluation method that estimates policy effects by comparing the differences between the treatment group (affected group) and the control group (unaffected group) before and after policy implementation. In the context of the policy of separating the three rights of rural land, the DID method can help us accurately identify the net effect of the policy on the growth of farmers' income, thereby better understanding the effectiveness of the policy. Parallel trend testing is an important prerequisite assumption of the DID method, which requires the treatment group and the control group to have similar trends before policy implementation. If the parallel trend assumption is met, we can be more confident that the differences after policy implementation are caused by the policy itself, rather than other external factors or differences in initial conditions. Therefore, the rationality of parallel trend testing lies in its ability to ensure that the policy effects we estimate are accurate and reliable. The implementation of the three rights separation policy is aimed at optimizing the allocation of rural land resources, improving land use efficiency, and promoting increased income for farmers. The target audience of this policy is the vast majority of farmers, who have similar economic characteristics and growth trends before the policy is implemented. In addition, policy implementation is usually carried out over a larger geographical range, which also helps to meet the parallel trend assumption, as a larger sample size can reduce bias caused by specific regional factors.

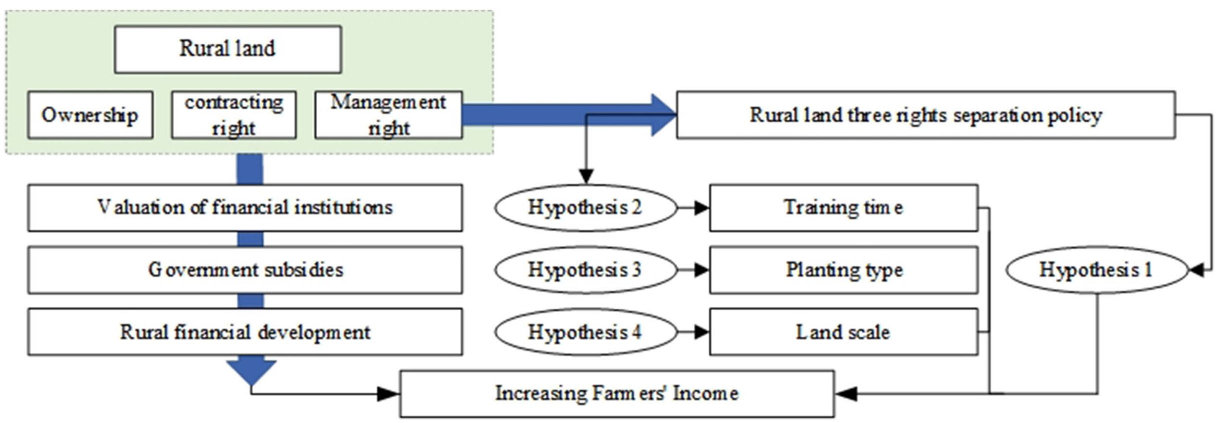

FIGURE 1
Assuming casual relationship diagram.

In practical situations, the rationality of meeting the parallel trend test can be demonstrated from the following aspects: first, the data before policy implementation supports the parallel trend hypothesis. By conducting statistical analysis on the income data of farmers before policy implementation, if it is found that the growth trends of the treatment group and the control group are similar without significant differences, then this can preliminarily support the parallel trend hypothesis. Secondly, the universality and indifference of the policy itself. The three rights separation policy is a universal policy implemented for the entire rural area, aimed at optimizing land resource allocation and improving land use efficiency, rather than targeting specific areas or groups of farmers. Therefore, the impact of policies on the treatment group and control group should be indistinguishable, which helps to satisfy the parallel trend hypothesis. In addition, the selection of control variables is also crucial to ensuring the validity of the parallel trend hypothesis. In the DID model, by introducing appropriate control variables, potential differences between the treatment group and the control group can be further reduced, thereby enhancing the validity of the parallel trend hypothesis.

3.2.1 Basic model design

The policy of rural land three rights separation was formally proposed by the central government in 2014 and was clarified in legal form through the *Rural Land Contract Law* in 2019. Before the central government proposed the policy of rural land three rights separation in 2014, provinces have not submitted any policy documents on agricultural land mortgage. During the period from 2014 to 2019, 21 provinces and cities have successively launched relevant policy documents. This article refers to Beck et al. (2010) time varying difference in difference method, and sets the model as follows:

$$\ln FI_{inc\,it} = \beta_0 + \beta_1 P_{it} + \beta_2 P_{it} L_{it} + \gamma Z_{it} + \omega_i + \mu_t + \varepsilon_{it} \quad (1)$$

Where, $\ln FI_{inc\,it}$ represents the logarithmic value of the household income of the i household in the t year (2011 is the base year).

P_{it} indicates that after the implementation of the policy of rural land three rights separation in 2014, whether the location of farmer household i has issued relevant regulations is the core explanatory variable. When the regulations were issued, the value is 1, otherwise it is 0.

L_{it} indicates that the location of the ith farmer household is clearly defined in legal form, and is included in the model together with the interaction item of P_{it}, indicating the policy lag effect of the implementation of the *Rural Land Contract Law* after 2019.

Z_{it} represents a control variable composed of a series of control variables, including household characteristics, business characteristics, regional characteristics, and wealth characteristics of farmers. Among them, family features include Age(Age_{it}), Gender ($Gender_{it}$), Education Level ($Education_{it}$). The business features include the Management Mode($Mode_{it}$) and the Farming Mode (Arg_{it}). Regional features include Area ($Area_{it}$), Agricultural Land Area ($Land_{it}$) and Customs ($Custom_{it}$). The wealth features include Absolute Poverty($Absolute_{it}$) and Relative Poverty($Relative_{it}$).

ω_i represents individual fixed effects, $\propto_t$ represents time fixed effects, and ε_{it} represents residual perturbation.

TABLE 1 Descriptive statistics of main variables.

Variable abbreviation	Description	Correlation coefficient	Mean value
$FI_{inc\,it}$	Income in 2011	-	6977.29
P_{it}	0 = no,1 = yes	0.233***	0.667
L_{it}	0 = no,1 = yes	0.259***	0.061
Age_{it}	*year*	0.004***	50.332
$Gender_{it}$	0 = female,1 = male	0.128***	0.845
$Education_{it}$	*year*	0.165***	7.449
$Mode_{it}$	0 = Hired, 1 = agriculture	0.007***	0.383
Arg_{it}	0 = Cultivation, 1 = Planter	0.146***	1.274
$Area_{it}$	0 = Northeast, 1 = East, 2 = Central, 3 = West	0.192**	1.332
$Land_{it}$	mu	0.261***	7.294
$Custom_{it}$	Gift expenses (yuan)	−0.043*	0.452
$Absolute_{it}$	Below the poverty line = 0, other = 1	0.094***	0.913
$Relative_{it}$	Below 50% of the provincial median *per capita* income = 0, other = 1	0.118***	0.674

*, ** and *** are significance level 10, 5 and 1%.

The correlation coefficient of policy pilot P_{it} in Table 1 is 0.233, indicating a positive correlation effect. Other indicators have also passed the significance level test.

3.2.2 Robustness check model

To evaluate the pilot effect of the rural land three rights separation policy, it is necessary to test the parallel trend of farmers' income in the dependent variable, and only when the parallel trend conditions are met can the implementation effect of the rural land three rights separation policy be analyzed. The parallel trend test can be verified using Formula (2).

$$\ln FI_{inc\,it} = \alpha_0 + \prod_{n\geq -2}^{6} \alpha_1 P_{it}{}^{n} + \prod_{n\geq -2}^{6} \alpha_2 P_{it}{}^{n} L_{it} + \gamma Z_{it} + \omega_i + \mu_t + \varepsilon_{it} \quad (2)$$

The placebo test is a commonly used experimental design method, mainly used to distinguish between real processing effects and effects caused by measurement errors and other potential confounding factors. Considering that other policies or random impacts may lead to changes in the trend of the treatment group and control group after the implementation of the land separation policy, it is necessary to conduct placebo trials using a randomized treatment group and control group approach. In year t, if there are m municipalities that have introduced policies related to the separation of land rights, m municipalities will be randomly selected from all 30 provinces in that year as a new pilot for the separation of land rights, forming a new farmer treatment group and a control group, and calculating the municipalities that have completed the placebo test.

3.2.3 Heterogeneity and mediation effect inspection model

The situation of farmers varies, and the impact of the separation of land rights policy on the income growth of different farmers will exhibit heterogeneity. Design a model considering three factors: farmer training, planting type, and relative land scale.

In order to test whether training other than academic education for rural households will trigger the impact of the policy of the rural land three rights separation policy on their income, a model can be designed as Formula (3):

$$\ln FI_{incit} = \beta_0 + \beta_1 P_{it} + \beta_2 P_{it} L_{it} + \beta_3 train_i P_{it} + \beta_4 train_i P_{it} L_{it} + \gamma Z_{it} + \omega_i + \mu_t + \varepsilon_{it} \quad (3)$$

Different types of planting farmers adopt different planting techniques, face different market environments, and planting cycles, which may lead to different impacts of the land separation policy on farmers' income. The design model is as Formula (4):

$$\ln FI_{incit} = \beta_0 + \beta_1 P_{it} + \beta_2 P_{it} L_{it} + \beta_3 food_i P_{it} + \beta_4 food_i P_{it} L_{it} + \gamma Z_{it} + \omega_i + \mu_t + \varepsilon_{it} \quad (4)$$

Based on Formula (1), add a dummy variable of the relative size of land ($scale_i$), and adjust the model as Formula (5):

$$\ln FI_{incit} = \beta_0 + \beta_1 P_{it} + \beta_2 P_{it} L_{it} + \beta_3 scale_i P_{it} + \beta_4 scale_i P_{it} L_{it} + \gamma Z_{it} + \omega_i + \mu_t + \varepsilon_{it} \quad (5)$$

The policy of three rights separation of land can promote farmers' income, but its impact mechanism needs to be further explored. The intermediary effect model is established as follows:

$$M_{it} = \alpha_0 + \alpha_1 P_{it} + \alpha_2 P_{it} L_{it} + \gamma Z_{it} + \omega_i + \mu_t + \varepsilon_{it} \quad (6)$$

$$\ln FI_{incit} = \delta_0 + \delta_1 P_{it} + \delta_2 M_{it} + \gamma Z_{it} + \omega_i + \mu_t + \varepsilon_{it} \quad (7)$$

In Formula (6) and Formula (7), M_{it} represents intermediary variables, including investment level, credit level, and non agricultural employment level. The total agricultural investment of farmers is used to reflect the investment level ($\ln TAI_{incit}$), the total credit amount of farmers is used to reflect the credit level ($\ln TC_{incit}$), and the non agricultural labor time of farmers is used to reflect the non agricultural employment level ($\ln NAE_{incit}$). The other variables have the same meaning as in Formula (1).

4 Results

Figure 2 shows the *per capita* income level and composition of Chinese farmers from 2010 to 2022, and it can be observed that there has been a significant increase in income over the past 13 years. The *per capita* total income increased by 1.90 times from 6919.01 yuan in 2010 to 20132.8 yuan in 2022. Among them, wage income increased the most significantly, from 2431.05 yuan to 6018.15 yuan, an increase of 2.47 times. There has been some fluctuation in operating income, but the overall trend has increased from 3832.8 yuan to 6971.5 yuan, an increase of 0.82 times. There was a significant leap in transfer income in 2013, which may have been influenced by some policy adjustments or external capital injections. Afterwards, the transfer income also maintained a certain growth momentum. The red area in Figure 2 represents property income, mainly through the transfer of land rights. Although it does not account for a high proportion of the total income, a significant increase of 1.52 times can be seen. Property income is mainly due to the economic benefits obtained by farmers through holding and managing property, which may come from various channels, including land transfer and other benefits brought by land property rights. Land transfer, as a form of property income, may lead to an increase in other income.

4.1 Benchmark regression analysis of the impact of farmers' income

Table 2 shows the benchmark regression results of the impact of the rural land three rights separation policy on farmers' income. The number without parentheses corresponding to the variable represents the regression coefficient, reflecting the magnitude and positive or negative direction of the correlation. The numbers in parentheses indicate standard error. These two types of numbers have been explained in the text according to the opinions. The total household income of farmers is a dependent variable. After adding control variables, all models can control individual fixed effects and time fixed effects. The calculation results in Table 2 show that the introduction of policy effects in column (1) only resulted in a 1.7% increase in income for farmers, with an increase of approximately 979.85 yuan per household, which passed the 1% level test. However, from the perspective of the amount of income increase, it is far from the total annual income of 57638.37 yuan. Column (2) introduces policy effects and legal effects, achieving control of the interaction between the two effects. Due to the promulgation of the Rural Land Contract Law, farmers' income increased by 2.3%, while the estimated parameter of policy effects decreased to 0.016, indicating that the policy bias effect has also been weakened. Columns (3) to (6) gradually control household characteristics, business characteristics, regional characteristics, and wealth characteristics of farmers based on each column. This indicates that the reliability of the estimated results is high. Since the introduction of the rural land three rights separation policy in 2014, especially the establishment and promulgation of the Rural Land Contract Law in 2019, it has brought a positive impact on increasing farmers' income. Based on this, hypothesis 1 is verified.

Considering that the confirmation of agricultural land rights is an important condition for the rural land three rights separation, and there are still many areas that have not been fully confirmed after the rural land three rights separation policy, further control has been exercised over the confirmation of rights and its interaction with the core independent variable ($P_{it}L_{it}$; column 3 of Table 3). Due to the fixed observation point data only providing village level property rights confirmation rates($landcert_{it}$) after 2018, this article only uses samples from 2018 to 2019 for analysis. It is worth mentioning that

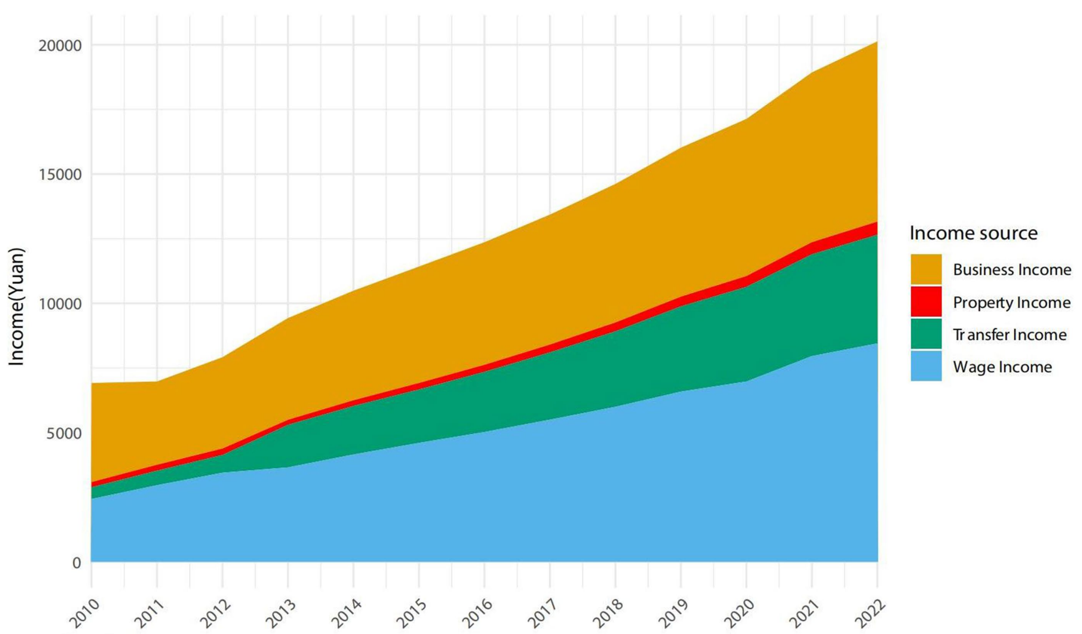

FIGURE 2
Income sources from 2010 to 2022.

there may be endogeneity issues in land tenure confirmation, and there may be a reverse causal relationship between land tenure confirmation and farmer income. Differences in farmer income can lead to differences in the process of land tenure confirmation. Therefore, this article refers to the approach of Boucher et al. (2005) and selects whether the city is a pilot city for property rights confirmation multiplied by the proportion of property rights confirmed by other county-level farmers in the prefecture level city, and the proportion of property rights confirmed by sample farmers in other prefecture level cities in the same province as instrumental variables for village property rights confirmation. In the fourth column, the lagged value of the rural land three rights separation is used as the instrumental variable, and the two-stage least squares method is used for estimation. The LM statistical statistic is 73.8, which is greater than the critical value and has a p-value of 0, strongly rejecting the null hypothesis. The instrumental variable is strongly correlated with the endogenous variable. The Wald F statistic, which is greater than the critical value at the 5% level, passed the weak instrumental variable test, indicating that the rural land three rights separation lagged for one period is not a weak instrumental variable. After four robustness tests, the vast majority of indicators passed the significance test at the 1% level, indicating that the impact of the rural land three rights separation policy on farmers' income is robust.

4.2 Robustness check

4.2.1 Parallel trend test

According to the regression results in Table 4 and Figure 3, it is found that the P_{it}^{n} was not significant before the issuance of the rural land three rights separation policy, indicating that there was no significant difference in the income increase effect between the treatment group and the control group before the implementation of the policy. The alpha coefficient started to be significant from year 0, and from year 1, 2, 3, and 4 after the policy was issued, the coefficient increased significantly, with significant differences observed between the control group and the treatment group. Especially in the fifth year after the policy was promulgated, which is the year of legislation in 2019, there was a greater jump in the coefficient value, indicating that it passed the parallel trend test (Figure 3).

4.2.2 Placebo test

Referring to the practice of Holden and Ghebru (2016), repeat the inspection process 1,000 times using Stata 18.0 to obtain 1,000 DID coefficients. According to statistics, it is found that the DID coefficient of farmers' income increase effect presents a mean value of approximately 0, and the actual result is a normal distribution of 0.0004 and 0.0002. From the perspective of counterfactual facts, it is verified that the policy of rural land three rights separation policy has a significant effect on farmers' income increase. In Figure 4, the X-axis represents the coefficient and t-test value, the y-axis represents the corresponding p-value, and the curve represents the distribution of the kernel density test.

The scatter plot of p-value is shown in Figure 5, where the horizontal short dashed line is $p = 0.1$, and the scatter below this dashed line indicates that the coefficient is significant at least at the 10% level. The figure shows the relationship between the rural land three rights separation policy and increasing farmers' income from a counterfactual perspective, showing a significant impact.

4.3 Empirical results of heterogeneity

4.3.1 Heterogeneity of farmer training

Based on Formula (1), Formula (3) adds a cross item between training and policy pilot variables, as well as a cross item between

TABLE 2 Benchmark regression under control features.

	(1)	(2)	(3)	(4)	(5)	(6)
	Policy effect	Policy effect and legal effect	Control family features	Control family business features	Control family, business, regional features	Control family, business, regional, wealth features
P_{it}	0.017*** (0.003)	0.016*** (0.003)	0.016*** (0.003)	0.015*** (0.003)	0.015*** (0.003)	0.014*** (0.003)
L_{it}		0.023*** (0.006)	0.023*** (0.006)	0.021** (0.006)	0.019*** (0.006)	0.018*** (0.006)
Age_{it}			0.016*** (0.004)	0.015*** (0.004)	0.014*** (0.004)	0.014*** (0.004)
$Gender_{it}$			0.105*** (0.005)	0.104*** (0.005)	0.104*** (0.005)	0.102*** (0.005)
$Education_{it}$			0.007*** (0.002)	0.007*** (0.002)	0.006*** (0.002)	0.006*** (0.002)
$Mode_{it}$				0.043*** (0.001)	0.041*** (0.001)	0.041*** (0.001)
Arg_{it}				0.097*** (0.003)	0.095*** (0.003)	0.092*** (0.003)
$Area_{it}$					0.041* (0.009)	0.041** (0.009)
$Land_{it}$					0.094*** (0.007)	0.093*** (0.007)
$Custom_{it}$					0.005 (0.006)	0.005 (0.006)
$Absolute_{it}$						0.001 (0.004)
$Relative_{it}$						0.011*** (0.004)
P_{it}	11.948*** (0.004)	9.536*** (0.009)	0.939*** (0.015)	0.884*** (0.034)	0.875*** (0.051)	0.836*** (0.067)
constant	9,846	9,846	9,846	9,846	9,846	9,846
n	9,846	9,846	9,846	9,846	9,846	9,846
R^2	0.798	0.798	0.799	0.800	0.800	0.801
Individual fixed	Yes	Yes	Yes	Yes	Yes	Yes
Time fixed	Yes	Yes	Yes	Yes	Yes	Yes

*, ** and *** are significance level 10, 5 and 1%.

TABLE 3 Endogeneity testing result.

Variable	(1) Excluding samples after legislation	(2) Excluding samples before policies	(3) Increase the variable of agricultural land ownership confirmation	(4) Using instrumental variables
P_{it}	0.013***(0.002)			0.107***(0.006)
$P_{it}L_{it}$		0.009***(0.003)	0.014***(0.002)	0.054***(0.005)
$landcert_{it}$			0.003***(0.002)	0.029**(0.004)
$P_{it}L_{it}landcert_{it}$			0.027*(0.003)	0.227(0.138)
R^2	0.736	0.745	0.692	0.743
Individual fixed	Yes	Yes	Yes	Yes
Time fixed	Yes	Yes	Yes	Yes

*, ** and *** are significance level 10, 5 and 1%.

TABLE 4 Heterogeneity analysis of region, provincial capital distance and planting type.

n	−3	−2	−1	0	1	2	3	4	5	6
α_1	−1.165 (0.010)	−1.064 (0.010)	−0.079 (0.019)	0.536* (0.039)	1.491** (0.073)	1.958** (0.075)	2.354*** (0.098)	2.602*** (0.126)	6.773*** (0.087)	6.932*** (0.092)

*, ** and *** are significance level 10, 5 and 1%.

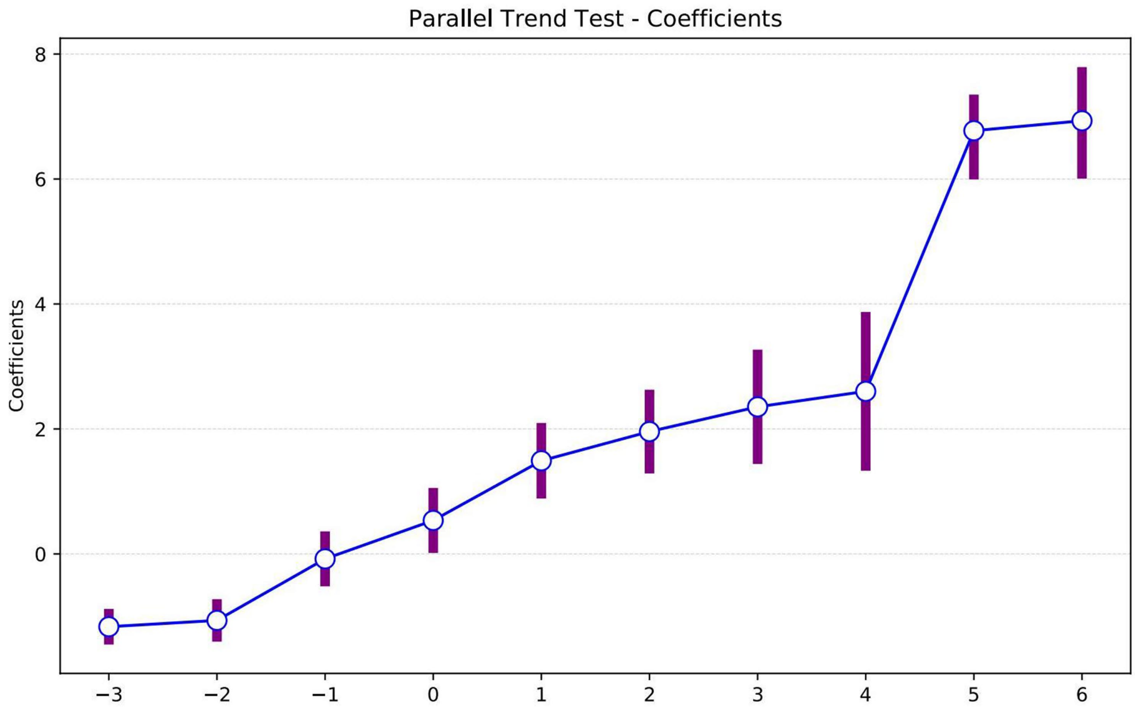

FIGURE 3
Parallel trend test chart.

training and policy pilot variables, and a clear cross item between policy and law. Among them, it is a dummy variable for farmers' training. If the farmer receives education or training for more than or equal to 12 h per year, the value is 1. If the time is less than 12 h, the value is 0. Column (1) in Table 5 shows that, and have all passed the test at the 1% level, with a positive direction. The coefficient of training interaction items and policy pilots reaches 9.247, and the coefficient of training interaction items and policy pilots and legal clarity reaches 9.883. This shows that farmers who actively participate in training are more significantly affected by the income increase effect of the rural land three rights separation policy, which validates hypothesis 2.

4.3.2 Heterogeneity of farmers' planting types

Based on Formula (1), Formula (4) introduces a cross item between planting type and policy pilot variables, a cross item between planting type and policy pilot variables, and a clear cross item between law and farmers. $food_i$ is used to represent the virtual variable of farmers' planting type. The area where farmers plant food crops is greater than or equal to 50%, and $food_i$ is 1. If the area where farmers plant food is less than 50%, they mainly plant cash crops or other crops, and $food_i$ is 0. The cross item coefficient is used to reflect the correlation between policy effectiveness and planting types. The regression in column (2) of Table 3 shows that P_{it} and $P_{it}L_{it}$ have passed the 5% level test, while $food$ and $food_iP_{it}L_{it}$ have passed the 1% level test, with positive directions. The coefficient between planting type and policy pilot is 3.397, and the coefficient between planting type and policy pilot and law clear is 3.462. The calculation results reflect that the planting type has a significant impact on the income increase of farmers, and food crop planting farmers are more significantly affected by the income increase brought about by the rural land three rights separation policy than cash crop farmers. This is the exact opposite of the previous hypothesis 3. China has always adhered to the policy of prioritizing itself and based on domestic food security. This means that the country attaches great importance to the stability and growth of food production to ensure the security of domestic food supply. As a fundamental industry of the country, the cultivation and production of food crops are heavily supported by Chinese policies. The implementation of the rural land three rights separation policy enables food crop farmers to better utilize land resources, increase food production, and improve planting efficiency. At the same time, the government has further stimulated the production enthusiasm of food crop farmers by implementing policies such as producer subsidies and establishing a minimum price purchase system. In contrast, although economic crop cultivation has higher economic benefits, its cultivation and sales are more influenced by market demand. Although the three rights separation policy provides more business options for economic crop farmers, factors such as changes in market demand and price fluctuations still have a

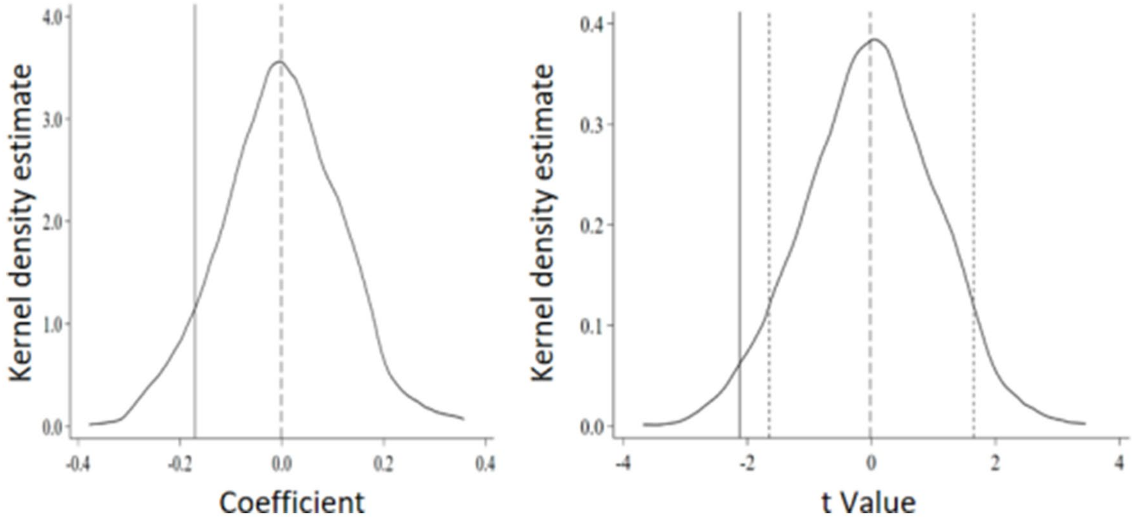

FIGURE 4
Kernel density estimation chart.

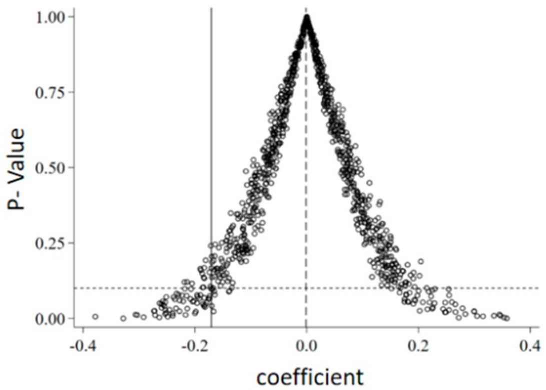

FIGURE 5
The scatter plot of the coefficient of *p*-value.

significant impact on them. Therefore, the rural land three rights separation policy may have a more significant impact on food crop farmers.

4.3.3 Heterogeneity of relative scale of farmers' land

In Formula (5), in order to overcome regional influence, the median operating area of the village where the farmers are located is selected for comparison and analyzed as an interactive project. If the operating area of a farmer is smaller than the median operating area of the rural land in the village, it is considered as a relatively small-scale farmer, and $scale_i$=0. If the operating area of a rural household is larger than the median of the rural household in the village, it is considered as a relatively large-scale household, and $scale_i$=1. In Table 3, regression (3) P_{it} and $P_{it}L_{it}$ passed the 1% level test, and $scale_iP_{it}$ and $scale_iP_{it}L_{it}$ passed the 5% level test. This means that relatively large farmers are more significantly affected by the policy of separating land ownership, land ownership, and land ownership, which validates hypothesis 4 (Table 5).

4.4 Mediation effect

4.4.1 Mediation effect of investment level

Based on the 2011 income reduction, the original value of assets at the end of the year is used for calculation. From Table 6, it can be seen that the intermediary effect of investment level is 0.482, accounting for 7.8%. The total agricultural investment of farmers is not significant after the promulgation of the rural land three rights separation policy, but has increased significantly after the enactment of the *Rural Land Contract Law*.

4.4.2 Mediation effect of credit level

The rural household credit has strengthened with the promulgation of the policy on the rural land three rights separation. The intermediary effect of the credit level is 0.215, accounting for 4.8% of the total. Both the promulgation of the policy and the overlap with the explicit laws have passed the significance test at the level of 5% or 1%. Table 7 shows that promoting farmers' income through financial and credit means is particularly important.

4.4.3 Mediation effect of non-agricultural employment level

Table 8 shows that the intermediary effect of the level of non-agricultural employment is 0.197, accounting for 3.9% of the intermediary effect, which has passed the significance test at the level of 5% or 1%. The rural land three rights separation policy will induce some farmers to reduce agricultural labor hours, thereby increasing non-agricultural employment time, and promoting farmers' income.

5 Discussion and conclusion

5.1 Discussion

In this article, we delve into the impact of the policy of separating agricultural and land rights on the growth of farmers' income based

TABLE 5 Heterogeneity analysis results.

Variable	(1)	(2)	(3)
P_{it}	4.475*** (0.045)	1.641** (0.033)	0.043*** (0.016)
$P_{it}L_{it}$	4.859*** (0.052)	1.897** (0.036)	0.037*** (0.017)
$train_i P_{it}$	9.247*** (0.068)		
$train_i P_{it} L_{it}$	9.883*** (0.077)		
$food_i P_{it}$		3.397*** (0.047)	
$food_i P_{it} L_{it}$		3.462*** (0.048)	
$scale_i P_{it}$			0.045** (0.015)
$scale_i P_{it} L_{it}$			0.038** (0.021)
Variable fixed	Yes	Yes	Yes
R^2	0.742	0.718	0.673
Individual fixed	Yes	Yes	Yes
Time fixed	Yes	Yes	Yes

*, ** and *** are significance level 10, 5 and 1%.

TABLE 6 Impact mechanism test results of investment level.

Variable	(1) $\ln FI_{inc\,it}$	(2) $\ln TAI_{inc\,it}$	(3) $\ln FI_{inc\,it}$
P_{it}	0.025(0.012)	0.018(0.008)	0.023***(0.010)
$P_{it}L_{it}$	0.047***(0.011)	0.019**(0.009)	0.021***(0.012)
$\ln TAI_{inc\,it}$			0.013***(0.007)
Constant	−0.942***(0.122)	−0.925***(0.117)	−0.874***(0.084)
Sobel test		$Z = 7.48$, $p = 0.000$ 0.482	
Variable fixed	Yes	Yes	Yes
Individual fixed	Yes	Yes	Yes
Time fixed	Yes	Yes	Yes
N	9,846	9,846	9,846
R^2	0.562	0.584	0.443
Proportion of indirect effects		0.078	

*, ** and *** are significance level 10, 5 and 1%.

on the DID model, and analyze the roles of heterogeneous factors such as training, planting type, and land scale in it. Through summarizing and comparing existing research, we found that the rural land three rights separation policy has significant theoretical and practical significance in promoting farmers' income growth.

At the theoretical level, the rural land three rights separation policy is an innovation and improvement of the rural land property rights system. By separating the ownership, contracting, and management rights of land, policies provide farmers with more possibilities for land transfer and scale management, thereby improving land use efficiency, which is consistent with existing research (Gao et al., 2019; Chen et al., 2022). At the same time, this policy has also stimulated the production enthusiasm and investment enthusiasm of farmers, promoting the improvement of agricultural productivity. In addition, our research also reveals a close relationship between policy effectiveness and heterogeneity factors such as training, planting type, and land scale, which helps us to have a deeper understanding of the mechanism and path of policy action.

From a practical perspective, the implementation of the rural land three rights separation policy has significantly improved the income growth level of farmers, and the research conclusions have enhanced the reliability of the relationship between rural land system and income (Cheng et al., 2019). By comparing the changes in farmers' income before and after the implementation of policies and in different regions, we found that the contribution of policies to increasing farmers' income is gradually increasing. It is particularly noteworthy that farmers who actively participate in training, grow food crops, and have a larger land scale have achieved more significant income increase effects in policy implementation. This indicates that policies have played a positive role in promoting the transformation and upgrading of farmers, optimizing planting structures, and expanding business scale. In addition, we also found that the impact of policies after legislation is more significant, which reflects the important role of laws in protecting the rights and interests of farmers and promoting rural economic development.

When discussing the heterogeneity of the impact of China's rural land three rights separation policy on farmers' income, we realize that this policy not only has profound practical significance in China, but also has certain reference value in the context of global land rights reform. Internationally, many countries have attempted to reform land rights with the aim of improving land use efficiency, promoting rural economic development, and safeguarding the rights and interests of farmers. Although the specific forms and implementation details of these policies may vary depending on national conditions, history, and cultural backgrounds, their common goal is to optimize land resource allocation and improve the living standards of farmers. For example, developed countries such as the United States and France have clarified the boundaries of rights between landowners and users through legislative means, promoting land transfer and concentration, thereby improving agricultural production efficiency. In developing countries such as Vietnam and India, land rights reform focuses more on the protection of land rights for impoverished farmers and the sustainable development of agricultural production. This global perspective comparison also helps us identify the challenges and problems that different policies may face in the implementation process.

Although the rural land three rights separation policy has achieved significant results in promoting the increase of farmers' income, there are still some problems and challenges. For example, the land transfer market in some regions is not yet perfect, and farmers may face problems such as information asymmetry and transaction risks during the land transfer process (Du et al., 2022). Furthermore, with the deepening of policies, it is also worth our attention to ensure that farmers continue to benefit and avoid widening income disparities(). In addition, though Hong Kong, Macao and Taiwan's land belongs to private ownership and is not easy to be included in the study of the rural land three rights separation policy, and the data of Tibet has not been included as well, it indeed raises concerns about the representativeness of the

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TABLE 7 Impact mechanism test results of credit level.

Variable	(1) $\ln FI_{inc\,it}$	(2) $\ln TC_{inc\,it}$	(3) $\ln FI_{inc\,it}$
P_{it}	0.025(0.012)	0.021***(0.008)	0.017**(0.011)
$P_{it}L_{it}$	0.047***(0.011)	0.020**(0.009)	0.018***(0.014)
$\ln TC_{inc\,it}$			0.014**(0.005)
Constant	−0.942***(0.122)	−0.846***(0.081)	−0.819***(0.075)
Sobel test		$Z = 8.62$, $p = 0.000$ 0.215	
Variable fixed	Yes	Yes	Yes
Individual fixed	Yes	Yes	Yes
Time fixed	Yes	Yes	Yes
N	9,846	9,846	9,846
R^2	0.562	0.747	0.435
Proportion of indirect effects		0.048	

*, ** and *** are significance level 10, 5 and 1%.

TABLE 8 Impact mechanism test results of non-agricultural employment level.

Variable		(6)	(7)
	(1) $\ln FI_{inc\,it}$	(2) $\ln NAE_{inc\,it}$	(3) $\ln FI_{inc\,it}$
P_{it}	0.025(0.012)	0.019***(0.009)	0.020**(0.009)
$P_{it}L_{it}$	0.047***(0.011)	0.024**(0.011)	0.032***(0.013)
$\ln NAE_{inc\,it}$			0.006***(0.003)
Constant	−0.942***(0.122)	−0.803***(0.068)	−0.799***(0.062)
Sobel test		$Z = 4.67$, $p = 0.000$ 0.197	
Variable fixed	Yes	Yes	Yes
Individual fixed	Yes	Yes	Yes
Time fixed	Yes	Yes	Yes
N	9,846	9,846	9,846
R^2	0.562	0.426	0.402
Proportion of indirect effects		0.039	

*, ** and *** are significance level 10, 5 and 1%.

data for readers. Therefore, future research will supplement relevant data, further strengthen the exploration and analysis of these issues, and provide more comprehensive and scientific decision-making basis for policymakers.

6 Conclusion

The stable income increase of farmers is an important part of comprehensively promoting rural revitalization and accelerating the construction of an agricultural power. This article is based on the national fixed observation point data of the Ministry of Agriculture and Rural Affairs from 2011 to 2020, and measures the heterogeneity of the impact of the rural land three rights separation policy on farmers' income increase. The DID model is used reasonably.

The rural land three rights separation policy can significantly improve the level of income increase for farmers, which has passed robustness tests such as parallel trend testing, placebo testing, adding control variables, and removing some samples. The improvement effect has become stronger and stronger with the promulgation of the policy and the establishment of the Rural Land Contract Law.

The income increase effect of the rural land three rights separation policy is significantly related to heterogeneity factors such as training, planting type, relative land scale, and policy issuance time. The income increase effect of farmers who actively participate in training, plant food crops, have relatively large land scale, and are influenced by policy issuance time is more significant. By using legal means to protect the stability of land contracting rights and mortgage loans, we can deepen the reform of China's agricultural land property rights system and release the dividends of the rural land three rights separation policy under the framework of inclusive growth. The government has increased the property income of mortgage loan farmers in the process of ensuring the circulation and profit rights of farmers' families and protecting their land contract management rights.

From the perspective of the impact mechanism of the separation of rural land rights on farmers' income, the investment level has no significant impact at the time of policy promulgation, but has a significant impact after legislation. Both the credit level and non-agricultural employment level have passed the significance test of 5% or 1%. From the perspective of farmers, the pilot policy of the three rights separation and the establishment of the *Rural Land Contract Law* have gradually allowed the management rights of rural land to be mortgaged and loaned, which has a promoting effect on the total credit amount of farmers. After farmers mortgage their land, they will enter cities or other non-agricultural fields to increase their wage income and have a positive impact on their non-agricultural employment level.

The government should increase investment in the agricultural sector, especially in agricultural technology research and development, infrastructure construction, and deep processing of agricultural products. By enhancing the level of agricultural modernization, improving agricultural production efficiency, and thereby increasing the operational income of farmers. Simplify the loan process, lower the loan threshold, and provide farmers with more convenient and flexible financial services. Through credit support, help farmers solve their financial problems and promote the sustainable development of agricultural production. The government should strengthen vocational skills training for farmers, enhance their employability and competitiveness, encourage them to work in cities or other fields, and increase their wage income. At present, the land transfer market mechanism within the policy framework is still not sound, with insufficient protection of farmers' rights and interests, and inadequate policy supervision. The government also needs to improve the market mechanism for land transfer, strengthen the protection of farmers' rights and interests, and strengthen policy implementation and supervision.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found at: data obtained from fixed observation points in rural areas nationwide using the Xiamen University Economics Research Sharing Platform (http://app.soe.xmu.edu.cn/elib/db_detail/22/), Peking University Treasure Database (https://www.pkulaw.com/law?cahannel=SEM-Topad2/), China Statistical Yearbook and China Rural Statistical Yearbook (http://www.stats.gov.cn/sj/ndsj/). These data are available for open access.

Ethics statement

Ethical review and approval were not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the patients/participants was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

SH: Writing – original draft, Writing – review & editing. ZF: Conceptualization, Formal analysis, Supervision, Writing – review & editing. ZC: Conceptualization, Funding acquisition, Writing – review & editing. QX: Investigation, Software, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. The paper is supported by the Guangdong Basic and Applied Basic Research Foundation under Grant (2023A1515011616), and the Guangdong Province Philosophy and Social Science Planning Project (GD24CYJ40), and the Special projects in key areas of ordinary universities in Guangdong Province under Grant (2023ZDZX4030), and the Guangdong Province Philosophy and Social Science Planning Project (GD22YDXZYJ02).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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TYPE Original Research
PUBLISHED 27 May 2024
DOI 10.3389/fsufs.2024.1384530

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RECEIVED 09 February 2024
ACCEPTED 06 May 2024
PUBLISHED 27 May 2024

CITATION
Santosa YT, Kurniasih B, Alam T, Handayani S, Supriyanta, Ansari A and Taryono (2024) Investigating the dynamics of upland rice (*Oryza sativa* L.) in rainfed agroecosystems: an in-depth analysis of yield gap and strategic exploration for enhanced production. *Front. Sustain. Food Syst.* 8:1384530. doi: 10.3389/fsufs.2024.1384530

Investigating the dynamics of upland rice (*Oryza sativa* L.) in rainfed agroecosystems: an in-depth analysis of yield gap and strategic exploration for enhanced production

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Introduction: Addressing the global demand for rice production necessitates innovative approaches to enhance upland rice yield in rainfed agroecosystems, considering the challenges posed by increasing population, limited land fertility, low productivity, and water availability.

Methods: In this study, our study investigated the impact of biochar and organic fertilizer on ten promising rice lines (G1 – G10) and two control (G11 – G12) cultivars under rainfed conditions. The experimental design used a split-plot design with four soil amendments as main plots, namely control, organic fertilizer, biochar, and biochar + organic fertilizer and 12 rice genotypes as subplot.

Results: The absolute attainable yield gaps, differentiating organic and control (GAP_1), biochar + organic and control (GAP_2), and biochar and control (GAP_3), ranged from 1.5 to 3.7 or increased of 91–580%, 0.8 to 3.5 (72–560%), and 0.6 to 2.58 tons/ha (58–472%), respectively. Notably, G2+organic exhibited the highest positive absolute yield gap, ranging from 1.1 to 5.38 tons/ha, based on the yield gap matrix. Furthermore, genotype main effect plus genotype-environment interaction (GGE) biplot analysis identified G2 as the most promising rice line, displaying superior yield performance for cultivation in biochar and organic amended soils.

Discussion: These findings provide valuable insights for farmers, governments, and stakeholders, offering a roadmap to optimize rainfed areas for rice production, serving as practical guidance to enhance overall rice productivity in rainfed agroecosystems.

KEYWORDS

biochar, organic fertilizer, soil management, upland rice, rainfed agroecosystem, yield gap

1 Introduction

Meeting the anticipated food demand resulting from Indonesia's population growth, which is expected to exceed 120% by 2050 (Alexandratos and Bruinsma, 2012; Rozi et al., 2023), rice production must be significantly increased. Being the primary food for nearly 80% of the population, with an average consumption of 1.6 kg *per capita* per week (Sitaresmi et al., 2023).

the nation faces a potential threat to food security due to an imbalance between consumption and production growth. Despite such high consumption levels, rice production has witnessed a decline from 59.2 million tons in 2018 to 54.7 million tons in 2022 (Statistics Indonesia, 2018; Khasanah and Astuti, 2022). Various factors, including genotypes, water availability, soil fertility, and farmers' skills, and climate change contribute to this production decline (Chen et al., 2008; Ansari et al., 2023). Addressing this gap requires identifying optimal agricultural practices for rice cultivation, focusing on field management and genotypes to enhance rice yield (Senguttuvel et al., 2021).

Fostering the development and optimization of rice cultivation in Indonesia's rainfed agroecosystem holds promise as a solution to increase yield amidst various pedologic, climatic, and hydrologic challenges. While rainfed areas constitute 30% of the total agricultural land in Indonesia, the average rice yield in these regions is approximately 3.7 tons/ha lower than that in paddy fields, which typically yield 5 tons/ha (Statistics Indonesia, 2021). Rainfed areas encompass lands outside the irrigated zone solely reliant on rainfall for irrigation (Devendra, 2012). A critical constraint in rainfed agriculture is the availability and sustainability of water, significantly impacting crop growth and yield (Rockström et al., 2010). Globally, rainfed crops exhibit a yield reduction of around 50% compared to irrigated conditions (Jaramillo et al., 2020). Additionally, research conducted in rainfed areas in various countries has documented yield decreases of 6 t/ha in China (Terjung et al., 1985), 0.7 tons/ha in Thailand (Sacklokham et al., 2020), and 0.5 to 4.3 tons/ha in India (Kumar et al., 2021). Addressing these challenges is imperative for sustainable and enhanced paddy production in rainfed agroecosystems.

To address the numerous challenges faced by rainfed areas, the application of soil amendments, specifically through biochar and organic fertilizer, emerges as a viable strategy to optimize rice growth while maintaining soil water availability (Głąb et al., 2020; Ansari et al., 2023). Biochar, primarily derived from the pyrolysis process involving the combustion of biomass or organic material under limited oxygen conditions and low temperatures (≤700°C), plays a crucial role in enhancing soil water retention and reduce nitrous oxide emission (Mukhtar et al., 2023; Rassaei, 2023, 2024). Physically, biochar is highly porous, thus its application to soil is considered to improve a range of soil physical and chemical properties including soil moisture content, plant available water content (PAWC) (Hardie et al., 2014), water retention capacity and nutritional status of rhizosphere (nitrogen, phosphorous, and potassium) (Ghassemi-Golezani et al., 2023). Moreover, this is achieved by reducing soil bulk density (Abel et al., 2013; Da Silva Mendes et al., 2021), increasing soil pore volume (Obia et al., 2016; An et al., 2022), and promoting soil aggregation (Herath et al., 2013; Islam et al., 2021). Specifically, rice husk biochar (RHB) has a great quantity of macropores (75–100 μm) and its application to soil enhances the addition of soil pore sized 6 to 45 μm (Lu et al., 2014). With the more water sufficiency, it can avoid suppressing leaf expansion and stomatal conductance thereby leads to maximize photosynthetic rate (Tardieu et al., 2014). Biologically, large amount of porosity and surface properties of biochar provides a suitable environment for soil microbial growth and reproduction, protecting beneficial soil microorganisms (Warnock et al., 2010). Some of the microorganisms inluenced by amendments of biochar including nitrogen-fixing bacteria (Kim et al., 2007), gram-positive bacteria, and actinomycetes (Purakayastha et al., 2019), arbuscular mycorrhizal colonization (Solaiman et al., 2010). Chemically, biochar addition can increase the soil organic matter content (Zygourakis, 2017) through promoting polymerization of small organic molecules through surface catalytic activity (Liang et al., 2010). In addition, biochar also increased the availability and reduced the leaching of nitrogen in the soil (Güereña et al., 2013), absorbing NH_3 to reduce nitrogen loss and improve utilization of nitrogen (Taghizadeh-Toosi et al., 2012). Meanwhile, Cation exchange capacity (CEC) also increased along with the addition of biochar. Soil with a high CEC is easy to adsorb $NH4^+$, K^+, Ca^{2+}, and Mg^{2+}, which can effectively improve the usage of nutrient ions and reduce the leaching of nutrients (Zhang et al., 2021). Structurally, the acidic aromatic carbon on the surface of biochar is oxidized to form abundant functional groups (–OH, –COOH), enhancing the adsorption capacity of cations and increasing CEC (Atkinson et al., 2010). In rice cultivation, the application of rice husk biochar (RHB) influences both vegetative and generative aspects, enhancing tiller number, root dry weight (Sang et al., 2018), panicle count, grain yield (Barus, 2016), 1,000-grain weight, and filled grain (Mishra et al., 2017). In addition to biochar, organic fertilizer proves beneficial in augmenting soil fertility and crop productivity. Biologically, organic fertilizer fosters increased soil microbial activity, as evidenced by elevated urease and sucrase activity, along with an enhanced soil respiration rate (LI et al., 2018). This is further reflected in higher soil microbial biomass carbon, soil microbial biomass nitrogen, and soil enzyme activity (Ren et al., 2019). From a chemical soil perspective, organic fertilizer stabilizes organic matter (Houot et al., 2009; Chen et al., 2022), augments nutrient levels, thereby promoting plant growth and yield (Zraibi et al., 2015; Ye et al., 2020). Regarding soil water retention, organic fertilizer indirectly influences an increase in soil water content by enhancing porosity and pore distribution (Lal, 2020). Incorporating these soil amendments presents a comprehensive approach to mitigate constraints in rainfed areas and optimize rice cultivation.

The yield gap analysis serves a functional role in quantifying the disparity between the average agricultural and potential crop yield under optimal conditions, considering factors such as sufficient water and nutrition, or the yield achievable through economic practices (EY) with optimal management (Evans and Fischer, 1999). This analysis is a powerful method not only identifies factors limiting current farm yields but also forms the basis for recommending improved agricultural practices to close the gap (Van Ittersum et al., 2013). Besides yields gap analysis (YGA), GEI (genotype-by environment interaction) is an important issue in crop breeding and production (Kang, 2004). Cultivar evaluation and mega-environment identification are among the most important objectives of multi-environment trials (Yan et al., 2000). A GGE-biplot graph can describe visual information related on the evaluation of genotype, environment, and their interactions and it has been widely used in various crops (Yan et al., 2007). The objectives of this research are twofold: (i) to investige, quantify, and evaluate the impact of biochar and organic fertilizer on rice yield under rainfed conditions and attainable yield (Yatt), actual yield (Ya), and yield gap (Yg) of different paddy genotypes with various soil amendments; (ii) to select suitable genotypes in each soil amendment trial. Notably, there is a gap in the literature regarding yield gap analysis and GGE biplot application in paddy cultivation, specifically in rainfed areas of Indonesia. Firstly, Indonesia faces significant challenges in rice production due to its reliance on rainfed agriculture, which is highly susceptible to climate variability and other environmental factors.

Through applying advanced analytical techniques such as yield gap analysis and GGE biplot, this study has the potential to provide valuable insights into understanding the productivity constraints and identifying opportunities for improving rice yield under rainfed conditions. Furthermore, addressing this research gap is important for informing evidence-based decision-making by policymakers, agricultural practitioners, and other stakeholders involved in rice cultivation in Indonesia. The findings of this study could offer practical recommendations for optimizing resource use, enhancing crop management practices, and mitigating yield gaps in rainfed paddy cultivation. This study can inform the recommendation of precise agronomic management practices involving different soil amendments and genotypes to benefit farmers, researchers, and other stakeholders.

2 Materials and methods

2.1 Study site

The experiment was conducted in Playen District, Gunung Kidul Regency, The Special Region of Yogyakarta (75º6'30" S to 75º9'0"S and 110º28'30″ E to 110º32'0″ E) (Figure 1), spanning from November 2021 to April 2022 (refer to Table S2 in Supplementary material). Geographically, the area exhibited an average air temperature of 25.54°C and a relative humidity (RH) of 83.90%. The soil type identified was Lithic Haplusterts, classified as vertisol according to USDA standards (Alam et al., 2020). Physically, the soil texture in the field was predominantly clay with markedly slow drainage (0.001 cm hour^{-1}). The soil possessed a water-holding capacity (WHC) of 40.36% and a total porosity of 38.64%. Chemically, the soil exhibited a cation exchange capacity (CEC) of 60.22 cmol (+) kg^{-1} (extremely high), a soil pH (H_2O) of 8.4 (alkaline), and a soil organic carbon (SOC) content of 1.80 (low). Additionally, total nitrogen (TN) content was 0.09% (extremely low), phosphorus availability (P) was 14 ppm (medium), and potassium availability (K) was 0.24 cmol (+) kg^{-1} (low). The soil also contained high levels of available of calcium (Ca) at 24.52 cmol (+) kg^{-1}, magnesium (Mg) at 2.23 cmol (+) kg^{-1}, and sodium (Na) at 0.85 cmol (+) kg^{-1} (Suryanto et al., 2022). Historically, in the experimental site, the previous crops were maize (*Zea mays*) cultivated from April to June and was fallowed until September because of low rainfall. Meanwhile, the rice cultivation is started in October to March because it coincides with the start of the rainy season.

2.2 Design of experiments and treatment application

In this research, soil amendment involved the use of locally harvested RHB, and organic fertilizer derived from milk sewage. The rationale behind choosing these specific soil amendments lies in their unique properties and their potential to address specific soil fertility constraints and improve crop productivity in rainfed paddy cultivation (Rassaei, 2022). Rice husk biochar is known for its ability to improve soil structure, enhance nutrient retention, and promote microbial activity, thereby increasing soil fertility and supporting healthier plant growth. On the other hand, organic fertilizer derived from milk sewage provides essential nutrients to the soil, improves soil organic matter content, and enhances soil microbial diversity, all of which contribute to improved soil fertility and crop yield. The RHB was produced through the kiln method (Kong and Sii, 2020), employing modified iron plates equipped with chimneys and shutters. Laboratory analysis revealed the chemical composition of the rice husk biochar, indicating a pH (H_2O) of 8.02, carbon (C) content of 34.60%, hydrogen (H) content of 4.23%, nitrogen (N) content of 0.47%, and oxygen (O) content of 31.70% (Kastono et al., 2022). On the other hand, the organic fertilizer was sourced from milk sewage generated by the Agrotechnology Innovation Centre at Universitas Gadjah Mada. Laboratory analysis of the milk sewage organic fertilizer indicated the presence of 44.90% organic carbon (C-organic), 5.86% total nitrogen (N), 9.96% phosphorus pentoxide

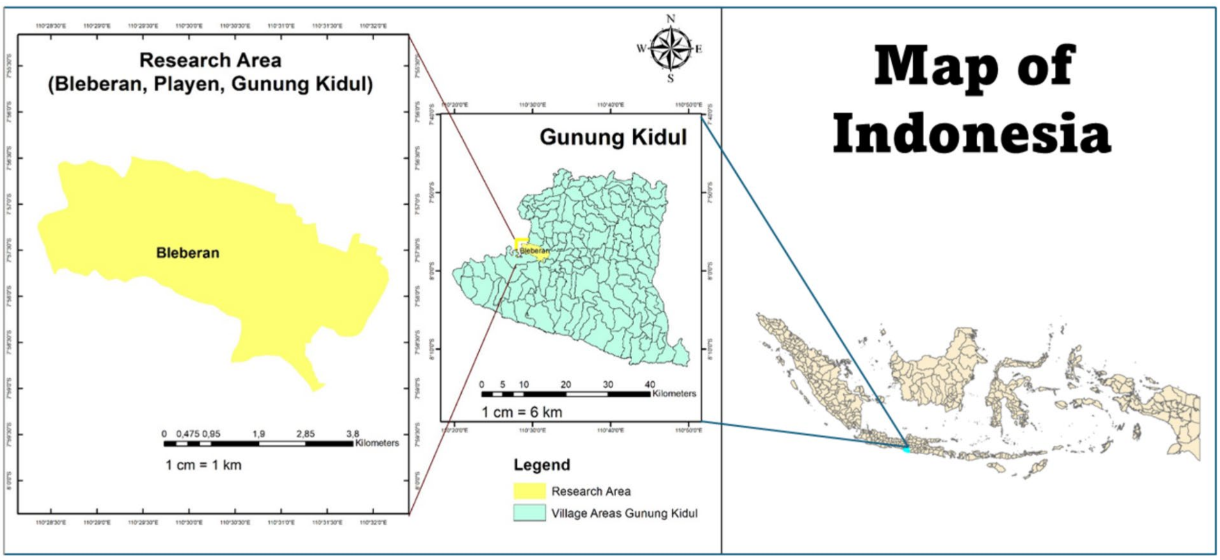

FIGURE 1
Geographical study area in rainfed agroecosystems.

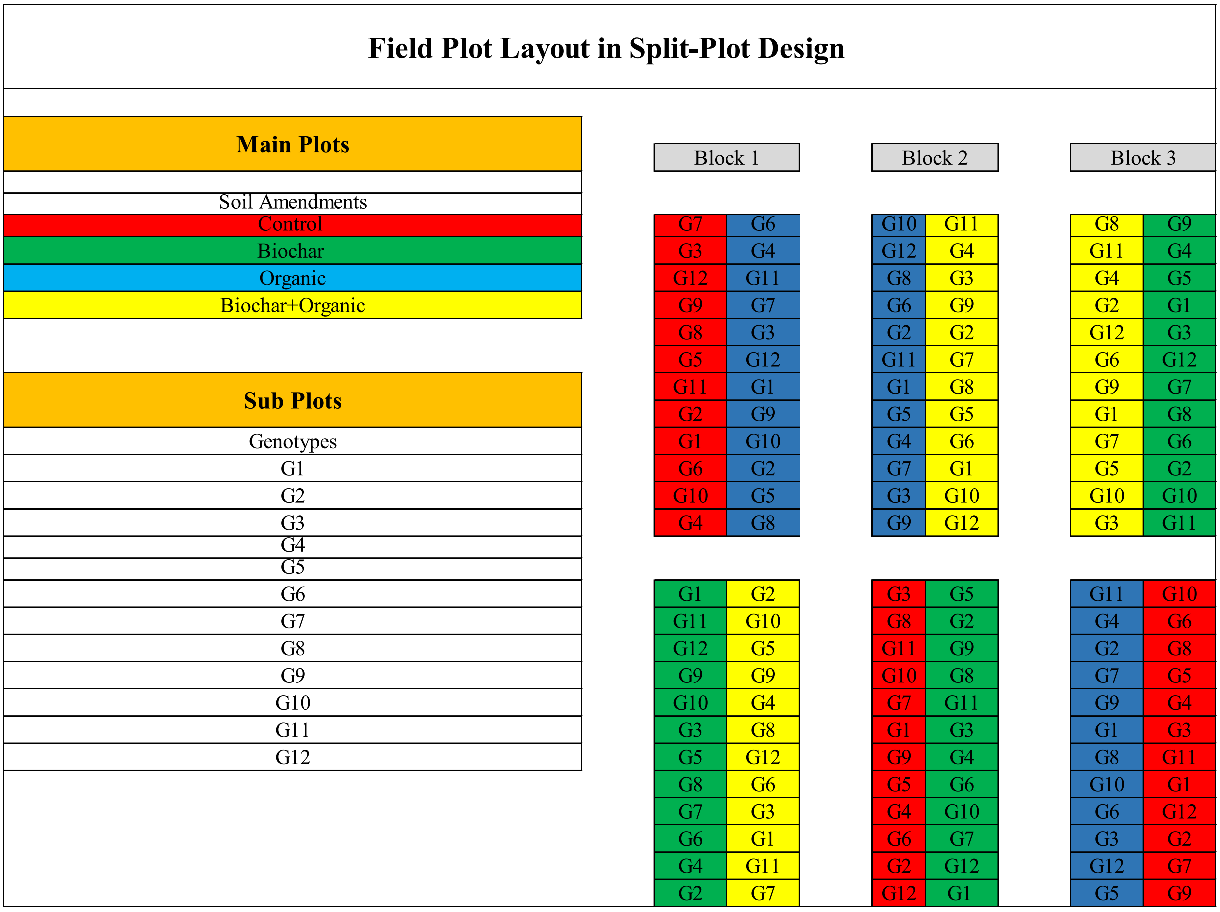

FIGURE 2
Split-plot design layout of the experiment.

(P_2O_5), and 0.17% potassium oxide (K_2O) (Taryono, 2022). The experimental design used a split-plot (Figure 2) with three replications and the randomization used R studio software package agricolae (de Mendiburu, 2021). The main factor was organic soil amendment consisted of control (without organic matter and soil amendment), organic fertilizer (compost sourced from milk sewage) with a dose of 20 tons/ha, RHB (20 tons/ha), and a combination of organic fertilizer (10 tons/ha) and biochar (10 tons/ha). The subplot was 12 genotypes of rice consisted of 10 promising rice lines sourced from Universitas Gadjah Mada, Indonesia (G1 - G10) and 2 rice cultivars as control sourced from the Indonesian Center for Rice Research (ICRR), West Java, Indonesia (G11 and G12). The split-plot design was chosen for its ability to efficiently address the complex interaction between the main treatment factors (such as soil amendments) and the subplot treatment factors (such as different rice varieties or planting densities) (Kowalski and Potcner, 2003). The land preparation was started 1 week before sowing the seed by agitating the soil surface using hoe and then applied biochar and organic fertilizer to soil in each plot with designated dosages based on the experimental design. Meanwhile, the seeds were soaked in the water 12 h before planting and were sown directly into the field with distance of 20 × 20 cm. Additionally, chemical fertilizers were utilized in accordance with local farming practices, employing varying dosages and products. Specifically, urea, SP36, ZA, and KCL were applied at rates of 300 kg/ha, 150 kg/ha, 100 kg/ha, and 150 kg/ha, respectively and it applied 3 times, namely 14 days after planting (Urea, ZA, SP36, KCl), 30 days after planting (Urea) and 60 days after planting (Urea, ZA, SP-36, and KCL). Pesticides were employed to mitigate pest and fungal infestations, including Plenum (containing pimetrozin as the active ingredient) for controlling *Nilaparvata lugens*, Prevathon (with klorantraniliprol as the active ingredient) for caterpillar control, Nordox to manage blast (*Pyricularia orizae*), and Bacterial Leaf Blight (*Xanthomonas oryzae*). Furthermore, irrigation in the field relied entirely on rainfall. Consequently, the planting schedule was synchronized with the onset of the wet season, commencing in November 2021. Moreover, monthly precipitations in Gunung Kidul from October 2021 to April 2022 were 145.7 mm, 344.8 mm, 409.9 mm, 199 mm, 188 mm, 403 mm, and 243 mm, respectively (Statistics Indonesia, 2023).

2.3 Data collection

For the calculation of yield components, rice yield observations were conducted using a digital scale during harvesting after the grains had been dried to a moisture content of 14%. The rice grain were weighed using a ACIS digital scale and grain moisture meter LDS-1G was used to measure the moisture content, following the methodology outlined by the International Rice Research Institute (IRRI, 2015). Statistically, the grain yield was measured by selecting harvested crops from a plot area of approximately 5 m^2 per plot. The obtained values were then converted into yield per hectare (ha) according to the standards outlined by IRRI (Gomez, 1972).

2.4 Statistical analysis

The data was required to be normally distributed with homogeneity variance assumptions. The normal distribution had a Q-Q plot and homogeneous variance with a residual vs. value graph (Welham et al., 1990). Comparisons of response variable was conducted using ANOVA ($p < 0.05$) and followed by the Scott-Knott test ($p < 0.05$) (Scott and Knott, 1974). ANOVA checks the impact of one or more factors by comparing the means of different samples and Scott-Knott test is statistical *post-hoc* analysis of grouping means, which distinguishes results without ambiguity (Bhering et al., 2008). The interaction between rice genotypes with organic matter and soil amendement was visualized using the GGE-biplot technique (Yan et al., 2007). The GGE biplot technique can be used to determine: (1) Which-won-where patttern in genotype and environment, (2) Average environment coordination (AEC) based on environment focused scaling of the mean value and stability of genotype, (3) Ranking of entries based on both mean and instability, and (4) Discriminativeness vs. representativeness. To assess the yield improvement achieved by each treatment, a yield gap analysis was conducted. The yield gap represents the difference in yield between genotypes in various treatments and is denoted by the symbol of the absolute attainable yield gap (*Yga*). In this research, the yield gap can be calculated using the equation proposed by Senthilkumar (2022):

$$Yga = Yatt - Yac \qquad (1)$$

Where *Yga* was the absolute attainable yield gap ($t\,ha^{-1}$); *Yatt* was the economically attainable/exploitable yield ($t\,ha^{-1}$) using 3 different soil amendments, namely biochar, organic, and biochar + organic treatment; the actual yield of control (*Yac*) was the yield of paddy ($t\,ha^{-1}$) with none of the additional soil amendments (Senthilkumar, 2022). Basically, yield actual (*Yac*) was the farmers' agriculture practice in a rainfed agroecosystem. Local farmers have followed these practices for a long time.

Specifically, to know the differences across the treatments, the absolute yield gap between each treatment was analyzed. $GAP_{1\ (Yatto - Yac)}$ was the absolute attainable yield gap between organic yield and control yield. $GAP_{2\ (Yattb+o - Yac)}$ was the absolute attainable yield gap between biochar + organic yield and control yield. $GAP_{3\ (Yattb - Yac)}$ was the absolute attainable yield gap between biochar yield and control yield. The data was analyzed using SAS 9.4 (Federer and King, 2006) and Rstudio software with metan (Olivoto and Lúcio, 2020), car (Fox and Weisberg, 2019), ggplot2 packages (Wickham, 2016).

3 Results

3.1 The yield of genotypes and yield improvement due to soil amendment on rainfed agroecosystem

The research findings indicate that the yield performance across various combinations of soil amendments and genotypes yielded mixed results. Graph show that all selected linear models had normally distributed data due to the points are on the line (Figure 3A) and homogeneous variance using a fitted value plot revealed that selected linear models had homogeneous because the points on the graph spread without a pattern (Figure 3B). The ANOVA analysis revealed significant impacts of soil amendments, genotype (G), and genotype × soil amendment (GEI) on grain yields (refer to Table S1 in Supplementary material). Notably, GEI exhibited a particularly high influence on grain yield ($p < 0.01$). Moreover, based on the contributions to variations in grain yield represented by the total sum of squares, the genotype factor emerged as the most significant influencer, followed closely by soil amendment. Specifically, the value of partial eta-square (ηp^2) value of soil amendments, genotypes, and interaction indicates a large effect ($\eta p^2 > 0.13$) with value 0.74, 0.76, and 0.43, respectively.

Figure 4 illustrates the yield and absolute yield gap of each genotype in different soil amendments within rainfed agroecosystems. Significance levels are denoted by lowercase letters above the bars,

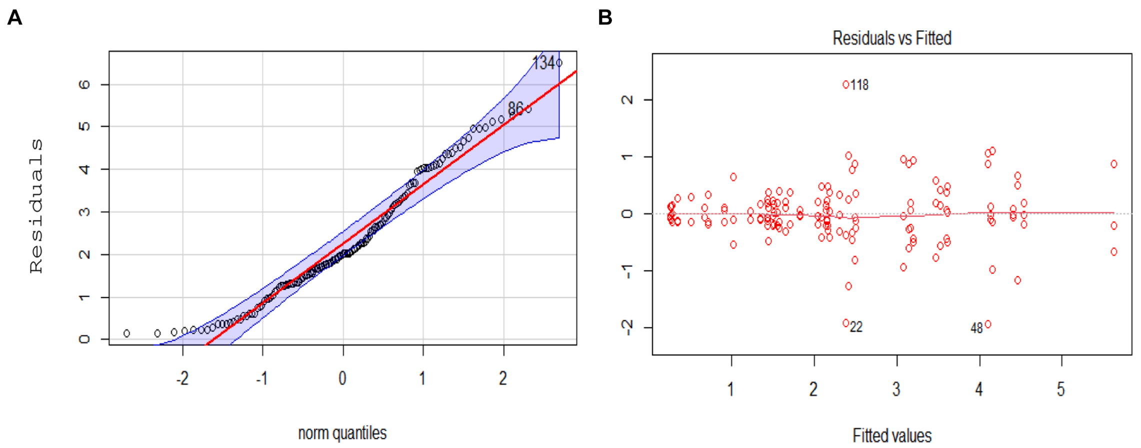

FIGURE 3
(A) Q–Q plot to evaluate the assumption of normally distributed variance; **(B)** Fitted value plot (residual against fitted value).

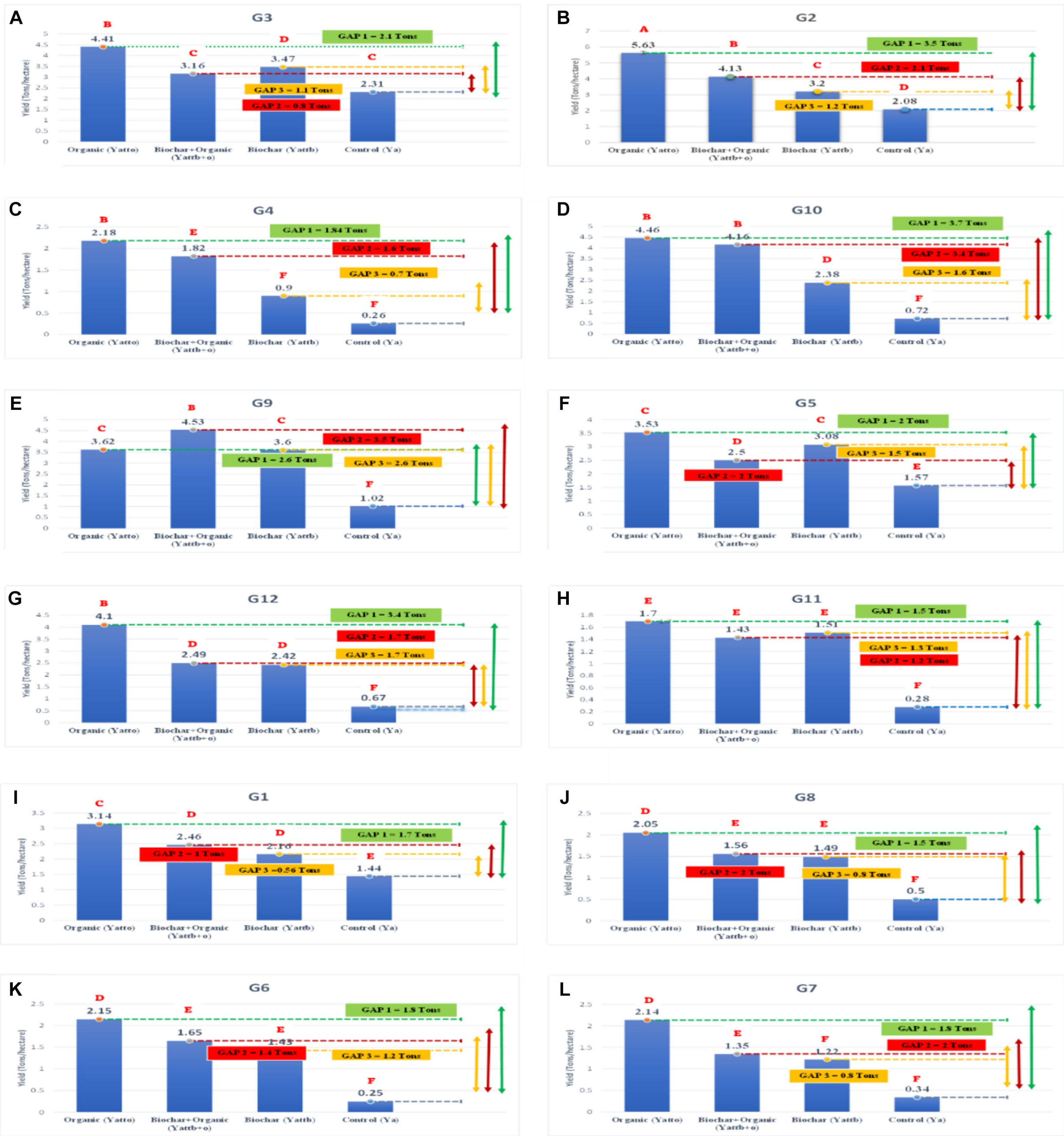

FIGURE 4
The yield and absolute yield gap of among genotypes **(A)** G3, **(B)** G2, **(C)** G4, **(D)** G10, **(E)** G9, **(F)** G5, **(G)** G12, **(H)** G11, **(I)** G1, **(J)** G8, **(K)** G6, **(L)** G7 in different soil amendment in rainfed agroecosystem. Different type lowercase letters above the bars indicated significantly different ($p < 0.05$, Scott-Knott grouping test).

indicating differences identified through the Scott-Knott grouping test. In general, most genotypes exhibited improved yields with the addition of biochar and organic fertilizer compared to the control. The best interaction was observed in G2 with organic treatment, displaying the highest yield at 5.63 tons/ha, surpassing other interactions (see Figure 3). Conversely, when clustered by genotypes, some of the lowest performances were observed in the control (without soil amendment) across most genotype interactions. Specifically, the interaction of control × G6 demonstrated the lowest yield, with a value of 0.25 tons/ha (see Figure 3). Further analysis revealed significant differences ($p < 0.05$) in yield values between organic and control, as well as between biochar + organic and control for each genotype. Meanwhile, biochar exhibited significantly different yields than the control for 10 genotypes, excluding G4 and G7. These results underscore the impact of soil amendments and genotype interactions on grain yield, providing valuable insights for optimizing agricultural practices in rainfed agroecosystems.

Moving on to Figure 5, it displays the absolute attainable yield gap between treatments, subdivided into GAP_1 ($Y_{atto\ organic}$ – Y_{ac}), GAP_2 ($Y_{attbiochar}$ + organic – Y_{ac}), and GAP_3 ($Y_{att\ biochar}$ – Yac). Each subfigure corresponds to a specific comparison, aiding in the assessment of yield differences across treatments. Based on the yield gap analysis

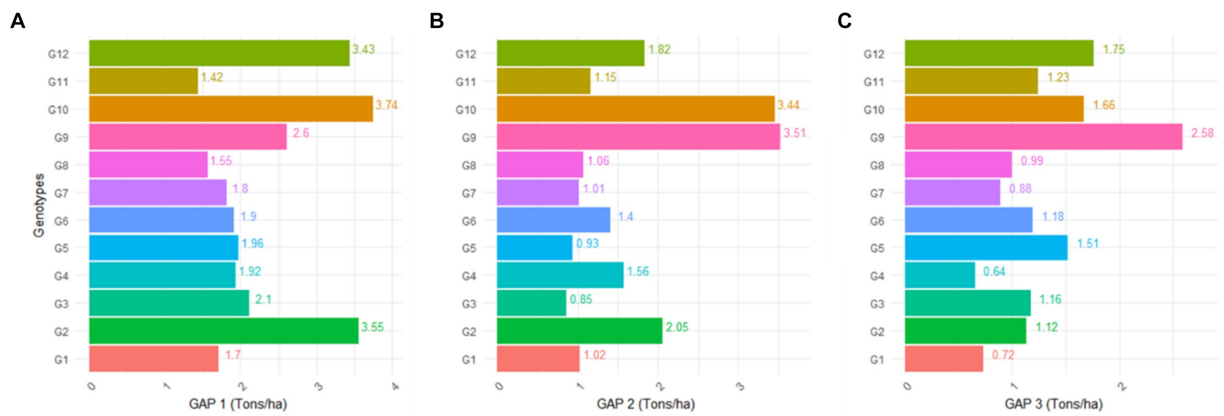

FIGURE 5
(A) The absolute attainable yield gap between each treatment was analyzed. GAP_1 (Yatto organic − Yac); **(B)** GAP_2 (Yattbiochar + organic − Yac); and **(C)** GAP_3 (Yatt biochar − Yac).

presented in Figure 5, it is evident that organic treatments consistently yielded the highest grain yields compared to biochar, biochar + organic, and the control, with the exception of G9. Specifically, the absolute attainable yield gap (GAP_1) between organic and control was observed across various genotypes, revealing substantial improvements. For instance, GAP_1 values were as follows for different genotypes: G1 (1.7 tons), G2 (3.55 tons), G3 (2.1 tons), G4 (1.92 tons), G5 (1.96 tons), G6 (1.90 tons), G7 (1.8 tons), G8 (1.55 tons), G9 (2.6 tons), G10 (3.7 tons), G11 (1.4 tons), and G12 (3.43 tons) (refer to Figure 3). The overall range for GAP_1, representing the absolute attainable or exploitable yield gap between organic (Yatto) and control (Ya), was found to be in the range of 1.5–3.7 tons across different genotypes or increasing of 91–580% than control.

The addition of biochar + organic also exerted a notable impact on paddy yield, surpassing the yield in the control for several genotypes. The yield of all genotypes demonstrated an increase with the application of this treatment. Specifically, among the different genotypes, the absolute attainable yield gap (GAP_2) between biochar + organic and control was observed as follows: G1 (1.02 tons), G2 (2.05 tons), G3 (0.85 tons), G4 (1.56 tons), G5 (0.93 tons), G6 (1.4 tons), G7 (1 ton), G8 (1.06 tons), G9 (3.51 tons), G10 (3.44 tons), G11 (1.15 tons), and G12 (1.82 tons). Importantly, the yield differences between biochar + organic and control were found to be statistically significant ($p < 0.05$) for all genotypes. Consequently, the range for GAP_2, representing the absolute attainable or exploitable yield gap between biochar + organic (Yattb + o) and control (Ya), was in the range of 0.8–3.5 tons across different genotypes or increasing of around 72–560%. Biochar demonstrated a positive impact on paddy yield compared to the control in select genotypes. The attainable yield gap (GAP_3) between biochar and control (Yatt biochar - Yac) for different genotypes was observed as follows: G1 (0.71 tons), G2 (1.12 tons), G3 (1.16 tons), G4 (0.64 tons), G5 (1.51 tons), G6 (1.18 tons), G7 (0.88 tons), G8 (0.99 tons), G9 (2.58 tons), G10 (1.66 tons), G11 (1.23 tons), and G12 (1.75 tons). The overall range for GAP3, representing the absolute attainable or exploitable yield gap between biochar (Yattb) and control (Ya), was found to be in the range of 0.6–2.58 tons across different genotypes or increasing around 58–472%. Furthermore, the yield differences between biochar and control were statistically significant ($p < 0.05$) in G6, G1, G8, G12, G5, G9, G10, G3, and G2. These results highlight the effectiveness of biochar in enhancing paddy yield in specific genotypes within rainfed agroecosystems.

A comprehensive view of the absolute yield gap for all combination treatments (soil amendment and genotype) can be observed in the absolute yield gap matrix (refer to Figure 6). Figure 6 presents the absolute yield gap matrix across environments (soil amendments) and genotypes. This matrix offers a comprehensive overview of yield gaps, facilitating comparisons between different combinations of soil amendments and genotypes. Specifically, the least yield gap was approximately 0.01 tons per hectare, while the largest gap reached 5.3 tons/ha. The most substantial yield gap was identified in the comparison between organic x G2 and control x G6, registering a value of 5.3 tons/ha. Analyzing all combinations of genotype and soil amendments based on the absolute yield gap matrix, G2 with organic soil amendments emerged as the most favorable combination. It exhibited a positive yield gap, averaging around 1.1–5.38 tons/ha, surpassing other combinations (refer to Figure 6). The second-best combination was biochar + organic and G9, with an average yield gap of approximately 0.07–4.28 tons/ha compared to others. Conversely, control × G6 and G4 were identified as the least favorable combinations, yielding around 0.25 tons per hectare and 0.28 tons/ha, respectively. This assessment is attributed to their negative absolute yield gap when compared with all other treatments.

3.2 Determination of genotypes that suitable in rainfed agroecosystem

To assess the information pertaining to the evaluation of genotype, environment, and their interactions, the GGE Biplot methodology was employed, presenting visual parameters for these indicators. The GGE-biplot in this research was displayed with four types, namely discriminative versus representative, mean versus stability performance, which-won-where pattern, and ranking genotypes (refer to Figure 5). Mathematically, the GGE biplot characterizes the singular values for the first principal component (PC1) and the second principal component (PC2) through the contribution of diversity (total eigenvalues) obtained from the Singular Value Decomposition

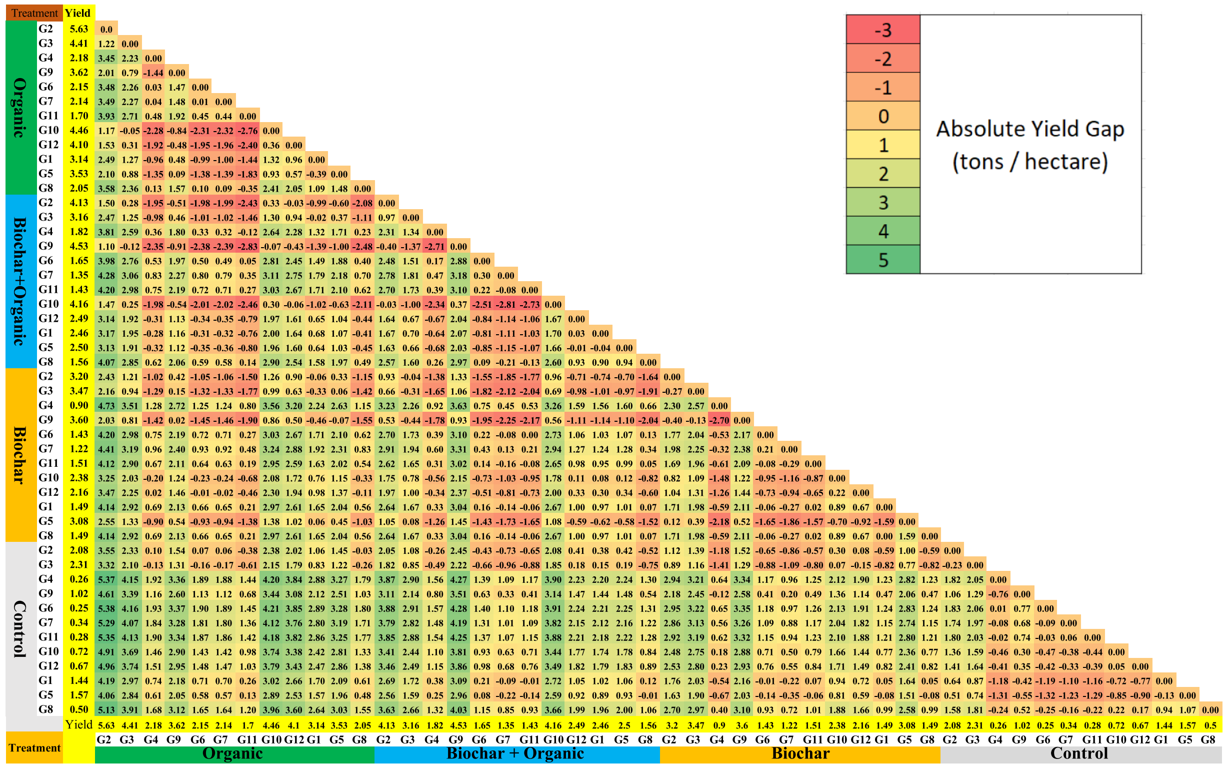

FIGURE 6
Absolute yield gap matrix across environment (soil amendments) and genotype.

(SVD) of environment-centered or environment-standardized genotype-by-environment data (GED). The total variation in genotype (G) and genotype-by-environment interaction (GxE) was captured by PC1 and PC2, accounting for 93.33% of the total G + GxE variation (PC1 + PC2). The PC1 score represents the yield of the lines, with PC1 > 0 indicating high-yield lines and PC1 < 0 indicating low-yield lines. On the other hand, the PC2 score reflects stability, with scores approaching zero indicating stable lines and vice versa. In short, genotypes G2, G3, G1, G5, G12, G9, and G10 can be classified as high-yield genotypes, as their PC1 values are greater than zero or their average yields surpass the overall average for all genotypes. Conversely, G4, G6, G7, G8, and G11 are categorized as low-yield genotypes due to their PC1 values being less than zero.

The "which-won-where" aspect of the GGE Biplot comprises an irregular polygon and a set of lines drawn from the biplot origin, intersecting each side at right angles (refer to Figure 7C). This representation reveals that G2 and G3 emerged as the most suitable genotypes in biochar and organic environments, demonstrating higher yields than others in these conditions. Additionally, G9 exhibited greater suitability in a biochar + organic environment, displaying the highest yield compared to other genotypes in that specific setting. Conversely, G4, G6, G7, G8, and G11 demonstrated poor performance across all environments, as indicated by the polygon vertices where no environmental indicators fall within that sector. This highlights the inadequacy of these genotypes in adapting to diverse environments and their suboptimal performance in comparison to other genotypes. The assessment of mean performance and stability in the GGE Biplot (refer to Figure 7B) is valuable in evaluating an ideal genotype, which should ideally exhibit both high mean performance and high stability within a mega-environment. The arrow sign on the Average Environment Coordinate (AEC) abscissa provides insight into the ranking of genotypes in increasing order. Based on the rank orders, G2, G3, and G9 emerged as the top three genotypes, displaying the highest mean performance. In contrast, G3 and G10 were identified as two of the least stable genotypes. Moreover, G2, G11, G12, G7, and G8 were recognized as the most stable genotypes in this research. This determination is based on their shorter lines near zero, indicating a higher level of stability across different environments.

The Discriminating Power vs. Representativeness analysis of GGE (refer to Figure 7A), or the evaluation of test environments, proves effective in identifying superior genotypes for mega-environments. In this context, biochar emerged as the most favorable environment for selecting superior genotypes, evident from its small angles with the AEC abscissa. On the other hand, biochar + organic and organic environments, characterized by long vectors and large angles with the AEC abscissa, were deemed suitable for eliminating unstable genotypes. Furthermore, based on the correlation, biochar and organic exhibited a stronger positive correlation compared to other environments due to the acute angle between them. This positive correlation implies that biochar and organic environments provided more similar information about the yield of genotypes. Consequently, this analysis aids in discerning environments that are better suited for identifying superior genotypes and those suitable for assessing stability in genotype performance. In this study, our study presented the ranking of genotypes based on the arrowed Average Environment Coordinate (AEC) abscissa and various concentric circles. The results revealed that some genotypes were positioned closer to the center of the concentric circles, while others were relatively distant from the origin of the circles. Notably, among the genotypes, G2 held a central

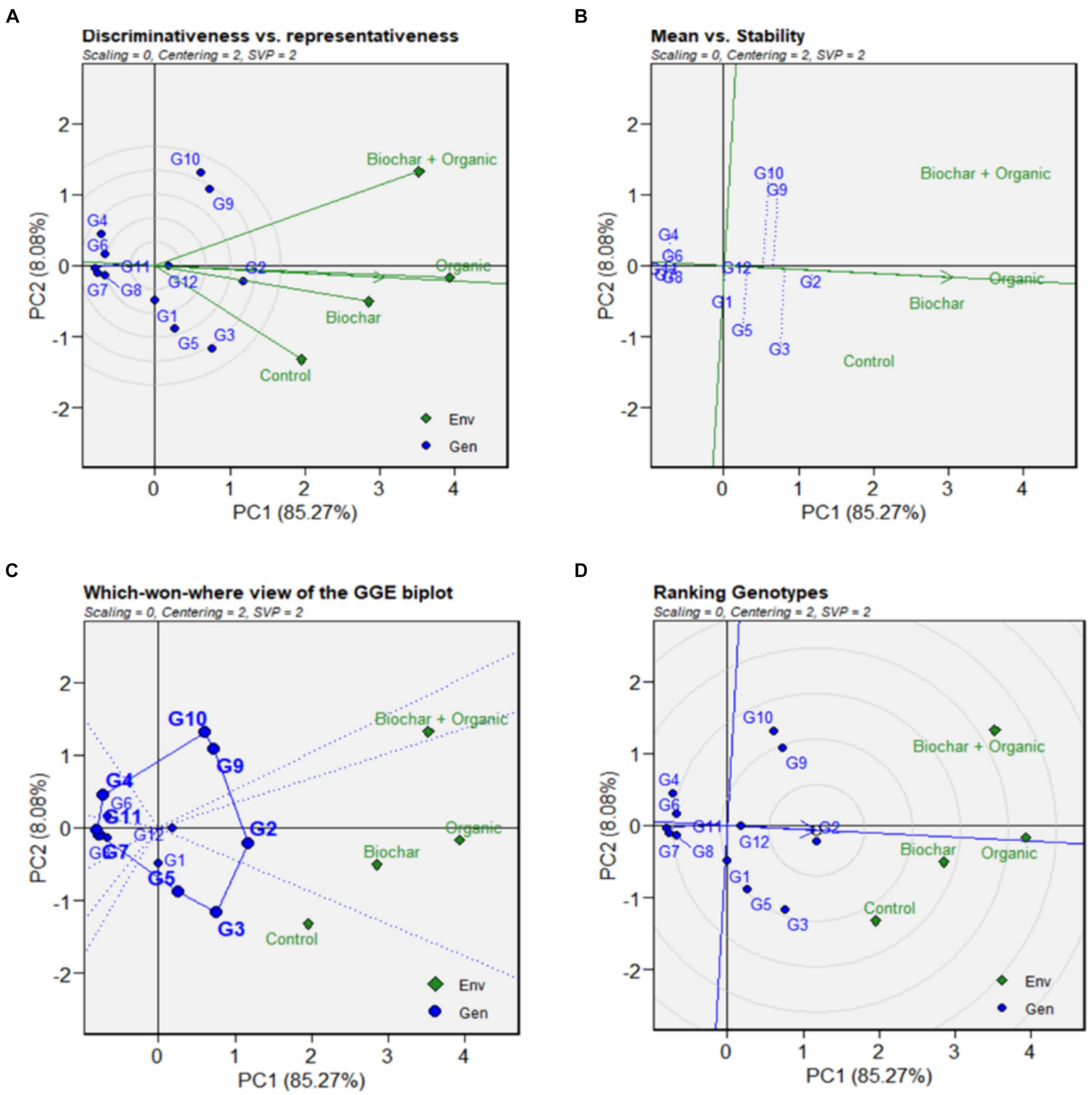

FIGURE 7
(A) GGE-Biplot visualization consisting of discriminative versus representative; **(B)** mean versus stability performance; **(C)** which-won-where pattern, and **(D)** ranking genotypes.

position near the center of the concentric circles, followed by G12, G3, G5, G1, and G9 (refer to Figure 6). Conversely, G4, G6, G7, and G8 were situated farther from the center of the concentric circles. In this context, G2 in the research can be considered as an exemplary cultivar., representing the ideal genotype with the highest yield and stability compared to other cultivars. This ranking provides valuable insights for selecting genotypes that exhibit a desirable balance of high mean performance and stability across different environments.

4 Discussion

Soil modification through the application of biochar and organic fertilizer emerges as a viable alternative to enhance paddy yield in rainfed conditions (Rassaei, 2022, 2024). Rainfed areas typically include critical zones vulnerable to water insufficiency, posing challenges to the growth and yield of plants. Cultivating paddy in such lands can detrimentally impact growth, development, and overall yield (Boonwichai et al., 2019). The observed improvement in paddy yield in this research can be attributed to the addition of biochar and organic fertilizer. The distinct values of absolute yield gap for each interaction highlight the significant influence of soil amendment management on paddy yield performance. The range values of GAP_1, GAP_2, and GAP_3, representing the absolute attainable yield gaps, are within the ranges of 1.55–3.74 tons, 0.85–3.51 tons, and 0.64–2.58 tons, respectively (refer to Figures 2, 3). This underscores the substantial impact of soil amendment practices on enhancing paddy yield in rainfed agroecosystems.

4.1 Absolute yield gap using organic fertilizer and biochar in tested genotypes

The yield variations observed across all genotypes underscore the impact of different soil amendments. Notably, the application of organic fertilizer consistently yielded the highest response in most genotypes, suggesting that organic amendments may enhance genotypes' ability to reach their yield potential more effectively than other amendments. Additionally, the addition of organic fertilizer significantly differed ($p < 0.05$) from the control in all genotypes (refer to Figure 4). Among all combinations, organic fertilizer demonstrated the highest yield for genotypes G1, G2, G3, G4, G5, G6, G7, G8, G10, G11, and G12, with values ranging from approximately 3.14 tons/ha to 5.63 tons/ha (refer to Figures 4, 5). Moreover, the absolute attainable yield gap with organic fertilizer exhibited the highest values for these genotypes (refer to Figure 5). The influence of organic fertilizer in improving yield is further highlighted by its longer vector in the GGE biplot analysis, indicating its higher impact compared to other environments (refer to Figure 7). Previous research has also shown yield improvements in paddy using organic fertilizer. For instance, the use of *Chromolaena odorata* (siam weed) compost (SWC) at 10 tons/ha resulted in the highest upland rice yield of 2.97 tons/ha, a 91.75% increase compared to the control without SWC (Suryanto et al., 2020a). Similarly, the application of livestock waste fertilizer (sewage sludge) increased plant productivity by up to 300%, reaching 6 tons/ha, compared to the control without sewage sludge, which yielded 2 tons/ha (Jatav et al., 2022). Considering genotype characteristics, previous studies have suggested that the yield performance of certain genotypes, such as G3 (GM 2), G2 (GM 28), and G11 (Inpari 33), is influenced by soil moisture content (Suryanto et al., 2020b). These genotypes have been observed to exhibit varying degrees of resilience and adaptability to environmental conditions, particularly in rainfed agroecosystems. In the current research, G2 emerged as particularly noteworthy, demonstrating remarkable suitability for organic environments. Notably, G2 displayed the highest yield and stability compared to other genotypes, as evidenced by its consistent performance across different soil amendments (refer to Figures 7B,D). This robust performance underscores the importance of genotype selection and adaptation to specific environmental conditions, highlighting the potential for optimizing agricultural productivity through targeted breeding programs and crop management strategies.

In this research, the utilization of organic fertilizer in the soil significantly improved the yield ($p < 0.05$). The positive impact of organic fertilizer on soil and crops is attributed to various mechanisms observed in previous studies. The application of organic fertilizer has been shown to enhance soil quality by increasing soil organic matter and influencing soil physical and chemical properties through mineral decomposition (Assefa and Tadesse, 2019). Additionally, (Pandey and Shukla, 2006) demonstrated that organic fertilizer application can increase soil moisture content by more than 3% compared to control conditions. Research by (Pagliai et al., 1981) indicated that applying 50 tons of sewage sludge organic fertilizer per hectare could significantly increase soil porosity by more than 50%, thereby enhancing the soil's water retention capacity. Moreover, organic fertilizer has been found to positively impact plant water status and proline content. Ye et al. (2022) reported a 94.20% increase in the relative water content of pear plants with the use of organic fertilizer compared to conditions without organic fertilizer. In terms of proline content, (Alinezhad et al., 2013) demonstrated that organic fertilizer application reduced proline content in drought-stressed barley plants by 30%. Additionally, (Duo et al., 2018) showed that nano compost and microbial inoculation under severe drought stress conditions could decrease proline content by more than 20% in *Festuca arundinacea*. Overall, the findings highlight the multifaceted benefits of organic fertilizer, including its positive impact on soil properties, moisture retention, and plant water status, ultimately contributing to improved crop yield.

The yield increased with the addition of biochar + organic fertilizer combinations. The absolute attainable yield (GAP_2) values for G1 to G12 were approximately 1.02 to 3.51 tons/ha. Overall, the absolute attainable yield with biochar + organic fertilizer was lower than organic fertilizer alone, indicating that the lower dosage of organic fertilizer in combination with biochar had a lesser impact on yield. Biochar primarily functions in nutrient transformation rather than providing nutrients to the soil (DeLuca et al., 2015). Research by (Schulz and Glaser, 2012) demonstrated that compost yielded 10% more tomato biomass compared to biochar when applied in the same amount (5% of soil weight). Moreover, the yield of genotypes with the addition of biochar alone improved, although to a lesser extent compared to organic and biochar + organic treatments. The yield increase (GAP_3) for G1 to G12 ranged from 0.72 to 2.58 tons/ha compared to the control (Figure 3C). Previous research has also demonstrated increased paddy yield with the application of biochar. Singh et al. (2018) reported that 10 tons/ha of RHB can increase tiller number and yield by over 50% in nutrient-poor agricultural soils. Additionally, (Dong et al., 2015) observed that rice straw biochar enhances paddy yield in waterlogged conditions.

The mechanism through which biochar improves soil conditions and enhances crop yield in rainfed areas involves physical, chemical, and biological amendment indicators, as observed in previous research. Biochar, produced through the pyrolysis process from carbon-based feedstock, plays a crucial role in the soil ecosystem. Biologically, its application fosters a conducive environment for soil microbial communities (Zhu et al., 2017). The two most commonly biological communities of mycorrhizal fungi arbuscular (AM) and ectomycorrhizal (EM) are often positively affected by biochar presence (Warnock et al., 2007). Specifically, Arbuscular mycorrhizal fungi (AMF) have demonstrated that AMF can improve the growth of host plants by promoting nutrient and water uptake to alleviate in drought stress condition (Bowles et al., 2018). Furthermore, these microbes can explore soil pores with the root hair to access water and nutrient sources (Li et al., 2019). On physically effects, biochar addition can reduce the overall tensile strength of the soil which therefore make root nutrient mining more effective, as well as allow seeds to germinate more easily as well as invertebrates to move through the soil easier (Lehmann et al., 2011). Moreover, biochar positively influences soil water retention due to its unique structure, characterized by a high internal surface area and numerous pores (Ghodake et al., 2021). Studies by Varela Milla et al. (2013) demonstrated that the addition of 0.5 kg of biochar per cubic meter of soil increased soil moisture content by 5%. Additionally, Wang et al. (2019) found that adding

1 gram of walnut shell biochar to 1 kilogram of soil increased water field capacity by approximately 20% in sandy loam soil. On chemical properties on soil, biochar can improve the electrochemical properties of the roots and thereby increase nutrient absorption by crops. Electrochemical properties of roots in the form of zeta potential and cation exchange capacity play an important role in the absorption of nutrients by plants and adding 25 g biochar to 1 kg of soil can amend electrochemical properties of roots, nutrients absorption, and growth parameters of safflower and mint (Farhangi-Abriz and Ghassemi-Golezani, 2023). The positive effects of biochar on water retention in soil also extend to plant water status and proline levels under drought stress conditions Akhtar et al. (2014) reported that increased water holding capacity (WHC) in soil due to biochar application enhanced leaf relative water content (RWC) in tomatoes subjected to deficit irrigation. Moreover, the application of biochar led to a reduction in proline content in various plants, including *Quercus castaneifolia* seedlings (Zoghi et al., 2019), *Rosmarinus officinalis* (Kasmaei et al., 2019), and perennial ryegrass (*Lolium perenne L.*) (Safari et al., 2023).

In the context of national production, the combination of specific genotypes and soil amendments demonstrated in this study holds significant promise for implementation in rainfed areas. Particularly noteworthy is the potential for these combinations to surpass the average national yield of 3.7 tons/ha, as reported by Statistics Indonesia (2021). This suggests that the findings of our research have practical implications for enhancing agricultural productivity and sustainability at the national level. Notably, combinations such as G2 + organic, G3 + organic, G10 + organic, G9 + biochar + organic, and G12 + organic exhibited yields surpassing the national average (Figure 2). Among these, G2 + organic emerged as the most favorable combination, displaying both high yield and stability across environments (Figures 4, 6, 7B,D). While G9 and G10 exhibited high yields, their stability warrants further investigation over the long term (Figure 5B). The yield gap analysis conducted in this research emphasizes the potential of soil management technologies in enhancing paddy productivity in rainfed areas. Moreover, organic treatment consistently resulted in the highest yields across genotypes compared to other treatments, except for G9. Conversely, the control treatment, representing conventional farmer practices without soil amendments, showed the lowest yields. This underscores the importance of incorporating soil amendments in rainfed agroecosystems to maintain ecological functions and enhance paddy yields over the long term. The long-term use of chemical fertilizers by farmers, leading to decreased soil organic matter, soil organism populations, soil compaction, and increased soil acidity, likely contributed to reduced yields (Pahalvi et al., 2021). Through identifying genotypes and soil amendments that can outperform the national average yield, our study offers valuable insights for policymakers, agricultural practitioners, and stakeholders seeking to improve agricultural outcomes in rainfed agroecosystems. Moreover, the adoption of these optimized combinations has the potential to contribute to food security, economic development, and environmental sustainability efforts on a broader scale. However, further validation and field trials are warranted to confirm the scalability and replicability of these findings across diverse agroecological contexts and farming systems. Through continued research and collaborative efforts through exploring additional soil amendments, assessing the long-term effects of different treatments, and investigating interactions between soil, genotype, using inhibitors, and environmental factors can leverage the findings of this study to advance sustainable agricultural practices and address the challenges of food production in rainfed areas more effectively (Yoshida and Horie, 2010; Yoshida et al., 2011; Lin et al., 2021, 2022a,b).

Developing paddy cultivation in rainfed areas presents numerous challenges associated with climatic variability (Boer et al., 2004; Naylor et al., 2007). The growth of paddy crops is inherently dependent on dynamic rainfall patterns, which vary annually and significantly impact yield outcomes (Ansari et al., 2021, 2023). Furthermore, it is essential to recognize that in this study, factors such as water evaporation and transpiration were not explicitly accounted for, which could provide valuable additional data to support yield assessments. Moving forward, it is imperative to incorporate comprehensive variables related to climatic conditions and soil water dynamics, including soil relative humidity, water evaporation, and transpiration rates (Ansari et al., 2019). Through integrating these factors into our analyses, this research can achieve a more precise and comprehensive understanding of paddy yield dynamics in rainfed agroecosystems (Alam et al., 2022).

The current study reveals several evident limitations that warrant discussion. Firstly, our focus on paddy yield measurements, while informative, represents a partial examination of crop performance. Regrettably, our analysis did not extend to encompassing crucial aspects of growth and physiology, such as leaf area, proline levels, chlorophyll content, and other physiological parameters. This oversight is noteworthy considering existing research that highlights correlations between these physiological factors and yield outcomes. Thus, the absence of such comprehensive physiological assessments in our study may restrict the depth of understanding regarding the mechanisms driving yield variations in response to soil amendment treatments. Secondly, the limitations of our study are compounded by constraints in water measurement conditions. Water dynamics, including absorption rates, crop water content, evaporation rates, and transpiration rates, exert significant influences on paddy growth and yield. However, our research did not thoroughly investigate these parameters, potentially overlooking critical factors affecting crop performance. Recognizing the importance of water management in agricultural productivity, future investigations should strive to incorporate more comprehensive assessments of morphological and physiological parameters of paddy plants, along with detailed analyses of soil water conditions. Through addressing these limitations and broadening the scope of inquiry, future research endeavors can contribute to a more nuanced understanding of the complex interactions between soil amendments, water dynamics, and crop performance in rainfed agroecosystems. Despite these limitations, our findings offer valuable insights into the potential of soil amendments to address the challenges of low productivity in rainfed conditions. Specifically, our research highlights the efficacy of biochar and organic fertilizer as alternative solutions for enhancing paddy yield in rainfed environments characterized by numerous agronomic and climatic constraints. By exploring innovative approaches such as soil amendment strategies, we can effectively mitigate the adverse impacts of climatic variability and optimize agricultural productivity in rainfed areas. These findings contribute to the ongoing dialog surrounding sustainable agriculture practices and offer tangible solutions to enhance food security and livelihoods in rainfed regions. The application of biochar and organic fertilizer has demonstrated promising outcomes in enhancing paddy yields within rainfed agricultural systems. However, it is essential to recognize that the effectiveness of these treatments may vary significantly across different environmental contexts. This variability stems from a complex interplay of integrated factors, including soil fertility, climatic conditions (especially rainfall intensity), and the genetic characteristics of paddy varieties. Consequently, it is imperative to conduct further comprehensive research across diverse environmental settings to fully understand the nuanced effects of these soil amendments by conducting studies in various environments to elucidate how different soil and climatic conditions interact with treatment applications, thereby refining our understanding of optimal agricultural practices for sustainable paddy cultivation.

5 Conclusion

In conclusion, our research underscores the substantial positive impact of soil amendments, particularly organic and biochar + organic treatments, on enhancing paddy yield in rainfed agroecosystems. Through rigorous analysis, we have identified significant absolute attainable yield gaps across different treatments, ranging from 1.5 to 3.7 tons/ha or an increase of 91 to 580% for GAP1, 0.8 to 3.5 tons/ha (72 to 560%) for GAP2, and 0.6 to 2.58 tons/ha (58 to 472%) for GAP3. These findings highlight the remarkable potential of targeted soil management strategies to substantially increase paddy yield in rainfed conditions. Of particular note is the outstanding performance of G2 with organic fertilizer amendments, which demonstrated a positive absolute yield gap and an average yield improvement of 1.1 to 5.38 tons/ha compared to other treatments. This underscores the effectiveness of organic amendments in boosting productivity and underscores the importance of selecting appropriate genotypes for specific soil environments. Moreover, our GGE biplot analysis reinforces these results by emphasizing the suitability of certain genotypes for specific soil environments. Notably, G2 and G3 excel in biochar and organic environments, respectively, while G9 shows exceptional performance in biochar + organic conditions. By evaluating genotypes based on both mean performance and stability, we have identified G2 as the top-performing genotype, providing valuable insights into cultivar selection for rainfed conditions. Overall, our study underscores the critical importance of sustainable soil management practices in optimizing paddy yield for long-term agricultural productivity in rainfed areas. Through leveraging the positive outcomes observed in this research, we can further advance our understanding and implementation of sustainable agricultural strategies, ultimately contributing to enhanced food security and livelihoods in rainfed regions. Additionally, future research efforts should explore additional soil amendments, investigate genotype-environment interactions in more detail, adding the substance to reduce GHG emissions, and assess the long-term sustainability of implemented soil management practices to continuously improve agricultural productivity in rainfed areas.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

YS: Conceptualization, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. BK: Methodology, Supervision, Writing – review & editing, Validation. TA: Data curation, Investigation, Validation, Writing – review & editing. SH: Data curation, Formal analysis, Investigation, Methodology, Writing – review & editing. Supriyanta: Data curation, Investigation, Methodology, Supervision, Writing – review & editing. AA: Data curation, Investigation, Software, Supervision, Validation, Writing – review & editing. Taryono: Conceptualization, Funding acquisition, Supervision, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. The authors thank the Agrotechnology Innovation Center of Universitas Gadjah Mada, which has provided facilities to support this research. This research is supported by Universitas Gadjah Mada through Final Project Recognition Grant Universitas Gadjah Mada Number 5075/UN1.P.II/Dit-Lit/PT.01.01/2023.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2024.1384530/full#supplementary-material

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frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 01 November 2024
DOI 10.3389/fsufs.2024.1393863

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OPEN ACCESS

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RECEIVED 29 February 2024
ACCEPTED 12 August 2024
PUBLISHED 01 November 2024

CITATION
Zeleke G, Kassawmar T, Tadesse M, Teferi E, Girma A, Anteneh Y, Gelaw F, Walsh CL and O'Donnell's G (2024) Dynamics in smallholder-based land use systems: drivers and outcomes of cropland–eucalyptus field–cropland conversions in north-west Ethiopia. *Front. Sustain. Food Syst.* 8:1393863. doi: 10.3389/fsufs.2024.1393863

Dynamics in smallholder-based land use systems: drivers and outcomes of cropland–eucalyptus field–cropland conversions in north-west Ethiopia

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During the last two decades, smallholder farmers in north-western Ethiopia have expanded eucalyptus fields into large areas of croplands until they recently started to reverse that trend. This study assessed the extent, drivers, and impacts of cropland to eucalyptus plantation changes during the 2000–2023 period and the recent land use reversal eucalyptus to cropland. It also analyzed the effect of the shift on land productivity and food security by comparing maize yields obtained from eucalyptus-cleared fields with those from permanent croplands. The assessment was conducted in the north-western highlands of Ethiopia and employed remote sensing techniques, yield difference comparisons, focus group discussions, and key informant interviews. Landsat-and Sentinel 2A-based multi-temporal image analyses were used to identify and map the coverage of eucalyptus plantation since 2000. Maize yield per plot was collected from 125 systematically selected paired 2mX2m plots, and yield differences were compared. One of the paired plots represented eucalyptus-cereal field changes, while the second represented cropland-maize plots. The multi-temporal image analysis result showed that eucalyptus plantation coverage was increased from 1000 ha in 2000 to 249,260 ha in 2023. Approximately 98% of that expansion was made onto crop fields. Latter, a large portion of that area was reconverted to cropland, mainly maize field due to substantial falls of market demand for eucalyptus logs. The oscillating land use changes imply that smallholders' land use decisions are informed by intrinsic and extrinsic economic considerations, not by scientific-evidence-based landscape suitability and ecological analyses. Moreover, to check the effects of eucalyptus on subsequent productivity of croplands, we compared maize yield differences between cropland-maize and eucalyptus-maize field plots. The yield comparison result showed 35% average yield increment from eucalyptus-maize plots than yields from cropland-maize plots. This finding tends to defy the widely held perception that 'growing eucalyptus tree plants on farmlands negatively affects the subsequent productivity of those plots'. However, this finding was based on a 1-year cross-sectional data. Further cross-sectional studies are important to arrive at conclusive results on the impacts of eucalyptus trees on productivity of those plots when converted to croplands.

KEYWORDS

cropland, eucalyptus plantation, food security, land use change maize yield, north-western Ethiopia, smallholder farmers' perception, land use systems

1 Introduction

Unsustainable land use and cropping system is one of the direct drivers of land degradation. For example, in Ethiopia, ample scientific evidences shows that inappropriate land use practices aggravate natural resource degradation (Zeleke and Hurni, 2001). Among the various land use systems planting eucalyptus trees has continued being a controversial issue for decades (Daba, 2016; Jaleta et al., 2016). Since the introduction of eucalyptus trees, Ethiopia's smallholder farmers have been planting eucalyptus previously on marginal landscapes (Alemayehu and Bewket, 2018) and in recent past on fertile croplands as well. The contribution of the tree in fulfilling firewood energy and construction demands of the population is tremendous (Dessie et al., 2019; Khanna, 1997; Kassa et al., 2022; Alebachew et al., 2015). In addition, its ecological importance in restoring degraded landscapes makes the plant an extraordinarily important species (Mulugeta, 2014; Pistorius et al., 2017; Tchichelle et al., 2017; Alemayehu et al., 2023; Michelsen et al., 1993; Jagger and Pender, 2003). In the highlands of Ethiopia, eucalyptus species (*Eucalyptus camaldulensis* and *Eucalyptus globulus*, hereafter referred to as Eucalyptus) are commonly integrated into the various farming systems, and their planting has resulted in high economic profitability compared with agricultural use of land for crop production (Lemenih et al., 2004). Partly as a result of this, over the past 2.5 decades, in some parts of the highlands of Ethiopia, a considerable increment in man-made forestry has been witnessed (Michelsen et al., 1993; Haregeweyn et al., 2012; Jagger and Pender, 2000; Jenbere et al., 2012; Melaku, 2021; Alemayehu and Melka, 2022). Particularly, in the northwest and central highlands of Ethiopia, an increasing trend in eucalyptus plantation has been reported (Alemayehu et al., 2023; Michelsen et al., 1993). That increase was achieved largely by converting croplands into eucalyptus woodlots (Alemayehu and Bewket, 2018).

Since the introduction of eucalyptus trees in the area, planting this exotic tree species around homesteads has been a common practice in West Gojam Zone (Alemayehu and Bewket, 2018; Melaku, 2021; Zerga et al., 2021; Mekonnen et al., 2007). Particularly, since 1985, when the government of Ethiopia was providing eucalyptus seedlings to farmers, the tree had been planted on non-cultivated and degraded landscapes for landscape restoration purposes (Kassa et al., 2022; Pistorius et al., 2017; Sang et al., 2023). The north-western part of Ethiopia, particularly part of the then West Gojam Zone, now North Gojam Zone, is renowned for growing eucalyptus trees for commercial purposes (Alemayehu and Bewket, 2018; Alemayehu et al., 2023). The communities in the study areas also plant eucalyptus along farm boundaries and the main road. They prefer eucalyptus because of its fast growth and high economic return though they are aware of the alleged myths that eucalyptus leads to the exhaustion of productive lands (Chanie et al., 2013). The nature and trajectories of land use systems related to eucalyptus plant have been so dynamic and unpredictable (Alemayehu and Bewket, 2018; Forrester et al., 2006; Asefa et al., 2020). The tree has become main source of hard currency (after 2005), and hence, during the last 2.5 decades, farmers have been aggressively planting eucalyptus on cereal fields, resulting in decline of grain yields (Jaleta et al., 2016; Alemayehu et al., 2023).

The uncontrolled expansion of eucalypts into productive farmlands has raised great concerns as eucalypts is blamed to have detrimental effects on soil fertility and land productivity (Daba, 2016; Jaleta et al., 2016; Forrester et al., 2006; Forrester et al., 2010). Most of the previous studies focused on space computation of the tree area coverage and its detrimental impacts on crop growth and yield (Jagger and Pender, 2003; Jagger and Pender, 2000; Matocha et al., 2003). Those studies are informed by the long-term deterioration of land fertility allegedly caused by eucalypts (Jaleta et al., 2016; Tesfaw et al., 2022) after the tree is planted in or close to farmlands, which some also argue that expansion of eucalyptus at the expense of croplands may cause crises in the food system, a condition triggered by upcoming competitive land use systems (Harvey and Pilgrim, 2011).

Nevertheless, there is no sufficient scientific evidence regarding those allegations against eucalyptus trees. While findings of some studies (Alebachew et al., 2015; Matocha et al., 2003; Yitaferu et al., 2013; Tadele and Teketay, 2014) did not say much about the adverse effects of eucalyptus, several other studies revealed the negative impacts of the tree on the environment. For example, Turner and Lambert (2000) reported soil nutrient exhaustion in plots planted with eucalyptus trees as compared to adjacent native forests in south-eastern Brazil. Similar researchers (Jagger and Pender, 2003; FAO, 2007; Chanie et al., 2013; Kidanu et al., 2004; Kidanu et al., 2005) documented negative effect of eucalyptus on neighboring crops. Tchienkoua and Zech (2004) reported proper rotation of crop lands with Eucalypts can improve soil productivity as the roots of the tree grow down to the very deep soil horizons and pull up or translocate leached down soil nutrients from the depth that otherwise is unreachable to most cereal crops (Chanie et al., 2013).

Considerable other studies reported the positive impact of eucalyptus tree species on soil health and grain yield. For example, according to Yitaferu et al. (2013), higher soil nutrients, grain yield, and organic carbon were obtained from crops grown in the clear-felling eucalyptus stands as compared to continuously cultivated crop lands (Yitaferu et al., 2013; Tchienkoua and Zech, 2004). The findings of several other studies argued that eucalyptus is a resilient tree that helps in effectively restoring degraded forests (Alemayehu and Bewket, 2018; Jagger and Pender, 2003; Lemenih et al., 2004; Jagger and Pender, 2000; Mekonnen et al., 2007) as it slows erosion and retains soil moisture. In Ethiopia, compared to many other tree species, eucalyptus has been reported as one of the best tree species to sink carbon proportional to its biomass (Tchienkoua and Zech, 2004; Ghaley et al., 2014).

Some literature also reported the economic benefits of the tree. For example, a study by Feyisa et al. (2018) found that income generated from eucalyptus was higher than income generated from cereal crops and contributed more than 50% of incomes to some households in the areas they studied (Jagger and Pender, 2000; Feyisa et al., 2018; Nasrallah et al., 2020). This economic consideration appears to be the main justification for the continued expansion of the tree and wide adoption by smallholder farmers who used to convert their fertile croplands to eucalyptus fields. A study by El-Khawas and Shehata (2005) strongly argued that implementing a rotation LUS between crop and eucalyptus is an efficient land management practice in terms of both economic and ecological values, but they also share the insight that the impacts of eucalyptus trees are governed by numerous and multifaceted factors that include time and space (location/site), species type, management (planning and tending operations) activities, etc. (El-Khawas and Shehata, 2005).

Recently, research revealed new insights about the root causes of the controversy abounding the ecological impacts of eucalyptus trees. The higher grain yield obtained from plots that were previously planted with eucalyptus than from plots which were continuously harvested with cereal crops is likely associated with soil niches that can be tapped up by the deep root system of the plant in the previous periods (Chanie et al., 2013; Alem et al., 2010). However, this has to be accepted with utmost caution as the revers could also be true depending on several factors. Thus, it requires further research to draw a valid conclusion.

On top of those contradictory findings about the effects of the plant, political instability in the neighboring Eritrea and Sudan and the intense internal civil war as of 2020 diminished the external market outlets and caused substantial falls in demand for and price of eucalyptus logs. Due to those drivers, since 2019/20, farmers in the North western part of Ethiopia farmers started converting eucalyptus plantations into cereal fields. By the time of data collection in 2023, farmers were aggressively clearing eucalyptus stands and converting those fields into croplands. Such changes in land use decisions are now commonly observed in the central and north-western parts of Ethiopia, mainly in North Gojam Zone, particularly the eucalyptus hotspot plantation area stretching from Bahir Dar City to some 100kms to the south west, the road crossing Durbete to Meshenti towns. Considering these land use dynamics, the authors conducted a research aiming to measure the rate, drivers, and outcomes of and the land use changes and assess their economic (measured in terms of yield) landscape/ecological implications.

Regarding research gaps, previous studies, which are pegged around the contested and contradictory findings about the tree, have the following major gaps: (i) they lack spatially explicit facts generated at a required scale (time and space); (ii) they made inaccurate estimates of the impacts as they did not draw data at required spatial scale; (iii) they lack emphasis on the dynamics of eucalyptus tree interaction with other land use systems; (iv) they lack comprehensive evaluation of trade-offs and complementarities of land use systems; and (v) they superficially implicate eucalyptus tree without accurate cause–effect assessments. Factual knowledge about the tree can only be generated through a comprehensive study that properly considers these multifaceted gaps relating to the ecological, economic, social, and political impacts of Eucalyptus. The present study took these research gaps as research questions and further examined the dynamics, state, pressure, drivers, and impacts of land use changes from crop fields to eucalyptus plantation and from eucalyptus plantation back to cropland.

The study specifically aimed to (1) identify and map the spatiotemporal dynamics of eucalyptus tree plantation and land use change since 2000; (2) examine the nature and drivers of the change and determine interactions of eucalyptus planation and other land use systems over the last two decades; (3) examine the impacts of land use changes; and Alemayehu and Bewket (2018) assess the gains and trade-offs of land use changes from eucalyptus plantation to maize production and the repercussions of the land use changes on the food systems, mainly food security at household level.

The present study has several scientific contributions among others, Zeleke and Hurni (2001) generates triangulated and credible evidence about the land use dynamics and impacts of eucalyptus trees; Daba (2016) makes important methodological contribution combining spatial and non-spatial methods; and Jaleta et al. (2016) clears confusions regarding the effects of eucalyptus plantations on water and soil are more of mythological than empirical.

2 Materials and methods

2.1 The study area

The study was conducted in smallholder-based mixed farming system in the highlands of Ethiopia. Specifically, among the eucalyptus conquered agricultural landscapes, the present study was conducted in North Gojam Zone of Amhara National Regional State, Ethiopia, considering 15 km buffer radius along the Dangila-Meshenti stretch, where dynamic conversion of crop fields to eucalyptus plantations and recently back to cereal fields (see Figures 1, 2).

Particularly, hotspot area where there is a recent and active conversion of eucalyptus lands back to cereal fields was vital. Furthermore, to understand the dilemma of eucalyptus and later linking the drivers, causes, and implications of a sudden land use conversion on the socio-ecological environment, hotspots were carefully selected for detailed analysis. Among the eucalyptus conquered agricultural landscapes, the north-western part of Ethiopia, particularly, the North Gojam Zone, was selected as a case study area for the present assessment. Very specifically, within the West Gojam Zone, authors took a 15 km buffer radius along the Dangila-Meshenti stretch (Figure 1). Geographically, the extent of the study area ranges between 1,235,069 m to 1,274,457 m North and 25,6234 m to 308,414 East (Figure 1).

The landscape is typically a floodplain characterized by a Nitisol. The main rainy season extends from mid-June to mid-September with maximum rainfall occurring between July and August. The mean annual rainfall is approximately 1,560 mm, and the mean annual temperature is approximately 20°C. Observation and reports from the zonal agriculture office show that the major land use system of the study area is annual crop production mainly cereal-based cropping system followed by pasture and woodlots (see photographs below). Within the 15 km stretch, four clusters of the study fall in four districts of the study zone, namely, South Mecha, South Achefer and Dangila.

The communities living in the study area are smallholders, who operate their fragmented and patched plots using the traditional method of farming with oxen-traction plows. As the landscape is largely flat, with deep red soils, it is suitable for various crops. However, since 2000, when timber service of eucalyptus trees became popular, planting eucalyptus trees around homesteads and cultivated landscapes became a common practice. Following massive plantation of the tree on previous croplands, eucalyptus woodlots become a big commodity in market outlets around and abroad. The major cross-border market outlets are Sudan and indirectly to Eritrea.

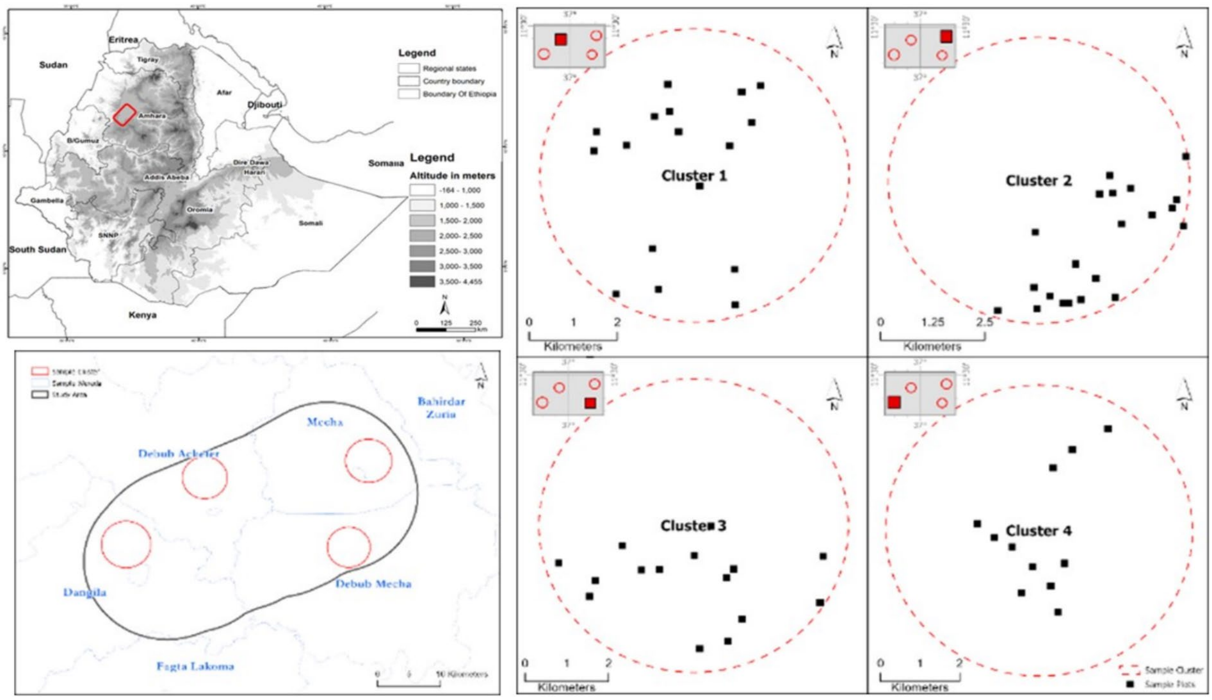

FIGURE 1
Location and clusters of the study area.

FIGURE 2
Peculiar mixed cropping system in a smallholder-based farming system. Farmers harvest dried maize crop grown in crop fields recently converted from eucalyptus plantation (center) and maize with pepper plots of a household (bottom left) and recently eucalyptus rotated cropping system. *Photo credit:* Alexander (2023).

2.2 Study approach

In smallholder-based mixed farming system, dynamic land use decisions happen at household and plot levels. The spatiotemporal dynamics of the varying land use and cropping systems change can be better understood when changes are properly linked with drivers and pressures using a well-designed research method and robust analysis framework. Therefore, for the present study, a widely used research framework, known as Drivers, Pressures, State, Impact, and Responses (DPSIR) model, was adopted from the European Environment Agency (EEA, 1999; Figure 3).

2.3 Data collection

The present study generated reliable facts from primary and secondary data sources by employing appropriate methods of data collection.

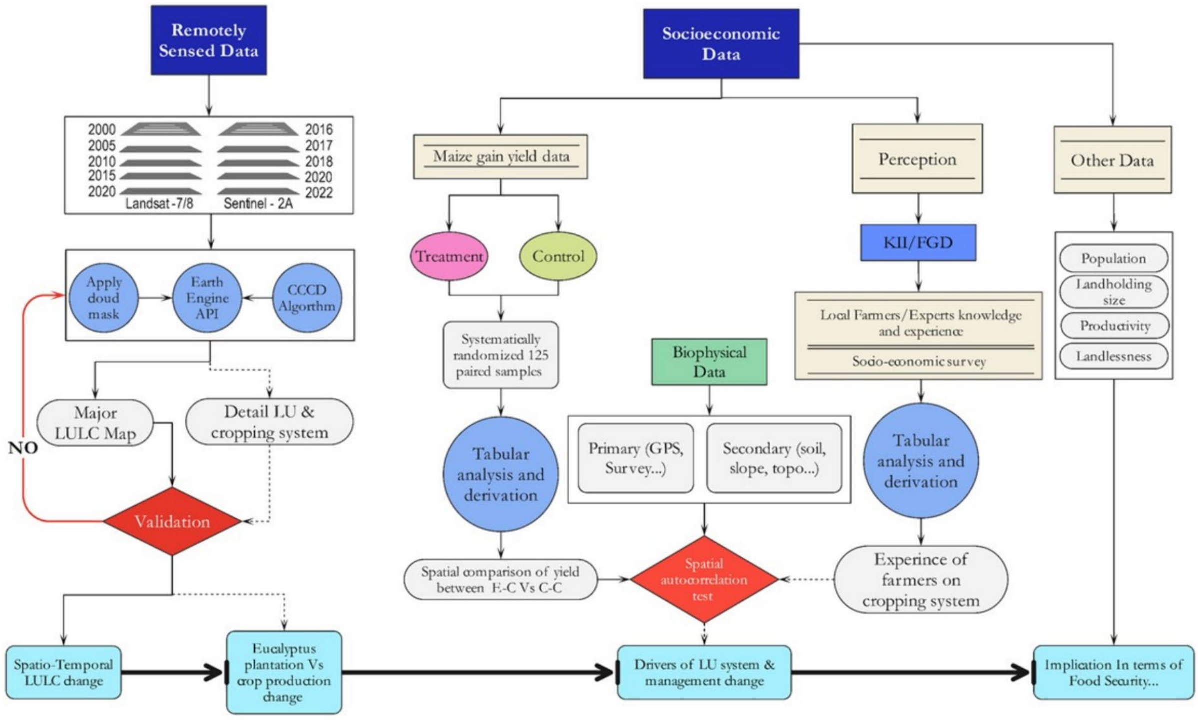

FIGURE 3
Schematic representation of the conceptual framework adopted from the DPSIR model.

2.3.1 Biophysical data

As indicated in Figure 2, the present study used remotely sensed data for three purposes (i) to identify and map major LULC types; (ii) to detect changes and assess the spatiotemporal dynamics between different LULC; and (iii) to geo-locate changes and estimate rate of conversion of cropland into eucalyptus plantation and vice versa since 2000. For the latter case, Sentinel 2A imageries, downloaded from Copernicus open Data HUB, for the period 2016 to 2022 were used. For the former two cases, as Sentinel 2A data are unavailable for the years before 2015, authors used Landsat imageries, archived from USGS using Earth Explorer. Moreover, the present study used several geospatial data from WLRC-AAU available as EthioGIS database series. Authors also collected several biophysical data using ground survey checklists and Focused Group Discussion (FGD) and Key Informant Interviews (KII).

2.3.2 Socio-economic data

Sample size: Prior to fixing the location of samples and their number, a preliminary survey of the entire study area was made. Based on facts obtained from the preliminary survey, approximately 150 paired samples for the entire study were proposed. To determine the specific location and size of samples, spatial overlay analysis of major determinant factors that govern yield of cereal crops was performed. The criteria considered while geo-locating sample plots were (i) biological factors such as slope variation, soil type, and drainage condition, and (ii) socio-economic variations such as farm management, wealth, and land holding size. Afterward, their locality and specific location was analytically determined using systematic random sample generation tool available in ArcGIS.

Identifying and geo-locating sample fields: A pair of sample represent two plots that were considered as control and treatment. The control was all the time Crop-Crop (C-C) plots, and the treatment was Eucalyptus-Crop (E-C) plots in the 2022 production year. However, geo-locating the position of each of the 150 paired samples needed to get a farm field owned by one HH with two adjacent plots. In selecting the paired sample plots, authors considered the following criteria: (i) the control and treatment plots should be adjacent and owned by the same HH; (ii) eucalyptus clear-felled stands should have a maximum of 3 years and a minimum of 1 year since conversion; (iii) the age of the plantation should be <20 years and have the first and second coppice of tree that used to be managed with rotation in 5–6 years; and (iv) both eucalyptus clear-felled stands and the adjacent croplands need to have similar land use history prior to afforestation. However, as getting farm fields that fulfill all these conditions was very challenging, authors went to the field and physically relocated each pair of samples that fulfill these criteria.

Sample plot replication and plot dimension: While geo-locating 125 sample fields, the exact location of sample plots was defined considering factors that could determine yield variation. To avoid biased yield data collection, in each control and treatment plot, two replica sample plots (2 m by 2 m dimension) were identified (Figure 4).

Qualitative data: Approximately 35 household heads of smallholder farmers who were growing maize or other crops in their clear-felled stands were purposively sampled to participate in the FGDs and KIIs. Detailed information regarding the effect of reuse of areas previously planted with eucalyptus for crop production on soil fertility as well as growth and yields of crops was, then, explored through interviews using a semi-structured questionnaire.

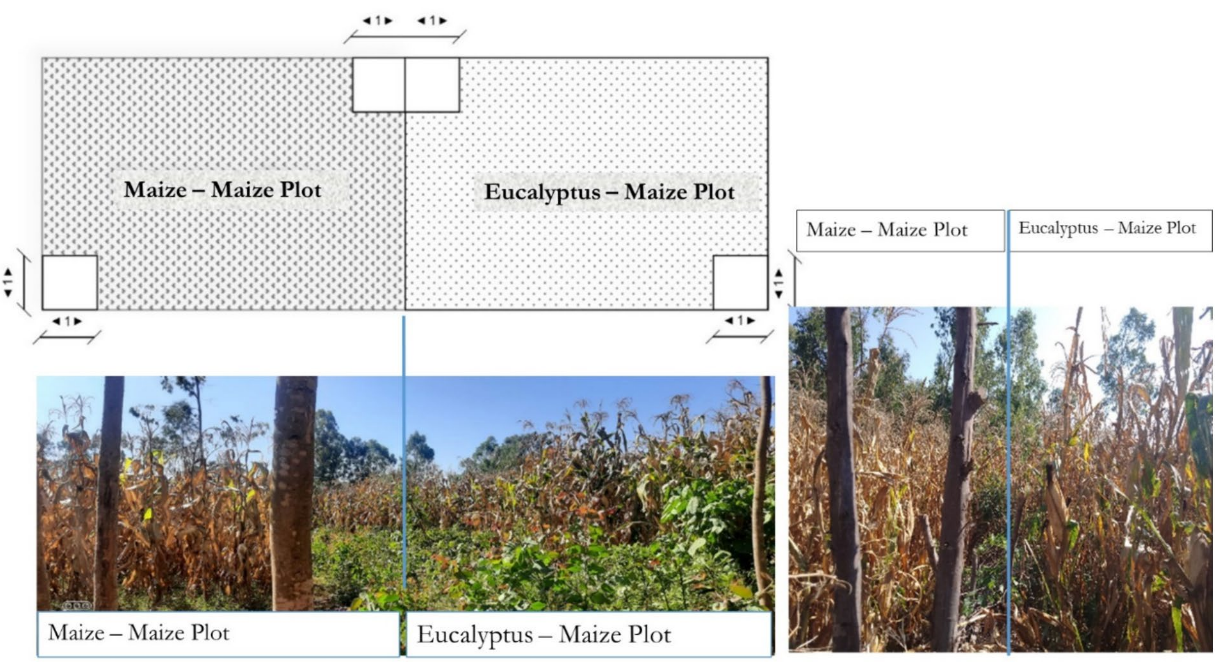

FIGURE 4
Chart depicting the sample plots designed to collect maize yield (top) and sample pictures of pair of sample farm fields (bottom and right).

2.4 Data analysis

Biophysical data analysis: To map LULC and LUS, two categories of mapping activities were implemented: (i) targeting detailed LULC and LUS mapping and (ii) focusing on specific LUS (eucalyptus stands). These two mapping and analysis activities were performed at two different spatial levels and time span. In the former category, the mapping and analysis of LULC and LUS was performed every 5 years from 2000 through 2020 using Landsat imageries covering the entire study area. The thematic details considered are approximately 10 detailed LULC types and are further grouped into four major LUS types (Table 1), namely, grain production, pasture production, timber and firewood production (forestry), and mixed/other use systems. In the latter category, focusing only on eucalyptus stands assessment, detailed mapping was done every year using Sentinel 2A and high-resolution Google earth imageries since 2016. This activity was performed only in four selected hotspots of clusters selected based on biophysical and agronomic factors such as types of crops, cropping calendar, and intensity of plowing.

Socio-economic data analysis: To properly identify the real drivers/causes of the land use shift in the study area, authors divided the study period into five parts. In addition, on the basis of the dynamism recorded on spatiotemporal eucalyptus plantation, four major time spans were identified: 2000, 2000–2010, 2010–2020, and 2020 onwards. The collected socio-economic data were summarized, and descriptive results were generated using SPSS, STATA, Excel sheet, and OriginPro software. The results were interpreted by judiciously integrating the classified and summarized socio-economic data with the spatiotemporal LULC changes that were detected using remotely sensed imagery and by relating that further with the drivers and causes of the changes.

Within the convertor group, we also compared maize growth and yield differences between eucalyptus-cleared plots and non-eucalyptus adjacent plots. The number of Combs per stand and per area, and grain weight (wet and air-dried) were used as parameters for maize growth and yield comparison. To describe the economic implication of converting eucalyptus stand into cereal field and vice versa, two types of assessments were made, namely, (i) cost–benefit analysis and (ii) Opportunity loss analysis (calculating the difference between the optimum equivalent payoff (including services) from the production area and the actual payoff made from that area). These two assessments were performed considering three categories of ecosystem services or land use services from those plots, namely, timber production services (production forestry system), grain production services (crop production system), and pasture production services (livestock production system). The overall impacts of the LULC changes were drawn by integrating the socio-economic results from these three categories of assessments with the temporal LULC changes detected.

3 Findings

3.1 Land use system dynamics

The spatiotemporal dynamics assessment made on major LULC and LUS types during the two decades 2000–2022 shows a tremendous expansion of timber production at the expense of grain/croplands (Figure 5; Table 1).

According to our physical observation and the FGD results, crop production, mainly the production of cereals such as maize, finger millet, and wheat are the dominant crops covering 95% of

TABLE 1 Temporal dynamics of the area coverage of major LUS types existing in the study area (in hectare).

LUS	2000		2005		2010		2015		2020		2021		2020	
	Area	%	Area	%	Area	%	Area	%	Area	%	Area	%	Area	%
Dominantly Grain production	65,071	48	68,877	51	67,512	50	63,370	47	62,667	46	64,059	47	66,752	49
Dominantly Pasture production	45,473	34	40,900	30	38,062	28	33,676	25	20,661	15	20,661	15	20,661	15
Mixed (timber & firewood) production	18,570	14	15,066	11	14,265	10	11,896	9	19,049	14	19,048	14	19,048	14
Timber (charcoal) eucalyptus plantation	2,536	2	4,034	3	9,268	7	20,269	15	27,696	21	26,304	20	23,612	18
Others/Mixed systems	3,552	3	6,325	5	6,095	5	5,993	4	5,132	4	5,132	4	5,132	4
Total	135,202	100	135,202	100	135,202	99	135,204	100	135,205	100	135,205	100	135,205	100

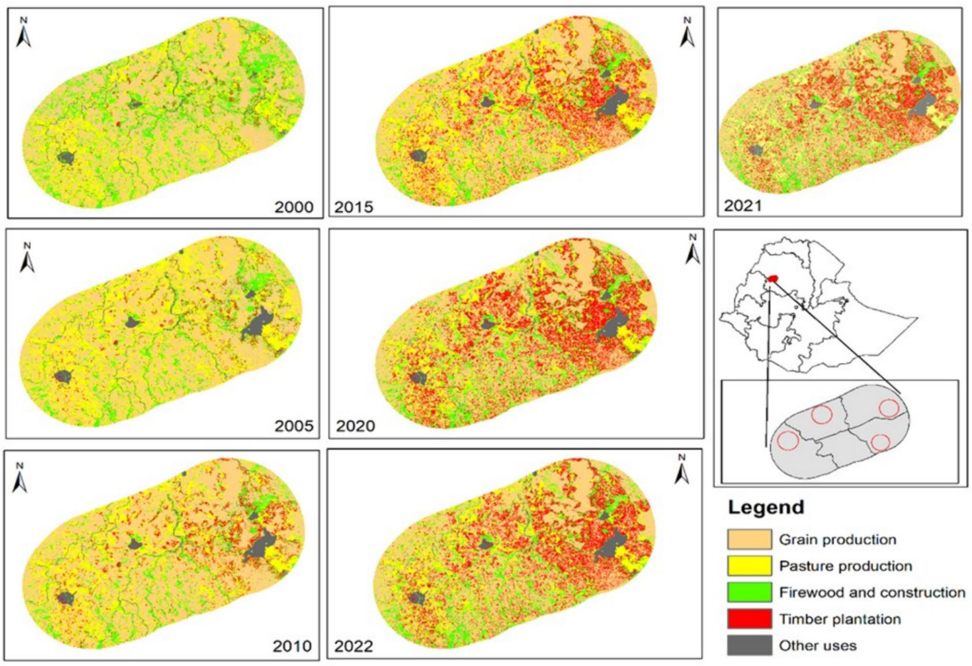

FIGURE 5
Spatiotemporal dynamics of major LUS identified in the study area (Source: Produced by Tibebu from Landsat 4, 5, 7, 8, and 9 Sensors).

the cultivated landscape in the study area. As depicted in Table 1 and Figure 5, cropland is the dominant land use system covering almost half of the study area.That is followed by eucalyptus plantation, pasture, natural woody vegetation, and other uses such as settlement and infrastructure covers the remaining 50% of the study area, ranked in their order of area coverage from higher to lower share. In fact, the distribution and coverage considerably vary in time and space. Looking at their percent cover change, cropland seems stable, but, if the spatiotemporal comparison is based on area (in ha), cropland is the most transformed land use. It covers approximately 48% of the landscape in 2000, but in 2005, its cover rise into 51% as a considerable grassland was converted into cropland due to land redistribution and consolidation happened in 2003/2004. However, in the period between 2005 and 2010, cropland lost approximately 1% and accounts again 50% share of the study area. According to the statistical facts, the period between 2005 and 2015 was the time when the coverage of eucalyptus plantation showed a substantial increment. As a result, cropland coverage reached 47% in the year 2015. In 2020, the LULC was almost stable, and after 2021, the area under crop field increased from 46% in the year 2020 to 47% in the following year and further up to 49% in 2022. Contrarily, except in the period between 2000 and 2005, pasture land has been continually declining since 2005. Other use systems (representing infrastructure and settlements) have considerably expanded between the year 2000 (3%) and 2010(5%), mainly at the expense of croplands. The natural landscape (a mixed natural vegetation) has continually suffered a massive degradation between 2000 and 2015.

3.1.1 Spatiotemporal dynamics of eucalyptus plantation, 2016–2022

The information generated from Landsat imageries can have 13–16% error as the accuracy of the maps ranges from 84 to 87%. The red pixels of the maps produced from Landsat imageries (Figure 6) represent eucalyptus plantation. Comparing the coverage of eucalyptus in 2015 (Figures 4, 5), the map produced from Sentinel image encompasses a larger coverage of eucalyptus plantation in the year 2016. Indeed, based on mapping results of Landsat imageries, a considerable eucalyptus area expansion happened in the period between 2005 and 2015. Because eucalyptus plantation can exist with a spatial extent lower than the pixel size of Landsat imageries, authors produced Sentinel-based eucalyptus maps for the period between 2015 and 2022, which implies that Landsat-based maps could underestimate eucalyptus plantation (13–16%). The present study made a focused assessment on eucalyptus plantation using Sentinel images (2016 till 2022).

As depicted in Table 1, the year 2017/2018 was the time when expansion of eucalyptus plantation reached its climax. In the assessment base year, the coverage of eucalyptus trees was trivial (2%). A double increment was recorded in the period between 2000 and 2005, and a triple rate of increment was recorded in the period between 2000 and 2010 (from 2 to 7%). Indeed, its temporal expansion was exponential until 2015.

3.1.2 Eucalyptus plantation dynamics at selected cluster of hotspots (2000–2022)

Still, the maps produced using Sentinel 2A imageries have overestimated and underestimated eucalyptus plantation. To clearly capture such LUS changes that happen at a smaller extent, authors further conducted a detailed assessment. Figure 7 depicts high-resolution-imagery-based LUS mapping performed in four systematically selected case study sites/clusters. The accuracy of these maps is above 95%, implying that there is no overestimation or underestimation of eucalyptus plantation. In all the clusters, eucalyptus plantation revealed a continuous increment with a varying intensity. Comparatively, among the four clusters, Cluster 2 experienced a considerable change on the landscape. Such change had happened mainly at the expense of pasture and croplands.

Approximately 30% of the landscape in Cluster 2 has been transformed from cereal and pasture producing landscape into eucalyptus plantation (Figure 7).

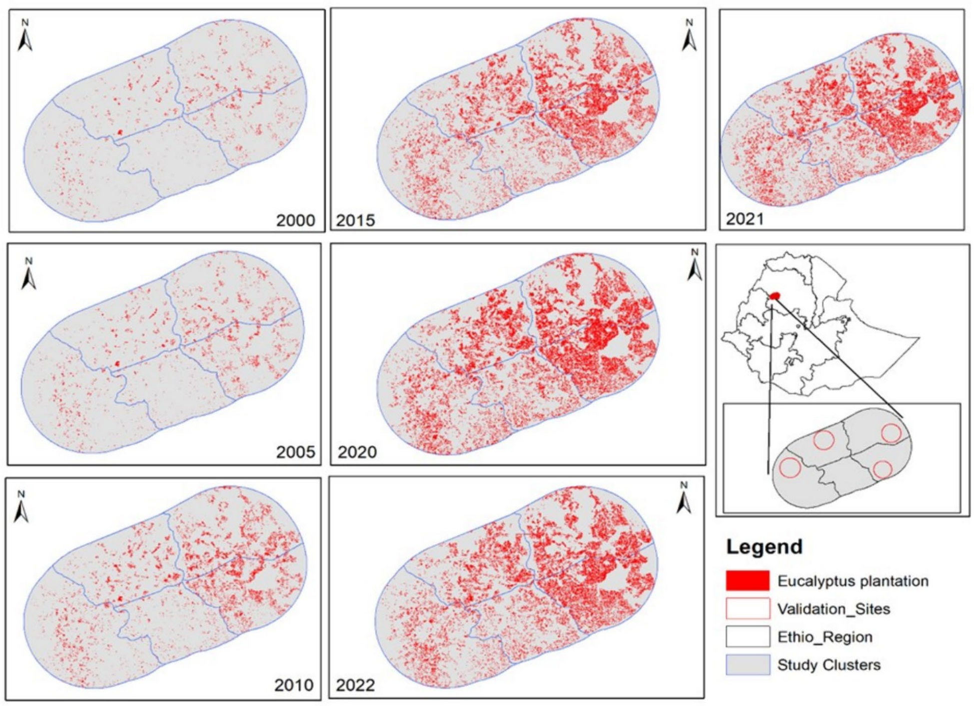

FIGURE 6
Spatiotemporal dynamics of eucalyptus stand (Sentinel-based mapping; Source: Produced by Tibebu from Landsat 4, 5, 7, 8, and 9 Sensors).

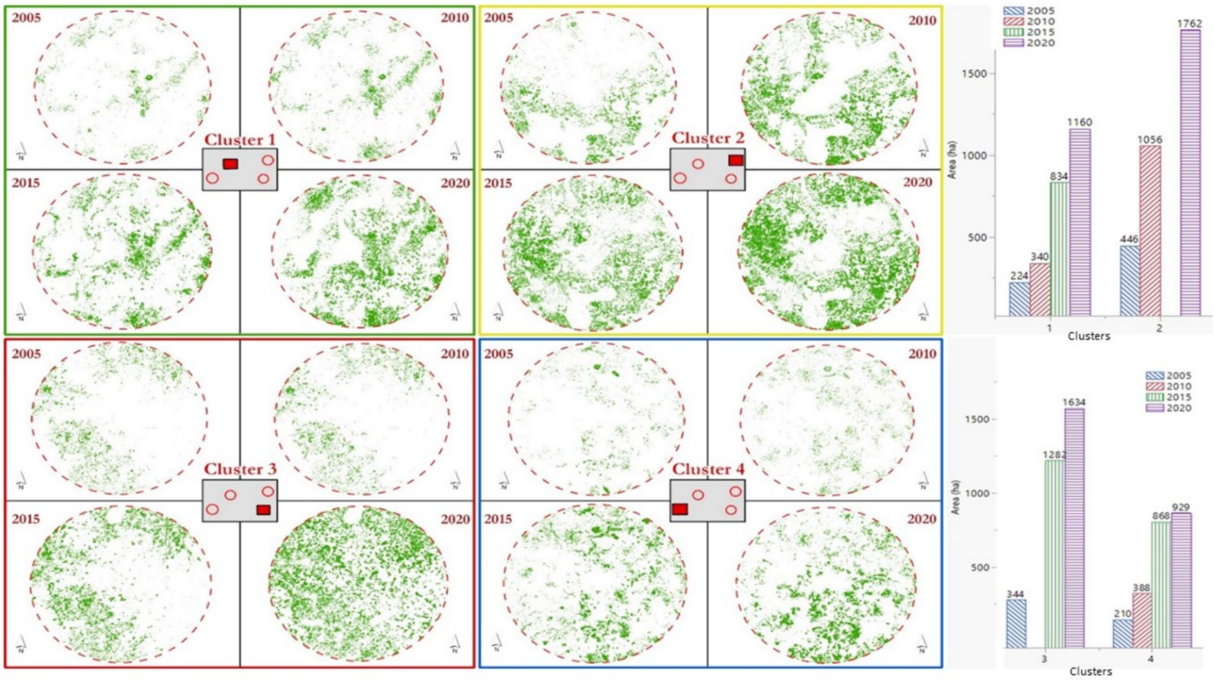

FIGURE 7
High-resolution-image-based eucalyptus stand dynamics mapping and change detection on selected hotspots and summary statistics. High-resolution (Google earth imageries with <1 m pixel size) 2005–2020 change analysis.

3.2 Intensity and direction of LUS transitions in the four clusters of hotspots

A recently emerging new land use practice, mainly, planting eucalyptus trees on productive croplands and pasture fields, brought a considerable transformation not only on the biophysical landscape but also on the socio-economic conditions However, given the practice of planting eucalyptus trees in a smallholder farmers' landscape at a very smaller spatial extent, lesser than the pixel size of Landsat even Sentinel imageries, the produced maps may not show the reality that happened on the ground. This in turn hindered authors to determine on map crop to eucalyptus and eucalyptus to crop conversions. To clearly map and characterize such important transformations, the authors did a detailed mapping and change analysis. For that purpose, on few selected clusters, the authors made a detailed mapping that integrates high-resolution Google earth, Landsat, and Sentinel 2A imageries supported by a comprehensive field survey. The field survey data include GPS-based tracing of un-mappable eucalyptus stands, insensible transitions and conversions, and historical land use systems. Change dynamics with direction of change (transition and trajectories that show the gain and loss or what changed from and to what) is provided in Table 2.

3.3 Areal gain and loss between eucalyptus plantation and other LUS in the four clusters of hotspots

As getting higher resolution imageries of the study area for every year was challenging, 'from… to…' change analysis was done taking four millstone periods of change that properly show the nature of changes. Table 2 presents the overall gains and loss between eucalyptus plantation and major LUSs, and Supplementary Figure 1 provides graphical representation of the trajectory of changes.

Based on higher resolution imagery-based change assessments made on specific hotspot areas, a decreasing trend in eucalyptus plantation was recorded in the period between 2020 and 2022, accounting for approximately 40% decline or area loss compared to the previous period (i.e., 2015 and 2020). Area wise, eucalyptus plantation was expanded to a total area of 1498 ha, 6842 ha, and 11,078 ha during the periods 2000–2005, 2005–2010, and 2010–201 but then reduced to 9642 ha during 2015–2020 and further down to 4672 ha during 2020–2022. Of these changes, higher areal gains for eucalyptus plantation were made at the expenses of natural vegetation and pasture, which, respectively, accounted for 59 and 19% of the expansion area during 2000–2005 and 22 and 40% during 2005–2010. In the periods after 2010, above 80% of the gains for eucalyptus expansion were from croplands.

As depicted in Supplementary Figure 1, the TP bar representing timber production service area (dominantly covered by eucalyptus Plantation) never lost to any LUS. In all the periods, the area coverage of TP (eucalyptus plantation) expanded continually and exponentially growing until 2020, but, in the year 2021 and 2022, the TP service area lost a considerable area to crop field, which is linked to substantial LUS transformation from plantation to cereal production.

3.4 Drivers and causes of conversion between eucalyptus trees and cereal crops

Based on the nature of change as well as the identified millstones of change, the present study identified pertinent drivers, classified

TABLE 2 Total gain and loss (area in ha) between eucalyptus plantation and other LUS (Supplementary data).

Years	Transitions	Timber Production(TP)	Grain Production (GP)	Pasture Production(PP)	Mixed (Timber and Firewood) Production (MFP)	No-Production (NP)	Total
2000	Gain	765	668	241	782	378	2534
	Loss	0	0	0	0	0	
2005	Gain	2534.22	333.4	279	876.7	8.4	1497
	Loss	0	0	0	0	0	0
2010	Gain	2421.7	2152	2215.5	2181.6	293.6	
	Loss	0	−556.6	−637.6	−357.5	−58.3	−1610
2015	Gain	9184.1	9058	1507.1	405.7	107.1	
	Loss	0	−37.2	−25	−13.9	−4.1	−80.1
2020	Gain	18680.1	6429	2003.4	1017.7	191.8	9642
	Loss		−975.3	−140.5	−429.5	−37	−1582
2022	Gain	20071.3	2899	423.5	1254.4	95.4	4672
	Loss		−6588	−520.4	−1065.7	−77	−8251

TABLE 3 Driver matrix produced from FGD and KII.

Drivers	Specific drivers	Positive drivers	Negative drivers
Economic	Demand (Timber)	New demand emerged for eucalyptus pols	
	Demand (Energy)	New demand emerged (Charcoal production from Eucalyptus)	
	Market	Market failure (grain)	Market failure (pools)
	Infrastructure	Improved access to market, road network, transport, etc.	Poor market, road Network, transport etc.
	Inputs	Rising of the cost of agricultural inputs	Lowering of the cost of agricultural inputs
Institutional	Tenure	Land distribution and certification	
	Peace	Peace and stability	Conflict and war
	Policy (National) and regional	Rehabilitating degraded lands through eucalyptus trees	Restriction of planting eucalyptus
Socio-cultural	Knowledge/information, Education	Rise of literacy level	Low literacy level
	House construction style/culture	Construction of corrugated iron based houses	
	Family size/labor	Lowering of family labor force	Better family labor force
	Land holding size	Lower	Higher
	Migration	Rural–Urban	Urban–Rural
Environmental	Fertility of soil	Land degradation (Loss of the productivity of land)	Improved fertility
	Vegetation cover	Loss of natural vegetation	Improvement of natural vegetation
	Physiology and Growth condition	Low operational cost	Allopathic nature
		Fast growing and adaptability nature of the species	
		Higher density of coppicing	

Source: FGD and KII conducted by the researchers, 2023.

them into four categories (socio-cultural, economical, institutional, and environmental), and further described their impact as positive or negative. Table 3 summarizes major drivers that contributed most to the expansion and those to the abrupt reduction of eucalyptus plantation in the study area.

As depicted in Table 3, the drivers and causes are listed according to their importance in a descending order. In our assessment, among the listed drivers, respondents/discussants ranked economic drivers first, followed by institutional and cultural factors. Environmental factors were ranked the least among the drivers. According to the results of the KII and FGD narratives, demand for fuelwood, and construction pols, market/price and accessibility (distance to road, market, and settlements) influence decisions of transforming from cereal to timber production landscapes or vice versa.

3.5 Implications of converting eucalyptus plots to cereal fields and vice versa

Impact and implication of LUS changes were assessed in three dimensions: (1) biophysical (physical landscape transformation), (2) socio-cultural (land use and/or management/practice change), and (3) economic indicators. The findings of the assessments are presented in the following sections.

3.5.1 Implications on biophysical landscape

In the study area, the expansion and removal of eucalyptus trees plantation lead to biophysical landscape transformation as an immediate and prominent impact (see Figures 8, 9; Supplementary Figure 1, for example). For instance, planting eucalyptus trees had been in cluster 2 covering only 7% during 2005. In the same area, over 15 years, eucalyptus covered almost 47% of the area, which transformed the physical landscape of the smallholders' land use system (Figure 6). Such amount of physical landscape transformation does have various socio-cultural, economic, and ecological implications.

3.5.2 Socio-cultural implications

3.5.2.1 A new land use/management system/practice emerged

Quite many times, literature has been blaming the practice of growing eucalyptus trees alongside of cereals due to its allopathic effect. The present study findings show that, for smallholder farmers who have very limited land and fragmented plots, the benefit of growing eucalyptus trees outweighs its perceived negative impacts. According to FGD respondents, and verified by author's field observation, against the alleged myths of the tree, the practice of the planting eucalyptus trees alongside cereal fields either as farm border or as striping between cereal fields is intensifying time to time. Pictures presented in Figure 10 show how smallholder farmers slowly reshaped their practice while domesticating eucalyptus trees species for agroforestry.

3.5.2.2 Implications of eucalyptus plantation to cereal conversion and vice versa on land tenure

Assessment findings revealed that converting cropland to eucalyptus plantation could have an indirect impact on tenure security and farmland holding size. Over the analysis period, approximately 23,000 ha of land, which could be cultivated, was converted into eucalyptus plantation. Equivalently, it would support the livelihood of above 30,000 HH to lead smallholder-based farming. In addition, dividing the total eucalyptus planation areas (Table 1; Supplementary Table 1) in the years 2000, 2005, 2010, 2015, and 2020 by the long-term average land holding size in study area (averagely 0.8 ha of land per a household), approximately 3,251, 5,172, 11,882, 25,986, and 35,508 households lost their chance to establish agrarian livelihood system or would become landless in each respective year. In other words, the conversion of the cropland to eucalyptus contributed to a decrease of the agricultural land holding size from 0.9 ha per household in the early 2000s to 0.5 ha in the early 2020s.

3.5.3 Ecological implications

The ecological implications of converting eucalyptus stand into cereal production were assessed taking three ecological impact indicators, namely, growth condition (# of stand per area), comb size and number (#/stand), and productivity (gross grain yield in terms of kg/area).

Effect on Maize stand and Maize comb: According to our physical observation and the information shared by the participants in the FGD and KII, an improved maize grown in sample plots where farmers cleared eucalyptus stand and planted maize showed higher growth performance than maize grown on plots that had been cereal fields in the previous year. According to the data collected from samples plots, approximately 7% of the sample plots in EC have 2/3 combs per stand, whereas only 3% of the CC samples have 2/3 combs per maize stand. A higher dry matter production were also recorded on maize plants established on clear-felled eucalypt stands.

Effect of clear-fell eucalyptus on cereal grain yield: Data on yield differences were collected from four representative clusters and 125 paired and adjacent sample plots. Alike the biomass (maize stand and Comb/stand), the yield difference assessment result showed a higher grain yield was recorded from plots with E-C plots than C-C plots. Detailed sample by sample yield differences is presented in Figure 11.

As depicted in Figure 11, in EC samples, the minimum and maximum wet weight ranged from 0.5 kg/m^2 to 1.2 kg/m^2. This is equivalent to 47–120q/ha, whereas in CC samples, wet weight ranged from 0.24 to 1.1, kg/m^2, which is equivalent to 24 to 94q/ha. The yield difference in each sample within a cluster or across clusters is presented in Figure 11. In general, the average yield differences recorded on EC samples from CL1, CL2, and CL3 exceeded the yield collected from CC sample plots by 19, 30, and 20%, respectively. Exceptionally, the average yield difference in CC exceeded the EC sample plots by 1%. Based on yield data recorded on CL1, CL2, and Cl3, we can generalize that the practice of converting e eucalyptus to cereal-based crop production gives a higher yield, at least in the first production year. Contrarily, the average yield difference between E-C and C-C samples revealed that half of the samples showed a higher yield in CC than EC, and half of the samples show there is a higher yield in EC than in CC. Thus, the recorded differences on sample plots of cluster 4 make such generalization difficult.

3.5.4 Economic implications

3.5.4.1 Cost–benefit approach

This section presents the results of the trade-off between agricultural production and timber (forestry) land use systems, which compares grain production (taking Maze crop) in agriculture land use against timber (eucalyptus pole) and non-timber products (firewood and charcoal) in eucalyptus plantation. For the purpose, cost–benefit analysis and service area-based comparative analysis were employed. The cost–benefit analysis was performed by comparing input applied/

production cost against outputs produced/benefits, across 2000 and 2020 production years (Supplementary Table 1). To obtain economic value of land use per hectare, the total revenue, cost, and profit of each land use option were divided by the total land area under cropping use versus eucalyptus plantation. Supplementary Table 1 presents the trade-off assessment results from the cost–benefit approach.

The study landscape that covers approximately 135, 400 ha of land, of which 50% used to produce grain, would generate above 117 million dollars per year. The cropped area dynamics estimated for five different periods revealed that approximately 67,071 ha, 68,877 ha, 68,415 ha, 63,370 ha, 62,667 ha, 64,059 ha, and 66,752 ha of land was converted from crop field to eucalyptus plantation. In monetary value, the net average equivalent monetary value is estimated to be 7, 17, 47, 88, and 116 million USD$ revenue in the respective periods. On the other hand, the monetary-based landscape productivity performance of the area is higher when used for cereal production than eucalyptus plantation. Contrarily, eucalyptus plantation-based land use shows a higher performance when evaluated from cost of production against total net benefits. In terms of total net economic benefit, cereal production surpasses eucalyptus plantation.

3.5.4.2 Service area-based trade-off assessment

Table 4 presents statistical facts about area-based opportunity lost or an equivalent opportunity that would contribute to ensure local level land supply to the grain production system, which in turn affect the tenure as well as the food security situation at large. By taking an alternative land use system, that is, maize crop instead of eucalyptus plantation, opportunity loss in terms of service area to be used for maize production was calculated. As indicated in Table 4, in the years 2000, 2005, 2010, 2015, and 2020, farmers in the community have planted eucalyptus on approximately 2,536, 4,034, 9,268, 20,269, and 27,696 ha of land, respectively, that implies an equal amount of land would have been used to produce grain in each year. Taking the average maize productivity of the area for each year (Table 4), approximately152,160, 229,938, 472,668, 972,912, and 1,606,368 quintal of maize grain would have been produced in each year. Taking 1.4 kg/day food as a food demand of a person per day, the total amount of food demand per year per person was calculated and accounts 5 quintal of food per year per person. Dividing the total maize grain that would have been produced in each year (Table 4), the total population that could be fed on the grain was estimated at 30,432, 45,988, 94,534, 194,582, and 321,274 in the years 2000, 2005, 2010, 2015, and 2020, respectively. Equivalently, the total maize grain produced in each year would contribute to sustain approximately 5,072, 7665, 18,907, 38,9176, and 80,318 households, in the years 2000, 2005, 2010, 2015, and 2020, respectively.

4 Discussion

The present study examined the type, extent, intensity, and impact of landscape transformation due to eucalyptus trees plantations in the

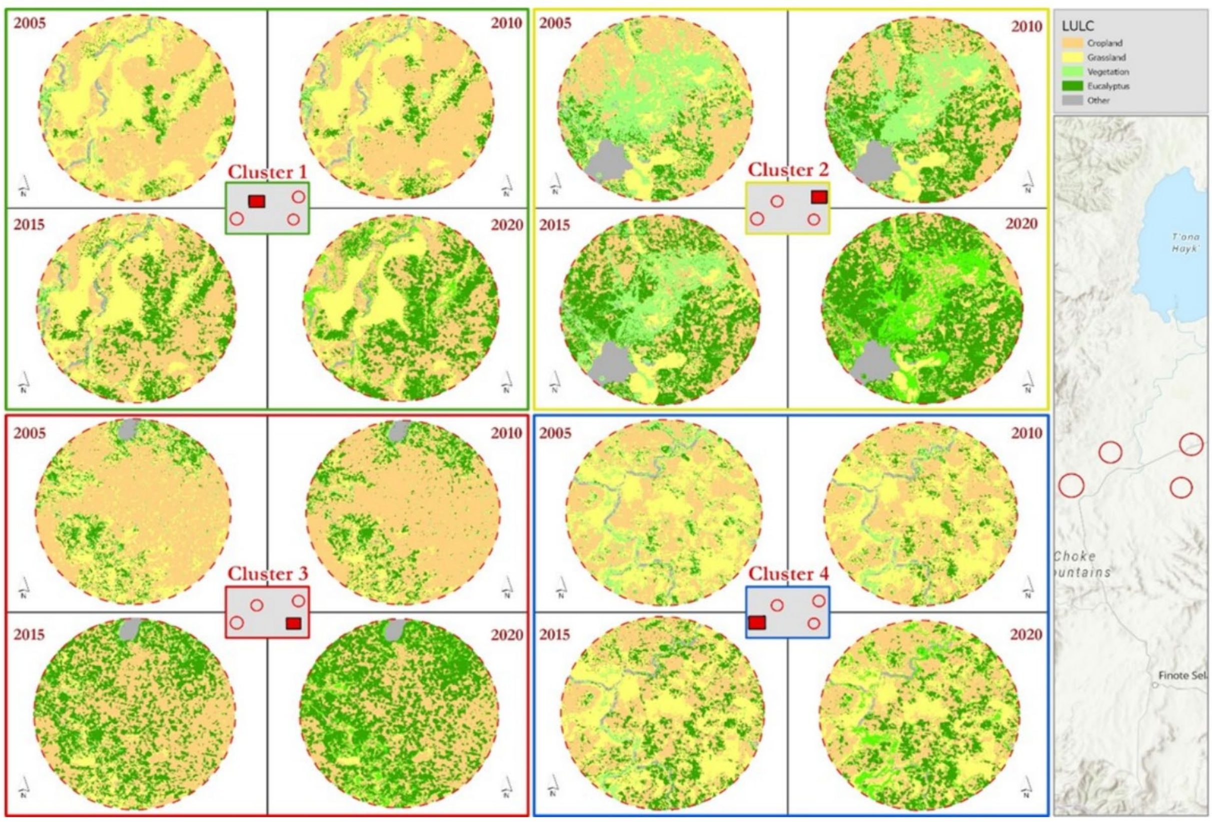

FIGURE 8
Spatiotemporal dynamics between major land use systems and eucalyptus planation in the study area, 2000–2020 (multi-source data outputs obtained from hybridized mapping and analysis approaches).

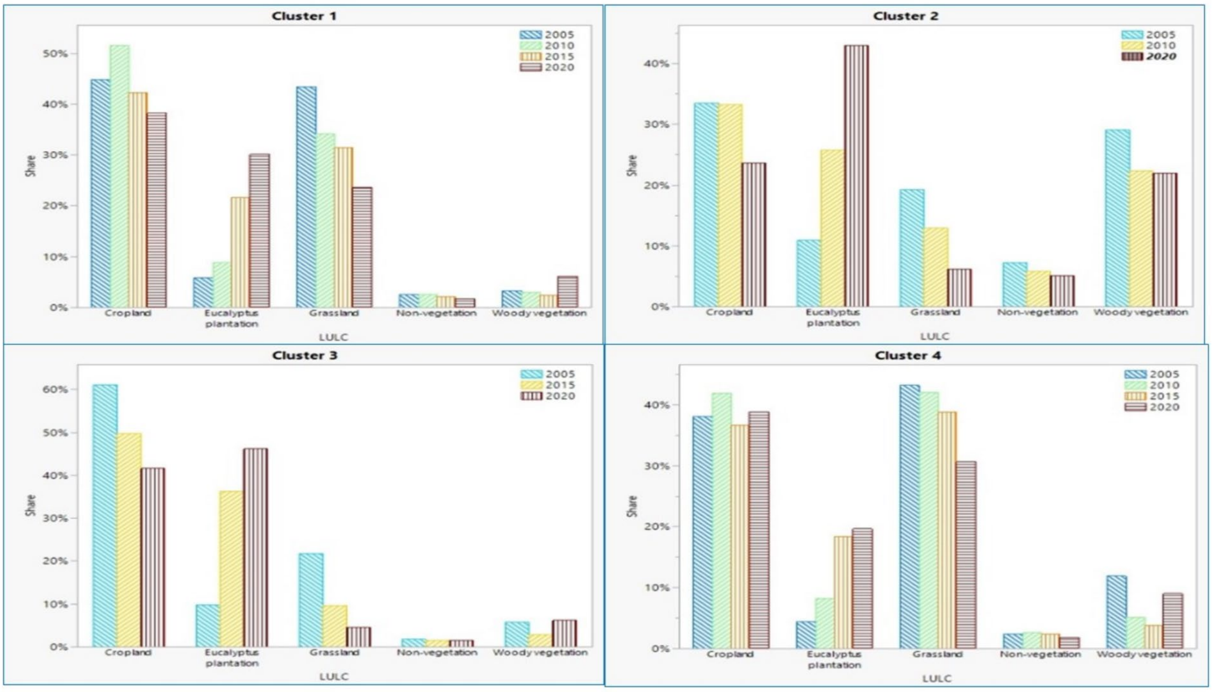

FIGURE 9
Statistical facts about temporal dynamics of major land use systems in the study areas, 2005–2020.

FIGURE 10
Top left, middle, and right pictures portray eucalyptus-maize field after harvest specific management where farmers do not allow the coppice to grow, (right), the farmer allows the coppice to grow, whereas the bottom left, middle, and right pictures portray another land management by farmers, where farmers allow eucalyptus to grow with maize crop. The later could indicate the process of acclimatization of eucalyptus trees in the cereal production landscapes of smallholder farming systems.

North Western part of Ethiopia. As far as concerned to the extent of landscape transformation, among the five systems, grain producing landscape is the most transformed land use as it happens in the entire rainfed agricultural area of Ethiopia (Kassawmar et al., 2018b). Of the assessment periods, the period between 2000 and 2005 is a time of massive transformation (Figures 5–9). A considerable grassland was converted into cropland attributed to land redistribution and consolidation happened in 2003/2004 (Takada et al., 2022). On the other hand, the period between 2005 and 2015 was the time when the coverage of eucalyptus plantation showed a substantial increment. These findings are supported by other similar research studies (Alemayehu et al., 2023; Jenbere et al., 2012). In the period between 2015 and 2020, exceptional change had happened. While the coverage of eucalyptus trees reached its climax in the year 2017/18, the coverage of croplands slightly reduced. As depicted on Tables 1, 2, except in the period between 2000 and 2005, pasture land has been continually declining since 2005, which is mainly eucalyptus plantation and land redistribution effects. The findings of similar studies such as (Gedefaw et al., 2020; Belay, 2010) also support our results. As far as concerned to natural vegetation dynamics (a mixed natural vegetation) has continually suffered a massive degradation between 2000 and 2005. However, as several studies confirmed that the years between even before 2000 are critical times as a relatively higher vegetation cover loss was recorded (Kassawmar et al., 2018b). Since 2010 up until 2015, periods were recorded as time of stability for natural vegetation which is linked to vegetation restoration movement (Mulugeta, 2014).

Mapping and monitoring land use system change in smallholder-based mixed farming is tricky (Kassawmar et al., 2018a). As learned from the assessment results of the present study (Tables 1, 2; Figures 5, 6), the intensity, rate, and direction of changes happening between different land use systems are very complex, which needs contextually designed assessment methodologies (Kassawmar et al., 2019). Applying even the best available imageries and state-of-the-art technologies, it is challenging to precisely show the dynamics between land use systems with eucalyptus plantation because eucalyptus plantation can exist with a spatial extent lower than the pixel size of imageries used to map and study the dynamics. Even authors produced Sentinel-based eucalyptus maps for some period, some important changes never been detected and estimated properly. Nonetheless, the results of the annual eucalyptus plantation mapping showed a climax expansion, which happened in the year 2017/18. A study by Alemayehu et al. (2023) has detected also a similar phenomenon. Compared to the decadal and bi-decadal assessment, mapping eucalyptus stand every year allows to not only improve the accuracy of the maps and generate accurate evidence but also understand the plantation management practices, mainly planting, harvesting, and land use conversion. Moreover, an interesting and unperceivable changes were detected when authors employed high-resolution imagery-based mapping and change analysis on smallholder farming systems. According to the facts recorded from a high-resolution imageries and change analysis, a revers transition is recorded since 2020. The coverage of eucalyptus plantation started to decline since 2020. In total, within 2 years (between 2020 and 2022), smallholder farmers have converted approximately 5% of their eucalyptus plantation to grain fields (Figures 7–9; Table 2). From the hotspot-based results, authors realized that earlier times expansion of eucalyptus was largely on the expense of natural vegetation and grasslands, while recent expansions were on the expense of croplands.

Several research studies have been conducted to know the drivers and discern the reasons of eucalyptus expansion (Jaleta et al., 2016; Alemayehu and Bewket, 2018; Alemayehu et al., 2023; Jenbere et al., 2012; Chanie et al., 2013; Tesfaw et al., 2022), but drivers and reasons to removing eucalyptus and replacing with cereals are unknown as such a practice is a recent phenomenon. Previous research evidence

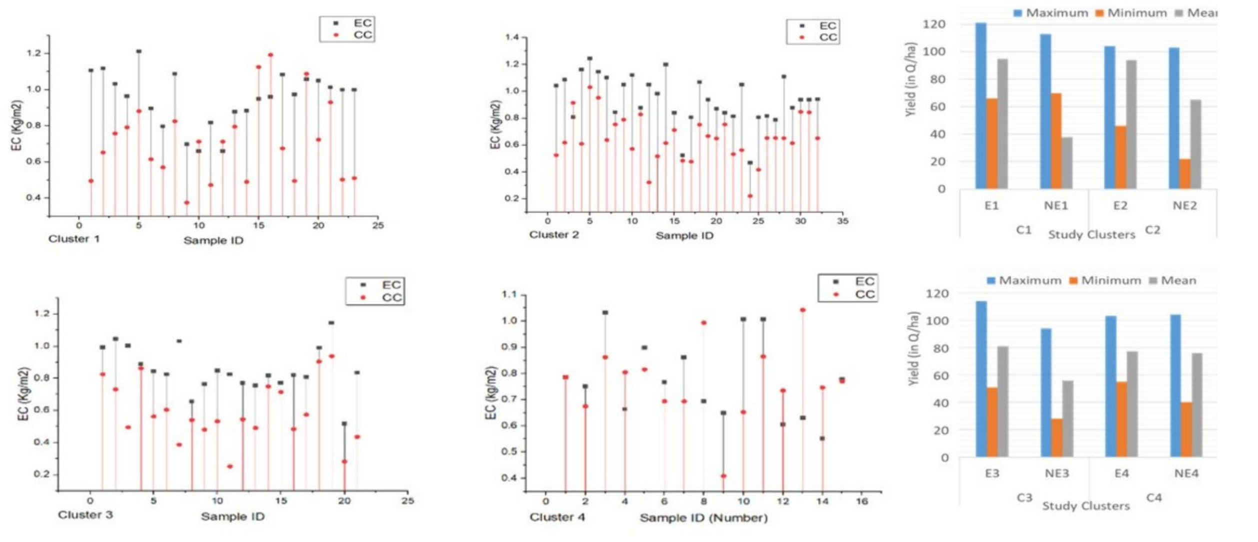

FIGURE 11
Yield differences recorded between E-C and C-C sample plots collected from four clusters of hotspots (the yield is an average value calculated from two samples each having 2*2 m, that is, but presented and expressed in terms of kg/m^2). Parallel left side charts present yield gap comparisons between the four clusters and the national and the local reference experimental yield of maize. The Y-axis represents the yield in terms of kg/m2, and the X axis represents sample cods in each clusters. The circular red dots represent the grain yield of a sample taken from C-C plots, and a rectangular black dots represent the grain yield of a sample taken from E-C plots. The black line shows the yield differences recorded between the paired plots.

TABLE 4 Implication of eucalyptus stand conversion to cereals and vice versa on the coverage of grain producing landscape.

The whole study area(135,202 ha)	2000	2005	2010	2010	2020
Planted area (ha)	2,536	4,034	9,268	20,269	27,696
Average productivity/yield of the study area (Qn/Ha)	60	57	51	48	58
A lost yield if the land was used for Maize production Yield (Qn)	152,160	229,938	472,668	972,912	1,606,368
Average food gap created (Qn) per year	152,160	229,938	472,668	972,912	1,606,368
Assuming 1.4 kg food is needed for a person per a day. Annual average food demand (in Quintal/person/year)	5	5	5	5	5
Average total population could be served	30,432	45,988	94,534	194,582	321,274
Average Number of People in a HH	6	6	5	5	4
Number of total HH could be served	5,072	7665,	18,907	38,9176	80,318

depicted that the common causes and drivers responsible to most land use system changes fall into three categories: socio-economic, institutional, and environmental (Alemayehu and Bewket, 2018). Facts generated by the present study on the nature of change as well as the identified millstones of change, approximately 20 specific drivers, falling in to four general categories (socio-cultural, economical, institutional, and environmental) of drivers were identified. Based on the FGD-based ranking of drivers, respondents identified economic factors mainly market failures, as the main reason for farmers to abandoning eucalyptus trees and growing cereals. This agrees with what Alemayehu and Bewket (2018) reported about high income earned from eucalyptus pols selling as a leading of the major drivers for the farmers to plant eucalyptus (Alemayehu and Bewket, 2018; Alemayehu and Melka, 2022). Although the majority of the respondents of the FGD ranked economy as the most decisive factor for the measured changes, the suitability and productivity of the landscape made Mecha district a known eucalyptus plantation belt.

LUS in smallholder-based farming tends to be affected even by modest pressures. The present study made a simple impact assessment, taking three evaluation measures/indicators: (1) biophysical (physical landscape transformation); (2) socio-cultural (land use and/or management/practice change); and (3) economic indicators. Change in land use practices could have multifaceted implications. According to the hotspot-based landscape transformation assessment findings, over 15 years of time, eucalyptus has invaded and transformed approximately 30–47% of the grain dominating landscape (Table 2; Figures 7–9). However, a reversing physical landscape transformation recently happening in smallholders' could be taken as an important supporting evidence that the main driver of planting eucalyptus plantation is economic and political factors (Table 2).

As smallholders are always questioning the performance, efficiency, and risks related to the newly emerged practices, the landscape is always in state of change driven by complex drivers and pressures (Jagger and Pender, 2003; Alemayehu and Melka, 2022; Sang et al., 2023). Since the time of commoditizing eucalyptus trees (as of 2000) in the area, the way smallholders used their fragmented and small farm plots has been continually transformed. Over the millennia, the dilemma of growing eucalyptus trees with crops remain a debatable issue due to its alleged allopathic effects (Jaleta et al., 2016; Feyisa et al., 2018). Against such alleged thoughts, smallholder farmers have been growing the tree alongside of cereal fields either as farm border or as striping between cereal fields (Alemayehu and Bewket, 2018; Jenbere et al., 2012). Ignoring about the risks and worrying more on land scarcity pressures, farmers continued growing the tree mainly for efficacy and profitability reasons (Alemayehu and Melka, 2022). When authors asked about their reasons of planting the tree regardless of the negative impacts, the majority of the respondents said that no other practices other than this magic tree helped us in fulfilling our immediate and critical demands (such as energy or fuelwood, construction/timber, and cash). Respondents underlined that it is not only the question of fulfilling their domestic fuel wood and timber demand but more about the income. As a result, growing eucalyptus trees is a dynamic agricultural practices evolving with different agricultural practices and has become a deep rooted agro-culture of the society to the level farmers are adapting the tree to make it an agroforestry tree (Kidanu et al., 2004; Kidanu et al., 2005; Ceccon, 2005; Sun et al., 2021; Rose and Adiku, 2001). Given landscape changes are driven by intricate and multifaceted drivers, they always accompanied by newly emerging land use systems evolved with unintentional land management practices. Interestingly, as detected by the recent satellite images and confirmed by FGDs, following a declining market demand for eucalyptus, the income from eucalyptus trees has declined (since 2020). As a result, farmers started to removing eucalyptus and planting cereals on the same field. Such dynamic land management systems confirm that smallholder farmers are risk-averters who can immediately apply an adaptive LUS in response to any unforeseen pressure or driver that negatively affect existing practices. Particularly, a new succession of land use system from eucalyptus fields to maize and vice versa is a transformative land use system, which could falsify the alleged myths about eucalyptus species in the agricultural sector (Daba, 2016; Jaleta et al., 2016). Although there is limited scientific evidence that shows planting eucalyptus trees is an agroforestry practice (Kidanu et al., 2004; Ceccon, 2005), authors got convinced that rotationally growing eucalyptus trees with cereals will be a likely agricultural practice.

Such overlooked implications of land use shifts deserve to be studied. FGD and KII results show that converting croplands to eucalyptus plantation is considered as an important indirect and underlying cause for inheritance linked loss of land holding and use rights, which instigated household level conflicts, and often ended up without migration and landlessness. On the basis of our FGD, KII, and survey findings, expansion of eucalyptus plantation escalated land scarcity and land-related conflicts spanning from household to community and state.

Land use transformation in the study area has direct and meaningful socio-cultural impacts. Over the analysis period, estimates show that above 23,000 ha of productive cropland was converted into eucalyptus plantation. If it were used for crop production, that land would equivalently accommodate above 30,000 HH or 100,000 persons (Table 4). In other words, the conversion of approximately 23 thousand hectare of cropland into eucalyptus plantation mean that an equivalent of 30, 00 HHs lose their farmland to eucalyptus, a situation which aggravates the extent of cropland to population ratio by half and subsequently high rural out migration among the rural youth. Also, the volume of grain production and the entire food systems and the livelihood of the society are negatively impacted by shifting the land use system.

The ecological implications of converting eucalyptus stand into cereal production have been thoroughly studied by several researchers (Daba, 2016; Jaleta et al., 2016; Michelsen et al., 1993; Chanie et al., 2013; Yitaferu et al., 2013; Nasrallah et al., 2020). Growing eucalyptus species can capture nutrients, reduce nutrient leaching, and improve soil water holding capacity sustainably compared to cropland (Tully and Ryals, 2017a; Tully and Ryals, 2017b). Nutrient recycling is required to maintain soil productivity at the field scale and biogeochemical cycling at regional and global levels (Ghaley et al., 2014). This is the reuse of organic residues from agricultural biomass and soil vegetation. Some studies also suggested that growing a mixture of eucalyptus species and N-fixing acacia also helps to stimulate the cycle of soil organic matter (SOM), N, P, Ca, Mg, and K by breaking down leaf residues compared to monoculture (Forrester et al., 2006; Forrester et al., 2010; Tchienkoua and Zech, 2004; Nasrallah et al., 2020; Lemma et al., 2006; Voigtlaender et al., 2019). Mixing N-fixing plants with eucalyptus is a good alternative for maintaining soil fertility by improving soil nitrogen cycling in fast-growing plantations established on tropical soils. In addition, a higher nutrient cycling can promote a positive nutrient balance in mixed plantation ecosystems (Tchienkoua and Zech, 2004).

The present assessment findings revealed that land use dynamics has direct and meaningful socio-economic impacts. In this study, although experimental research studies and laboratory analysis were not done, assessment on the ecology was performed taking three ecological impact indicators, namely, growth condition (# of stand per area), comb size and number (#/stand), and productivity (gross grain yield in terms of kg/area). Based on the facts obtained from samples plots, approximately 10% of the sample plots in EC have multiple combs per stand, whereas only 5% percent of the CC samples have multiple combs per maize stand. This finding is in agreement with a study by Desalegn et al. (Tadele and Teketay, 2014), which states that maize crop grown on clear-felled eucalypt stands were taller and developed larger leaf areas than those grown on continuously cultivated farms. Not only on growth performance, dry matter production, and comb per stand, maize fields established on clear-felled eucalypt stands have showed better performance in grain yield per unit area. Indeed, this calls for further studies to be conducted considering a wider range of eucalyptus species, site conditions, management practices, soil properties, and cost of removing stumps. To attest this, yield variation assessment was performed from four representative clusters and 125 paired and adjacent sample plots. Alike the biomass (maize stand and comb/stand), the yield difference assessment result showed a higher grain yield was recorded from plots with E-C plots than C-C plots. Detailed sample by sample yield differences is presented in Figure 11.

Based on yield data recorded on sample plots of three cluster (less cluster 4), one can generalize that the practice of converting eucalyptus to cereal-based crop production gives a higher yield, at least in the first production year. However, a contradicting fact recorded from cluster 4 samples falsifies such generalization. Indeed, a recent study by Desalegn et al. (Tadele and Teketay, 2014) reported approximately 50–60q/ha yield EC fields compared to 30–40q/ha on CC fields. Regardless of the factors associated with it, such findings will enhance the predicament of the tree. We learned that yield differences between E-C and C-C considerably vary in spaces than perceived and need in-depth study. At least, evaluating the relationship that could exist between the dependent variable (yield) and the explanatory variables such as soil depth, soil types, slope, and soil quality factors like pH at required temporal and spatial scales is critical to come up with conclusive evidence applicable for all conditions. Authors confess that the facts presented by the present study will never end the long-standing alleged controversy with eucalyptus except long-term monitoring.

The monetary-based evaluation of trade-offs existing between grain production (taking Maze crop) in agriculture land use against timber (eucalyptus pole) and non-timber products (firewood and charcoal) when used for eucalyptus plantation revealed extraordinary differences. As per the cost–benefit analysis result, opportunity cost of converting crop fields into eucalyptus fields is approximately 600,000 Quintal of maize per 135,000 ha area of a landscape. In other words, this could feed approximately 120,000 people or 24,000 HH every year. Contrarily, the people residing in the study area should purchase or import an equivalent amount of grain demand to feed the society. While cereal production excels eucalyptus plantation from landscape productivity perspective, eucalyptus-based land use system better performs from input versus output (benefit) perspective. Due to this reasons, a majority of HH who have very small land holding size preferred to plant eucalyptus on their limited farmland and out-migrate seeking another livelihood options.

Children of a household that had more plots planted with eucalyptus are likely to be landless, and hence, most of them migrate out to towns as they lose interest to rent-in plots planted with perennial trees. An interviewee farmer recapitulated how planting eucalyptus on crop fields breeds landlessness and migration of the youth. Here are his accounts:

> I have five plots of land, which altogether make 1ha of land. I intentionally planted eucalyptus on all of my plots, postulating that my children will lose interest to inherit any plot planted with Eucalyptus. I produce my household food on croplands, which I rented in from others. In the end, all of my children migrated and I retained tenure of all the plots.

This research showed that converting crop fields to eucalyptus plantation is an underlying cause for increasing landlessness and massive rural outmigration.

As a result, in smallholder-based mixed farming, regardless of the monetary benefits, eucalyptus plantation will continue as important land use system and livelihood option for smallholders who suffered by land scarcity. Although the presented evidence remains short to draw conclusions, it still reveals interesting ecological and economic implications between such a competitive land use systems (agricultural production and forestry).

5 Conclusion and recommendations

The present study demonstrates the dynamics of land use changes between croplands and eucalyptus tree expansion in the study area over the last two decades until 2023. Dynamic LULC changes were detected and mapped where much cropland and pasture land were converted into eucalyptus plantation fields for much of the period covered by the study, but a reversal trend is on the roll during the last 5 years in general, during the last 2 years in particular. It was also found that farmers' land use decisions are informed largely by economic considerations, not by scientific land use planning and ecological contemplations. When market demand for eucalyptus logs and income from the sale of eucalyptus were high, farmers converted large areas of crop and pasture lands to tree plantations, but during the last 5 years, they cleared the eucalyptus from more and more plots and restored cereal crops following the fall of demand for eucalyptus tree products. Land use changes have important bearings on household and community level livelihoods, food security, and the whole continuum of the food systems. Shortage of farmland and landlessness are immediate consequences of those changing land use systems.

Another notable conclusion to be drawn based on the evidence generated by this study contests the widely held seemingly mythological misconception that 'eucalyptus plantation negatively affects soil fertility and leaves plots dry and unproductive'. Contrary to that misconception, higher maize yields were obtained from eucalyptus-cleared fields compared to from non-converted crop fields. Cleared fields also required less supply of farm inputs such as fertilizers. This shows that landscapes which had been covered with eucalyptus plantation are rather more productive when reconverted into cropland for cereal crops production. In addition to the spatiotemporal dynamics, assessment results imply smallholders' land use decisions are dictated more by temporal economic considerations than by the ecological impacts of eucalyptus trees.

The findings contest the alleged popular myths about eucalyptus trees as smallholder farmers in the case study area often make rational choices and land use decisions based on socio-economic imperatives instead of sticking to alleging eucalyptus based on its traits. In smallholder farming system, where land has become a scarce resource, focus shall be given to a multiple benefit (economic, social, and ecological) land use planning as their contribution to enhance land use efficiency is imperative and essential to ensure a sustainable land use system. On the other hand, in contexts where conversions into eucalyptus tend to have high economic opportunity loses, land policy issues, specifically tenure security, in turn will have far-reaching bearings on food production, availability, food security, and the entire food systems. Nonetheless, to arrive at a conclusive result, using time series data, further empirical studies need to be conducted at different geographic areas in the country (such as south, east, west, and central parts of Ethiopia).

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical review and approval were not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the patients/participants or patients/participants legal guardian/next of kin was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

GZ: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. TK: Conceptualization, Supervision, Validation, Visualization, Writing – original draft, Data curation, Investigation, Methodology, Software, Writing – review & editing. MT: Conceptualization, Data curation, Validation, Visualization, Writing – review & editing. ET: Writing – review & editing. AG: Data curation, Formal analysis, Software, Writing – review & editing. YA: Writing – review & editing. FG: Methodology, Project administration, Resources, Writing – review & editing. CW: Funding acquisition, Project administration, Resources, Supervision, Visualization, Writing – review & editing. GO'D: Data curation, Formal analysis, Project administration, Software, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. This research was supported by the Water Security and Sustainable Development Hub which is funded by the UK Research and Innovation's Global Challenges Research Fund (GCRF), grant number: ES/S008179/1.

Acknowledgments

The authors express their sincere gratitude to the editors and reviewers for their insightful comments and constructive suggestions, which significantly enhanced the quality of the manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2024.1393863/full#supplementary-material

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frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 06 November 2024
DOI 10.3389/fsufs.2024.1420700

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OPEN ACCESS

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RECEIVED 20 April 2024
ACCEPTED 23 September 2024
PUBLISHED 06 November 2024

CITATION
Kassawmar T, Teferi E, Tsegaye S, Bewket W, Zeleke G, Abraha L, Walsh CL and O'Donnell G (2024) Spatiotemporal variation in grain production performance and efficiency of the cultivated landscapes in Upper Blue Nile Basin of Ethiopia: the impact of residual moisture-based farming on water and food security.
Front. Sustain. Food Syst. 8:1420700.
doi: 10.3389/fsufs.2024.1420700

Spatiotemporal variation in grain production performance and efficiency of the cultivated landscapes in Upper Blue Nile Basin of Ethiopia: the impact of residual moisture-based farming on water and food security

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Analysis of grain production performance can provide reference information to explore multiple cropping options and further improve the resource use efficiency of farming methods. This study investigated the spatiotemporal dynamics of grain production performance and efficiency of major crop production systems (CPS) in the Ethiopia's Blue Nile Basin. The results show that only 39% of the basin is currently cultivated, although a significant cropland expansion (10%) was recorded between 1985 and 2020. The study identified 11 major CPS, mostly practiced in the basin. Of these, single cropping based on the main rainy season (Meher-Only) covers the largest area (26%), followed by Meher-Residual-Intermittent (12%) and Meher-Belg-Dependable (11%). Extended-Meher, Meher-Residual-Dependable, Meher-Residual-Intermittent, and Meher-Belg-Dependable are the four more powerful CPS with higher efficiency. Comparatively, CPS practiced in Wet-Woyna-Dega and Wet-Dega have better overall performance. Findings confirm that agricultural space management (land) and green-water (rainfall) utilization are the most influential factors, followed by land use planning and land use systems (CPS) invention. As landscape suitability for grain production governs future performance, in the low elevation and flood plains parts of the basin, the possibility of creating additional space into the food system is very high. In mountainous and high-altitude regions, the efficiency of grain production will decrease because incorporating additional arable land into the food system is trivial. In the last three decades, in BNB, only 10% of arable land (equivalent to 30 million quintals of food) has been added to the good system, which can support approximately 6 million people. Compared to the population growth of the basin (12 million 1985–2020), its contribution to the food system was less than 50%. This confirms that multiple cropping systems, such as Residual moisture-based CPS, have played a significant role in boosting the food system in the basin. Therefore, improving grain production performance/efficiency requires targeted investments, including the invention of more adaptable crop varieties, efficient cropping practices, and the introduction of advanced agricultural space and water management technologies. The results of the study will help identify important policy gaps and suggest possible options to enhance residual farming and other multiple cropping systems.

KEYWORDS

residual farming, grain production, Blue Nile, water security, food security, soil moisture, Ethiopia, land use efficiency

1 Introduction

As a developing agricultural country, Ethiopia relies heavily on rainfed agriculture for almost 95% of its food production, making its development strategies a global topic of discussion (Ahadu, 2019). With the population expected to double in 20 years (CSA, 2020), Ethiopia must develop a strategy to double food production accordingly (Endalew et al., 2015). In 1990, the food requirement for 45 million people was 350 million quintals per year (Taddese, 2001; CSA, 2014). By 2020, this need increased to almost 1 billion quintals for over 120 million people (CSA, 2020; Tekeste, 2021). Increasing food shortages have resulted in increasing food insecurity (Wani et al., 2009; Rahmato, 2003; Zerssa et al., 2021; CSA, 2020). Opinions differ on the reasons for Ethiopia's increased grain production: some attribute this to land management and inputs, while others point to the expansion of cultivated areas. The literature shows that total grain produced from the area under cereal crops has increased significantly, from 60 to 80 million quintals in 1980/85 to 316–350 million quintals in 2020/23—an overall increase of 300% (CSA, 2020). The CSA attributes this growth primarily to productivity improvements. Non-spatial data show that the cultivated area of the country increased from 5 to 6 million hectares in 1980–85 to 14–17 million hectares in 2020–23, with productivity increasing from 10 to 12 quintals per hectare to 26 to 28 quintals per hectare (CSA, 2020; Teshome, 2014). Overall, existing data on grain production are inconsistent and do not provide a clear picture of spatiotemporal trends, potentially leading to misjudgment of the development trajectories of the country.

The main data source for agricultural production in Ethiopia is the Central Statistical Agency (CSA) (Teshome, 2014). Although CSA national census data are detailed and spatially comprehensive, they have limitations in temporal coverage and accessibility. Annual agricultural surveys provide more consistent temporal data but lack detail and representativeness. Regional and seasonal variations in crop production systems (CPS) create inconsistencies in the literature and make it difficult to understand trends in cropland and grain production at larger scales (Teshome, 2014). Although case study data can provide greater accuracy, its inconsistencies and terminological differences hinder scalability to the national level. Therefore, conducting spatially explicit analyses of spatiotemporal trends in grain production and productivity is challenging. In addition, outdated and poorly managed information makes it difficult to integrate and update, further hindering effective planning and evidence-based decision-making. In summary, there exist about four main limitations that lead to data inconsistencies in grain production: (i) methodological issues, (ii) different definitions and meanings, (iii) lack of thematic detail and scope, and (iv) spatial and temporal limitations with (v) data management issues. To address these root causes, the authors have identified four key research gaps: (1) the need for spatially explicit and multi-temporal data, (2) limited local knowledge about the potential and challenges of crop production systems (CPS), (3) financial and methodological challenges in regularly assessing land use or cultivation practices, and (4) technical limitations.

Data inconsistencies are mainly caused by differences in definition, meaning, and approach and lead to incorrect assumptions (Kassawmar, et al., 2018b). Many studies typically attribute changes in grain volume to (a) changes in arable land (Teshome, 2014) and (b) changes in inputs (Silva, et al., 2021). However, other particularly overlooked factors include land allocation strategies and land use shifts as well as changes in crop production systems (CPS) (Korbu, et al., 2020). The former deals with land use and land cover changes (LULC), while the latter refers to changes in land use systems (LUS). The spatiotemporal dynamics of grain production reflect the diverse types and forms of land use systems (LUS) and crop production systems (CPS) across the globe, influenced by local variations in climate, soil, economic factors, social structures, and historical contexts (Yu et al., 2021; Lesur-Dumoulin et al., 2018; Panigrahy et al., 2011; Wu et al., 2015). The nature of CPS in Ethiopia is extremely complex as they are conditioned by unpredictable spatiotemporal dynamics of the two governing factors: agricultural space/land and water coupled with farmers' knowledge (Lairez et al., 2023; Abera, 2017). Spatiotemporal changes in grain production are primarily driven by two key farmers' decisions: (i) shifts in land use or reallocation and (ii) the introduction of new CPS. As water and land are limited resources, increasing grain production should focus on efficiency, rather than unlimited expansion of inputs such as space and water (Nasrallah et al., 2020; Biswas et al., 2006; Zhao et al., 2021). Instead, land use decisions and CPS should focus on continuously improving grain production levels through effective land allocation and reallocation as well as enhancing the land utilization performance of farming systems (Liu J. et al., 2020; Berhanu et al., 2021). This can be achieved by co-designing appropriate land use plans and co-inventing efficient CPS, and making evidence-based land use decisions (Panigrahy et al., 2011). To realize a food-secure society in the basin, developing effective land use plans and high-performance CPS, effectively managing agricultural spaces and green water is crucial. These strategies require spatially explicit evidence of natural capital and proper understanding of the various CPS. Integration of such data can improve planning and decision-making through detailed assessments of land use performance (LUP) and land use efficiency (LUE). However, there is a lack of comprehensive studies assessing cultivated land dynamics and CPS at the required scale and level of detail. The first important move is generating multi-temporal cropland data, map and characterize existing CPS, and conduct in-depth assessments of rainfed grain production performance and its impacts on economic development, food security, and water security at the catchment scale.

Previous LUE studies have been performed from input–output perspective (Nasrallah et al., 2020; Silva et al., 2021). However, as grain production efficiency is largely governed by the inherent potential of the natural capital (space, water, climate, etc.) and the performance of the land use practice or efficacy of a particular CPS in response to inputs, studying the performance of CPS and cropping practices has paramount importance (Lairez et al., 2023; Sun et al., 2021; Biswas et al., 2006). Very recently, grain production research tended to focus on large-scale and multidimensional approaches to spatial econometric analysis, which allows analysis of the level of grain production, spatial distribution, and contribution of each production factor at the regional scale from an economic standpoint (Liu J. et al., 2020) or analysis of regional food security by measuring food production capacity and potential (Nkwasa et al., 2023). However, a common research gap is overlooking the incorporation of the space and time dimensions in the assessment, which, in turn, hinders a synoptic perspective of grain production dynamics.

Existing studies on LUE have two focuses: (i) single-use and (ii) combined-use system-oriented assessments. While the former ignores the synergy and trade-off that exist between several possible LUS, it emphasizes only on single and specific land use systems, for example, the cultivated land use system (Liu J. et al., 2020). Indeed, from a specific category of LUSs, various sub-categories can exist; for example, within a cultivated landscape, varying crop Production/cropping systems (CPS/CRS) exist. In that case, the performance assessment may require to single out specific practices, as residual soil moisture farming can be selected and assessed. However, still the former category of LUS performance and efficiency assessment approach disregards the interplay between CPS in a given landscape. The second category of performance assessment gives an equal focus for all existing land use systems, such as grain production, timber production, pasture production, and urban and settlement, which fulfills multidimensionality. It helps evaluate the performances of different LUS from the perspectives of resource utilization and strives to explore the relationship between the LUE of varying LUS and its link with socioeconomic development (Wang et al., 2022). According to Liu J. et al. (2020), such an approach allows to evaluation of the synergy and trade-off, while evaluating the performance and efficiency of LUS and/or CPSs. Nonetheless, previous studies mainly focused on the comparison of regional grain production differences but ignored the spatial interaction and impacts among land use sub-category performances/efficiencies and the vast variances in crop production within the same area. This necessitates the need to undertake a synoptic assessment of cropland change and CPS applying a multidimensional land use performance/efficiency assessment framework (Liu J. et al., 2020).

Recognizing the need to better understand the spatiotemporal trends in grain production, this study was conducted with the following specific objectives: (1) to map and assess the spatiotemporal dynamics of grain-producing landscapes of the UBNB; (2) to map and characterize major CPS targeting the spatiotemporal variation in grain production; and (3) to assess the performance and efficiency of rainfed-based CPS with special focus on Residual soil moisture Crop production System (RCS).

2 Materials and methods

2.1 Description of the study area

The study area is the Upper Blue Nile Basin (UBNB) commonly known as the Abbay River basin (Nkwasa et al., 2023; Roth et al., 2018). UBNB is part of the greater Nile River, covering only the Ethiopian part. It is located in the Northwestern part of Ethiopia's highlands covering approximately 200,000 km^2. The geographical location, extent, and basic spatial data about UBNB are presented in Figure 1. UBNB hosts approximately 79.6 million people (Teshome, 2014). It is the frontier area of Ethiopia's water and agricultural development basin, with a national land area of 1.12% carrying a population of 5.78% and a total economic output of 10.22% due to its superior geographical location and mild climate. Nevertheless, the area also suffers from severe resource shortage, with a *per capita* arable land area of only 0.75 ha/hh, which is below the national (0.78 ha/HH). With rapid economic and social development, regional water development has a significant crowding effect on agriculture and ecological space (Wani et al., 2009). As with other basins in Ethiopia, UBNB has also faced development constraints such as intensified conflicts in water utilization and space utilization for competing land uses, degradation and reduction in cultivated land resources, environmental damage, loss of biodiversity, and widening development gaps between regions. More importantly, as a typical economically less developed area in Ethiopia, the UBNB basin serves as an excellent example of regional development for other areas in Eastern and Horn of Africa developing countries (Hurni et al., 2013). Particularly, it presents a typical case study for assessing land use sub-category efficiencies and coordinating conflicts based on food production, economic development, and ecological protection.

2.2 Data types and sources

Several socioeconomic and biophysical data, with spatial and non-spatial nature, were collected from multi-sources and applying different data collection methods, such as (I) field visit/ground survey, (II) socioeconomic survey, (III) remote sensing, and (IV) other secondary sources.

2.2.1 Socioeconomic survey

Applying FGD and KII tools, basic socioeconomic data, such as total cropped land, productivity, production systems, cropping systems, and cropping calendar, were collected at the village/Kebele level. However, for some specific assessments, data collected at the village level remain scarce to obtain representative facts. Thus, for detailed assessments such as yield gap and food demand, comprehensive data were collected from systematically selected zones and districts found in the UBNB (CSA, 2020).

2.2.2 Remote sensing data

Fifteen-day composite NDVI (Normalized Difference Vegetation Index) products of two sensors, Sentinel 2A and MODIS satellite sensors, were important inputs for the analysis. Using Google Earth Engine (GEE), the bimonthly NDVI data, for the year 2015–2022, were systematically collected from October to May (Lebrini et al., 2021). The reasons to use only these periods are (i) due to cloud cover problems

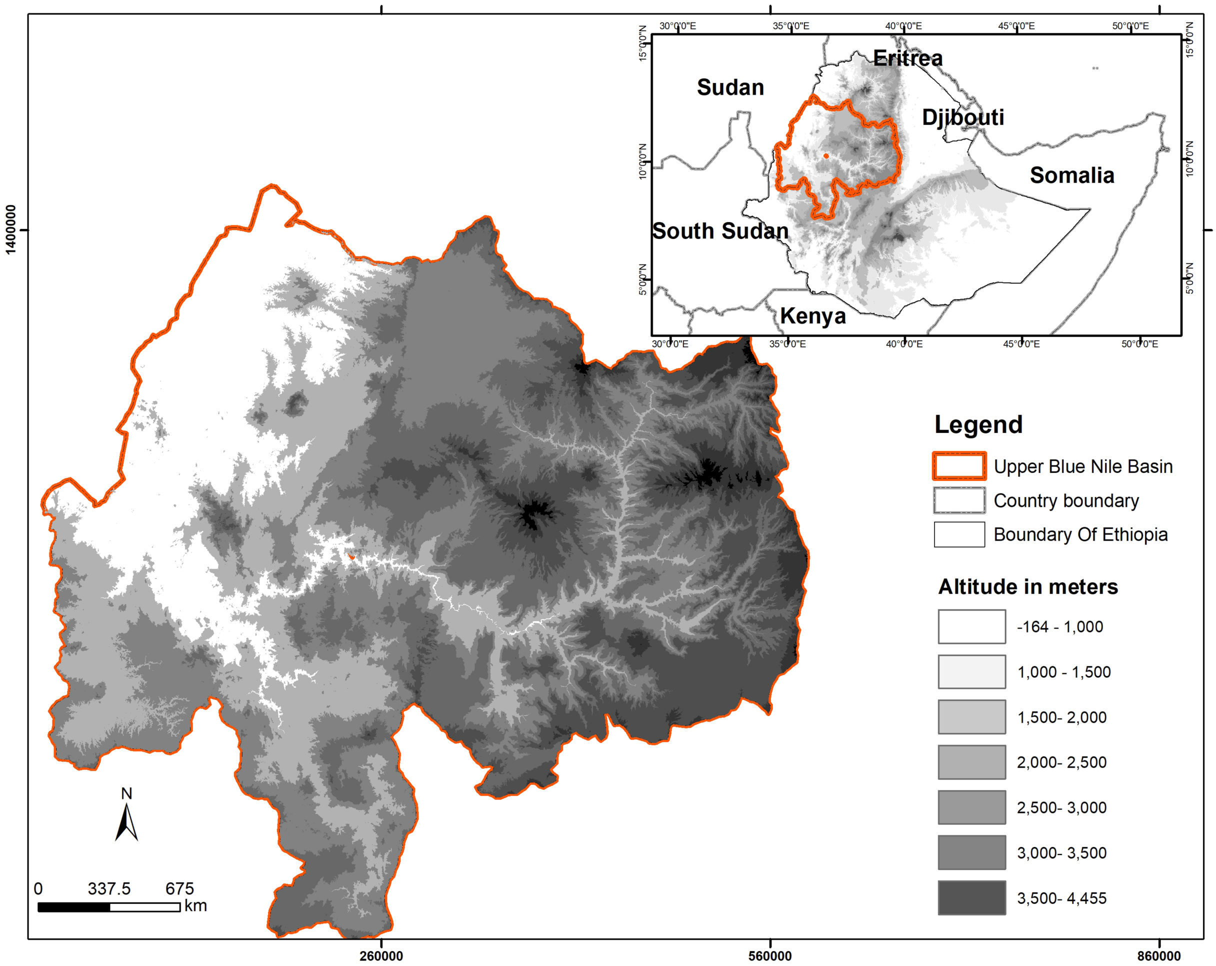

FIGURE 1
Geographic location of the study area (UBNB) with basic topographic and climatic information.

in the rest of the months of the year and (ii) the targeted CRSs, i.e., RSM and BRF cropping systems, are practiced only during these months of the year. Multitemporal NDVI data-based spectral profile was generated for each CPS taking representative sites in terms of AEZ, crop types, cropping practices, etc. (Liu L. et al., 2020; Peng, 2012). Using a fifth-order polynomial fitted model, the beginning and end dates of cropping cycles were computed, which were used to identify the spectral emergence and spectral maturity date (Cheng et al., 2023; Panigrahy et al., 2005). In order to compute the total duration (di) of a cropping system, 10 days was added at the beginning (15 days for rice crop) and 10 days at the end of each crop-growing period (Qiu et al., 2023). These days account for the duration of field preparation, the gap between sowing and spectral emergence, and the gap between spectral maturity and the harvest of the crop (Panigrahy et al., 2005).

2.2.3 Other secondary data

Three categories of secondary-sourced geospatial data were used: (1) bio-climate; (2) edaphic, and (3) detailed LULC maps (Kassawmar et al., 2018a). In the former case, World Bio-Climatic data, containing approximately 19 determinant factors/variables, were used to identify CPS and cropping systems and further explore the link between RSM-based CPS and determinant factors and further predict the spatial distribution of the practice. Bioclimatic variables are sourced from the freely available WorldClim 1.4 database for scientific research purposes, as indicated in Supplementary Figure 1. Historical climate data, essential for assessing the impact of climate change, will be acquired from the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC5 or CMIP5) at a spatial resolution of 30 s (1 km)[1] from 1900 to 1990.

In the later case, detailed LULC data, produced by the lead-author was used and available at ethiogis-mapserver.org, https://www.ethiogis-mapserver.org. Detailed inforamtion is available at Kassawmar et al, 2018a and 2018b.

These datasets are presented as Supplementary Figure 2.

2.2.4 Field survey

Various spatial and non-spatial first-hand data were collected through recursive field visits and extensive ground surveys on systematically selected villages. Data were collected from the ground, and secondary data were obtained from pertinent governmental offices at different levels. Eventually, a holistic database comprising various information about the

1 https://www.worldclim.org/

biophysical and socioeconomic aspects of the different CPS and cropping practices was developed.

2.3 Data analysis

2.3.1 Processing data

Mapping cropped pixels and clustering of CPS/CRS zones over large and complex landscapes characteristically depict smallholder farming, which is not trivial (Reckling et al., 2016; Liu J. et al., 2020; Yu et al., 2021; Kassawmar et al., 2018b). From clustering and a classification point of view, two categories of datasets were used: non-spectral and spectral datasets (Reckling et al., 2016). The present study used both multi-source and multi-scale spatial datasets to produce crop production systems zones (CPSZ), thereby mapping and characterizing cropping practices.

2.3.2 Non-spectral approach

Specialists in the field suggest that applying non-spectral solutions out of image analysis techniques (Kassawmar et al., 2018a; Reckling et al., 2016) can help a lot to minimize the challenges. Non-spectral cluster analysis can be strategized based on several premises (Kassawmar et al., 2018a), one of which is stratifying the landscapes based on major characterizing features such as cropping system similarities (Kassawmar et al., 2018a). Given the characteristics of different CPS can be explained and described using non-spectral information that exists in various determinate factors, the world bioclimatic datasets, containing 19 layers, were used as an important dataset for stratification. Before using the World Bioclimatic datasets for clustering, spatial dependency and redundancy were tested by applying PCA. From the PCA result, five datasets, with a varying number of principal component images, were generated. From these generated PC images, it is evident that most of the information has been concentrated in the first three PC images as shown in Supplementary Figure 1.

2.3.3 Spectral approaches

This study used multi-temporal raw satellite imageries, transformed indices, and produced CPSZ and cropping practices (Kassawmar et al., 2018a). Unlike images containing raw reflectance values, multi-temporal but transformed images are effective in identifying and map complex CPS (Aziz et al., 2023; Cheng et al., 2023). Thus, to gain a couple of benefits, composite multi-temporal indices were produced: (1) simplification of the classification process, (2) enhancing the inherent potential of multi-temporal and multi-spectral imageries (Cheng et al., 2023). Therefore, appropriate MODIS image data collection was done in Google Earth engine and required MODIS data were composite NDVI images as an important input to create HCPZ and further identify and map cropping systems. The creation of multi-temporal and multi-spectral NDVI datasets was designed to accomplish three major objectives of the study: (1) producing HCPZ and (2) identifying, mapping, and assessing major cropping systems and practices (3) undertaking reliable land use and cropping system performance assessment. In the former case, important factors that govern CPS such as growing seasons, LGP and AEZ were considered while creating a composite NDVI map. In the latter case, the phenology of major crop types and cropping calendar for major cropping systems were considered. While downloading and producing composite NDVI data, phenology of crops was assumed to be the same in 10–15 time (Peng, 2012). From the available multi-temporal images within the defined 15 15-day phenology period, first, a maximum NDVI value was selected and one NDVI raster dataset was created. Each NDVI raster dataset represents one phonological stage of the dominant crop, for instance, planting or seeding. Then, a series of NDVI maps representing the full range of the crop phenology over a defined growing period (Crop calendar) were created. Later, the intra-annual multi-temporal NDVI raster dataset was staked and a composite NDVI raster dataset with two bands in a month and six bands in 3 months was created (Lebourgeois et al., 2017). This allowed us to capture the intra and inter-annual phenology dynamics, which can be used to classify farm fields managed under different CPSs (Rose and Adiku, 2001; Griffiths et al., 2019).

2.3.4 Clustering and classification

Mapping and delineating of CPS demand the identification of major crops and accordingly delineation of their growing regions/boundary through an iterative clustering process by which the Homogeneous Crop Production zones (HCPZ) can be created (Nath et al., 2022).

2.3.5 Identification and scoping of CPS types

Proper delineation of CPS requires explicitly defining a specific type of CPS and practices targeted to map and characterize. The present study targeted to map and characterize only rainfed-based CPS and CEP.

2.3.6 Creating a database

A hybridized and multi-stage clustering approach was implemented. For this purpose, at the pre-processing stage, two categories of geodatabases containing non-spectral and spectral layers were separately created. Some of the datasets, included under the non-spectral category are World Bio-Climatic data, AEZ maps, administrative boundary-based crop production data, and other auxiliary spatial layers. On the other hand, LULC maps, cropped pixels, crop phenology, and vegetation indices are some of the datasets included under the spectral category. Eventually, one raster layer, containing about 25-factor maps or layers, was produced. Depending on the level of dependency, redundancy, and importance of the non-spectral factors, about five composite datasets, with varying bands (19, 17, 15, 10, and 5), were created using layers included under the non-spectral geodatabase.

2.3.7 Creating of homogeneous spatial units

Using the five composite datasets, random homogeneous spatial units (HSU) were separately generated by applying the ISODATA clustering algorithm. The generated HSUs were iteratively checked with our primary data collected to identify and describe the different types of CPS. Using this reference information and HSU generated by a specific composite dataset, the effect of inclusion or exclusion of a particular factor/layer in delineating CPS was evaluated. The generated smaller HSU polygons helped us know the appropriateness of a particular factor/layer. By cross-checking the boundary of the HSU with multi-temporal spectral behaviors of surface vegetation cover (such information available from the spectral datasets), generalization and grouping of smaller HSU maps helped us to cluster areas with similar growing seasons. A major growing season zone map was eventually produced by integrating several secondary geospatial data, such as AEZ, farming systems, livelihood zones, and land use systems zone maps (Vintrou et al., 2012; Grytnes and Vetaas, 2002).

2.3.8 Creating training samples

Integrating various socioeconomic primary data, such as Village/Kebele level crop production data (polygonal level training sample dataset), FGD, KII, as well as ground-based physical observation data (point level training sample datasets), training datasets were developed. Accordingly, a sufficient, representative, and accurate training sample dataset was produced. Approximately 459 sample points, on average 30 samples from each growing season zone map, were systematically developed. Using the training sample dataset, spectral signatures for each GS and CPS were iteratively generated and checked. Approximately 30% of them were used for validation and the remaining 70% were used to train the clustering algorithms.

2.3.9 Creating of homogeneous crop production zones and crop production systems

Through iterative execution of the above steps, the actual clustering of HCPZ was performed by producing a refined composite dataset developed by selectively taking important layers from both categories of the geodatabase (spectral and non-spectral). Two clustering approaches were tested; unsupervised and supervised. For the former case, we chose Random Forest and Support Vector Machine algorithms, and for the latter case, we took ISODATA and K-Means algorithms. Recursive evaluation of these clustering algorithms was performed at different scales; local, meso, and basin scales. The evaluation results confirmed that the ISODATA algorithm gave a better accuracy and good quality boundary of growing seasons and varying CPS zones. Thus, a final HCPS zone map was produced by applying an iterative unsupervised clustering approach on the multi-source composite dataset (spectral and non-spectral) by applying the ISODATA clustering algorithm. Finally, approximately 45 HCPS clusters were generated that could represent the complex rainfed CPS of the UBNB. Involving eight experts in the field, expert knowledge, coupled with the comprehensive ground survey, GPS, quantitative and qualitative socioeconomic survey as well as other secondary data, the ground reality representation of each cluster was systematically checked and verified. The HCPSZ map is provided as Supplementary Figure 3.

2.3.10 Creating indicator layers and producing indices

Using multi-source data, pertinent indicators useful for the identification, mapping, and performance assessment of cropping practices in each CPS were produced (Supplementary Table S1 and Figures 2,3). For simplification and generalization purposes, continuous quantitative values in each index were further classified and reclassified into qualitative values as such; very high, high, medium, low, and very low. Detailed information and maps of the input layers used for the assessment are presented in Figure 2.

2.4 Land use performance/efficiency assessment framework

As far as rainfed-based multiple (CPS/CRS) potential and performance assessment is concerned, available pertinent studies on land use systems efficiency have two main focuses: (i) single-use and (ii) combined use system-oriented assessments. While the former ignores the synergy and trade-offs exist between several possible LUS, it emphasizes only on single and specific land use systems, for example, the cultivated land use system (Lin and Hülsbergen, 2017; Yerseitova et al., 2018) and industrial land (Xie et al., 2018). Indeed, from a specific category of LUSs, various sub-categories can exist, for example, within a cultivated landscape, varying (CPS/CRS) exist. In that case, the performance assessment may require to single out specific practices, like RSM and/or BRF can be selected and assessed. However, still the former category of LUS performance and efficiency assessment approach disregards the interplay between CPS in a given landscape. The second category of performance assessment gives equal focus to all existing land use systems such as grain production, timber production, pasture production, and urban and settlement from a multidimensional perspective such as sustainability. The second category helps evaluate the performances of different LUS from the perspectives of resource utilization and strives to explore the relationship between the LUE of varying LUS and its link with socioeconomic development (Masini et al., 2018), urban growth (Halleux et al., 2012; John et al., 2019), environmental constraints (Saikku et al., 2017; Searchinger et al., 2020), and economic transformation (Guastella et al., 2017; Lu et al., 2018).

To evaluate the performances and efficiency of different CPSs, we applied multidimensional land use performance and efficiency evaluation frameworks widely used for similar purposes (Liu J. et al., 2020). According to Liu J. et al. (2020), a multidimensional land use and crop production performance/efficiency analysis has three major dimensions, namely: (1) food production, (2) economic development, and (3) ecological maintenance. After thoroughly assessing the assessment framework, we customized the framework because (i) Liu J. et al. (2020) demonstrated the framework by taking all types of land use systems and taking three important sustainability dimensions. Although they demonstrated the framework for general LUS evaluations, authors considered only crop production as important in the evaluation of the land use system element. Moreover, contextually adapting the framework, the present assessment was performed after systematically identifying seven evaluation categories/dimensions: (1) natural land capacity and Technical feasibility measures (it compares the natural capacity of the landscape and environmental/ecological suitability of the landscape for a particular LUS/CPS); (2) land utilization performance measures (it evaluates the performance of CPS/CRS in terms of utilizing the land resources or the natural capital/land quality to produce grain); (3) production performance measures (it evaluates the performance of a particular CPS/CRS in terms of the production of grain per unit of inputs mainly land, water and time against the inherent the inherent capacity); (4) economic development measures (it evaluates the economic development contribution of a particular LUS/CPS in a particular landscape in terms of economic value of the produced grain over a given period of time); and (5) ecological maintenance measures (it measures the balance between production service against the regulatory and supportive functions); and (6) implication measures (it measures the overall grain production performance of a particular LUS/CPS in reference to food security. (ii) Given the framework is very young, as it stands, obtaining the required data for all indicators used in all three dimensions is difficult, specifically, regional expectation, overhead room, land use efficiency, and unused potential evaluation, we focused only on the performance and efficiency evaluation parts of the framework. (iii) As presented in Liu

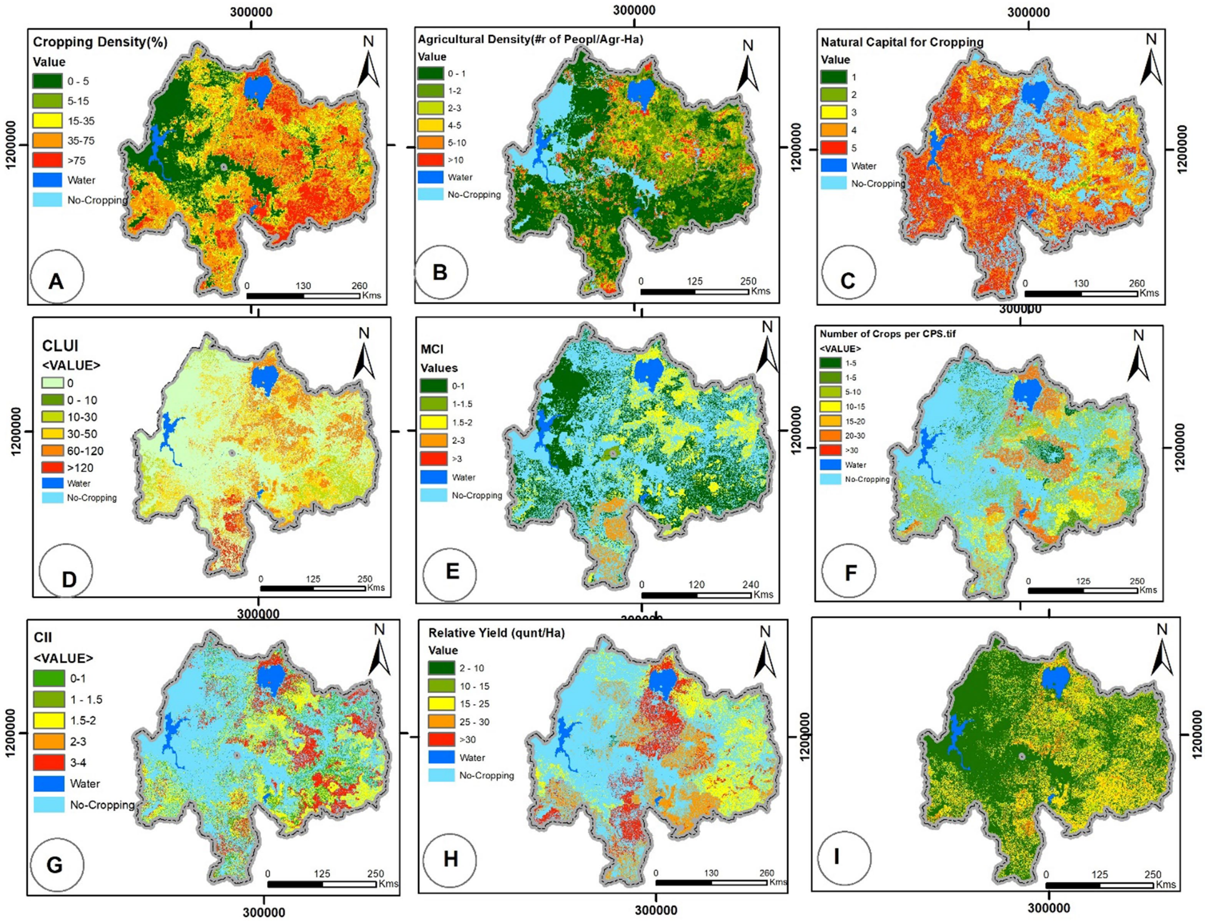

FIGURE 2
Actual values of variables/indices used to assess the land utilization and production performance/efficiency of different CPS: CDI **(A)**, AGDI **(B)**, Natural capital for crop production **(C)**; CLUI **(D)**, MCI **(E)**, AGDI **(F)**, CII **(G)**, RYI **(H)** and GGSI **(I)**.

J. et al. (2020), the framework is demonstrated using dimension by dimension and composite or overall performance and efficiency indicators. While testing the framework, authors found that the dimension-by-dimension approach of the framework could hide some important facts that could unveil the reasons for some land use trade-offs. Thus, in addition to dimension-by-dimension (combined/composite) evaluation, authors needed to implement the framework applying discrete/individual and categorical indicators level assessment. Contextually adapting the implementation procedure of the framework, the performance assessment was performed at three stages/levels: individual, categorical, and composite levels. The third stage/level performance assessment requires combination of all individual indices or categorical indices and create one new composite index. However, in order to avoid double counting, the evaluation process was performed categorically.

Before the evaluation process, the present study identified 15 pertinent indices widely used to evaluate the performance and effectiveness of 13 CPSs. Continuous pixel values of each indicator were produced using data generated from multi-sources. The continuous quantitative values in each index were further classified and reclassified into qualitative values, such as very high, high, medium, low, and very low. While creating the nominal indices, rescaling and reclassification were done by applying natural and geometric breaks algorithms, available in ESRI ArcGIS software. Depending on the context, manual breaks techniques were also applied. The assessment was performed in two modalities: categorical modality, i.e., dimension-by-dimension evaluation and overall modality, where the evaluation is performed by aggregating all the indicators in all dimensions. The former modality is useful as it allows us to easily link the evaluation or assessment indicator values with possible factors that determine the performance/efficiency of CPS. The assessment was performed in two phases: (I) actual grain production evaluation and (II) attainable or possible grain production.

2.4.1 Spatiotemporal variation in grain production performance

2.4.1.1 Dimension-by-dimension evaluation of grain production performance

$$E\_LUPdi = \sum_{d=1}^{n} \text{Iidi} * \text{WIdi} \qquad (1)$$

where E_LUP_{di} denotes the existing grain production performance of a particular landscape managed under a specific CPS in the dith

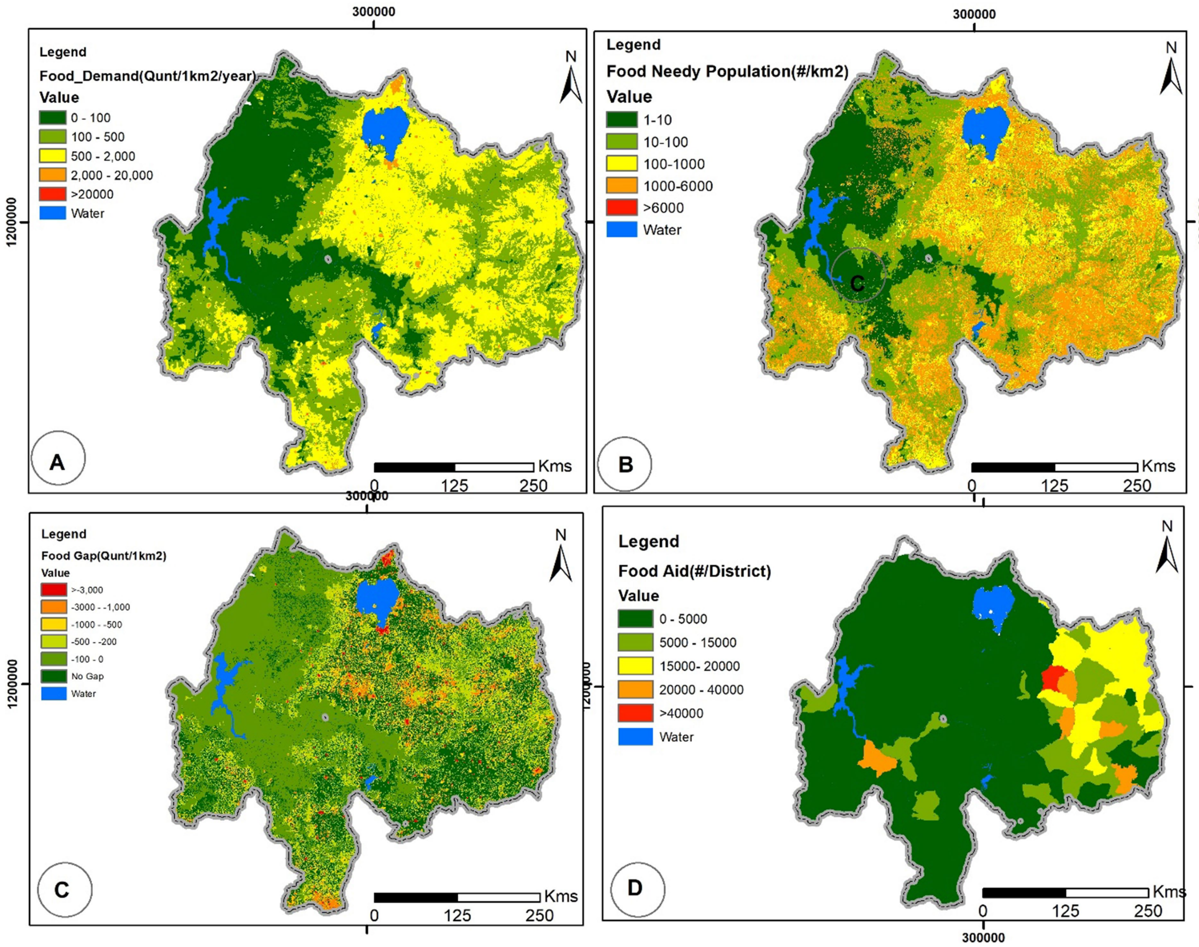

FIGURE 3
Actual values of variables/indices used to assess the implications of land utilization and production performance/efficiency of different CPS on food systems: food supply index **(A)**, food demand **(B)**, food gap **(C)**, and food needy population **(D)**.

dimension; Iidi denotes specific indices used to measure the performance of the landscape in the dith dimension; WIidi denotes the weight given to the Iith indicator in the dith dimension; and n represents the number of dimensions considered in the evaluation.

2.4.1.2 Overall performance

$$OE\_LUPdi = \sum_{d=1}^{n} \mathrm{E\_LUPdi} * \mathrm{Wdi} \qquad (2)$$

where OE_LUP_{di} denotes the overall existing/actual grain production performance of a landscape managed under a specific CPS estimated considering all indicators in all dimensions, E_LUPdi denotes the existing land use performance of the landscape in the dith dimension (Equation 1), and Wdi is the weight given to the dith dimension.

2.4.2 Spatiotemporal grain production efficiency

2.4.2.1 Dimension-by-dimension evaluation of efficiency

$$A\_LUEdi = \frac{E\_LUPdi}{\sum_{di=1}^{n} \mathrm{E\_LUPdi}} X100 \qquad (3)$$

where A_LUEdi denotes attainable grain production efficiency of a particular landscape managed under a specific CPS estimated considering a particular dith dimension. It reflects the degree to which an attainable cultivated land (space) and other natural capitals (soil and climate) are efficiently utilized to produce grain in the corresponding dith dimension; Iidi denotes specific indices used to measure the performance of the landscape; n represents the number of dimensions considered in the evaluation.

2.4.2.2 Overall evaluation of efficiency

$$OA\_LUE = \sum_{d=1}^{n} \mathrm{A\_LUEdi} * \mathrm{Wdi} \qquad (4)$$

where OA_LUE denotes the overall attainable grain production efficiency of a particular landscape managed under a specific CPS estimated considering all dimensions. It reflects the overall degree to which an attainable cultivated land (space) and other natural capitals (soil, water, and climate) are efficiently utilized to produce grain; WIdi denotes the weight given to dith dimension.

Given several factors determine the performance of different CPS (Cano et al., 2023); applying a multidimensional performance assessment framework was critically important (Liu J. et al., 2020). To

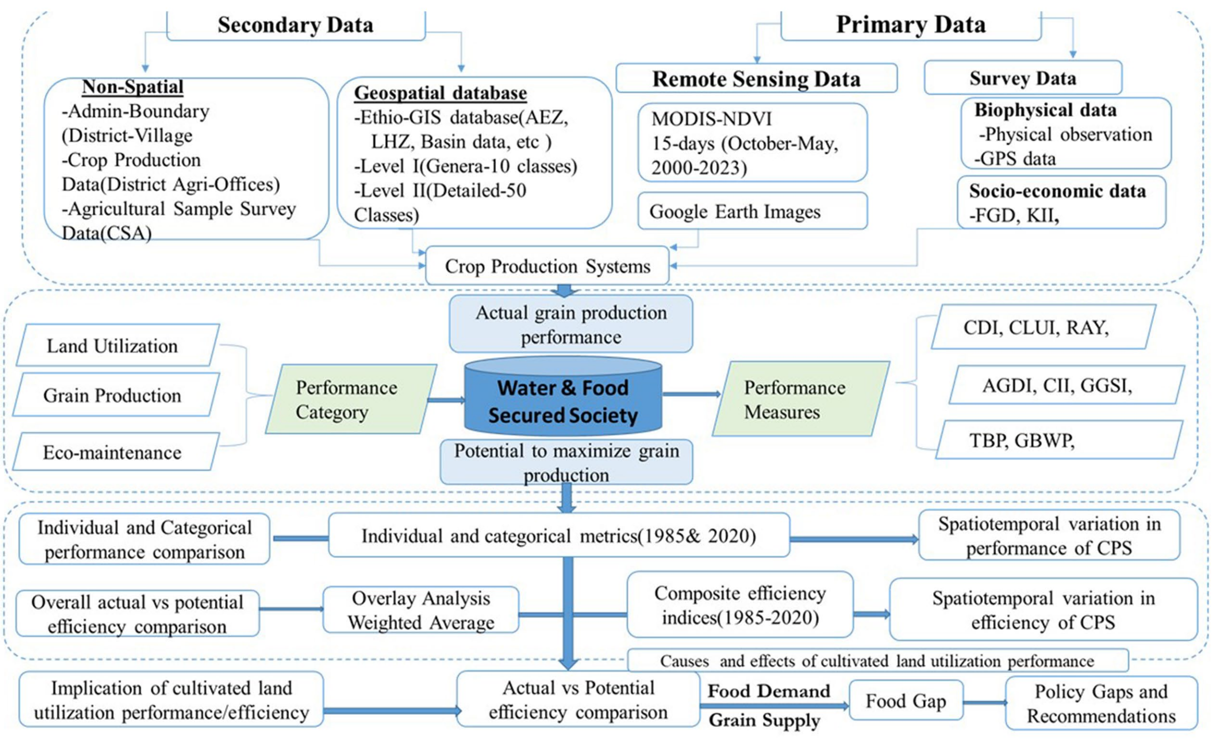

FIGURE 4
Overall methodological framework of the study.

clearly identify the major bottleneck of cropping intensifications, individual measures/indices-based CPS performance assessment has paramount importance. However, discrete-level performance evaluation has shortfalls as some indices overestimate and others underestimate performances. To overcome these limitations and obtain the benefits of individual indicators-based performance assessment, contextually modifying the multidimensional assessment framework was needed. Keeping the concept of a multidimensional assessment framework, the performance assessment was performed at three stages with three levels: individual, categorical, and composite. The third stage/level performance assessment requires us to combine all individual indices or categorical indices and create one new composite index. This was done by applying spatial overlay techniques. The multidimensional performance approach was adopted from Liu J. et al. (2020). To create workable indices, usable at all stages, the original indices values were converted into common nominal values (1–5). While creating the nominal indices, rescaling and reclassification were done by applying natural and geometric breaks algorithms, available in ESRI ArcGIS software, were used. Depending on the context, manual breaks techniques were also applied.

To generalize the performance/efficiency level of the different CPS, a composite index approach was implemented (Abdollahzadeh et al., 2023), two generalization assumptions and/or options do exist (De Montis et al., 2021): (i) each of the selected factors has the same level of influence and (ii) each of the considered evaluation factors has different levels of influence. In the former case, linear arithmetic mean rule can be applied whereas a weighted average rule can be applied for the latter case. For the latter case, involving eight experts in the field, an assignment of weight to each factor was given applying AHP.

2.4.3 Grain production implications

The performance of CPS has a profound linkage with ecosystem services (Bommarco et al., 2013). Studying CPS and assessing their performance has a vital role in understanding the implication on food systems (Amin et al., 2022). This study made a brief implication assessment of water and food ecosystem services although CPS implications go beyond these two ecosystem services. The overall research methodology and workflow is presented in (see the maps and descriptions presented in section 3.5) Figure 4.

3 Results

3.1 Major crop production systems and cropping systems

The entire UBN basin (100%) is served by rainfed farming systems, but currently, only 39% is used for grain production, meaning the remaining 69% does not produce grain. Grains/food are produced using different systems practiced in the basin however, the present study identified and mapped about 12 major CPS. Of the major CPS identified and mapped, Meher-Only (3) accounts for approximately 26%, Meher-Residual-Dependable (7) represents (12%), Meher-Residual-Dependable (8) covers 12%, and Meher-Residual-Dependable (8) covers approximately 26%. Belg Synergy (6) covers approximately 10% of the basin area.

TABLE 1 Multi-temporal area coverage of cropped pixels in each CPSZ.

CPS				1985			2005			2020		
Code	Major types	Area (km²)	Percent out of UBNB	Area (km²)	Out of CPS zones (%)	Out of the basin (%)	Area (km²)	Out of CPS zones (%)	Out of the basin (%)	Area (km²)	Out of CPs Zones (%)	Out of the basin (%)
1	Meher-Belg-Dependable	1,639.0	0.8	814.5	49.7	0.4	809.0	49.4	0.4	916.4	55.9	0.5
2	Meher-Belg-Intermittent	11,312.0	5.7	5,734.5	50.7	2.9	5,592.6	49.4	2.8	6,608.7	58.4	3.3
3	Extended-Meher	20,345.0	10.2	4,950.3	24.3	2.5	5,508.8	27.1	2.8	9,412.6	46.3	4.7
4	Short-Meher-Only	6,650.0	3.3	860.8	12.9	0.4	1,358.9	20.4	0.7	1,197.2	18.0	0.6
5	Meher-Only	52,280.0	26.1	12,320.2	23.6	6.2	13,418.2	25.7	6.7	17,589.6	33.6	8.8
6	Meher-Residual-Belg-Synergy	20,406.0	10.2	10,598.0	51.9	5.3	10,063.6	49.3	5.0	12,206.7	59.8	6.1
7	Meher-Residual-Dependable	24,253.0	12.1	11,648.0	48.0	5.8	13,020.7	53.7	6.5	14,905.3	61.5	7.5
8	Meher-Residual-Intermittent	22,903.0	11.5	6,024.9	26.3	3.0	6,587.0	28.8	3.3	9,739.7	42.5	4.9
9	Meher-Shifting-Cultivation	19,608.0	9.8	1,751.1	8.9	0.9	2,148.2	11.0	1.1	3,103.2	15.8	1.6
10	No-Cropping	75,679.3	37.8	145,245.6	67.0	72.0	141,441.1	65.0	70.7	124,268.7	66.0	62.0
11	Total Cropped	124,268.7	62.0	54,702.4	33.0	28.0	58,506.9	35.0	29.3	75,679.3	44.0	38.0
12	Total/Average in the basin	199,948.0	100.0	199,948.0	100.0	100.0	199,948.0	100.0	100.0	199,948.0	100.0	100.0

Figure 5A shows the distribution of the main CRSs that are mostly practiced in the UBNB. Details about the types of major crops grown in each CPS and their proportional coverage is presented in Figure 6 and more information also provided as supplementary figure (Supplementary Figure 2). According to the statistical summary of the coverage of major crops in each CPS, important cropping systems, such as.... Maize, Teff and Sorghum(20%), Finger Millet, Teff, and Wheat(11%) and Potato, Beans and Barely(10%), cover the majority of the landmass of the catchment area.

3.2 Cultivated landscapes and cropping systems

As shown in Figure 6 and Table 1, the cultivated landscape of the UBNB covers only 39% of the catchment area and the remaining 61% of the catchment area provides various ecosystem services managed under different LUSs. As shown in Table 1 and Figure 6, the cultural landscape of the UBNB is managed by various rainfed CPS, of which Meher-Only (3) represents the larger part of the basin (Table 1. Multi-temporal area coverage of cropped pixels in each CPSZ).

As shown in Figure 6 and Table 1, the basin experienced an average increase in grain area of 10% over the past four decades. However, the dynamics of cultural landscapes vary considerably over time and space. Between 1985 and 2005 the increase was modest at only 2%, while the period from 2005 to 2020 observed a significant increase in acreage (Supplementary Figure 2 and Supplementary Table 2). Figure 6 shows that there have been both gains and losses across grain production landscapes. Long-cultivated areas experienced slight losses, while recently plowed landscapes, particularly in flood plains and lower elevations, experienced significant increases in grain production area. Detailed multi-temporal information about various information on various LULC types is provided as supplementary figure (Supplementary Figure 3).

3.3 Spatiotemporal variation on the performance of CPS

The analysis results show that accurate mapping of crop areas, cropping systems, (Figure 5, Supplementary Figure 2, crop types Supplementary Figure 2 and Supplementary Table 3) and relevant spatial factors related to grain production improves the understanding and characterization of the spatio-temporal variations in the performance of rainfed crop production systems (CPS) at the local scale. Although approximately 10 indices were used, for simplicity reason, outputs from individual indicators are not presented. Figures 7A–D show the results of this dimensional and overall performance evaluations outputs, respectively.

3.3.1 Land utilization performance of the different CPS

As shown in Figure 7A (top left), about half of the cultural landscape of UBNB has moderate land use performance, while almost a third has low performance. Currently, approximately 25% of the catchment area has very good cultivated land use performance. When ranking crop production systems (CPS) by land use performance, Meher-Belg-Dependable (1) and Meher-Residual-Dependable (7) are at the top, with approximately 58 and 45% of their cultivated areas showing high and very high performance, respectively. Extended-Meher (3), Meher-Residual-Belg Synergy, and Meher-Belg Intermittent also perform well in the use of their cultural landscapes.

3.3.2 Productivity and grain yield performance

According to Figure 7B and Table 2, approximately 50% of the UBNB cultural landscape has moderate productivity and medium grain yield, while approximately 37% has high performance (above the national average). However, over 10% of the landscape is below the national average. When ranking crop production systems (CPS) by productivity and yield, Meher-Residual-Dependable (7) and Extended-Meher (3) perform excellently, with approximately 90 and 80% of their areas having high and very high performance, respectively. Other systems such as Meher-Belg-Dependable (1), Meher-Residual-Belg Synergy, and Meher-Only also show good productivity. As shown in Figure 7B, areas of high productivity are concentrated in the central, southern, and southwestern parts of the basin, particularly in the Lake Tana floodplain, central mid-elevation highlands (East and West Gojam), and the south upper Dedessa and lower Dhabus subbasins. In contrast, despite the possibility of double cropping, the eastern region struggles with low productivity during the Meher-Residual-Belg season, mainly due to soil acidity problems.

3.3.3 Economic development performance

The economic performance of various crop production systems (CPS) is shown in Figure 2I and Supplementary Figure 4 with the average annual gross grain supply index (GGSI) for the basin estimated at approximately 10 billion quintals on 55,000–75,000 km^2 of arable land. Based on average grain prices, this equates to approximately 1.2 trillion Birr in annual sales. The top performing CPS by grain volume are Meher-Only (23%), Meher-Residual-Dependable (21%), and Extended-Meher (16%). However, Meher-Residual-Dependable (27%), Meher-Only (19%), and Extended-Meher (15%) generate the highest revenue. This discrepancy arises from factors such as greater plant diversity (AADI) and the cultivation of more valuable crops in systems such as Meher-Residual (Figure 2, Supplementary Table 4, and Supplementary Figure 4). Economically, the central, southern, and southeastern parts of the basin perform better, while the northwestern, western, and eastern regions lag behind.

3.3.4 Overall performance

Single or category-based performance assessments do not capture the full picture of the reality on the ground and require an overall assessment that combines all indicators. Figure 7 shows the results of this comprehensive performance evaluation. The composite score, reflecting existing performances, highlights, highlights Meher-Residual-Dependable (7), Extended-Meher (3), and Meher-Residual-Belg-Synergy (6) as the best-performing CPS at 50, 33% and 31% respectively of their landscapes each have higher overall performance values. In contrast, the Short-Meher (4) CPS has poor overall performance. In areas with multiple CPS, such as Residual and Meher-Residual, overall performance values are above average due to higher values of the Cropping Land Utilization Index (CLUI) and the Cropping Intensity Index (CII).

3.4 Grain production efficiency assessment

3.4.1 Dimension-by-dimension assessment

CPS performance assessments often do not demonstrate the gap between existing and potential production levels for each system. Land use system efficiency (LUS) reflects this gap by comparing achievable versus actual performance. Figure 9 shows both categorical and overall efficiency for large CPS and shows that none exceeds 60% efficiency. This suggests that most of the CPS are not utilizing even half of its rainfed grain production potential. Although the individual performance metrics for RCS are higher than other CPSs, the efficiency metrics show minimal differences compared to them, indicating significant room for improvement across systems.

The low individual and categorical efficiency scores in areas practicing RCS or MCS indicate a significant gap between potential and actual performance. This suggests that current management practices are inadequate and are preventing farmers from achieving their maximum production potential. In addition, crucial indicators such as regulatory services and ecological maintenance are missing from the overall efficiency assessment. The lower efficiency scores for RCS may be attributed to this weak evaluation approach as important factors such as soil health and the regulatory roles of each CPS were overlooked, impacting the perceived efficiency of RCS compared to others.

The production performance and efficiency indicators better reflect the impact of RSM and other MCS on grain production. As shown in Figures 9A–C, the land use efficiency indicators revealed little difference between different CPS, while the economic development indicators show different efficiency values. This discrepancy arises from two main factors: (1) economic indicators were generated by combining government data with our primary data and (2) the market values of crops grown under different CPS vary significantly (e.g., Grasspea vs. Teff). Furthermore, the weighting used in the assessment did not adequately take these important differences into account.

3.4.2 Overall efficiency assessment

The overall efficiency of grain production was assessed using both the linear arithmetic mean and weighted average approaches, as shown in Figure 9D. The results show that the most efficient CPS are Meher-Belg-Dependable (1), Meher-Residual-Dependable (7), and Extended-Meher (3), with 45, 43, and 41% of their respective landscapes achieving overall efficiency scores above 40. In contrast, Short-Meher (4) showed poor efficiency across all time periods. The moderate overall efficiency of all CPS indicates significant untapped potential, suggesting that grain production could be increased by 40%.

3.4.3 Temporal variation in overall efficiency

The differences in efficiency between different CPS are obvious. To illustrate the spatiotemporal changes in overall effectiveness,

TABLE 2 Summary of the grain production performance of major CPS exist in UBNB.

Performance		Major rainfed crop production systems exist in UBNB									UBNB
Dimension	Ranks	(1) Meher-Belg-Dependable	(2) Meher-Belg-Intermittent	(3) Extended-Meher	(4) Short Meher-Only	(5) Meher-Only	(6) Meher-Residual-Belg Synergy	(7) Meher-Residual-Dependable	(8) Meher-Residual-Intermittent	(9) Meher-Shifting-Cultivation	Average rank
Cultivable landscape utilization	1	0.0	0.0	0.4	0.1	2.5	0.0	0.0	0.0	17.1	2.2
	2	2.3	15.9	13.1	76.0	38.2	14.6	11.2	30.4	57.5	28.8
	3	37.7	48.7	43.1	23.3	45.3	49.6	44.4	55.9	24.2	41.4
	4	58.6	35.4	22.7	0.6	13.3	35.7	44.1	13.5	1.2	25.0
	5	1.3	0.0	20.8	0.0	0.7	0.1	0.3	0.1	0.0	2.6
Production and productivity	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	2	6.1	6.0	0.2	53.7	12.8	0.5	0.4	1.2	8.8	9.9
	3	34.4	75.4	17.6	46.2	63.9	47.1	9.7	59.9	78.7	48.1
	4	59.5	18.3	55.9	0.1	20.5	48.2	55.9	37.0	12.5	34.2
	5	0.0	0.3	26.4	0.0	2.8	4.1	34.0	1.9	0.0	7.7
Economic development	1	0.7	1.1	12.5	62.3	13.8	1.4	2.6	10.5	58.5	18.2
	2	52.1	35.5	30.7	12.0	31.3	32.3	30.4	34.8	11.4	30.1
	3	43.2	30.7	8.4	25.3	34.9	48.3	19.2	18.8	25.5	28.3
	4	3.5	31.1	40.3	0.5	18.8	16.3	40.5	33.2	4.5	21.0
	5	0.4	1.6	8.2	0.0	1.2	1.6	7.3	2.7	0.0	2.6

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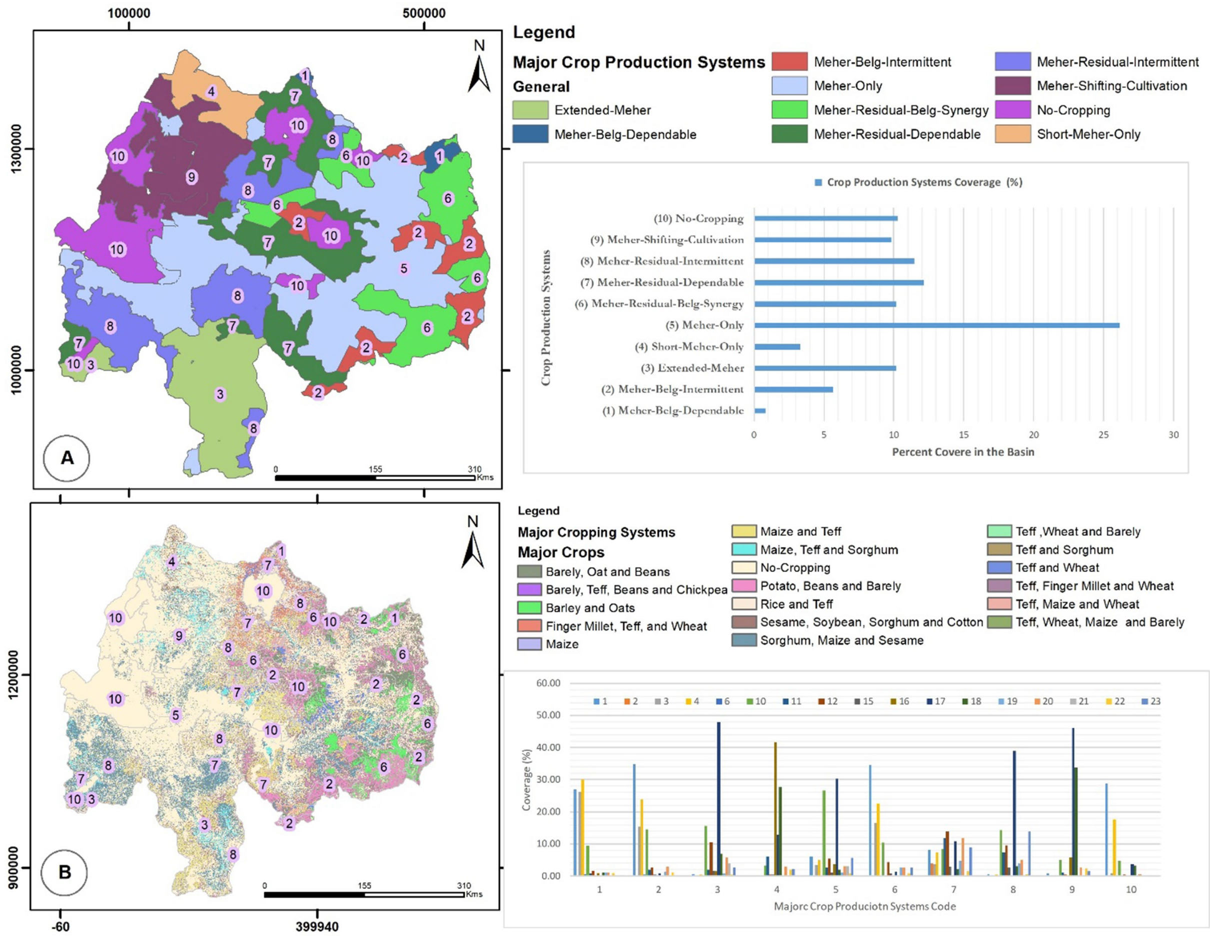

FIGURE 5
Major Crop Production Systems (CPS, **A)** and Cropping Systems (CRS, **B)** widely practiced in the basin and the respective statistical facts.

overall efficiency maps for two points in time (1985 and 2020) were compared, as shown in Figure 10. The results show that no CPS achieved overall efficiency scores above 60.

In several areas of the basin where multiple CPS, such as Residual, Meher-Residual, and Meher-Residual-Belg, are practiced, overall efficiency values were below 30 in 1985 but rose above 50 by 2020. This indicates that the introduction and widespread implementation of RCS significantly improved the overall grain performance in the basin.

3.4.4 Temporal variation in overall performance

The spatiotemporal dynamics of CPS performance are evaluated using the overall gain and loss of cropped areas in each CPS zone. Figure 8 illustrates this variation, showing significant negative changes (green pixels) in the eastern and central high mountain regions, while positive changes (red pixels) are concentrated in the central and western flatlands and floodplains. There was a notable shift in grain production from the eastern and central parts of the basin to the southern and southwestern regions, with a trend of shifting production from higher to lower elevations. Among the CPS, the Meher-Residual-Dependable, Meher-Residual-Intermittent, Meher-Residual-Belg, and Meher-Belg systems have shown the greatest improvements.

3.5 Implications

Analyzing the food gap serves as a key indicator for evaluating the grain production performance and efficiency of CPS. Figure 11 and Table 3 show the relevant indicators used for this analysis at the grid level. According to the GGI, surplus grain production is rare. Given that the eastern, central, and southern parts of the UBNB are highly populated, directly comparing CPS with food supply and demand can be misleading (Figure 11).

The assessment findings indicate that approximately 10% of the non-agrarian and 45% of the agrarian population in the UBNB meet their food demand through the current rainfed-based CPS. This means that approximately 60% of the total population—90% of non-agrarian and 55% of agrarian households—fulfill their subsistence food needs from other sources, such as livestock production and various agricultural and non-agricultural activities (Table 3).

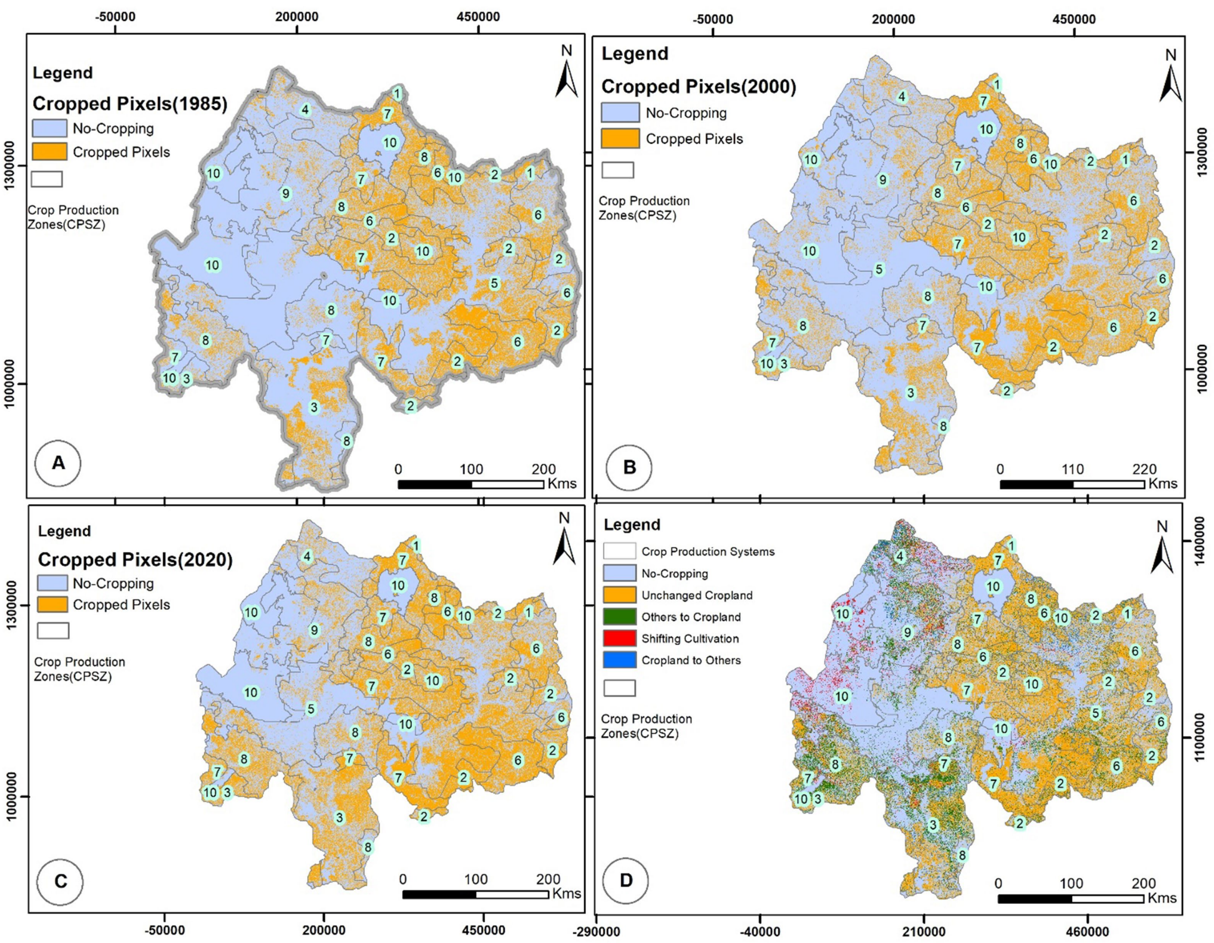

FIGURE 6
Multi-temporal cropped pixels map overlaid with major crop production systems (CPS) at different years: 1986 **(A)**, 2000 **(B)**, 2020 **(C)**, and major cropland changes **(D)**.

In regions where smallholder farmers primarily practice double cropping, such as Meher-Residual, the percentage of food-insecure individuals is relatively lower. However, interpreting the data requires a deeper analysis due to the complex factors at play. For instance, long-term crop cultivation on hilly terrain in the eastern basin has led to significant unproductivity, with many areas abandoned for grain production. Additionally, this region is home to a large population that exceeds its natural capacity. Conversely, frequent crop failures in areas reliant on Belg and Residual-Only CPS lead farmers to abandon the main production season due to risks like frost, floods, and pests, prompting them to pursue alternative livelihoods. Overall, linking grain production directly to food insecurity necessitates detailed data and thorough investigation. In areas where Belg-only, Meher-Only, Residual-Belg, and Residual-only CPS are prevalent, there is a high level of food deficit and a significant number of food-insecure individuals. In contrast, Meher-Residual and Meher-Residual-Belg CPS demonstrate relatively low food deficits due to their superior production performance, resulting in surplus grain in areas practicing Meher-Residual. CPS that synergize with RSM show enhanced food production and security. The performance of these CPS improves with greater synergy between Meher and RSM, highlighting the substantial contribution of RSM-based CPS to the food system, in both gross grain supply and crop diversity.

4 Discussion

Rainfed agriculture system of Ethiopia faces numerous challenges despite its significant potential (Oweis et al., 2007). Smallholder grain production is constrained by various biophysical and socioeconomic factors, including poorly designed policies (Wani et al., 2009; Ahadu, 2019). Rainfed farming often serves as a testing ground for unproven strategies (Ahadu, 2019; Pretty, 1999).

Official data in Ethiopia are limited to zone-level information, making it difficult to assess smallholder grain production systems. While agricultural areas have generally increased, including in UBNB, the trend is irregular (Muluneh, 2010). The annual increase in cropped area is minimal compared to the rapidly growing population (Hurni et al., 2005; Wondie et al., 2016; CSA, 2019). Available data, including government sources, have poor spatial and temporal coverage and problems with accuracy. This highlights the need for in-depth research to better understand rainfed farming systems (Asfaw et al., 2021; Pretty, 1999). This study achieved three key milestones: (1) producing

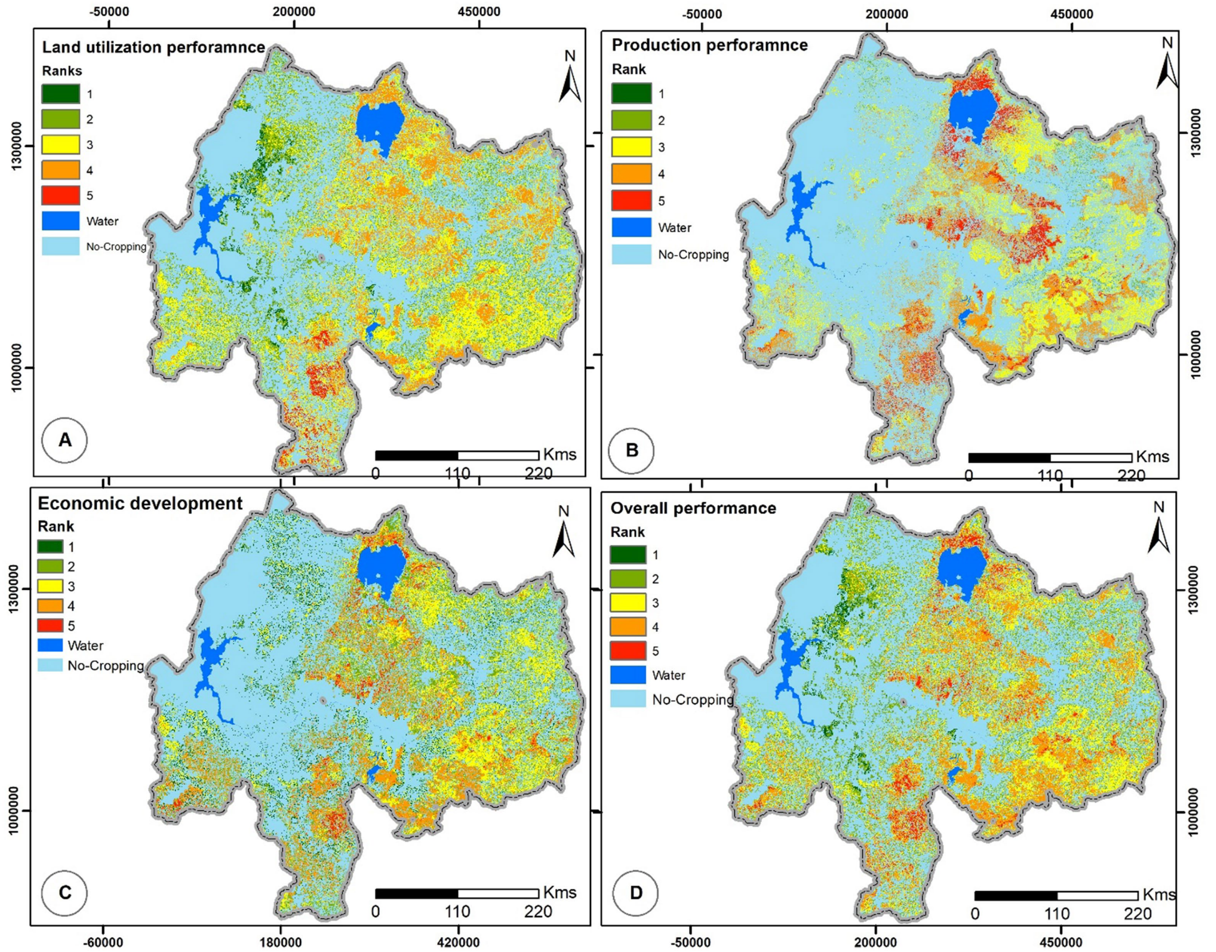

FIGURE 7
Categorical spatial variation in CPS performance: land utilization performance **(A)**; production performance **(B)**, economic development performance **(C)**, and overall performance **(D)**.

accurate cropland data at the 30-m pixel level for the years 1985, 2005, and 2020; (2) identified and mapped complex, dynamic cropping systems; and (3) evaluates the performance and efficiency of these (Equations 1–4). The assessment found that the entire UBNB is theoretically suitable for rainfed farming systems, with an average annual minimum rainfall of over 800 mm (Samy et al., 2019), sufficient for various crop production systems (Hurni, 1998). However, only 39% of the UBNB is currently used for grain production, while 61% is used for other purposes. Several studies show that Ethiopia's cereal crop productivity has grown significantly (Quddus et al., 2022; CSA, 2020; Belachew et al., 2022), although yields have varied over time and space. While some attribute this increase to expanded farmland (Belachew et al., 2022), others cite improved varieties, enhanced extension services, and increased fertilizer (Berhanu, et al., 2021). However, none of the previous studies provide spatial evidence to validate their findings. Inconsistencies in available data on grain production are mainly due to incorrect assumptions about arable land and yield (Berhanu, et al., 2021 and Silva et al., 2021). The authors emphasize the need to examine the causes of these inconsistencies—such as definitions, approaches, scope, and methods—in order to address the problems. A major argument against previous analysis is the misattribution of changes in food production area to grain volume mainly emanated from the lack of spatially related evidence. The undeniable fact is that changes in grain volume, apart from changes in arable land or production input, are due to two main causes: (i) land allocation strategies and land use shifts and (ii) changes in crop production system (CPS) or cropping systems. The former explains land use and land cover change (LULC) and the latter explains land use system (LUS) and land management changes (Korbu et al., 2020 and Reckling et al., 2016).

The study found that in some areas, despite a trivial change in net-cropped area (1985–2020, Tables 1 and 3), grain volume increased significantly (Figure 12 and Supplementary Table 2). This shows that grain production can rise due to farmers' intensification strategies or changes in land allocation and use, even without expanding cropped areas (CSA, 2014, 2020). For instance, as land becomes depleted, farmers may shift grain production from less productive areas such as hillsides to more fertile areas such as floodplains (Table 3). In some regions, the amount of grain increased due to changes in land use systems (LUS). Even with the same farmland size, LUS or management changes increased production. As population pressure and land scarcity become more critical, more efficient farming systems are

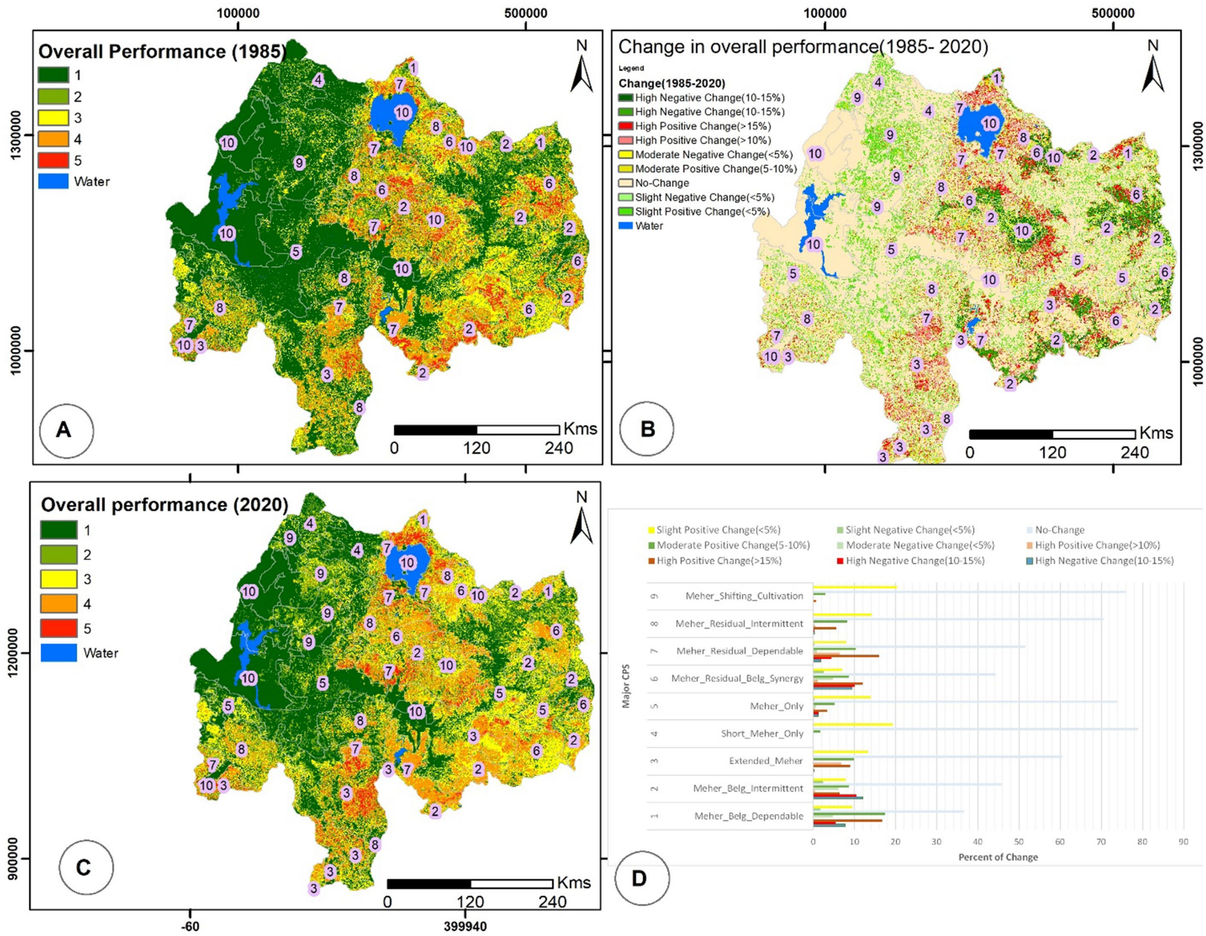

FIGURE 8
Temporal aspect of the overall grain production performance of CPS: overall grain production performance in 1985 **(A)**; overall grain production performance in 2020 **(C)**; overall change in grain production performance between 1985 and 2020 (top **B**); statistical summary for overall grain production performance **(D)**.

emerging (Table 3). The authors have investigated that two prominent transformations on LUS are responsible for such processes: (i) the flourishing of multiple cropping systems and (ii) the shift in farming systems from livestock to grain production (conversion of pasture to cropland, Figure 6 and Supplementary Table 2). A key example of both transformations is the residual soil moisture-based crop production system (RCS). It converts waterlogged areas into arable land and enables farmers to grow grain two times a year on black cotton soils, which was uncommon a few decades ago (Supplementary Table 2). While RCS currently plays a major role in grain production, its socio-economic and ecological impact has not been fully studied.

Such crop production systems (CPS) are not included in the Annual Agricultural Sample Survey (CSA, 2019), which only considers crops grown in the main rainy season (Meher). Without detailed data on (i) land use shifts and allocations and (ii) the types of CPS used by smallholder farmers, it is impossible to understand trends in grain production and link its impact on food security. To make evidence-based decisions to address food shortages, the authors suggest three categories of spatiotemporal information on grain production; (i) natural capital, population distribution; (ii) cropped area and productivity; and (iii) description of crop production systems (CPS) including the land use and crop types. LUS changes, such as some aspects, like crop selection and multiple cropping, have contributed more to grain production than to the expansion of arable land. However, the impact of land allocation and CPS changes varies over time and by region.

This study identified 11 major crop production systems (CPS), with Meher-Only single cropping covering the largest share (26%) of the UBNB, followed by Meher-Residual-Dependable (12%), Meher-Residual-Intermittent (12%), and Extended-Meher (10%). Short-Meher-Only accounts for a smaller portion (3%). Between 1985 and 2020, the spatiotemporal LULC change assessment revealed a 10% increase in cropland added to the food system. Attributing the 10% increase in cropland directly to grain volume in the UBNB is misleading. While a 10% cropped area increase over four decades (1985–2023) is minor compared to the doubling population every 20 years, it still has a significant overall impact on grain volume. Between 2005 and 2020, the cultivated area in the UBNB increased from 58,506 km^2 (30%) to 75,679 km^2 (38%). Recent years (after 2005) show larger temporal and spatial fluctuations in grain production than earlier periods (1985-2005) (CSA, 2020). Changes in the total cropped area vary by crop production system (CPS), with the Meher-Shifting cropping zone showing the largest increase, followed by the Meher-Residual-Intermittent and Meher-Residual-Dependable

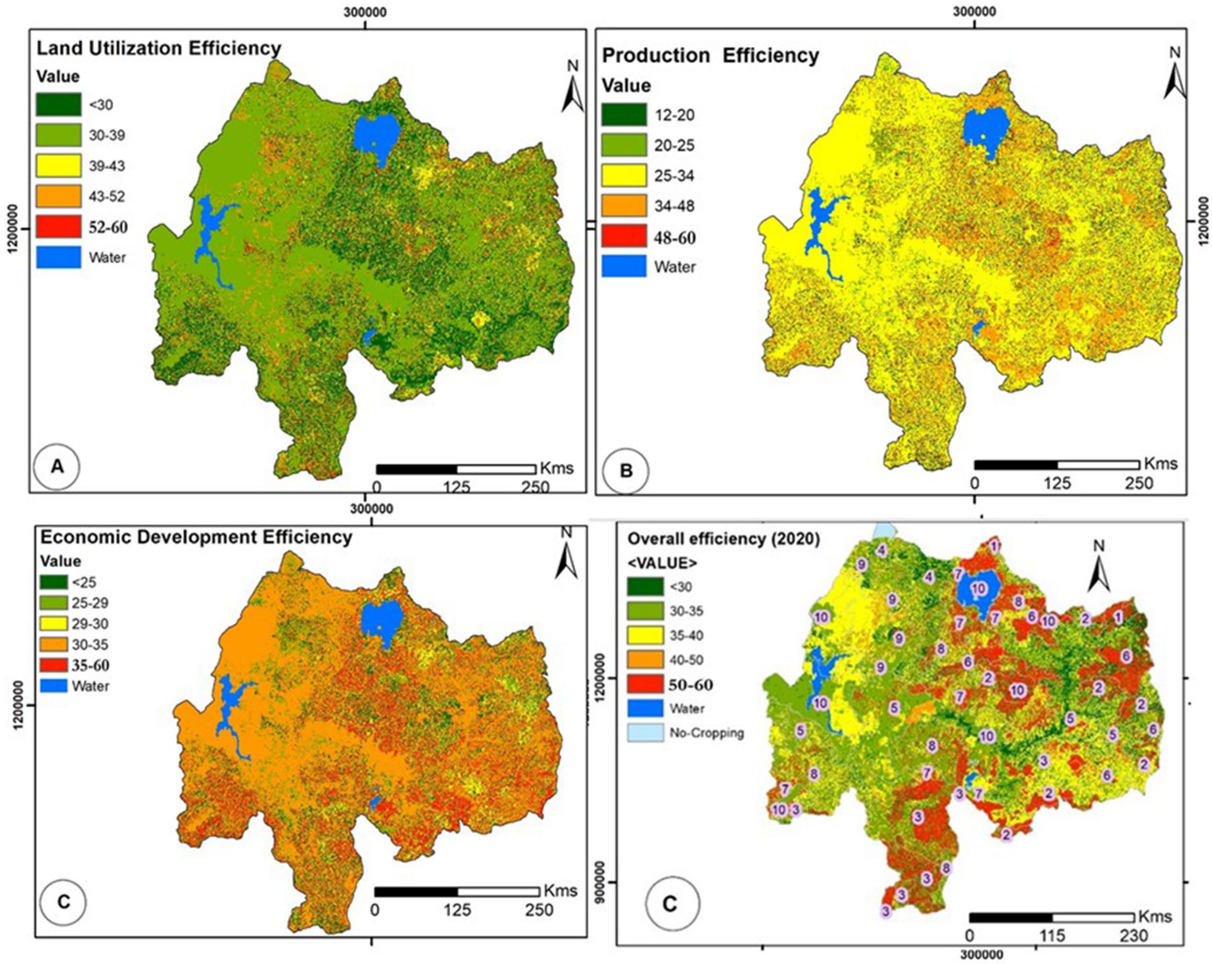

FIGURE 9
Individual and Categorical spatial variation in CPS efficiency: Land Utilization Efficiency **(A)**; Production Efficiency **(B)**, Economic development efficiency **(C)** and Overall efficiency **(D)**.

zones. The conversion of extensive black cotton soils in flood plains, such as those around Lake Tana, contributed significantly to this increase (Abera, 2017; Korbu et al., 2020; Debele and Deressa, 2016; Elias et al., 2022). Specifically, landscapes managed under Meher-Residual-Dependable CPS increased from 5% in 1985 to 8% in 2020 (Figure 10 and Table 3). In contrast, MCS showed a declining trend in high-elevation regions with minimal net change in Meher-Belg. The performance of different crop production systems (CPS) varies significantly in time and space Figure 10–Figure 13. An increase in the area under grain cultivation directly increases the efficiency of specific CPS. There have been significant improvements in the use of cultivated land, particularly in low-lying areas such as the Lake Tana floodplain. Conversely, some high-elevation regions, particularly in the eastern and central areas, experienced a decline in grain production landscapes, as seen in CPS in the Wet and Dry-Dega ecoregions such as Meher-Belg. The analysis results suggest that overall CPS in these high-altitude areas have revealed a poor performance (Figure 10).

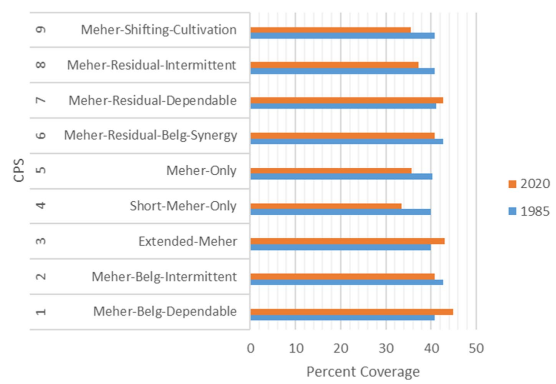

FIGURE 10
Statistical summary of the overall efficiency of major CPS practiced in the UBNB.

Several factors influence the spatiotemporal dynamics of grain production, including location, altitude, population distribution, technology, and land management (Zerssa et al., 2021; Abdollahzadeh et al., 2023). Geographically, there has been a significant shift in grain production from the eastern and

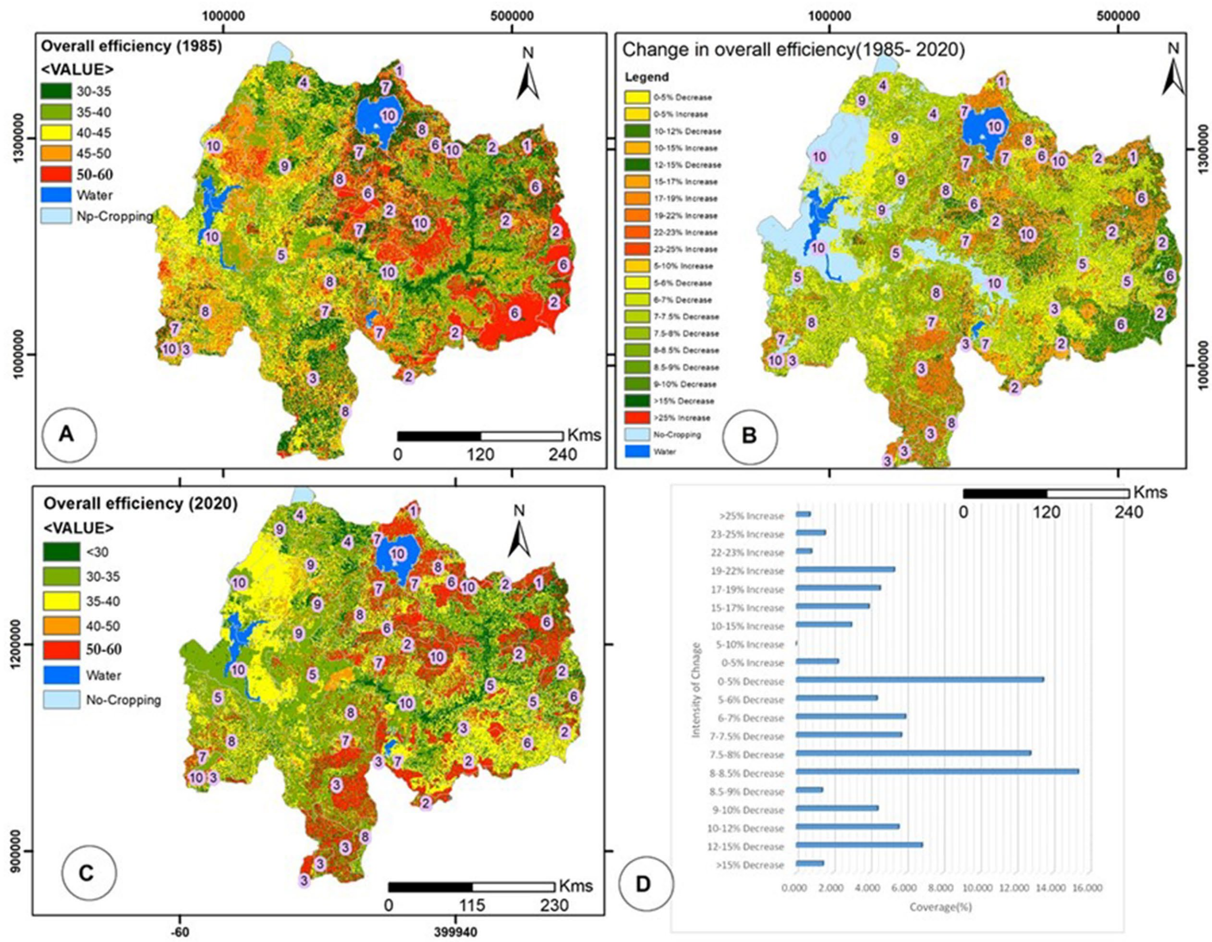

FIGURE 11
Temporal aspect of the overall grain production efficiency of CPS: Overall grain production efficiency in 1985 **(A)**; Overall grain production Efficiency in 2020 **(C)**; Overall change in grain production efficiency between 1985 and2020 (top **B)**; Statistical summary for overall grain production efficiency **(D)**.

central parts of the basin to the southern and southwestern regions. Altitudinally, production has moved from high and mid-altitudes to lower ones. Unproductive landscapes, like the Lake Tana floodplain, have been transformed into surplus grain producers, while other areas, such as the Awi Zone, have become less productive (Desta et al., 2021). In contrast, high-altitude landscapes, which have significant potential for double cropping and improvement, are deteriorating over time (Zerssa et al., 2021). Furthermore, poorly designed strategies, such as providing food aid to rehabilitate land, have undermined the development of adaptive solutions to these challenges (Figure 10).

In the eastern and central high mountain areas, particularly in the Meher-Belg and Belg CPS, significant losses in grain production efficiency were observed (indicated by deep green pixels in Figure 9). Elevation comparisons show that although high and mid-elevation landscapes lost overall grain efficiency, lower-elevation and mid-elevation floodplain landscapes showed an improvement in production efficiency. Significant improvements in grain production efficiency occurred in the central and western parts of the basin, particularly in flat areas and floodplains (represented by deep red pixels in Figure 9). This transformation is largely due to the shift from no-cropping and Meher-Only systems to Meher-Residual and Meher-Belg CPS. Among the CPS, the most notable improvements were observed in the Meher-Residual-Dependable, Meher-Residual-Intermittent, Meher-Residual-Belg, and Meher-Belg systems (Figures 9–11).

The findings from the spatiotemporal dynamics assessment can inform planners and decision makers about the existing CPS and its both direct and indirect implications for water and food security (Zhao et al., 2018). Assuming a direct relationship between the expansion of cultivated area and the amount of food, the 10% increase in cultivated area contributed significantly to grain production. Since 1985, the total gross grain volume of the basin has increased by an average of 153 million quintals per year (Figure 13 and Table 3). While agricultural area increased by approximately 10% over the last four decades, the total amount of grains added to the food system is estimated at 17% (30 million quintals) (Supplementary Figure 4).

This estimate aligns closely with the National Agricultural Sample Survey (CSA, 2019), which reported an annual grain production of approximately 173 million quintals for all zones

TABLE 3 Implication of practicing rainfed crop production systems on food systems.

Major crop production systems		Area coverage	Grain volume (10^4)		Total population (10^3)			Food needy population (10^3)					
Code	Names	km^2	Gross supply (Ton/Year)	Grain gap (Ton/Year)	None agrarian society	Agrarian society	Sum	None agrarian society	Agrarian society	Sum	Non-agrarian (%)	Agrarian (%)	Percent sum
1	Meher-Belg-Dependable	1,625	127	(97)	94	212	306	92	102	194	98	48	64
2	Meher-Belg-Intermittent	11,325	1,339	(401)	127	1,560	1,687	114	688	803	90	44	48
3	Extended-Meher	20,338	2,093	(568)	190	1,816	2,006	183	953	1,136	96	52	57
4	Short-Meher-Only	6,626	131	(72)	3	167	170	3	142	144	100	85	85
5	Meher-Only	52,265	3,200	(987)	104	3,659	3,763	94	1,881	1,975	91	51	52
6	Meher-Residual-Belg-Synergy	20,358	2,349	(681)	238	2,761	2,999	224	1,140	1,364	94	41	45
7	Meher-Residual-Dependable	24,174	3,262	(1,050)	698	3,529	4,227	647	1,455	2,102	93	41	50
8	Meher-Residual-Intermittent	22,901	2,084	(650)	307	1,992	2,299	291	1,008	1,299	95	51	57
9	Meher-Shifting-Cultivation	19,597	416	(106)	15	248	264	9	203	212	57	82	80
	Total/Average	179,209	15,001	(4,613)	1,775	15,947	17,722	1,657	7,573	9,230	90	55	60

within the basin (CSA, 2019). However, such assessments can be misleading because they focus solely on yield differences over time and not on sustainable grain supplies, which directly reflect levels of food security. A better indicator is the maximum number of people supported by the additional acreage. Between 1985 and 2015, the population of the basin grew by approximately 12 million (from 6 to 19 million) (Teshome, 2014), suggesting that the new farmland could support approximately 6 million people. This raises the question of how to meet the food needs of the remaining population. One can speculate that other food sources such as multiple cropping, intensive agriculture, improved productivity, and food aid probably helped meet the food needs of the rest of the population.

The potential of the catchment for multiple cropping has steadily increased, but productivity faces challenges due to various biophysical and socioeconomic constraints, including climate change, pests and diseases, and lack of government support (e.g., credit, improved seeds, and pesticides) (Tekeste, 2021; Mekonen and Berlie, 2021). Efforts to realize the potential of double cropping in areas where RCS is used have been limited in addressing existing constraints. Given continued population growth and inadequate land management, opportunities for multiple cropping will continue to remain untapped (Nkwasa et al., 2023). Researchers emphasize that improving grain production requires targeted investments, including developing adaptive crop varieties, adopting advanced agricultural technologies, and implementing effective land management practices (Liu J. et al., 2020). In addition, the government should introduce various incentive mechanisms, such as improving road network, market infrastructure, value chains, input subsidies, and capacity building to encourage smallholder farmers to focus on double cropping systems (such as RCS), particularly Meher-Residual, Meher-Belg, and Meher-Residual-Belg CPS. In summary, the CPS assessment approach demonstrated in this study can be extended to national assessments. The results can help identify the challenges in grain production and enable planners and decision-makers to find effective and high-performing CPS at different levels. This will strengthen efforts to address food security challenges as strategies to improve the grain production system are based on accurate evidence (Korbu et al., 2020).

5 Conclusion and recommendations

Agricultural growth strategy of Ethiopia faces significant challenges, with food security a major concern due to its large population. Despite the potential for efficiency of agricultural area of the UBNB, grain production performance is average or below average. Rapid population growth and competing land uses necessitate careful assessment of land use systems (LUS) and crop production systems (CPS). Evaluating spatiotemporal variations in grain production across different CPS is crucial for a country reliant on rainfed agriculture. To improve the performance and efficiency of crop production systems (CPS), four input-oriented strategies are commonly recommended: Space, natural capital, chemicals, and institutional and technology. *Space Input*: While adding more land for grain production is an option, the study found that suitable slopping and high-altitude areas are largely exhausted forintensive grain production. *Natural Capital Inputs:*

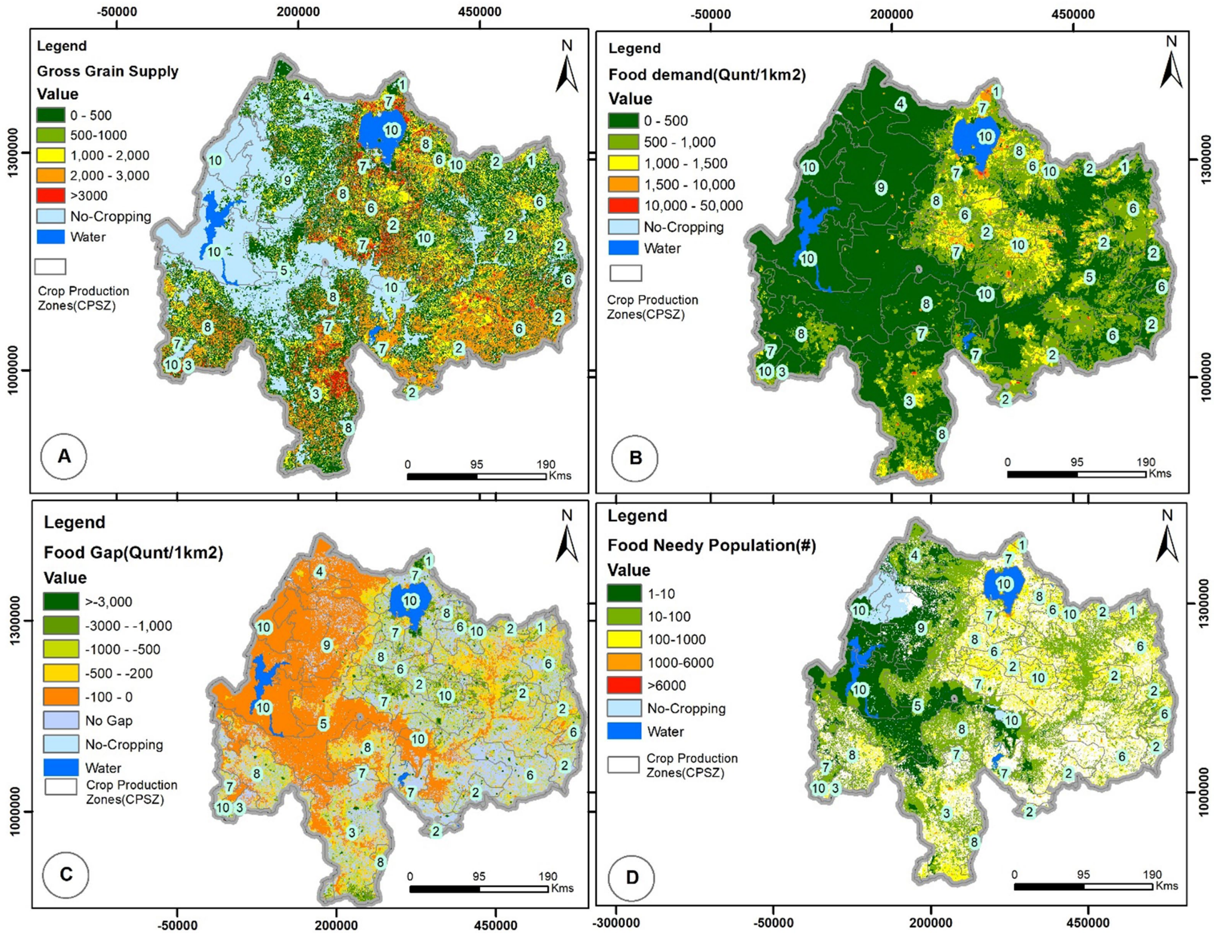

FIGURE 12
Implications of grain production performance/efficiency of CPS: existing food gap **(A)**; existing food gap **(B)**; existing food needy population at grid level **(C)** and long year food needy population at district level **(D)**.

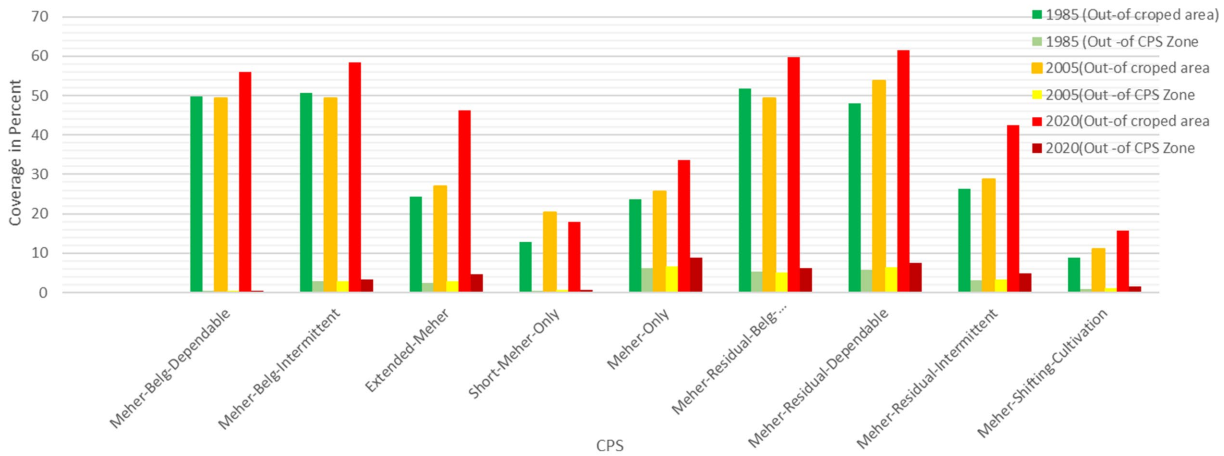

FIGURE 13
Multi-temporal cropped area dynamics in each CPS.

Despite rich natural resources of Ethiopia, existing CPS performance is poor. Enhancing how grain is produced on current landscapes is crucial, along with maintaining and improving land quality to boost efficiency. *Chemical Input*: The limited use of agricultural inputs due to lack of finance, such fertilizers and pest control, hampers smallholder farmers' productivity. However, without detailed data on land quality and crop needs, applying these inputs may not yield positive results. Further research is needed in this area. *Institutional and Technological Inputs:* Traditional CPS suffer from inadequate agricultural infrastructure and low technological adoption. Lack of attention on multiple cropping, absence of required institutional or fragile setup hindered to enhance grain production. To foster innovative CPS, the sector requires better financing and advanced facilities.

In an effort to realize the above strategies, four categories of contributions from the present study can be identified, namely:

1) Methodological contributions (context-assessment approach): Proper and comprehensive grain production assessment demands not only detailed and accurate spatial data but also a holistic and multidimensional assessment approach. The present study has demonstrated a multidimensional and holistic assessment approach to evaluate the grain production performance/efficiency of rainfed CPS practiced in UBNB (Equations 1–4). The assessment approach presented in this study could help to boost existing research dimensions and further promote the efficient utilization of agricultural space, green water, and land resources, in addition to providing a basis for improving food production efficiency.
2) Spatial and multi-temporal data contributions: The success of such comprehensive assessments depends on the generation of detailed input data at the required spatial, temporal, and thematic scales, including cropland area, crop types, cropping systems, and production determinants. This study successfully created several spatial datasets, creating a database for future research. However, due to limited resources, the authors failed to include some important indicators from the analysis such as yield of each crop at different years.
3) Scientific evidence and knowledge generation: Previous studies often lacked comprehensive national or basin-level performance assessments due to data limitations, limiting insight into crop production systems (CPS). Many attempts focused on single-factor analyses such as sown area or yield rather than comprehensive assessments. The analysis presented here not only uncovers current CPS characteristics and spatial variations in grain production but also improves understanding of CPS and their performance and efficiency. Furthermore, this framework provides a foundation for future research, with the data generated serving as valuable input for future studies.
4) Policy: The results of this study will benefit policymakers in four ways: (i) refining the basin-level agriculture-oriented economic development strategies, (ii) assisting planners and decision-makers in understanding rain-based crop production systems (CPS), (iii) identifying effective solutions to improve grain production efficiency for smallholder farmers who still practice traditional rainfed CPS, and (iv) informing food security policies and optimizing resource allocation in the agricultural sector.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

TK: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. ET: Data curation, Investigation, Methodology, Supervision, Validation, Visualization, Writing – review & editing. ST: Data curation, Formal analysis, Methodology, Software, Writing – review & editing. WB: Investigation, Project administration, Supervision, Validation, Writing – review & editing. GZ: Funding acquisition, Investigation, Project administration, Resources, Supervision, Visualization, Writing – review & editing. LA: Data curation, Formal analysis, Investigation, Methodology, Software, Writing – review & editing. CW: Funding acquisition, Investigation, Project administration, Resources, Supervision, Validation, Visualization, Writing – review & editing. GO'D: Investigation, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. This research was supported by the Water Security and Sustainable Development Hub, which was funded by the UK Research and Innovation's Global Challenges Research Fund (GCRF) (grant no. ES/S008179/1).

Acknowledgments

The authors express their sincere gratitude to the Water and Land Resource Centre of Addis Abeba University (WLRC-AAU) for the facilitation of the data collection and provision of other required resources to undertake this research.

Conflict of interest

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2024.1420700/full#supplementary-material

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TYPE Original Research
PUBLISHED 22 November 2024
DOI 10.3389/fsufs.2024.1412058

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RECEIVED 04 April 2024
ACCEPTED 12 November 2024
PUBLISHED 22 November 2024

CITATION
Zhao T, Wu X, Cheng Y and Liu W (2024) Does disaster resettlement reshape household livelihood adaptive capacity in rural China?
Front. Sustain. Food Syst. 8:1412058.
doi: 10.3389/fsufs.2024.1412058

Does disaster resettlement reshape household livelihood adaptive capacity in rural China?

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To bolster ecological conservation efforts and foster human well-being, the Chinese government has implemented the disaster resettlement program. Rural households encounter various environmental and social challenges regarding disaster resettlement. One of the priorities of disaster resettlement in China is to implement reforms to mitigate disaster losses and improve the livelihoods of households. The research on the livelihood adaptive capacity of households and their research framework provides a new perspective for the livelihood survey of the resettlement population. This article assesses Household Livelihood Adaptive Capacity (HLAC) and further explores how it is impacted by disaster resettlement. Taking Ankang Prefecture in Southern Shaanxi Province as a case, this study investigates the endogeneity and selection bias of resettlement. It employs the Propensity Score Matching method to empirically test the effect of disaster resettlement on household awareness, action, and ability to measure HLAC. The results show that: (1) disaster resettlement significantly reduces HLAC, and (2) poverty alleviation relocation, centralized resettlement, and short-distance relocation have a significant negative impact on HLAC. The Chinese government has tried to use disaster resettlement to address ecological protection and social development problems, and it plays a crucial role in China's development programs. We provide evidence that disaster resettlement leads to a decrease, rather than an increase, in HLAC. Therefore, we suggest that more follow-up assistance policies should be developed to enhance HLAC.

KEYWORDS
disaster resettlement, relocated households, sustainable livelihoods, livelihood adaptive capacity, China

1 Introduction

The international disaster database (EM-DAT) has reported over 26,000 major disasters globally since 1900 (Ritchie et al., 2023). The total number of global disasters has relatively increased by 214% since 1970 (Asgary et al., 2024). With significant natural hazards, climate change, and environmental degradation around the world, people who reside in impoverished regions in developing countries face enormous survival challenges (Chen et al., 2017). Disaster resettlement solves the problems of communities living in disaster-prone areas, which are often exposed to the dangers posed by riverbanks, coastlines, and mountain slopes, by relocating them to new areas away from such hazards (Pormon et al., 2023). Disaster resettlement plans are adopted as a preventive measure to cope with the increasing risk of disasters (Pormon et al., 2023; Contreras et al., 2013). It is believed that this action constitutes not only a geographical movement but also a change in production, lifestyle, and the reconstruction of social networks for households (Xu et al., 2022). Meanwhile, it is a potential option for households confronted with the need to respond to risks and disasters (Sina et al., 2019a,b). Post-disaster resettlement policies can be considered the lifeblood of post-disaster resettlement projects (Siriwardhana and Kulatunga, 2023). One such policy, the Southern Shaanxi Disaster Resettlement (SSDR) program, is designed for people to move voluntarily from ecologically fragile, steep, remote mountain areas to towns or plains to restore ecosystems and critical ecosystem services, alleviate poverty, and enhance livelihood security. Like other conservation and human development policies worldwide, multiple stakeholders, including local households, are involved in the SSDR. Disaster risk seriously affects the life and property safety and sustainable development of households in disaster areas (Yang et al., 2021; Yang et al., 2023). Relocation, as a solid external shock and policy intervention, poses particular risks to household livelihoods (Xu et al., 2022). Therefore, one of the greatest challenges is to better understand the immediate and potential influences of the SSDR on household well-being and livelihood activities to achieve sustainability goals (Li et al., 2015).

In areas severely affected by climate change, effective adaptation of households is crucial for their survival and development (He et al., 2023). Previous research examining disaster resettlement has mainly focused on population and satisfaction issues (Pormon et al., 2023; Wilmsen and Webber, 2015; Lo and Wang, 2018), the ecological environment, and natural resources problems (Li et al., 2015; Liu and Wu, 2023); however, there are relatively few studies on household sustainable livelihoods and livelihood adaptive capacity within the context of disaster resettlement at the household level. According to Chambers and Conway (1991), livelihood is a family's ability to earn a living and find a way to make a living based on the ability to own capacity, assets, and activities. Much of the literature on livelihood draws on the Sustainable Livelihoods Framework (SLF) (Wu et al., 2023). In recent years, scholars have increasingly focused on the correlation between disaster resettlement and household livelihoods. For instance, Liu et al. examined rural household livelihood vulnerability under disaster resettlement (Liu et al., 2023). Yang et al. investigated the influencing factors and interrelationships between rural resilient livelihoods and sustainable livelihoods in resettlement communities following significant disasters (Yang et al., 2023). Similarly, Liu et al. (2020a) adopted the framework of livelihood resilience proposed by Speranza et al. (2014), taking the disaster resettlement setting as the research object. The study measured household livelihood resilience and tested how it was impacted by disaster resettlement. Livelihood vulnerability, resilience, and adaptive capacity are pivotal concepts within household livelihood systems that are intricately interconnected and complexly intertwined. Few studies employ quantitative methods to identify and measure rural household livelihood adaptive capacity (Chen et al., 2018; Liu et al., 2022). These existing studies have examined the status of households under disaster resettlement from a livelihood perspective, but there is little research that explores changes in their livelihood adaptive capacity in the context of disaster resettlement from a more detailed angle. From the standpoint of disaster resettlement, this study aimed to conduct a quantitative assessment of rural Chinese household livelihood adaptive capacity (HLAC) to investigate the impact of disaster resettlement on HLAC.

The concept of livelihood adaptive capacity refers to the system's ability to adjust and modify its characteristics to effectively mitigate damage, capitalize on opportunities, or cope with the impacts of unexpected events (Jones et al., 2010; Thulstrup, 2015; Nyamwanza, 2012). Livelihood adaptive capacity is viewed as a positive property and is critical in fostering sustainable adaptations (Engle, 2011). Household livelihood adaptive capacity (HLAC) refers to the capacity of households to predict and respond to natural or human-induced disturbances, mitigate their impacts, and recover quickly from the consequences (Maldonado and Sanchez, 2014). Some research found that HLAC relies heavily on accessible capital assets, particularly natural capital and biological resources (Chen et al., 2018; Zamasiya et al., 2017; Yin et al., 2019). Many scholars have used the Sustainable Livelihoods Approach Framework (SLA) proposed by the United Kingdom Department for International Development when studying adaptive capacity (Wu et al., 2023; Pagnani et al., 2020), which is a popular integrated approach and pointed out that the framework can describe the complexity of livelihoods at the household level, mainly through human capital, financial capital, social capital, physical capital, and natural capital. While previous studies have detailed the applicability of the method, most studies have yet to address the acquisition of individual abilities. Acosta et al.'s' framework applies fuzzy logic analysis to combine 12 socioeconomic indicators to generate an adaptive capacity index (Acosta et al., 2013). In the past, the assessment of the HLAC mainly focused on income, poverty, and welfare, which proved challenging in achieving scientific objectivity. Therefore, it is feasible and practical to measure HLAC using the framework applied by Acosta et al., particularly given the analytical framework and indicator quantification. Wu et al. argued that combined capital enhances household adaptability (Wu et al., 2023). The complementary effects of incentivizing livelihood capitals (i.e., material, natural, social, and human capital) can improve HLAC (Wu et al., 2023). The changing dynamics of livelihood capital and the interrelationships among different livelihood capitals influence HLAC (Thulstrup, 2015). Furthermore, the improvement or decline of HLAC is related to the results of micro-individual adaptation, coping with relocation shocks, policy interventions, and climate perceptions (Rogers et al., 2019; Mairura et al., 2021). Its function determines whether households can optimize their livelihood models or fall into the livelihood dilemma (Liu et al., 2020b). Moreover, some studies have combined the vulnerability of household livelihood to analyze and explore changes in HLAC (Chen et al., 2017; Zamasiya et al., 2017; Mekonen and Berlie, 2021). Lower adaptive capacity increases the livelihood vulnerability of households (Mekonen and Berlie, 2021). Among these studies, the evaluation index system constructed by Liu et al., which examined three dimensions—awareness, action, and ability—is conducive to evaluating HLAC (Liu et al., 2022). To dig deeper and provide relevant empirical evidence, based on our previous study, this paper examined whether disaster resettlement can reshape HLAC and the impact of relocation characteristics on HLAC, which is a possible contribution of this paper.

This study is based on survey data relating to 657 households in three counties of Ankang Prefecture, Southern Shaanxi Province, China. Following our previous studies, this article measures HLAC from three dimensions: awareness, action, and ability. It employs Propensity Score Matching (PSM) to examine the influence of disaster resettlement and its characteristics on HLAC. This article may provide helpful information for formulating and implementing policies related to disaster risk management. Compared with previous research, this study makes the following contributions: (1) We assess the level of HLAC under the background of disaster resettlement and supplement relevant studies with cases and evidence; (2) We explore the influence of disaster resettlement and its characteristics on HLAC, which is of great theoretical significance in studying livelihood adaptive capacity at the household level; (3) We study rural households from typical undeveloped areas of the Southern Shaanxi Province, China. The research results could be a reference for developing disaster resettlement prevention systems in other developing regions. As highlighted here, disaster resettlement can alter household livelihood and societal structures, necessitating the transformation of the country's socio-economic systems into more sustainable states (Chen et al., 2018; Yin et al., 2019). Investigating the effects of disaster resettlement on HLAC holds considerable practical relevance. This study addresses two issues: 1. What is the level of HLAC in the research areas? 2. What is the correlation between HLAC and disaster resettlement? The following sections of this paper are structured as follows: Section 2 outlines the study materials and methods, Section 3 contains the analysis results, and Section 4 presents the discussion and conclusions.

2 Materials and methods

2.1 Study area

This research study was carried out in Ankang Prefecture, one of three prefectures in Southern Shaanxi Province, China, where disaster resettlement programs were implemented (Figure 1; Li et al., 2021). Ankang Prefecture is situated in the central area of the Qinba Mountainous Area, an essential national biodiversity and water conservation ecological area (Liu and Wu, 2023). Rural households have high poverty vulnerability, and many impoverished individuals reside in isolated mountainous regions characterized by severe natural conditions, fragile ecosystems, and inadequate infrastructure development. Relocation in this area affects 220,000 rural households characterized by high levels of livelihood vulnerability, a major livelihood project of concern to the Chinese government, and many of its relocation experiences and practices have been replicated at the national and provincial levels. From 2011 to 2020, the relocation project in Southern

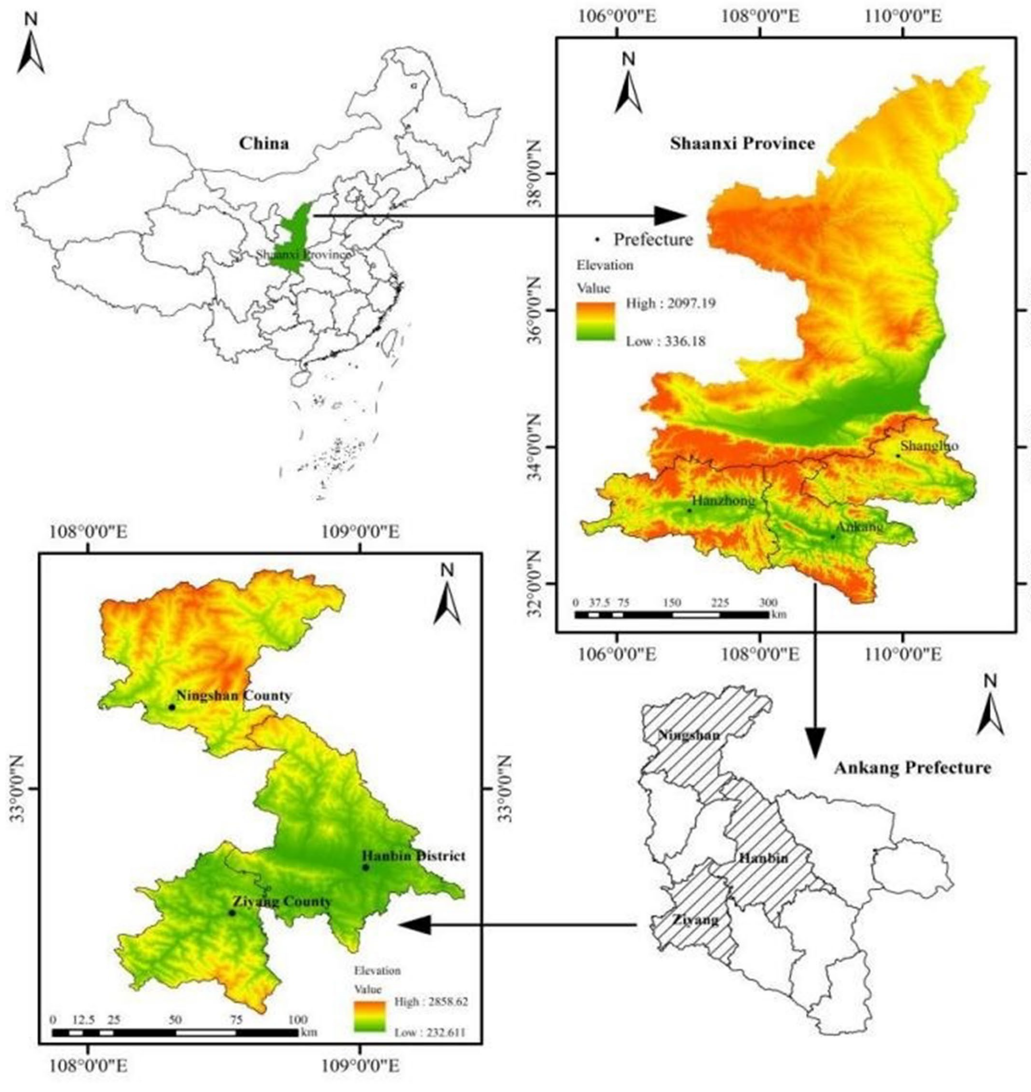

FIGURE 1
Location of the study area (Liu et al., 2020a).

Shaanxi Province involved 226,000 rural households in Ankang Prefecture. Moreover, all three surveyed counties are designated as critical national poverty alleviation and development areas with relatively high poverty incidence rates within their jurisdictions. Therefore, the survey area can serve as a representative site for exploring ways to reduce vulnerability, improve HLAC, and improve human well-being.

2.2 Data collection

This study utilizes data from the survey examining rural household livelihood in Ankang Prefecture, located in Southern Shaanxi Province. In the sampling process, three typical concentrated resettlement communities in Ziyang County and eight administrative villages in four towns in Ningshan County and Hanbin District were randomly selected, and questionnaire surveys were conducted among households during the survey period (Liu et al., 2022). Ankang Prefecture is a gathering place for several conservation and development policies, and the case points selected in this survey are representative. Survey data were collected through individual interviews by a trained team of researchers with heads of households or adult family members. During collection, various quality control methods were employed to ensure the accuracy and objectivity of the data collected. A total of 657 valid questionnaires were obtained with a response rate of 98.06%, including 459 respondents who had been relocated and 198 non-relocated households.

2.3 Measuring HLAC

According to the definition of HLAC, we identify HLAC at three levels: awareness, ability, and action. The methodology also provides a practical way to select indicators of HLAC. Households' awareness of environmental changes and disasters, including whether they are aware that external factors such as climate change and policy shifts may impact their livelihoods, affects their actions. Still, this action depends on the present ability of the person, and different types of situations produce various types of actions or behaviors. Here, the authors suggest selecting HLAC indicators from three levels and six dimensions at the household level. Based on existing literature and experience from past scholars in the context of HLAC, the most relevant indicators are selected (Table 1). In the research framework, awareness is represented by the dimension of experience (Sina et al., 2019b; Alam et al., 2016), which captures how relocated households have responded to previous environmental changes. Households with more extensive experience tend to be more astute in their decision-making when confronted with environmental changes. In this paper, household experience is predominantly represented by work history (Li C. et al., 2017). Ability is reflected across three dimensions: material resources, infrastructure, and technology. Material resources directly reflect the economic capabilities of households, where cultivated land area (Liu and Wu, 2023) and housing type (Li C. et al., 2017) are used. The infrastructure is mainly represented by the distance of the household to the main highway and the products and tools owned by the household; the increase in physical capital helps households shift away from agriculture to non-agriculture and contributes significantly to their income (Shi et al., 2017). Technical skills refer to the household's skill level and social relations (Li M. et al., 2017), as well as their ability to utilize social networks and resources to cope with changes in the external environment of livelihood systems, including participation in skills training and relationships with village cadre relative (Liu and Wu, 2023). Actions include economic resources and flexibility, characterized by financial assistance, housing value, and agricultural income. Flexibility refers to the ability of households to sustain their livelihoods in the face of external environmental disturbances (Li C. et al., 2017) and how new systems can be reconstructed, including non-agricultural income and household size (Sina et al., 2019b). In summary, based on the quantitative analysis of household surveys, this paper selects 13 indicators to measure HLAC under the background of disaster resettlement.

TABLE 1 Measure of household livelihood adaptive capacity (HLAC) indicators.

HLAC	Determinants	Index measure	Index	Formula	Formula
Awareness	Experience	Household head age	E_1	$E = 0.5*E_1 + 0.5*E_2$	$A_1 = E$
		Previous work experience	E_2		
Ability	Material resource	Housing type	M_1	$M = 0.5*M_1 + 0.5*M_2$	$A_2 = M + I + T$
		Cultivated land area	M_2		
	Infrastructure	Distance to the main highway	I_1	$I = 0.5*I_1 + 0.5*I_2$	
		Products and tools	I_2		
	Technology	Skill training	T_1	$T = 0.5*T_1 + 0.5*T_2$	
		Village cadre relative	T_2		
Action	Economic resource	Economic assistance	R_1	$R = 0.3*R_1 + 0.4*R_2 + 0.3*R_3$	$A_3 = R + F$
		Agricultural income	R_2		
		Housing value	R_3		
	Flexibility	Household size	F_1	$F = 0.5*F_1 + 0.5*F_2$	
		Non-agricultural income	F_2		
Gross value of HLAC					$HLAC = A_1 + A_2 + A_3$

To further analyze HLAC, this study adopts the method of bias normalization, eliminating the influences of different scales and dimensions and ensuring comparability of the indicators. In addition, questions with multiple-choice answers are specified as specific values on a scale ranging from 0 to 1. For example, housing structures define 1, 0.33, and 0.67 values. The range standardization method is used to standardize each indicator variable, which can eliminate the influence of different dimensions and orders of magnitude of the original data. Thus, we can obtain the HLAC by adding the indicators in Table 1.

2.4 Econometric method

Scholars usually select multiple regression models, plausible irrelevant regression models, and instrumental variables to examine the influencing factors of HLAC. Our study uses Propensity Score Matching (PSM) method to analyze the impact of disaster resettlement on HLAC and to solve the endogeneity and selection bias of disaster resettlement (Li et al., 2015; Ouya et al., 2023). PSM is primarily used to address sample selection bias resulting from non-random assignment, making the treatment and control groups more comparable in terms of covariates. The free choice of whether to participate in disaster resettlement may be endogenous, resulting in non-randomness of the sample and, thus, self-selection problems. The management choices of policymakers regarding project allocation and implementation will also affect disaster resettlement and HLAC. Therefore, these problems will lead to bias in the model estimation results and low reliability. In econometrics, the instrumental variable method, social experiment, and PSM are usually used to solve the above problems. However, the instrumental variable method is highly controversial. Social experiments are challenging to carry out and can be impossible to implement. The PSM method can address issues of bias and low reliability in model estimation results. Moreover, the PSM method is widely applied because of its advantages in reducing the degree of bias of the estimated effect.

For the analysis, considering the sample feature X and the indicator variable T, the propensity score is:

$$P(X) = \Pr(\mathrm{T} = 1 | \mathrm{X})$$

Thus, the average treatment effect of the disaster resettlement policy is:

$$\mathrm{ATT}_{\mathrm{PSM}} = \mathrm{E}_{\mathrm{P(X)}|\ \mathrm{T}=1}\left\{\mathrm{E}\left[\mathrm{Y}^{\mathrm{T}}|\ \mathrm{T}=1,\mathrm{P}(\mathrm{X})\right]-\mathrm{E}\left[\mathrm{Y}^{\mathrm{C}}|\ \mathrm{T}=0,\mathrm{P}(\mathrm{X})\right]\right\}$$

Further, the average effect of the project ATT can be written as follows:

$$\mathrm{ATT}= \frac{1}{N_T}\left[\sum_{i\in T}\left(Y_{i2}^{T}-Y_{i1}^{T}\right)-\sum_{j\in C}\omega(i,j)\left(Y_{j2}^{C}-Y_{j1}^{C}\right)\right]$$

Among them, T indicates that households participated in relocation, C indicates that they did not participate, N is the sample size of participating households, and W (i, j) is the matching weight. For further details about the PSM method, please refer to Li et al. (2015).

According to the analysis framework of HLAC and the actual situation in the study area, the dependent variable of the PSM model is set as HLAC and its three aspects: awareness, ability, and action. Furthermore, in this paper, we use the expert evaluation method (Sharp, 2003) to determine the weights of each indicator variable, and eliminate the overlap between indicators and subjective assumptions about indicator design as much as possible. Based on the actual situation of previous studies and surveys, the independent variables selected in this paper are the education of household heads, household size, children, livelihood diversity, officers (whether a household member is an official), whether the household participates in the sloping land conservancy program (SLCP), and participation in collective affairs (the number of participations in collective affairs). Xu et al. calculated the degree of livelihood diversification (Xu et al., 2019). Each livelihood activity in which households participate is assigned a value of 1. If a family engages in three livelihood activities (i.e., farming, planting, and migrant work), the livelihood diversification index is 3. The specific definitions and descriptions of each variable are shown in Table 2. In addition, according to the relocation approach, the resettlement is divided into poverty alleviation relocation, disaster avoidance relocation, and ecological restoration relocation. According to the relocation type, it is divided into centralized relocation, non-centralized relocation, long-distance relocation, and short-distance relocation.

3 Results

3.1 Rural household characteristics in Ankang prefecture

Using field survey data gathered from Ankang Prefecture, this study briefly analyses the sample's fundamental characteristics. Of the 657 samples, 459 were relocated, and 198 were non-relocated. Among the sample of relocated households, 109 (23.75%) households were relocated under poverty alleviation relocation, 40 (8.71%) under ecological restoration relocation, 64 (13.94%) under project-induced relocation, 201 (43.79%) under disaster avoidance relocation, and 45 (9.80%) for other reasons. Household relocation commonly involves relocating within local communities, local townships, neighboring townships, and other areas. Local communities accounted for the most significant portion of these options, accounting for 54.47%. Following closely behind were local townships at 35.73% and neighboring townships at 4.36%. From the perspective of relocation approaches, 354 households were involved in centralized relocation, 43 in scattered relocations, 52 in self-determined relocations, and 10 households chose other methods. In other words, 77.12% of the households were relocated through centralized relocation, including transferring an entire village to a customized community. According to the length of time since relocation, households were categorized into short-term (less than 3 years), medium-term (between 3 and 5 years), and long-term resettlers (over 5 years). The majority fell into the short-term category (211 households), followed by long-term (141 households) and medium-term resettlement (103 households).

Households choose a variety of livelihoods when faced with disaster resettlement; migrants were divided into four categories: non-farm households, pure farming households, and diversified households, while 45.21% of households chose to work in non-agricultural sectors. 38.66%

of households were engaged solely in nonfarming activities, while those involved in pure farming activities accounted for just 16.13%.

3.2 Household livelihood adaptive capacity and resettlement characteristics

In this paper, Stata version 15.1 was used to regress the valid sample of household data. The results of independent variable selection and the estimation results of the probit model are shown in Table 3. Overall, the Pseudo R^2 value estimated by the model was 0.12, the chi-square statistic was 92.11, and the log-likelihood value was −352.79, indicating that the overall fitting effect of the model is good. At the same time, the selection of each independent variable met the balance requirements. Table 3 shows the impact of each variable inputted into the model on the household's participation in disaster resettlement. In the probit model, the education of household heads had a significant negative impact on the involvement in disaster resettlement. This indicates that, with the improvement of the efficiency of target identification by resettlement policies, rural households with low education levels are more likely to be identified as target households and can achieve "relocation" under the guidance of policies. In addition, rural households with children tend to participate in disaster resettlement, and one of the most essential incentives is that rural children are offered the rare opportunity of gaining access to equitable education. The livelihood diversification index for participation in collective affairs, the number of public officials, and the level of involvement in SLCP significantly negatively affected participation in disaster resettlement. The following households did not want to participate in resettlement: households with a higher livelihood diversification index for participation in collective affairs had relatives who were officials or had participated in SLCP. Households with high levels of participation in collective affairs were less likely to participate in disaster resettlement. This may be because, although they had actively participated in collective affairs and moved closer to the local government, certain relocation costs prevented them from moving into the resettlement community. Therefore, the relocation policy has become an effective means to accurately identify vulnerable groups and people living in deep poverty, contributing to the Chinese government's efforts to address rural poverty issues tangibly.

3.3 The impact of disaster resettlement on HLAC

According to the estimation results of the probit model, the Kernel matching method was selected to calculate the probability that each household would participate in relocation, poverty alleviation relocation, disaster avoidance relocation, ecological restoration relocation, centralized resettlement, non-centralized resettlement, long-distance relocation, short-distance relocation, and non-participation in relocation. This is also termed the 'propensity score'. To test the matching results of the propensity scores of each sample, Figures 2a–h presents the propensity score density matching graphs for various household samples before and after matching,

TABLE 2 Definitions and descriptive information of the determinants of participation in disaster resettlement.

Variables	Definitions and description	Mean	SD	Maximum	Minimum
Education of household head	Continuous variable	2.35	0.93	6.00	1.00
Household size	Continuous variable	4.50	1.61	9.00	1.00
Children	Yes = 1, No = 0	0.58	0.49	1.00	0.00
Livelihood diversity	Continuous variable	1.88	0.98	4.00	0.00
Officers	Yes = 1, No = 0	0.21	0.40	1.00	0.00
Sloping land conservancy program (SLCP)	Yes = 1, No = 0	0.69	0.46	1.00	0.00
Participation in collective affairs	Continuous variable	3.72	1.45	5.00	1.00

TABLE 3 Probit model estimation of households participating in disaster resettlement.

Variables	Regression coefficients	SE	*Z* statistics	*p* value
Education of household head	−0.15**	0.0593	−2.52	0.012
Household size	0.04	0.0391	1.05	0.295
Children	0.23*	0.1238	1.83	0.067
Livelihood diversity	−0.43***	0.0602	−7.15	0.000
Officers	−0.36***	0.1315	−2.74	0.006
Sloping land conservancy program (SLCP)	−0.31**	0.1262	−2.45	0.014
Participation in collective affairs	−0.07*	0.0387	−1.77	0.077
Cons	1.96**	0.3063	6.41	0.000
Log likelihood	−352.79***			
Pseudo R^2	0.12			
LR $chi^2(7)$	92.11			

***, ** and * denote significance at the levels of 1, 5, and 10%, respectively.

indicating the disparity between the treatment group and control group, both pre- and post-sample matching.

Based on the propensity score calculated above, this study matched the propensity values of relocated households, different relocation types of rural households, different relocation approaches, and different relocation distances between rural households and non-relocated households. We used the livelihood adaptive capacity of matched non-relocated households as the counterfactual capital of relocated households and other households in the absence of relocation. Table 4 shows the estimated effects on HLAC, awareness,

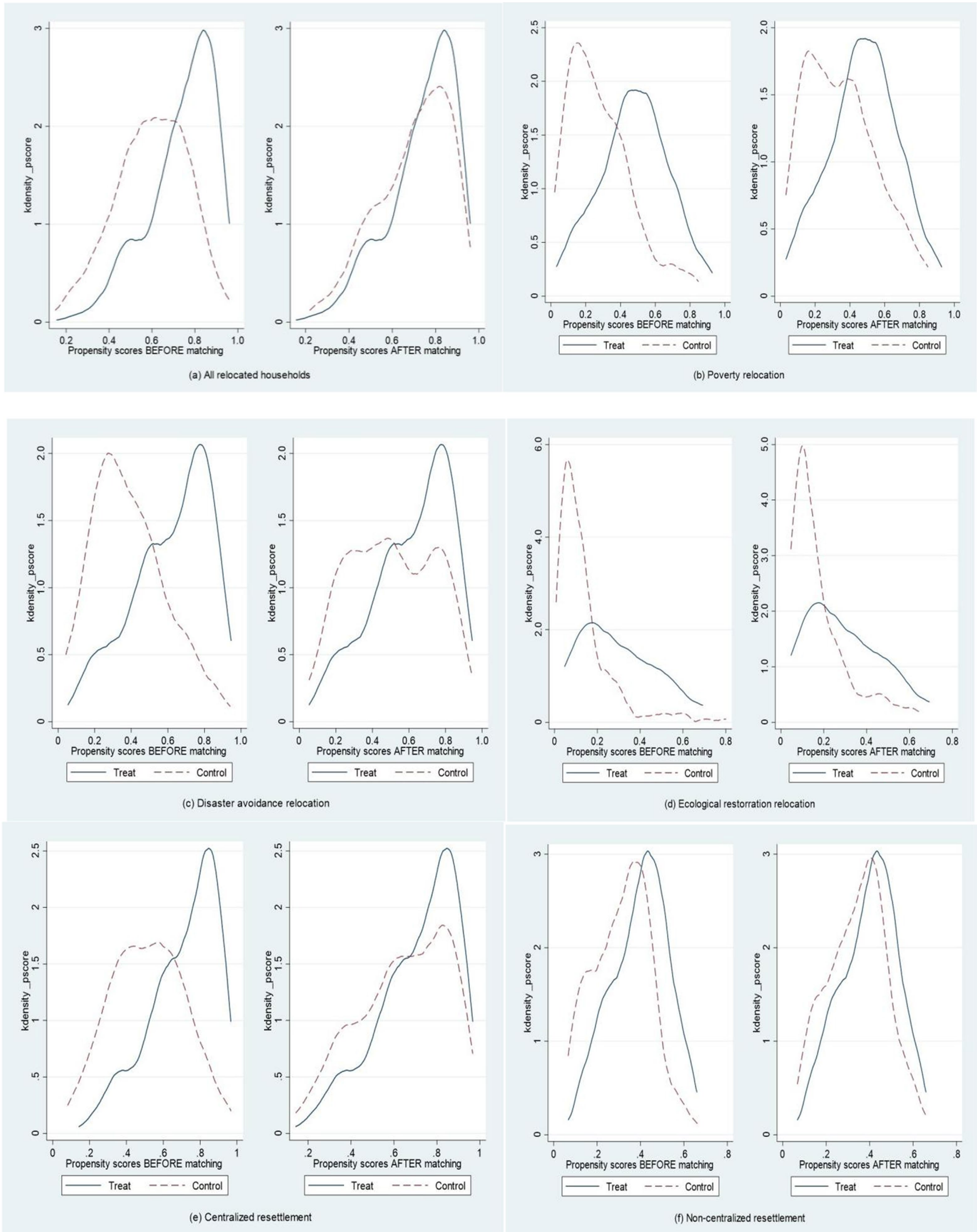

FIGURE 2 (Continued)

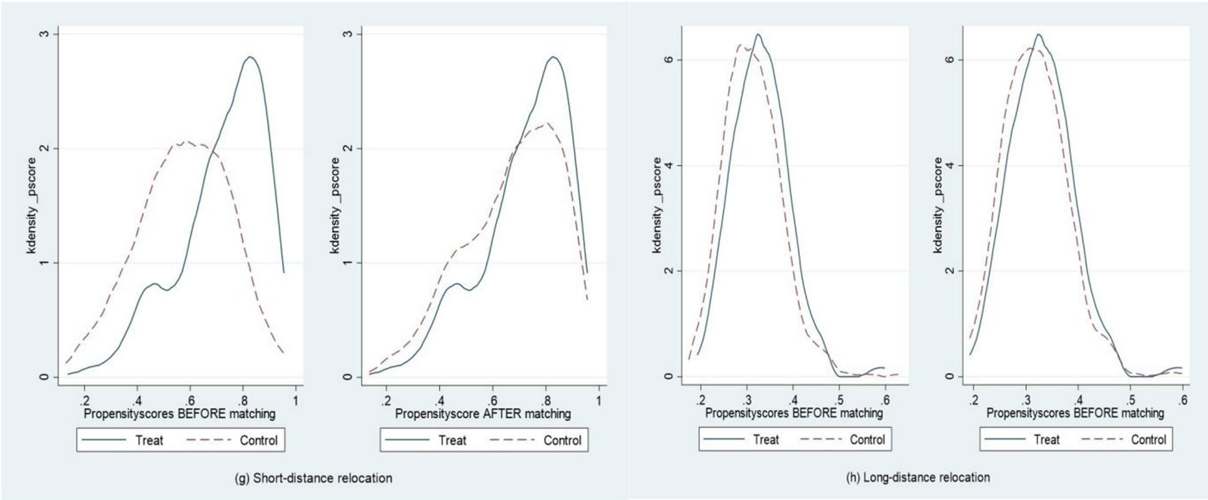

FIGURE 2
(a–h) Density distribution of propensity score.

TABLE 4 Impact of different relocation approaches on livelihood adaptive capacity (HLAC) by Kernel matching.

Variables	All relocated households		Poverty alleviation relocation		Disaster avoidance relocation		Ecological restoration relocation	
	ATT	*t* value	ATT	*t* value	ATT	*t* value	ATT	*t* value
Awareness	−0.01	−0.40	−0.02	−1.35	−0.01	−0.56	0.02	0.89
Ability	−0.11	−3.19***	−0.16	−3.64***	−1.11	−2.74***	−0.15	−2.96***
Action	0.04	1.86*	0.05	1.77*	0.04	1.37	0.04	1.13
HLAC	−0.08	−1.70*	−0.13	−2.33**	−0.09	−1.62	−0.09	−1.26

ability, and action based on econometric models of disaster resettlement and relocation types. Disaster resettlement can negatively reduce HLAC and the actions of rural households. Poverty alleviation using relocation can decrease HLAC.

The influence of disaster relocation approaches on HLAC varied. Centralized resettlement had a significant negative impact on HLAC, as shown in Table 5. This finding can be explained as follows: As a result of household resettlement, households lost the land they had originally occupied, significantly reducing the cultivated land area. At the same time, when the resettlement subsidy for rural households ceased, household channels for accessing funds were restricted. Households were unable to cope with the livelihood pressure associated with disaster resettlement. Therefore, HLAC has declined dramatically. In terms of the relocation distance, Table 5 shows that the impact of short-distance relocation on HLAC was significant. After the short-distance relocation, due to changes in the environment and resources, for example, residents' living habits have also changed. Indeed, moving to a new area requires people to adapt to new folk customs, production modes, and lifestyles. Therefore, it is unsurprising that HLAC, using this relocation method, has experienced a decline.

Under the PSM method, the matching effect must be tested to determine whether the matching result can be used as a counterfactual result. In this study, the reliability of the conclusions in Tables 4, 5 was tested, and the balance test results of the matching of relocated and non-relocated households were determined, as shown in Table 6. We found that the absolute value of the deviation of all variables in the kernel matching was less than 10%. The t-test revealed no significant difference between the treatment group and the control group after all variables were matched. This indicated that the respective variables could no longer provide new information regarding the participation of households in relocation after matching. The matching effect met the test requirements. Therefore, the results of the balance test are satisfactory, and the findings reported in Tables 4, 5 were deemed reliable.

4 Discussion

Disaster resettlement is a vital development strategy to mitigate natural disasters and promote the livelihood transformation of rural households. Our study found that disaster resettlement had a significant negative impact on HLAC, which is similar to the findings of previous studies, which suggested that disaster resettlement increases the vulnerability of resettled households (Chen et al., 2017; Sina et al., 2019a; Galarza-Villamar et al., 2018); indeed, an increase in vulnerability level implies a decrease in HLAC (Liu et al., 2022). According to their research, disaster resettlement indirectly reduces HLAC. Many studies show that households' recovery and adaptation can take 3–5 years or longer. In the short term, especially within 5 years, their livelihoods will face a slow recovery process. Despite government efforts, challenges in policy implementation often lead to a decline in livelihood adaptation. Continued government support is crucial for long-term development. Therefore, some planned

TABLE 5 Impact of different relocation approaches on livelihood adaptive capacity (HLAC) by Kernel matching.

Variables	Centralized resettlement		Non-centralized resettlement		Long-distance relocation		Short-distance relocation	
	ATT	t value	ATT	t value	ATT	*t* value	ATT	*t* value
Awareness	−0.00	−0.32	0.00	0.06	0.03	1.12	−0.01	−0.84
Ability	−0.14	−3.63***	−0.05	−1.16	−0.14	−2.88***	−0.11	−2.96***
Action	0.03	1.41	0.04	1.66*	0.06	1.49	0.04	1.75*
HLAC	−0.11	−2.20**	−0.01	−0.12	−0.06	−1.07	−0.08	−1.70*

TABLE 6 Balance test for sample matching.

Variables	Sample	Mean		Bias/%	Reduce bias	*t*-test	
		Treated	Control			*t*	*p>t*
Education of household head	Unmatched	2.27	2.52	−27.9	77.0	−3.28	0.001
	Matched	2.27	2.21	6.4		0.98	0.326
Household size	Unmatched	4.51	4.46	3.3	6.4	0.39	0.695
	Matched	4.51	4.46	3.1		0.46	0.647
Children	Unmatched	0.61	0.51	20.4	94.1	2.41	0.016
	Matched	0.61	0.61	1.2		0.18	0.856
Livelihood diversity	Unmatched	1.68	2.31	−69.0	93.2	−7.91	0.000
	Matched	1.68	1.72	−4.7		−0.0	0.486
Officers	Unmatched	0.17	0.29	−28.0	67.2	−3.41	0.001
	Matched	0.17	0.21	−9.2		−1.46	0.144
Sloping land conservancy program (SLCP)	Unmatched	0.65	0.80	−33.7	91.0	−3.83	0.000
	Matched	0.65	0.64	3.0		0.42	0.675
Participation in collective affairs	Unmatched	3.72	3.75	−1.6	85.5	−0.19	0.852
	Matched	3.72	3.68	3.0		0.44	0.661

relocation programs may be counterproductive in the short term (Fernando and Jayasinghe, 2023). Furthermore, government-driven, recovery-focused policies may not contribute to the long-term sustainability of rural household livelihoods (Yang et al., 2023). Resettlement has significant positive environmental and social impacts (Liu et al., 2023; Rogers et al., 2019; Li C. et al., 2017; Wang et al., 2018); a significant increase in households' average and total income and more excellent employment opportunities following disaster resettlement have been reported (Liu et al., 2020a; Rogers et al., 2019; Liu et al., 2020b; Li C. et al., 2017). Resettlement also significantly improves the overall livelihood capital of households, especially physical capital (Liu et al., 2020a). However, the vast costs of resettlement generate a heavy financial burden, which may pose significant challenges for households (Lo and Wang, 2018; Liu et al., 2020a; Lo et al., 2016). As a result, households' livelihoods change with the various livelihood capitals that they have at their disposal, which simultaneously reshapes HLAC. Therefore, identifying ways to improve HLAC and household livelihoods is complex.

The effects of disaster resettlement characteristics on HLAC differ. Among the reasons for relocation, only poverty alleviation relocation had significant negative impacts on HLAC, whereas disaster avoidance relocation and ecological restoration relocation had no considerable effect on HLAC. The adverse effects of resettlement became evident in the pre-relocation stage (Nikuze et al., 2019). As one of the relocation approaches, poverty alleviation relocation will weaken household livelihood resilience (Liu et al., 2020a). As a result of anti-poverty relocation, the socio-economic conditions surrounding the relocated households change (Nikuze et al., 2019). Changes in livelihood assets and the economy after relocation will impact HLAC. Among relocation types, centralized resettlement had a significant negative effect on HLAC. After centralized resettlement, rural households lost the land they had originally occupied and had less cultivated land. Therefore, households that had once relied on cultivation found themselves in a situation whereby their cash incomes were lost (Li C. et al., 2017). This led to a decline in HLAC. In addition, centralized resettlement households are more inclined to choose expansion strategies and have already begun transitioning faster from predominantly agricultural lifestyles to more diverse and non-agricultural ones (Li C. et al., 2017). Moreover, government follow-up support is lacking (Rogers et al., 2019).

Regarding relocation distance, the current study found that short-distance relocation adversely affected HLAC. According to Lo et al. (2016), long-distance relocation and short-distance relocation can affect resettlement outcomes. However, we found that only short-distance relocation significantly impacted HLAC. Short-distance relocation households enjoy land compensation rights in the resettlement area, particularly in terms of government support. Land compensation rights significantly mitigate the effects of land loss on households. In the long run, most households are overly reliant on land and fail to broaden their livelihood methods, which will still lead to a decline in their HLAC. Furthermore, the proximity to urban centers means that many long-distance relocation households find it easier to secure non-agricultural employment and job positions such as builders, cooks, drivers, and cleaners (Lo and Wang, 2018). Therefore, compared with long-distance relocation, households that are relocated short distances away find it more difficult to adapt in terms of their livelihoods. Thus, the government should provide financial assistance and ensure the livelihoods of households participating in short-distance relocation to promote better adaptation. Finally, factors including the education level of household heads, whether there are children in the household, livelihood diversity, participation in collective affairs, the number of public officials, and participation in SLCP all had significant negative impacts on participation in disaster resettlement.

The study has some limitations. First, it only examined the current impact on HLAC, and there is a need to carry out follow-up studies to explore how HLAC changes over time. Second, selecting HLAC indicators may not be perfect, and each indicator will mean different things in different contexts (Chen et al., 2018). Multiple socio-economic indicators should be included. Third, weights for each indicator were determined using the expert evaluation method. However, to ensure greater data accuracy, comparisons should be performed using different analytical methods. Finally, this paper selected the southern region of Shaanxi Province, China, which limited the scope of the survey, research findings may vary in different localities, so the results may only apply to less developed areas.

5 Conclusion

Under the background of disaster resettlement and sustainable development, the importance of household livelihood has gradually come to the fore (Chen et al., 2017; Sina et al., 2019a; Yang et al., 2021; Peng et al., 2022; Salgueiro-Otero et al., 2022; Yuhan et al., 2021). The current study provides empirical evidence that highlights the impacts of disaster resettlement on HLAC. The results show that disaster resettlement and its characteristics negatively affected HLAC. The main findings of this study are as follows: First, disaster resettlement significantly reduced HLAC. Second, relocation under a poverty alleviation program undermined HLAC. Third, centralized resettlement and short-distance relocation led to a dramatic decline in HLAC.

Disaster resettlement can significantly reduce HLAC. Adaptation is a complex process, and anticipative or designed adaptation is not always effective. Indeed, public policy and adaptation strategies have not always been successful. There is a pressing need to evaluate the implementation of adaptative guidance and resilience strategies. Future research that considers adaptation strategies, adaptive outcome, and livelihood risks in the context of disaster resettlement are needed. Relocated households, especially those with children, are more eager to receive a good education than non-relocated households. This study advocates that the government should implement preferential educational policies in the resettlement areas to meet the desire of relocated households to improve their children's education. Follow-up support should consider more influential indicators such as school district placement, skills training, employment assistance, and public facilities to improve the HLAC of relocated households. It is essential to assist relocated households in rebuilding and adjusting their livelihoods for sustainable development. Poverty alleviation relocation, centralized resettlement, and short-distance relocation can lead to a pronounced reduction in HLAC. Therefore, in formulating subsequent assistance policies, there should be a certain degree of bias toward poverty alleviation relocation, centralized resettlement, and short-distance relocation for households to ensure fairness and justice while enhancing the well-being of relocated households. The views of households should be considered when formulating policies related to sustainability (Mairura et al., 2021). Early and effective communication of project details and the involvement of affected households in decision-making can help to safeguard their livelihoods (Nikuze et al., 2019). The purpose of planned relocation should focus not only on relocating groups away from hazardous areas but also on the social, economic, political, and institutional causes of vulnerability, which should be addressed (Fernando and Jayasinghe, 2023). In addition, effective community participation is conducive to resettlement (Jamshed et al., 2018; Jamshed et al., 2019). Therefore, after resettlement, we should also pay attention to the effective participation of the community. Although the results may vary among different survey sites, the studied area was very representative, and our findings are likely to apply to other less-developed regions worldwide. The constructed index system of the influencing factors of HLAC can serve as a specific supplement to micro-level research on disaster resettlement. It provides typical cases for studying households under different backgrounds. The research findings offer a basis for formulating targeted policy recommendations and are of important theoretical and practical significance.

Livelihood adaptive capacity is currently a priority topic in global development. Disaster resettlement is regarded as an opportunity to improve the livelihood adaptive capacity. However, resettlement projects can also have adverse effects, such as poverty, sudden changes in livelihood choices (Mohit et al., 2010), and disruption of social capital (Contreras et al., 2013). These factors may lead to dissatisfaction with relocated households (Aulia and Ismail, 2013). This study provides specific information on the link between the context of disaster resettlement and HLAC. Future research on HLAC, in the context of post-disaster relocation, should continue to examine its spatiotemporal changes, refine the HLAC indicator system, compare results across different research methodologies, and focus on adaptation strategies and outcomes among these populations. Through longitudinal studies, track and research the adaptation strategies of resettled populations to enhance the HLAC.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

TZ: Writing – review & editing, Visualization, Project administration, Conceptualization. XW: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Funding acquisition, Data curation. YC: Writing

– original draft, Supervision, Software. WL: Writing – review & editing, Validation, Supervision, Resources, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. This work was partially financed by the National Natural Science Foundation of China (No. 71803149; 72022014; 723B2019, and 72474173), the Ministry of Education Humanities and Social Science Research Youth Fund Project (No. 22XJC630007), the Natural Science Foundation of Shaanxi Province (No. 2023JCYB607 and No. 2024JC-YBQN-0758), and the Social Science Foundation of Shaanxi Province (No. 2023R290).

Acknowledgments

The authors are very grateful to the many people interviewed for their patience and assistance.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2024.1412058/full#supplementary-material

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frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 26 November 2024
DOI 10.3389/fsufs.2024.1393124

OPEN ACCESS

EDITED BY
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RECEIVED 28 February 2024
ACCEPTED 29 July 2024
PUBLISHED 26 November 2024

CITATION
Kassawmar T, Tadesse M, Desta G, Bantider A, Teferi E, Bewket W, Abraha L, Zeleke G, Walsh CL and O'Donnell G (2024) Unlocking horizontal and vertical cropping intensification potentials to address landlessness and food security challenges of rainfed crop production systems in Ethiopia: potential, performance, and gap assessment. *Front. Sustain. Food Syst.* 8:1393124.
doi: 10.3389/fsufs.2024.1393124

Unlocking horizontal and vertical cropping intensification potentials to address landlessness and food security challenges of rainfed crop production systems in Ethiopia: potential, performance, and gap assessment

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Knowledge-based evidence about potential and existing rainfed cropping is crucial for decision-making for sustainable land use and food security. Using multi-criteria spatial analysis techniques, this study assessed the current status of cropland availability and projected impacts on future crop production in Ethiopia. The study primarily defined the extent of the Rainfed Cropping Area (RCA) and assessed the performances of different cropping practices. After precisely mapping cultivated area, cropping intensification potentials were estimated. Subsequently, disregarding the existing cultivated area, completely unsuitable areas, and protected and intact forest areas, the potentially available arable land using suitability analysis techniques was determined. In addition, the performance of existing crop production systems was evaluated against the natural potential. The findings reveal that RCA covers ~60% of the country's landmass, of which cropping is practiced in only 33%. The coverage of Potentially Available Cropland (yet uncultivated) accounts for 16% of the country's RCA. This is dominantly located in sparsely populated western and southwestern parts of the country. This study confirms that Horizontal Cropping Intensification (HCI) in the RCA of Ethiopia reaches only 33%. On the other hand, Vertical Cropping Intensification (VCI) practices cover only 10%, while about 1/3 of the RCA is suitable for VCI strategies at various levels of suitability. The performance of existing VCI-oriented cropping (which covers only 10% of the RCA) is very poor. Challenges to the use of the available cropland and ways of addressing land shortage for needy farmers are highlighted to inform efforts to readdress landlessness and food insecurity in Ethiopia.

KEYWORDS

cropland, potential cropland, intensification, land suitability, rainfed agriculture, landlessness, food insecurity, Ethiopia

1 Introduction

Agriculture in Ethiopia is age-old and renowned for its diverse farming landscapes (Hurni, 1985) and accommodates over 80% of 120 million people relying on rainfed systems (Abdollahzadeh et al., 2023; Asfaw et al., 2021). Some argue there's no more land left to expand grain production, while others believe there are still uncharted and untapped landscapes, possibly larger than what's currently used (Hurni, 1983). Considering polarized scientific views over rainfed farming, the authors sought to address four research gaps that could lead to invent strategies to unlock the RCA's potential and address landlessness and food insecurity problems of Ethiopia's smallholder farmers: (i) research focus, (ii) data and knowledge, (iii) methodology, and (iv) policy gaps. Previous research has exhaustively covered the challenges of rainfed farming to intensify food production faced by Ethiopia's smallholder farmers, including land degradation, poor cropping methods, land fragmentation, low input use, traditional practices, and single-crop systems, resulting in low yields. With average landholdings below 1 hectare per household, food security for a family of 4–5 is unattainable without intensification strategies (Endalew et al., 2015). Forthcoming efforts to increase yields are further constrained by diminishing farm sizes (Hurni et al., 2015), climate change, and the land tenure system (Rahmato, 2003). Enhancing grain yields and resolving land scarcity is challenging due to high input costs, limited technology, and undulating terrain (Teshome, 2014). Additionally, limited knowledge, weak institutions, poor land use policies, and population pressure make rainfed agriculture an inefficient and unreliable farming system (Hurni, 1988). The majority of reports from such research pronounce recurrent socio-ecological crises like drought, famine, migration, and displacement are peculiar characteristics of rainfed systems (Taddese, 2001). Contrarily, a different scientific perspective like the book "Sufferings in God's Environment" by McCann (1995) highlights Ethiopia's RCA potential and argues that many Ethiopians suffer due to a lack of understanding of this potential. Another key study is the highland reclamation research from the early 1980 (Hurni, 1983), which comprehensively evaluated Ethiopia's rainfed farming and reported that by applying existing traditional cropping practices, the RCA can support approximately 250 million people (Hurni, 1985). Indeed, while much research has addressed the challenges of rainfed agriculture, less attention has been given to its potential for improving food security and addressing landlessness (Lambin and Meyfroidt, 2011; Pretty, 1999; Nkwasa et al., 2023). As a result, biased research emphases have led to generate inconsistent facts about the opportunities and potentials of Ethiopia's RCA. Given these scientific insights, this study targets a synoptic assessment of the potential and performance/efficiency of Ethiopia's rainfed farming systems.

In developing countries like Ethiopia, a lack of inclusive studies has hindered the creation of reliable knowledge. Efforts to ensure food security have been weakened by the absence of evidence-based spatial information on suitable and usable extra land for crop production (Pretty, 1999; Lotze-Campen et al., 2010; Lambin, 2012; Wirsenius et al., 2010). Though data about natural capitals, like cultivated land size within Rainfed Cropping Area (RCA) and Potentially Available Cropland (PAC) are crucial, they are often lacking in the necessary scale and accuracy (Mandryk et al., 2015).

Data and knowledge gap about Ethiopia's rainfed farming is partly due to definition limitations (agriculture or cropland/cultivated land). For instance, there is no agreed definition of Rainfed Agricultural Area (RAA) or RCA and highland region of the country. RAA is widely used to characterize varying types of agricultural practices that rely on rainfall (Wani et al., 2009). Since it includes diverse practices like forestry, livestock farming, and crop production, its meaning is always contextual. Under Ethiopia's complex agricultural practices, some studies have used the definition and boundaries of highland, RAA, and RCA interchangeably. Therefore, such interchangeable use of terms has led to inconsistent estimates of agricultural or cultivated areas (Hurni et al., 2015). Moreover, the boundary and extents of RCA are not yet clearly defined spatially, nor updated and improved in a timely manner. Such methodological issues in research have led to growing doubts on the potentials and opportunities of Ethiopia's RCA, which clearly justifies the third research gap authors have identified. Therefore, in the quest for cropping intensification (CI) strategies, as cropping factors vary over time and space, not only properly delimiting the RCA but also regularly updating both definitions and boundaries as per the context is essential. In defining RCA, mapping the potential, suitability, and availability of landscapes for crop production, and characterizing the spatial distributions of croplands across the various altitudinal gradients and agro-climatic zones is crucial (Hurni, 1998). In delimiting the spatial boundary of RCA, theoretically, altitude, which controls precipitation and temperature, is the most important indicator (Hurni, 1998). Factors such as soil type and slope are also important to further classify and elaborate the level of suitability of the landscape for specific cropping.

When aiming to provide policy evidence to unlock rainfed-based intensification potentials of Ethiopia, local-scale comprehensive research and primary data covering the whole RCA are essential, though challenging (Kassawmar et al., 2018c). Because the national-level datasets provide generic information and are therefore of limited use for assessing national- and regional-level natural capitals and ecosystem services, including intensification (Nachtergaele, 2008). In Ethiopia, most of the available spatial evidence about RCA are either from specific case studies only, which are sparse (Muluneh, 2010), or at the national level, which is outdated and varied due to differences in approach, extent, and purpose (Kassawmar et al., 2018a). This highlights the importance of the second research gap identified by the authors: the need for national-scale, high-resolution, and accurate spatial data on natural capitals, such as detailed Land Use and Land Cover information (LULC), land use, farming, livelihoods, and cropping systems. In developing countries, where resource allocation for knowledge generation is limited, generating comprehensive evidence about the natural capital of Ethiopia's RCA is not a trivial task. In Ethiopia, on top of limited investment for data generation, methodological and technological challenges contribute to the lack of reliable evidence for complex smallholder farming systems over large areas. In the pursuit of national-level spatial evidence for decision-making (Muluneh, 2010; Tadesse et al., 2014), researchers face not only financial limitations but also technical, technological, and infrastructural challenges. Consequently, researchers often choose to conduct their studies on a smaller spatial scale. Experiences have shown that, to produce and provide comprehensive data in large, complex areas like Ethiopia's RCA, researchers recommend applying advanced technology and substantial resources (Liu L. et al., 2020). To generate reliable and synoptic spatial evidence, advancements in remote sensing and geoinformatics privileged cost-effective and accurate methods compared to ground survey (Qiu et al., 2023). However, the intrinsic challenges of generating spatial evidence and knowledge over large and complex areas cannot be fully resolved by high-resolution imageries and advanced techniques like machine learning alone (Kassawmar et al., 2018a,c). Experiences indicate that local knowledge and secondary data are crucial for selecting relevant imagery and designing effective, context-specific mapping approaches.

Authors have theorized that the primary key to unlocking Ethiopia's RCA intensification potential lies in effectively understanding and utilizing the two relatively neglected natural capitals: agricultural space (land) and green water (rainfall). This would need to apply remote sensing technologies, ground-truthing methods, and participatory approaches to engage with smallholder farmers. By building a comprehensive datasets and robust analytical frameworks, we can better assess the relationship between farming practices and natural capital, leading to more informed decisions and policies (Lambin, 2012; FAO, 2007). However, the issue of unlocking intensification potential of Ethiopia's RCA goes beyond definition, delineating its extent and mapping and assessing its natural capitals. The success of any effort to intensify grain production will depend on the availability of an enabling policy environment and commitment in implementing it. In Ethiopia, much of the studies condemn existing land tenure systems and land use policies as never encourage intensification (Praveen et al., 2023; Zhang et al., 2021). This justifies the fourth category of research gap authors identified. Thus, in the quest for intensive food production, spatial evidence need to be generated, aiming to design and formulate context-specific and appropriate policy frameworks that allow to develop a sustainable strategy to alleviate food insecurity in the country (Endalew et al., 2015).

To this end, this study aimed to fill knowledge and information gaps in: clarifying the extent of the RCA and defining its boundaries with relevant criteria, and estimating the suitability, availability (PAC), and usability of land for horizontal (spatial expansion) and vertical (temporal cropping frequency) intensifications, as well as evaluating the performance of existing crop production systems. Specific objectives of the study are (i) to assess the vertical/spatiotemporal cropping intensification potentials of Ethiopia's RCA, (ii) to explore and propose solutions to address landlessness and food insecurity among smallholder farmers in Ethiopia, and (iii) thereby to explore and generate policy-relevant knowledge to design intensification strategies. The high-quality national-scale spatial evidence generated will bridge knowledge gaps, enhance cropping intensification potential, and provide a foundation for understanding the RAA's natural capital and regular monitoring of crop production. This research will help advocate for agricultural space-water management as a key solution to landlessness and food insecurity for smallholder farmers relying on rainfed systems.

2 Study area and data

2.1 Study area

The present assessment considered the entire Ethiopian boundary to delimit the extent of the Rainfed Cropping Area (RCA); detailed assessments of agricultural suitability were also made on the RCA, the vast proportion of which is often referred to as 'highland.' The highlands, which account for about 45% of the country's total land area, are home to 90% of the total population and about 75% of the 33 million livestock population (Hurni, 1998). The larger part of the highland areas of the country, where smallholder traditional agricultural system has been practiced for thousands of years (Zeleza and McCann, 1997; McCann, 1997), has agro-climatic zones that are favorable to rainfed agriculture (Figure 1). Ethiopia is an agrarian country where the economy of the majority (>80%) of the population is exclusively dependent on rainfed-based farming. According to Zeleza and McCann (1997), the Ethiopian highlands (with elevation range > 1,500 m a.s.l.) have been inhabited by humans far longer than most places in the world. As a result, the highland areas face many environmental degradation problems due to long-standing agricultural activities, intensified by population pressure (Hurni, 1985).

Given that about 80% of Ethiopia's population is dependent on agriculture, high population growth (2.5% in 2016) affects the RCA's capacity in providing required ecosystem services (Teshome, 2014). According to the Central Statistical Agency of Ethiopia (CSA) (CSA, 2019), the country's population was 22 million in the first National Sample Survey in 1967. It reached an estimated 100 million by 2014 (Teshome, 2014; CSA, 2019) and is expected to be 125 million in 2025. It is Africa's second-most populous country. The growing population size has led to steady increase in the extent of cultivated land over the last half century but a decline in *per capita* cultivated land area. In 1950, on average 35 people shared 1 km^2 of cultivated land; in 2014, 1 km^2 of cultivated land was shared among 270 people (Teshome, 2014). According to projections, the Ethiopian population will double every 20–30 years (Teshome, 2014). This population growth could lead to acute land scarcity for crop production, with serious repercussions for food security (Hurni et al., 2005). The current household-level landholdings of the majority of Ethiopian highlanders is very small—46% of households possessed <1 ha in 2014 (CSA, 2019) and about 10% of the highland household is landless.

The impacts of climate change and extreme environmental degradation resulting from undesirable land use and land cover change (LULCC), as well as population pressures, would hinder sustainable development in Ethiopia (Wondie et al., 2016). For example, land degradation contributes to a decline in agricultural productivity and persistent food insecurity (Taddese, 2001; Tadesse et al., 2014). Continued population growth (Hurni et al., 2005) and fragile institutional frameworks (Pretty, 1999) further expose the highlands to continuous land degradation and conversion (Taddese, 2001; Zeleke and Hurni, 2001). As a result, the small-scale farming system in the highlands has become less profitable, and the carrying capacity of the land has extremely declined. In the current situation, increasing yields per hectare alone cannot ensure food security at the household level (average 4.5 family members) (Teshome, 2014). In the country's highlands, grain production to feed the growing population is a concern that requires the implementation of alternative remedies, taking into account the realities of individual agricultural plots (Tadesse et al., 2014). Effective remediation measures on highly fragmented plots and patchy landscapes require detailed spatial information. Therefore, research that determines the extent of RCA (land currently cultivated and unused but suitable for growing rainfed crops) is important to support efforts to reshape Ethiopia's development policy in the right direction.

2.2 Data types and sources

This study required the integration of various spatial datasets at the national level. The main datasets used include LULC, climate, topography, soil, and surface rockiness maps (Figure 2). For 2016, a detailed LULC map was created from Landsat-8 images with a pixel

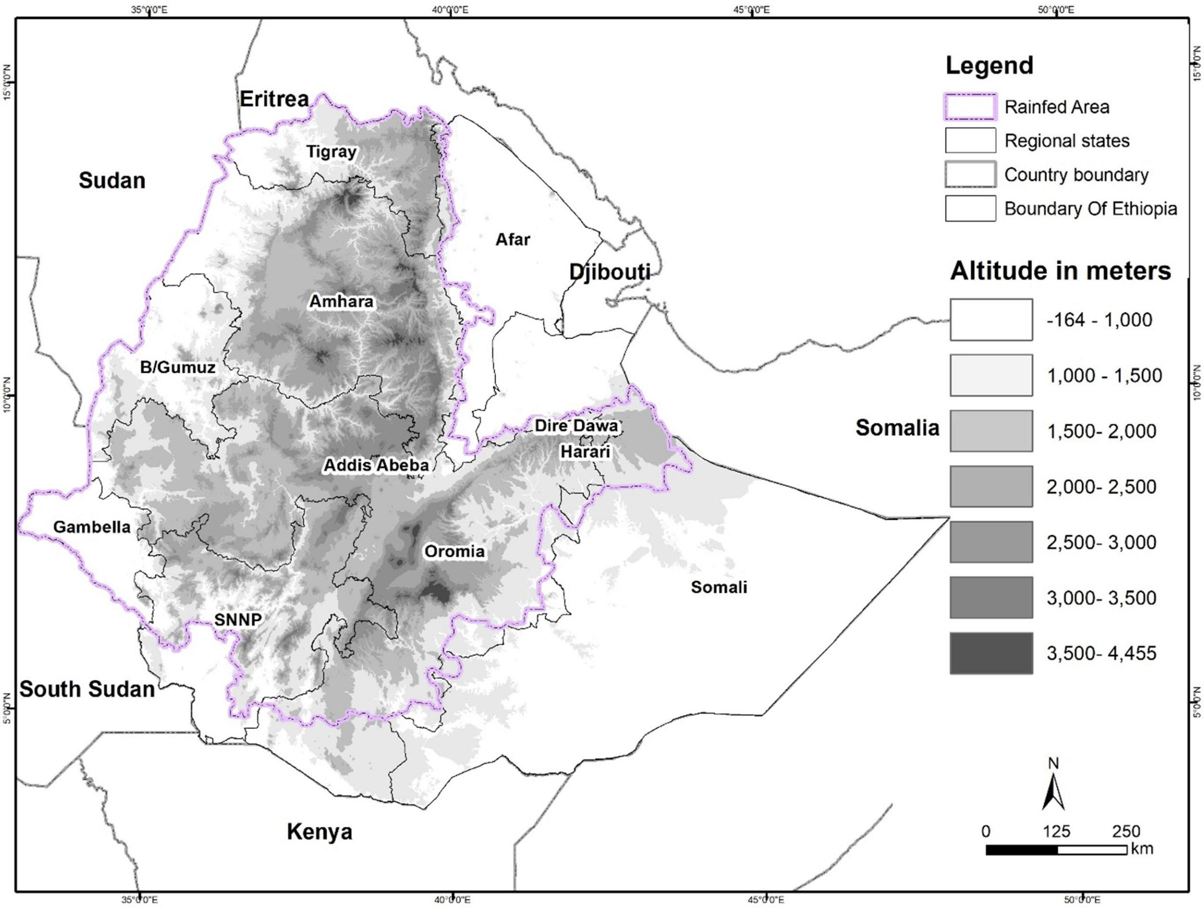

FIGURE 1
Location of rainfed agriculture areas in Ethiopia.

resolution of 30 m. A classification approach explained in Kassawmar et al. (2018a) was used, which takes the heterogeneity of the landscape into account. In addition to the LULC maps, complementary geospatial datasets were used including data on institutionally bounded areas (e.g., protected areas and settlements) obtained from government agencies and sources identified in Young et al. (2020) and the UNESCO database (IUCN, UNEP-WCMC, 2015). Other geospatial datasets used include: agroecological zones (Hurni, 1998); datasets on topographic variables such as slope and elevation ranges (SRTM at 30 m resolution from NASA (EarthExplorer[1]); datasets on climatic variables such as precipitation and temperature from the Ethiopian Meteorological Institute (EMI) and WorldClim data (WorldClim); soil data from the Water and Land Resource Center (WLRC[2]); and socio-economic data such as the Agricultural Area Survey Report, population census, and landholding sizes (CSA, 2019)). Improved versions of many of these geospatial datasets are available from WLRC as a series of geospatial database packages known as EthioGIS.II.[3]

1 usgs.gov
2 https://www.ethiogis-mapserver.org
3 www.wlrc-eth.org

3 Materials and methods

The data were analyzed in five main steps: (Hurni, 1985) defining the RCA (Abdollahzadeh et al., 2023) assessing the overall LULC composition in the RCA (Asfaw et al., 2021) estimating the currently cultivated and available (but uncultivated) cropland using sustainability analysis techniques (Hurni, 1983) mapping and estimating VCI indices by integrating primary and secondary data, and (Endalew et al., 2015) assessing the opportunities, challenges, and gaps of VCI and HCI.

3.1 Defining the extent of RCA

To redefine the RCA, the following steps were followed. First, we reclassified four important determinant factors (precipitation, temperature, altitude, and slope) into different value ranges (eight classes). Taking into account the agro-climatic suitability, a multi-criteria spatial analysis of the main factors of rain-based crop production was carried out (Lambin, 2012; Hurni, 1998). To assess and estimate the cultivated and uncultivated areas within the RCA, we constructed a detailed LULC map as described in Kassawmar et al. (2018c), which applies a second-level classification scheme with approximately 40 classes. Since the focus of the study was on the cultivated landscape, a

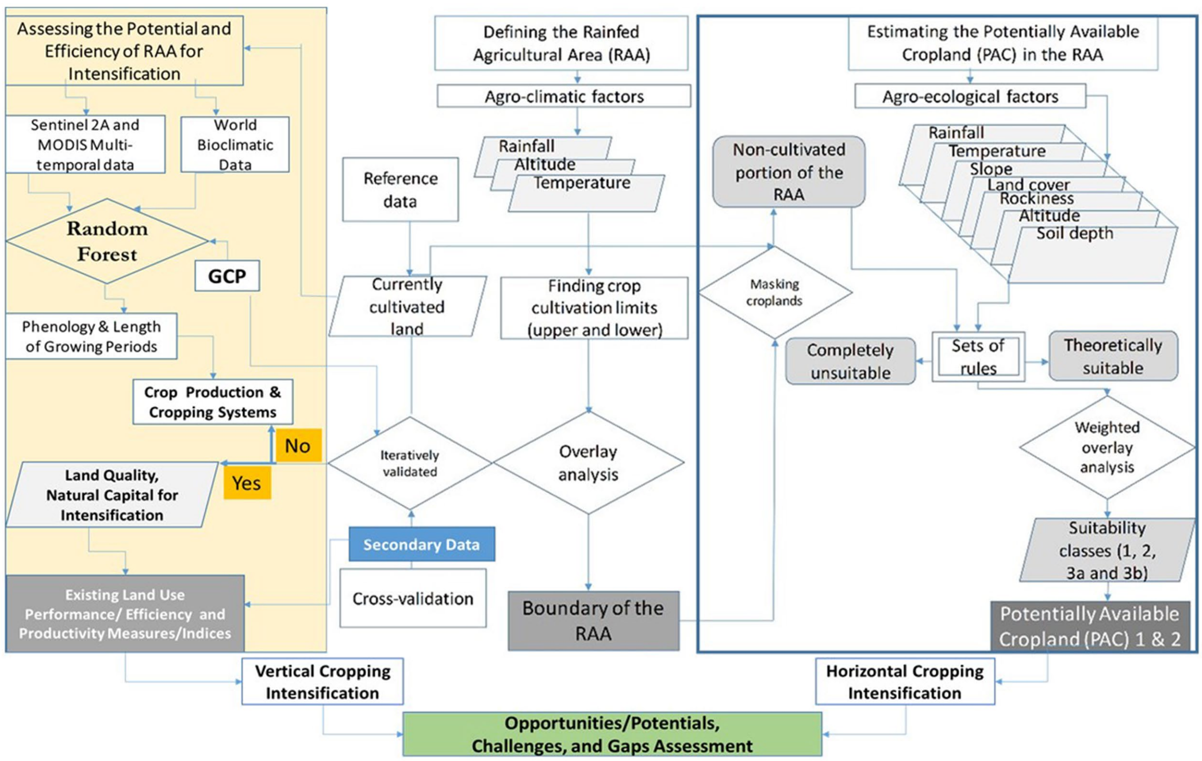

FIGURE 2
Schematic representation of methodological framework.

special classification technique was used to create the LULC map. To obtain a reasonable and accurate estimate of cropland area from Landsat images, we followed a context-oriented, practical, and applicable approach for Ethiopia (Kassawmar et al., 2018a). To know the upper and lower limits of existing crop production practices, we reclassified the LULC data into two classes: cultivated and uncultivated, so that potentially available cropland in the currently uncultivated landscape could be assessed. Subsequently, we performed iterative spatial analyses by overlaying cultivated pixels over the maps of the reclassified major determinant factors. Then, the presence of pixels representing cultivated areas in each newly classified area of determining factors was examined and statistically analyzed to determine the presence and absence of cropland in each class as well as the relationship between the determining factors and cultivation practices. A recent map (2020) showing the cultivated areas was used to determine the currently cultivated area and later iteratively validate the boundary of the RCA. Based on spatial association rules and overlay analysis techniques, the lower and upper limits of the determinant factors for crop production under rainfed systems were determined. Later, the boundary of RCA was determined using the upper and lower limits of major factor relationships that exist with crop production systems.

3.2 Mapping and assessing farming, livelihood, and land use systems in the RCA

Recent and improved farming, livelihood, and land use systems for the RCA were produced by updating previous datasets available from the FUSNET database of FAO (Medhin, 2011) employing several geospatial data integration and analysis complemented by ground survey and secondary data sources. The production of detailed LULC maps in this study (Level II) enabled us to significantly improve both the content and accuracy of these maps (Supplementary Figure S1 and Supplementary Table S3).

3.3 Rainfed crop production potential and performance assessment

With the aim of demonstrating the multi-faceted challenges of smallholder farmers of Ethiopia, whose livelihood is largely dependent on rainfed-based food production systems, such as food insecurity and landlessness, initially, two categories of solutions were anticipated: (i) land use systems and land management-oriented solutions and (ii) institutional/policy solutions. For the former case, detailed natural capital, land quality, and ecological suitability/environmental sustainability analyses were carried out to test two CI options that could address the prevailing challenges: (1) HCI option (Hurni, 1985) HCI options, i.e., how much extra cultivable land does exist on currently uncultivated portion of the RCA; and (2) VCI option (Abdollahzadeh et al., 2023) VCI, i.e., to what extent Multiple Cropping System (MCS) can be implemented practically without adding more space on the existing cultivated landscape of the RCA. To explore options and solutions of the first category, a detailed crop production suitability assessment on currently uncultivated landscapes of the RCA was performed and PAC was estimated. In the latter case, the performance of existing CPS was evaluated against the potential of RCA to apply MCS. Eventually, the findings were narrated in relation to the potential and possibility of addressing food security and landlessness challenges of inhabitants of the RCA of Ethiopia. For the latter solution resettlement, outmigration, and land policy (such as land redistribution, land consolidation, land allocation/reallocation, population control, and land tenure) were assessed and discussed. Supplementary Tables S2, S3 present the identified indicators with their formula/equation and basic description of the indices used to assess the performance of different CPS.

3.4 Cropping intensification potential and performance assessment

The potential and performance/efficiency of LUS and CPS can be assessed from varying dimensions, but scholars have widely used the three sustainability pillars, namely ecological, economical, and social dimensions (Wirsenius et al., 2010; Biswas et al., 2006; Liu J. et al., 2020). This study adopted a new holistic performance/efficiency framework that allows us to perform a multidimensional land use performance and efficiency developed by Liu J. et al. (2020). The potential of the RCA and existing CPSs were assessed using three categories of performance/efficiency evaluation measures: Natural Capital, Land Use Performance, Production, and Economic Performance. In the first category, Cropping Density Index (CDI), Agricultural Density Index (ADI); in the second category, Cultivated Land Utilization Index (CLUI), Multiple Cropping Index (MCI), and Cropping Intensity Index (CII); and in the third category, Area Diversity or Crop Diversity Index (CDI), Relative Yield/Productivity Index (RYI), and Unit Productivity Index (UPI) were used.

3.4.1 VCI potential, performance, and gap assessment

According to the present assessment, VCI is meant to produce food/grain applying multiple times (>2 times) crop production strategies over a single year in the same land, such as multiple cropping systems (MCS) and agroforestry systems using only rain water. A list of MCS, CPS, relevant CI indicators/measures, indices with formula, equations, used to assess the performance of CPS, and descriptions of indicators are provided as Supplementary Tables S2, S3.

3.4.2 Potential of HCI and gaps assessment

According to Lambin (2012), suitability of potentially available cropland (PAC)—sometimes referred to as land reserve, underutilized land, or spare land—is a category used to distinguish land areas considered moderately to highly suitable for cropping, which could be brought under cultivation in the near future. Two main approaches are often used to estimate PAC: residual and categorical approaches (Lambin, 2012). The residual approach involves simply excluding currently cultivated areas from the entire agroecologically suitable region (Ramankutty et al., 2002). The residual approach is used when spatially explicit, detailed land requirements information is not available and/or when the scope of the analysis is very wide, e.g., global or continental (Campbell et al., 2008). The use of the categorical approach requires detailed land quality requirements that allow the integration of various biophysical determinants of crop production (see Supplementary Table S1). The output can be categorized into different levels of suitability classes. The categorical approach is therefore best suited for spatially explicit and interlinked analysis made at the local/regional level (Lambin, 2012; Campbell et al., 2008). To assess the present and project the PAC in the RCA, we followed the FAO Land Suitability Assessment Framework (FAO, 2007). The following steps were performed: (Hurni, 1985) First, we took the 2016 LULC map of the RCA and defined the Actually Available Cropland (AAC), which is the currently cultivated landscape of the RCA. Next, the total uncultivated area of the entire RCA that is considered environmentally sustainable and theoretically usable for crop production was determined by excluding the AAC pixels from the RCA (Abdollahzadeh et al., 2023). Then we identified completely unsuitable (N) and theoretically suitable (S) landscapes within the RCA using the detailed land requirement factor maps (see Supplementary Table S1). From the LULC datasets, the N landscape includes settlement, water bodies, exposed rocks, afro-alpine, infrastructures, and river courses (Asfaw et al., 2021). Then, we identified institutionally constrained areas, such as parks, sanctuaries, reserves, conservation priority areas, ritual sites (churches and mosques), priority forests, and hunting areas. To map the PAC within the RCA, we need to determine the degree of suitability of the uncultivated area based on various crop production factors (slope, rainfall, temperature, land cover, soil depth, and altitude) (Hurni, 1983). Therefore, in the last step, we determined the degree of suitability of S-pixels within the RCA. This means that S has expanded the suitability classes according to both biophysical and socio-economic aspects. To further map and estimate the suitability level of S landscapes, which could indicate the temporal dimension of conversion (likelihood of being used for crop production), a multi-criteria spatial analysis technique was carried out, covering the entire rainfed agricultural area. This was done after excluding currently cultivated areas, completely unsuitable areas, protected areas, and intact forest areas; later evaluating the biophysical suitability of the remaining areas using multi-criteria decision rule techniques. Finally, the usability of the PAC was transcribed using a systematic assessment of the PAC and its availability from a socio-political perspective, such as population density, settlement, landholding size, landlessness, agricultural/livelihood system, policies, and history in the country.

3.5 Overall potential and performance assessment and implications

The overall performance of existing CPS against the inherent potential of the RCA was evaluated taking the average values of each performance index from all categories (with the assumption of having equal weights of each factor). The overall implication of the existing grain production performances of the various CPS was assessed by comparing food supply potential of the rainfed landscape against the existing food/grain demand of the society residing at 1 km^2 grid. Taking the overall average performance values of each CPS, gaps and future policy directions were identified by comparing the existing performance against the inherent natural capital or potential of the RCA to practice any cropping intensification options (CI).

4 Results

4.1 Extent of the RCA and current state

As identified by the newly defined RCA of Ethiopia (Figure 3), crop growing altitudinal limits of Ethiopia's RCA vary between 500 and 3,800 m a.s.l. depending on the latitudinal and longitudinal

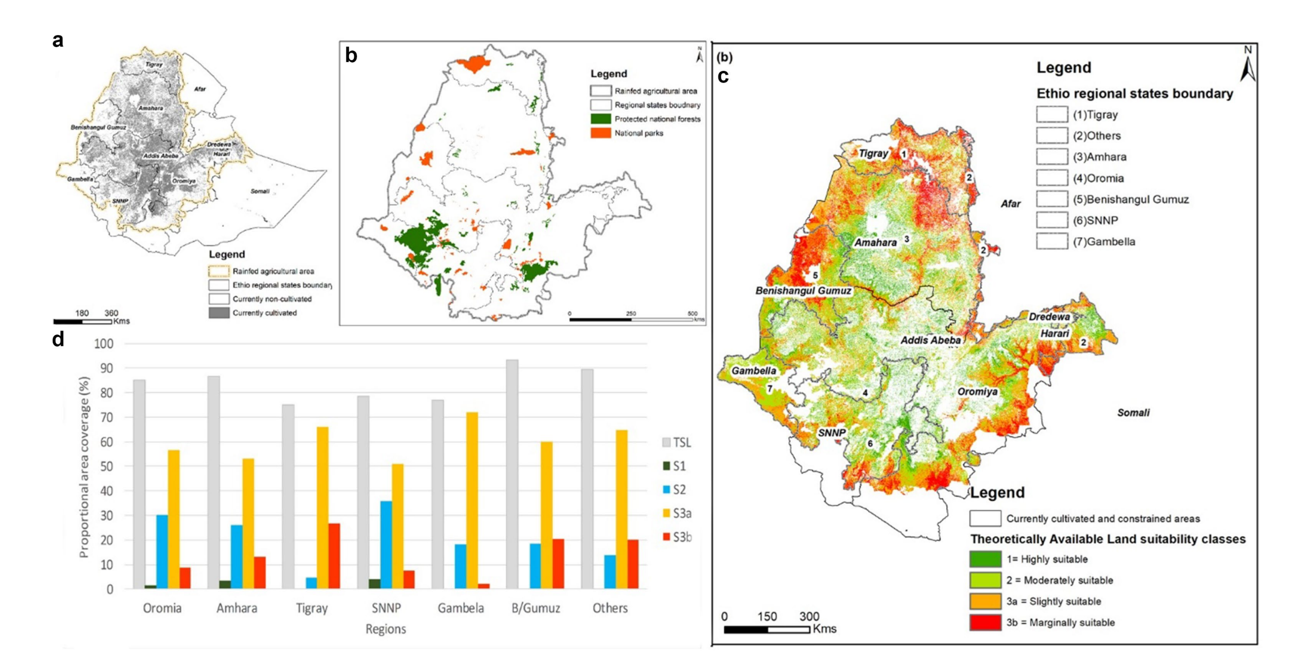

FIGURE 3
The redefined RCA supper imposed on the currently cultivated area (top-left-**A**) and the PAC within the RCA (right-**C**), institutionally restricted areas for cropping (top-middle-**B**), and proportion of theoretically suitable land (sum of S1, S2, S3a, and S3b) with different suitability classes in the RCA summarized according to administrative regions of Ethiopia (bottom-left-**D**).

influence on crop production. The RCA covers 667,094 km^2, making up about 60% of the country's land mass. The upper and lower elevation limits of the RCA include both currently cultivated land cover (221,653 km^2 or 33% of the RCA); 67% (445,441 km^2) of the RCA is uncultivated.

The RCA landscape features very complex LULC and LUS types (Supplementary Figure S1 and Table 1). As per the facts generated from the LULC maps, currently, the cultivated landscape covers about a third of the RCA. The uncultivated part of the RCA is dominantly covered by woody vegetation (37%), forest (12%), grassland (12%), and non-woody vegetation (7%).

4.2 Rainfed-based crop/food production systems in the RCA

The type, spatial distributions, and coverage of major growing seasons are provided as a Supplementary Figure S2. The location, coverage, and nature of crop growing season within the RCA vary considerably, being dependent on the rainfall pattern. Spatio-temporal variations in the amount, intensity, onset, and offset times of rainfall seasons are the main cause for diversity in crop production systems. Statistical facts generated from Supplementary Figure S2 confirm that about 38% of Ethiopia's RCA is used for food production, applying only one main rainfall season (locally called Meher season; June–September).

In some parts of the RCA, a second rainfed-based crop production system, known locally as the Belg rainfall season, allows a significant portion of the population to produce grain 1–3 times in a year. Additionally, a third growing season—residual soil moisture-based crop production—exists but lacks sufficient attention from the government and scientific community. This system is typically practiced after the main rainy season ends, with farmers also utilizing residual moisture left in the soil after the Belg rainy season.

Although the widely known residual moisture-based CPS represents a growing season that starts from the end of the main rainy season, in some areas, farmers also use residual moisture left in the soil after the end of the short rainy season (Belg). Thus, a fourth category of CPS exists in some places where overlapping of the first, second, and third growing seasons happens. Indeed, farmers rarely use such growing season for a complete crop production; instead, farmers use it to support the growth of crops planted either during the main growing season and/or during short rainy seasons. Such practices are commonly observed in high-altitude areas where evaporation is minimal. Supplementary Figures S1, S2 present major rainfed-based growing seasons and major CPS.

As depicted in Supplementary Figures S1, S2, the start and end of the second growing season (Belg or short rainy season) are extremely variable, which makes the spatial and temporal boundary fuzzy. As a result, in areas where there is a high synergy between these rainy seasons, the total length of growing periods (LGP) is higher, which allows farmers to grow perennial and permanent crops like coffee, false banana (locally called Enset), mango, avocado, banana, papaya, and several types of root crops. According to the facts generated from the maps depicted in Figure 4, in the majority of the RCA, which accounts for 38%, crop production is practiced using the main rainfall growing season (Mehere), followed by Meher-Residual-Belg complex synergy (12%), Meher-Residual (~10%), and Meher-Residual-Belg overlapping (5%).

4.3 Determinants of rainfed-based food production in Ethiopia

This study identified major determinant factors and evaluated several biophysical and socio-economical constraining factors that could hinder expansion of the extent of existing crop production on uncultivated landscapes of the RCA. The type and spatial distribution

TABLE 1 Composition of major LULC types and land use systems in the RCA (Kassawmar et al., 2018a) by administrative regions.

S. No.	Class	National level		Regional level						
		Area (Km^2)	Area (%)	Oromia	Amhara	SNNP	Tigray	B/Gumz	Gambela	Others
1	Forest	79,767	12.0	39,276	8,691	17,222	1826	6,150	5,977	626
2	Woodland	116,079	17.4	40,572	20,519	13,220	6,458	19,041	6,575	9,693
3	Shrub/bush	126,104	18.9	39,520	27,499	10,839	15,697	13,660	7,963	10,925
4	Cropland	221,653	33.2	101,489	59,176	33,857	15,975	5,534	605	5,016
5	Grassland	77,702	11.6	25,128	19,319	7,804	5,971	6,073	6,899	6,507
6	Barren land	31,992	4.8	4,390	17,534	1,051	5,190	152	149	3,528
7	Wetland	2,697	0.4	461	309	81	0	8	1839	0
8	Water body	6,634	1.0	1717	3,283	1,568	30	4	24	8
9	Afro-alpine	2,250	0.3	1,382	868	0	0	0	0	0
10	667,094	2,216	0.3	979	467	217	157	23	11	363
	Total	667,094	100	254,915	157,665	85,858	51,304	50,645	30,042	36,666

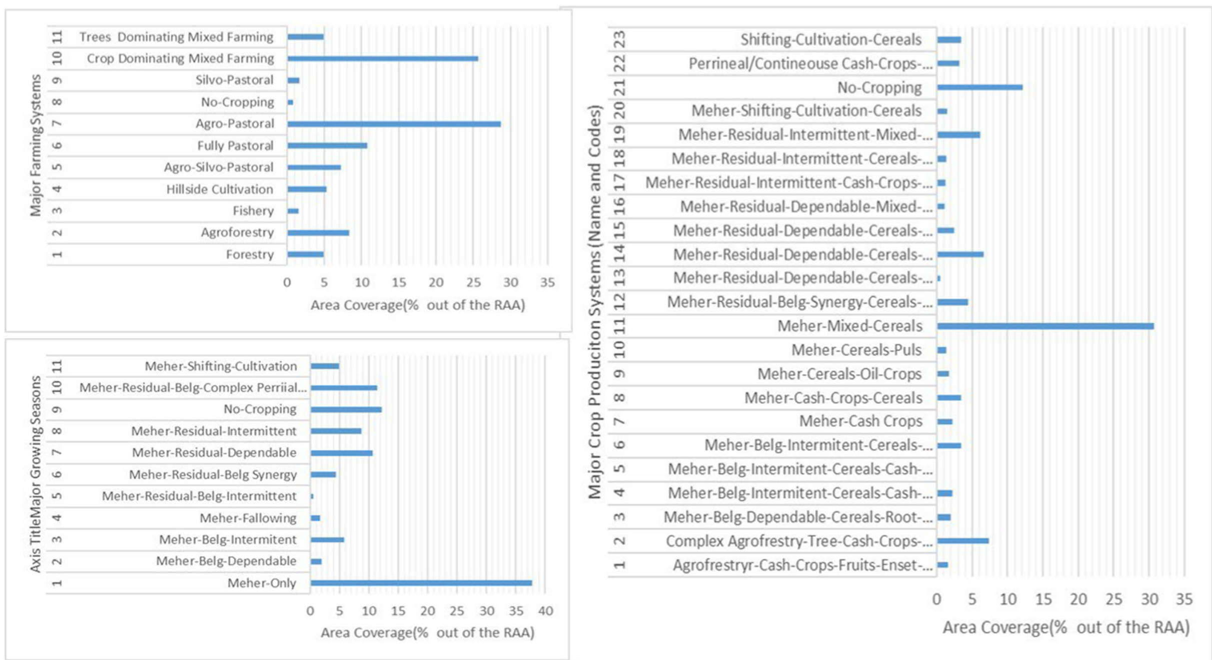

FIGURE 4
Major farming systems (top left), major growing seasons (bottom left), and major crop production systems (right).

of most important and direct constraining factors of rainfed-based crop production were identified from the detailed LULC map. Before assessing the level of suitability, which was decided based on the identified determinant factors, non-cultivable areas were excluded from the analysis.

According to the definition given by this study, parts of the RCA landscapes that are biophysically constrained are areas technically infeasible, economically not viable, or ecologically unsustainable to produce grain or food. In that case, these landscapes represent areas where crop production remains infeasible and unprofitable when applying existing knowledge, technology, and efforts. These landscapes are easily discernable from our detailed LULC map and include classes such as exposed rocks, extremely degraded hills, exposed sand surface, river course, water bodies, settlements, and permanent wetlands, as well as landscapes having slope > 50%. Moreover, the entire currently uncultivated RCA is not usable for crop production, even if theoretically and biophysically suitable. Unless we checked the institutional constraints. Institutionally constrained areas identified by this study include parks, sanctuaries, reserves, conservation priority areas, ritual sites (churches and mosques), priority forests, and hunting areas (Supplementary Figure S2 and Supplementary Table S4). These classes in total account for about 6% of the RCA.

4.4 Cropping intensification potential

4.4.1 Potential of the RCA for HCI

4.4.1.1 Theoretically available cropland (TAC) in the RCA

The current cultivated landscape is taken as actually available cropland (AAC), which implies a landscape has never been constrained by any biophysical and socio-political factors for grain production (Table 2). Theoretically available area (TAC) which was estimated by subtracting the completely unsuitable portion of the RCA from the sum of the currently uncultivated area (CUA) and the currently cultivated area (CCA) (Table 2). This implies that the portion of existing uncultivated landscapes, less cultivated landscapes, and the constrained areas (Section 4.3) gives theoretically available area to expand crop production in the RCA of Ethiopia.

4.4.1.2 Potentially available cropland (PAC) in the RCA of Ethiopia

The TAC is a portion of the RCA that cannot be fully used in the short term due to several constraints, such as knowledge, technology, and resources. Thus, only a portion of TAC on which the society can utilize the land with the available knowledge and technology is PAC. The availability of more space for grain production in the RCA were estimated at four different suitability classes (S1, S2, S3a, and S3b), showing the degree of conversion to cropland. The suitability classes S1 and S2 (from which we have adopted PAC) together represent areas to be exploited in the near future. According to the estimates, about 15,797 km^2 are highly suitable, while the moderately suitable landscape covers 94,051 km^2, accounting for about 4 and 21% of the RCA's currently uncultivated area, respectively. In total, both account for approximately a quarter (25%) of the RCA's currently uncultivated area and 16% of the total RCA, respectively. The remaining, currently uncultivated area, however, is assessed as slightly suitable (56%) and hardly suitable (12%) of the RCA. The spatial distribution and the administrative regional proportional coverage of the CCA and the PAC are shown in Figure 3.

About 67% of the RCA in Ethiopia is currently not cultivated, and over half of the RCA in each region is non-cultivated (Table 3). Considerable proportions of non-cultivated RCA are found in Gambela and Benishangul-Gumuz regional states. The *theoretically suitable land* (S) of the RCA is about 419,338 km^2 (63%). S assumes that all such areas could be converted from their current land use systems to crop cultivation. However, landscapes are subject to constraints from a variety of biophysical, socio-economic, and institutional factors. Excluding those areas that refer to completely unsuitable (N) areas from a biophysical perspective, the theoretically suitable land is reduced by 4% (i.e., from 67% [column "ci"] to 63% [column "ei"]) (Table 3). According to our assessment, about 6% of Ethiopia's RCA is institutionally constrained in terms of possible land use. Broken down into administrative regional states (see Figure 3), more land in Gambela is institutionally restricted (20% of the RCA of the region), followed by SNNP (15%), Tigray (15%), and Oromia (9%). Amhara region has the smallest (2%) percentage of institutionally restricted land. However, this analysis only refers to landscapes subject to state-level institutional restrictions. If local-level institutional restrictions were considered (e.g., community enclosures), the estimated PAC area would likely shrink significantly.

TABLE 2 Political administrative level statistical summary of PAC and its implications for addressing landlessness.

S. No.	Region	Total population in millions for	Average family size	Total estimated rural households (HH in millions)	Landless population (%)	Average land holding size (in ha)	Highly suitable PAC that can be immediately (in ha)	Moderately suitable PAC, usable in near future (in ha)	Estimated households that the S1 PAC can accommodate	Estimated households that the S2 PAC can accommodate
		a	b	c = a/b	d	e	f	g	h = f/e	i = g/e
1	Oromia	35.6	6	5.8	13.6	1.3	547,100	3,937,800	420,846	302,9,177
2	Amhara	20.8	5	4.2	9.8	0.8	496,200	2,348,900	620,250	2,936,125
3	Tigray	5.2	4	1.3	11.1	0.5	63,900	128,500	127,800	257,000
4	SNNP	18.7	7	2.7	17.6	0.3	228,300	1,423,700	761,000	4,745,767
5	B/Gumz	10.1	7	0.15	14.4	1.8	36,500	416,200	20,277	231,222
6	Gambela	0.42	7	0.06	0	1.5	170,600	773,600	113,733	515,733

Source: CSA (2012, 2014, 2016, 2019), Teshome (2014) and authors analysis.

TABLE 3 Currently non-cultivated, permanently unsuitable, and theoretically suitable areas of the RCPA.

Regional states	Region area (km^2)	RCPA area (km^2) (b% = b/a × 100)	Total non-cultivated area (%) from total RCPA (ci = c/b × 100)		Completely unsuitable area (N) (out of the RCPA) d = c−N; (di = d/b × 100)		Theoretically suitable land (S) (out of the RCPA) (e = c−d; ei = e/b × 100)	
	(a)	(b)	(c) in km^2	(ci) in %	(d) km^2	(di) in %	(e) in km^2	(ei) in %
Oromia	299,676	254,667(85)	152,869	60	4,980	2	147,889	58
Amhara	157,928	157,671(100)	100,372	64	11,143	7	89,229	57
Tigray	51,401	51,332(100)	35,625	69	4,012	8	31,613	62
SNNP	108,668	85,916(79)	50,762	59	1,971	2	48,791	57
Gambella	30,286	30,265(100)	30,076	99	951	3	29,125	96
B/Gumuz	50,595	50,595(100)	44,809	89	285	0.6	44,524	88
Other	439,936	36,653(8)	30,482	83	2,315	6	28,167	77
Total/average	1,138,488	667,094(59)	444,995	67	25,657	4	419,338	63

"Other" includes regional states that partly overlap with the RCPA boundary, namely Afar, Somali, Harari, and D/Dawa.

4.4.2 Vertical cropping intensification (VCI) potentials and gaps

4.4.2.1 VCI potentials of the RCA

The VCI potential of the RCA, assessed by comparing existing practices against the potential, is presented in Figure 5, expressing the suitability of the RCA to intensify crop production using existing knowledge and technologies. The assessment was made on both CCA and PAC parts of the RCA. According to the potential assessment results, about 50% of the RCA of Ethiopia can support rainfed-based Multiple Cropping Systems (MCS) with a varying level of suitability. Specifically, around 14 and 25% of the RCA features moderately and slightly suitable landscapes for double cropping. The CI potential and the existing CI practices are presented in Figure 5.

In contrast, only 9, 0.2, and 0.3% of the RCA are highly, moderately, and slightly suitable for perennial/continuous cropping, respectively, indicating that 10% of the RCA can support such systems without significant land use changes or investments. Despite this potential, single cropping remains dominant in 70% of the RCA. Double cropping is consistently practiced in 7% of the CCA, intermittently practiced in 9%, and both double and perennial cropping are intermittently practiced in 6% of the RCA.

4.5 Potential and performance of existing CI practices

The performance assessment focused solely on currently cultivated landscapes, using a multidimensional approach to evaluate CI potential and the performance of existing CPS. Figure 6 displays the spatially explicit performance assessment results, organized and summarized by major growing seasons.

The CDI represents the percentage of cropped pixels within a 1 km^2 area of the PAC, reflecting how well existing CPS enhances HCI. There is significant spatial variation in CDI values across the RCA, with the central and northeastern regions showing relatively higher CDI values (>50%). In contrast, the peripheries have low CDI values, indicating substantial areas remain uncultivated. As shown in Figure 6, regions with intermittent Meher-Residual-Belg seasons are the most densified. Figure 6 illustrates that the CDI values closely resemble the AGD values, though not uniformly.

A higher CLUI indicates that farmers use CPS involving either multiple cropping methods, resulting in more frequent grain production, or single-season crops grown over extended periods. Landscapes managed with the former approach have higher CII values due to increased grain yield within a single production season. In other words, extensively cultivated land is covered by crops for longer periods or cultivate the land multiple times in a year.

Cultivated landscapes in the southern, southwestern, and central parts of the RCA, with CLUI values above 50, cover a considerable area. Areas managed under perennial/continuous CPS, residual-based CPS, and Meher-Residual and Meher-Residual-Belg-based CPS also exhibit high CLUI values. The MCI assesses CPS performance by comparing the total area used for grain production to the total available cropland per year. Typically, if the available land is used for a single-crop production annually, the MCI value is 1.

In the northern, western, northwestern, and partly southern parts of the RCA, where there is typically only one growing season and the available land is used for cropping a maximum of once per year, the MCI value is <1. However, in areas with intermittent double-growing seasons and double cropping practices, the MCI value can exceed 1. For example, in regions where Belg rainfall and residual moisture-based CPS are practiced intermittently, MCI values are influenced by the success or failure of these moisture sources. Figure 7 displays the overall potential and performance assessment results, which were obtained by applying PCA to each index for every dimension.

Performance comparisons in Figure 7 also reveal that the central part of the RCA generally performs better than the southern and southwestern regions.

4.5.1 Cropping intensifications gaps and implications

As discussed, the overall performance of existing CPS varies significantly based on the RCA's potential and land use and production performances of the applied CPS. To better understand the performance of LUS and CPS and its implications, a spatially explicit evaluation was conducted, comparing food supply potential with

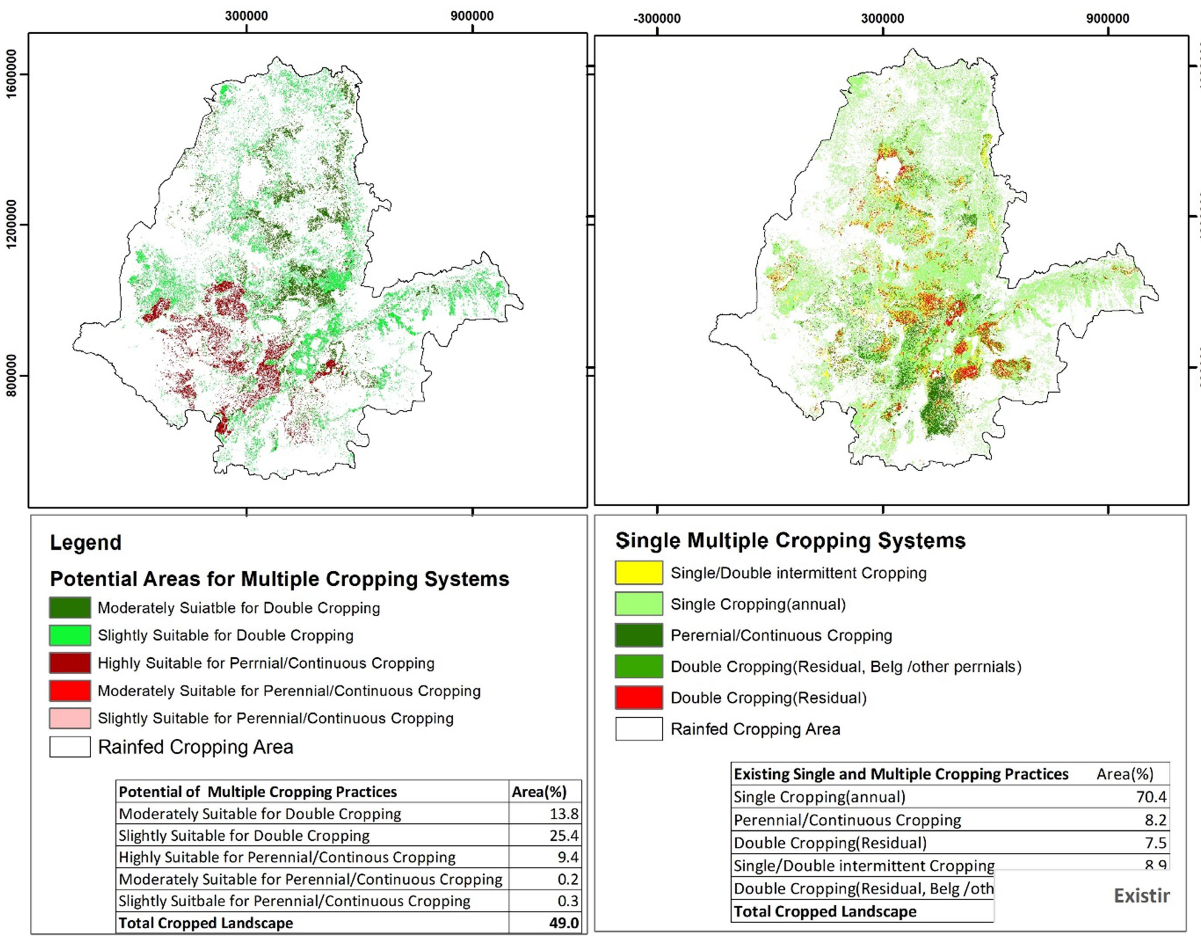

FIGURE 5
Multiple cropping system (MCS)-based CI (potential left) and existing (right) in the RCA of Ethiopia and statistical comparisons (bottom).

existing food/grain demand at a 1 km^2 scale. Figure 8 illustrates the food gap and the total number of food-needy people at a 1 km^2 grid scale. The map shows that a significant portion of the central and part of the north-central RCA has no food gap, indicating these areas produce a surplus of grain relative to the food demand. However, contrary to our by CPS performance evaluation, the southern and southwestern parts of the RCA show a higher food demand and gap. Indeed, our food demand and gap analysis did not account for non-grain crops, permanent tree crops like False Banana, other forest products, or livestock products. As shown by official data on long-term food insecurity and food aid (Figure 8, bottom right), regular food aid has been provided by the government to people in high-potential districts in the southern parts of the RCA.

5 Discussion

5.1 State of Ethiopia's RCA

In Ethiopia, there have been few attempts to delineate the boundary and estimate the extent of RCA, e.g., Hurni (1998) and Hedberg (1970). According to Hurni (1998), 3,800 m a.s.l. is the uppermost altitude limit of cropping, while the lower altitude limit varies depending on the climate, mainly the relationship between rainfall and evaporation. As indicated by research findings of Hurni (1998) the limit varies spatially; in the western side of the country, it can reach up to 800 m a.s.l.; in the eastern side of the country, it reaches up to 1,200 m a.s.l. Researchers in the field also identify clear temporal trends of land use practices related to change in agro-climatic factors, which shift the lower and upper altitudinal limits of crop production (Hurni, 1998; Ramankutty et al., 2002; Harvey and Pilgrim, 2011). Moreover, ecological and technological adaptations also push the temporal boundaries of CPS (what can be cultivated and where). This study highlights not only the importance of continually redefining the physical boundaries of Ethiopia's RCA but also presents the techniques for regularly defining it in a manner that is spatially consistent and temporally fitting with existing cropping practices in relation to the dynamic determinant factors of rainfed-based crop production, like climate. Moreover, establishing such boundaries alone does not help to know the suitability level or the potential of the RCA for food production, as several biophysical, socio-economic, and institutional factors could control food production system.

5.1.1 Options and alternative solutions of HCI

The pixel-level HCI assessment determined the PAC with various levels of suitability. The PAC estimates indicate the highly (S1) and

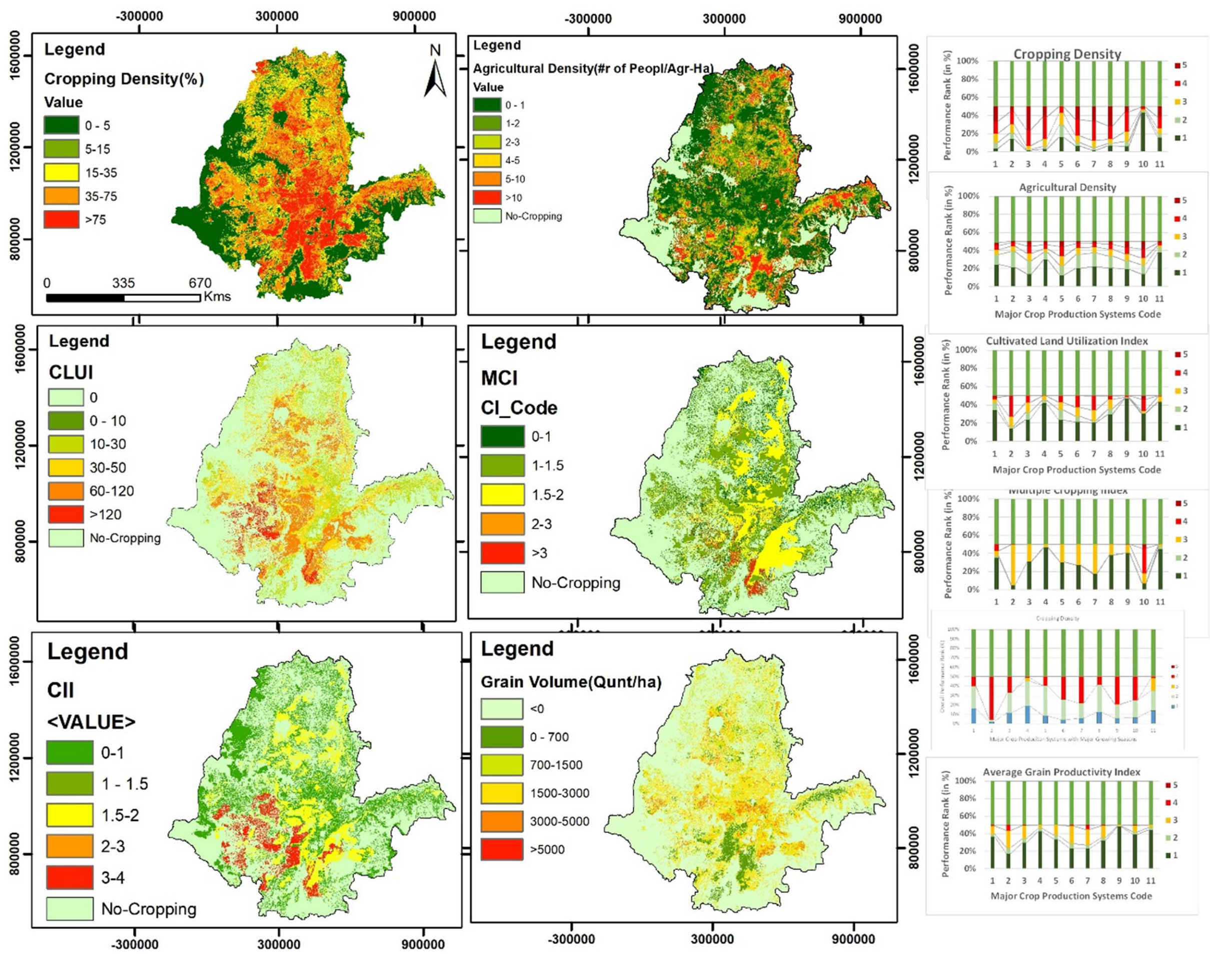

FIGURE 6
Performance of different CPS: CDI (top left), AGDI (top middle), CLUI (left middle), MCI (middle middle), CII (bottom left), AYI (right bottom).

moderately (S2) suitable portions of the RCA that remain uncultivated. Figure 9 shows the cropping eligibility ranges after accounting for biophysical, institutional, and socio-economic constraints. According to our assessment, Ethiopia's PAC is the sum of highly (S1) and moderately (S2) suitable areas, which is about 109,848 km^2 and accounts for 25% of the currently uncultivated area of the RCA. This means that an additional 16% of Ethiopia's RCA could be used for rainfed-based crop production in the future. This value appears small when compared to the percentage of marginally suitable areas (S3a and S3b). Theoretically suitable (S) and potentially available (PAC) RCA for crop production compared to landless populations varies significantly among regional states in Ethiopia (Figures 7, 9b and Table 2). For example, less populated regions such as Gambela and Benishangul-Gumuz regions have relatively large proportions of uncultivated landscape. However, most of these landscapes in the region are not particularly suitable compared to the highland landscape (Figure 9). This limits the usability of the uncultivated landscape in these regions. In contrast, populous regions such as SNNP and Amhara have large numbers of landless people and a low proportion of PAC, making it difficult to address landlessness through agricultural livelihood options. The spatial variation in land availability within PAC and the population-to-land ratio vary widely across regional states. That implies, while reducing pressure on the environment and other ecosystem goods and services, expanding acreage within each regional state and attaining the required area *per capita* to achieve equitable economic benefits may not be possible. Under such circumstances, the implementation of alternative policies (e.g., resettlement/reallocation and intensification) largely depends on the existence of an enabling policy environment (Pretty, 1999; Lotze-Campen et al., 2010; Harvey and Pilgrim, 2011). Therefore, how to utilize the larger area (67% of the currently uncultivated RCA) to address landlessness and food insecurity is an important strategic challenge that needs to be resolved. Some of the possible solutions and pertinent challenges to effectively utilize the PAC are discussed below.

5.1.2 The challenges of HCI

5.1.2.1 Outmigration and resettlement options

In the highly degraded, densely populated, and food insecure highland areas of Ethiopia, migration and/or resettlement of smallholder households have been considered as alternative policy options to address the problems of drought, famine, landlessness, and food insecurity (Rahmato, 2003). For example, Ethiopia's 2002 food security strategy presents resettlement as one of the pillars of its' approach. Apart from the directed flows and forms of migration, these measures focused primarily on planned and

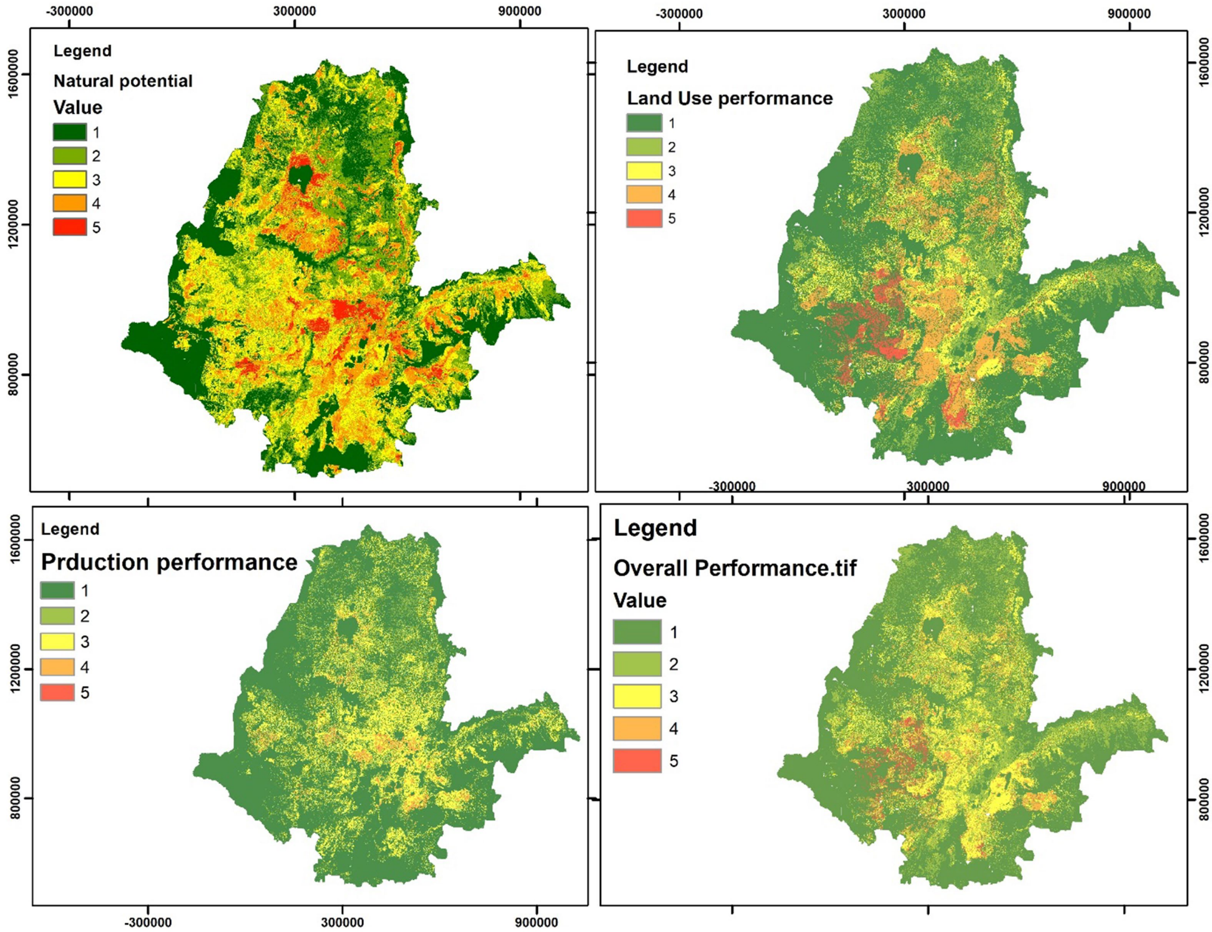

FIGURE 7
Overall average natural capital/land potential of the RCA for cropping intensification (top left), average land use performance (right top), average production performance (left bottom), and average overall performance (bottom right) of CPS in RCA.

large-scale rural-to-rural migration (Rahmato, 2003). However, in our view, strategies to combat landlessness that emphasize rural-to-rural migration must first examine two critical factors, namely: (Hurni, 1985) the availability (area) and spatial distribution of PAC; and (Abdollahzadeh et al., 2023) the existence of an enabling policy environment for implementation. Regarding point one, the spatial distribution of PAC in Ethiopia varies significantly from region to region. Rural–rural outmigration or resettlement (sporadic or planned) could be seen as a major option for regions such as Tigray, Eastern Amhara, and Eastern Harerghe in view of the lack of PAC (Rahmato, 2003). These regions have already utilized most of their suitable areas for crop cultivation (Figure 6 and Table 2). Their remaining areas are subject to institutional bans (see Rural Land Administration and Use Proclamation, Proc. No. 456/2005). These imply that resettlement and rural–rural migration are right measures in view of factor 1.

However, the second critical factor—the need for an enabling policy environment—reveals complications: Ethiopia's population policy, adopted in 1993 and described in strategy papers (Abesha et al., 2022), discourages rural–rural migration (small or large resettlements). In effect, inter- and intra-regional planned resettlement is prohibited after 2005. Furthermore, resettlement programs aiming to move people from degraded, densely populated areas to supposedly fertile, sparsely populated areas are highly contested from a variety of ecological, political, and socio-cultural perspectives (Lemenih et al., 2004; Hammond, 2008). In recent years, the political face of the issue is more complicated by ethnic-based resource use and protection, which is leading to 'ethnophobia.' There are also criticisms that administrative and executive efforts are weak to resolve those problems. There is also ample evidence that large-scale resettlement programs in Ethiopia have failed to achieve their goals (Rahmato, 2003). Thus, intra-regional resettlement and rural–rural migration are not supported by enabling institutional, administrative, and political climates.

Overall, programs of rural–rural migration and/or planned resettlement of landless rural households appear problematic and unsustainable both in the short term and the long term (Hammond, 2008). The prospects of using such strategies to address landlessness and food insecurity in Ethiopia were further diminished with the adoption of a decentralized land administration policy. The evidence generated on PAC in the different regional states can be utilized to revisit and analyze the intra-regional resettlement policy options and help to steer again resettlement and migration policy making.

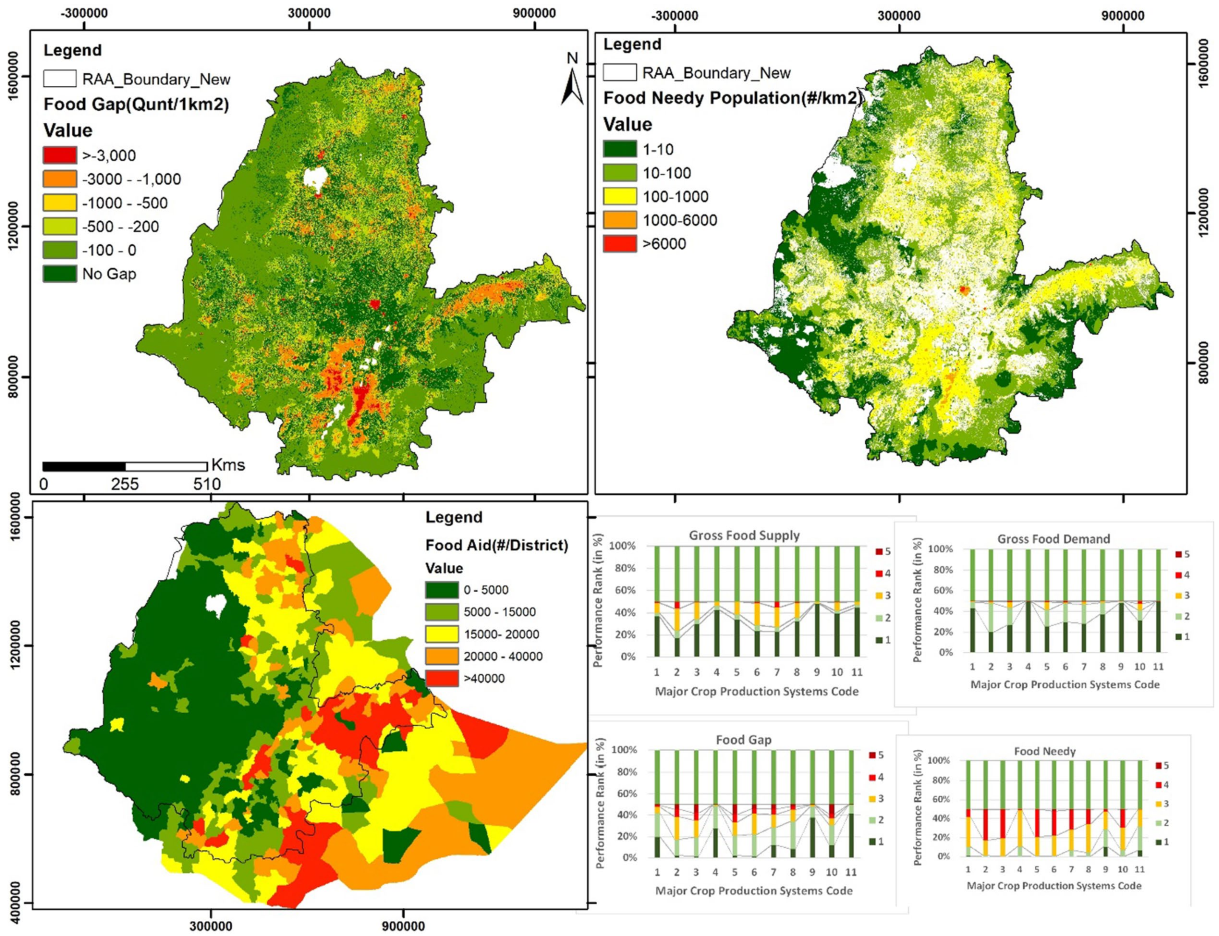

FIGURE 8
Socio-economic implications of existing CPS: GGI (top left), G/FDPI (top right), food aided population (bottom left), and statistical facts about each indicator (bottom right).

5.1.2.2 Land distribution/redistribution, allocation/reallocation options

Efforts toward addressing landlessness may require land distribution/redistribution and allocation/reallocation. Following the overthrow of Ethiopia's imperial regime in 1974, the land use right was transferred from the former landlords to the poor peasants under the motto "land to the tiller" by Proclamation No. 31/1975. Since then and until the late 1990s, allocation and reallocation (redistribution) of land were undertaken as important means of addressing landlessness (Rahmato, 2003). However, until 2005, the land use arrangements (especially cropland expansion) and legal land redistribution were made untenable (Hurni et al., 2005; Zeleke and Hurni, 2001). This is mainly because the redistribution considers addressing landlessness, non-land suitability, and productivity. As a result, major portions of RCA landscapes gradually deteriorated due to inappropriate land use conversion, improper crop production practices, and a lack of entitlement or ownership within a functioning tenure system. Land redistribution can only work where the plots of land are large enough to support individual households under any possible strategy of CI or sustainable use of land (Teshome, 2014). Some researchers have criticized previous repeated land redistribution efforts for transforming Ethiopian agriculture from small-scale agriculture to micro-agriculture, hampering food security at the national level (Teshome, 2014). It may be feasible to redistribute land in some regions or areas of Ethiopia, for example, in Oromia, Somalia, and Gambella regional states where redistribution was not implemented. However, considering that efforts to redistribute currently cultivated land would negatively impact Ethiopia's food security and thwart its Green Economy development strategy, land redistribution was banned (Hammond, 2008).

Concerning the second option (land allocation and reallocation), land reserve is required to support a growing future population, especially for youths who have no option to inherit land from their family. Given that about 10% of the highland rural households in Ethiopia are currently landless (Table 2), such options are very important. According to projections, Ethiopia's population will grow to 120 million by 2025 and 150 million by 2050 (based on the 2007 national census; see Figure 9) (Teshome, 2014). This implies a doubling of Ethiopia's current landless households (from 10% to 20%) and serious shortages of land for cultivation. Under such conditions, land allocation/reallocation

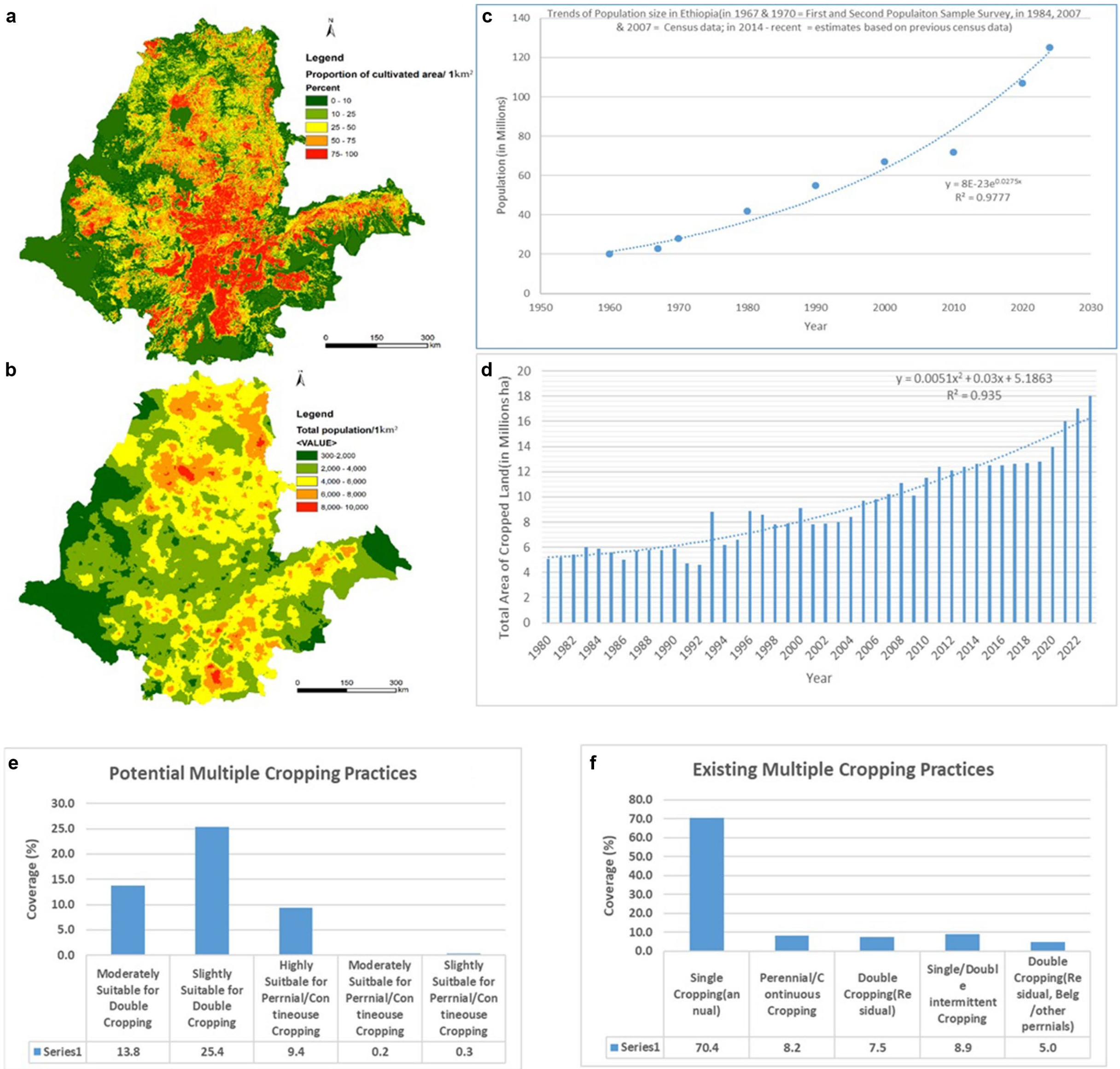

FIGURE 9
(a) Cultivated/Cropland density index (currently cultivated area per km^2) (source: present study) and **(b)** comparison of rural population density, **(c)** national population growth, and **(d)** cropland expansion (source: CSA, 2019, 2014, 2016), potential MCP **(e)** and existing MCP **(f)**.

could be an important option to utilize the available uncultivated land for crop production (Benin and Pender, 2001). In this regard, the 67% of currently non-cultivated land within Ethiopia's RCA would be a huge resource to address landlessness and related food insecurity. Viewed nationally, disregarding the currently cultivated land areas, a maximum of 25% of the currently non-cultivated portion of the RCA is available (i.e., S1 and S2) for near-term use. At the sub-national level, the potentially available land could accommodate about 10% of the current landless population in Oromia, 25% in Amhara, 19% in Tigray, 37% in SNNP, and 15% in Benishangul Gumz regional states (see Table 2). In the long term, there is also the possibility of using marginally suitable (S3a and S3b) land and landscapes, as these areas could be made suitable for cultivation through massive land rehabilitation and management measures, use of improved crop varieties, and agronomic practices. The former option, however, has a much longer time horizon, as major efforts to rehabilitate degraded lands have already been underway for two decades (Kassawmar et al., 2018b). Given that existing policies do not favor redistribution of currently cultivated land, allocation of PAC to the landless and producing grain shall be seen as an important option (Wubneh, 2018). However, it is well understood that, while rural land use and administration policy does foresee expansion of cultivable land, there are conflicts with environmental protection goals and development strategies of the country, such as investment policies, that need much of the PAC. Therefore, this option can be useful only if appropriate land use and sustainable land management measures are implemented as part of land allocation programs and the country's agricultural development strategies (Haregeweyn et al., 2012).

5.2 The potentials of VCI in Ethiopia's RCA: options and alternative solutions

Present trends in global agricultural development are oriented toward VCI of agriculture through technology improvement and knowledge transfer. In Ethiopia, some observers view VCI as a means to meet future food demand with less environmental impact and to prevent inappropriate expansion of cropland (Harvey and Pilgrim, 2011). As shown in Supplementary Figure S1 and Figures 3, 9, Ethiopia's RCA has immense potential for practicing diverse farming systems (FS) and land use systems (LUS) and for supporting various livelihood systems. Comparisons between existing and potential rainfed MCSs in the RCA (Figure 5) show that, with few exceptions, there is only one main rainy season in the northern and central parts. In contrast, the southern and southwestern regions benefit from an extended main rainy season (over 6 months) and a shorter rainy season. Although there is minimal rainfall in the northern and northwestern parts, farmers in these areas often adopt effective cropping systems that make optimal use of the limited rainfall available in a short period of time (approximately 1 month). In the eastern and central-eastern parts of the RCA, a bimodal rainfall pattern in some areas supports MCS, such as Meher-Residual-Belg. However, rugged terrain and inappropriate land use have led to severe land degradation, reducing the effectiveness of these MCP systems (Zhang et al., 2021). Conversely, the southern and southwestern parts of the RCA, with their extended rainfall season (over 6 months), are well suited for permanent and perennial/continuous cropping, allowing for double and triple food production per year.

According to the assessment results, about one-third of the CCA in the RCA could benefit from VCI through MCP. However, the level of suitability for intensification varies significantly over time and space. For example, only about 10% of the RCA is highly suitable for MCS, where complex CPS have integrated complex and mixed annual and perennial crops, including fruits, tree crops, and root crops, within the same field. Contrarily, the majority of the RCA is currently underutilized, as 70% of the landscape is managed by single cropping practices. The Cropped Area Diversity Index (CADI) value-based CPS performance shows that most of the RCA has values above 10, indicating that approximately 10 different crops can grow in a 1 km^2 area. This represents an exceptional potential for food and nutrition security. However, according to the AGDI, the rainfed-based livelihood system supports an average of about five people per a hectare of cropland. Although explicit data (Figure 9) reveal that only 33% of the TAC or suitable landscapes in the RCA are used for crop production the average CDI for the RCA is below 50%, meaning that only 50% of each 1 km^2 of suitable land is effectively utilized for grain or crop production. This indicates that Ethiopia has substantial HCI potential for increasing and intensifying food production, but achieving this will require more efficient land use and cropping systems and enabling policy (Benin and Pender, 2001).

In some areas, such as the western and northwestern regions and the peripheries of the RCA, AGDI values can reach up to 10, indicating a person-to-cropland ratio of 1:10. CLUI values confirm that while some landscapes are overused, many parts of the RCA remain underutilized. CLUI estimates show that about 45% of the RCA have CLUI values below 50%, indicating that the current CPS only utilize about half of the year for food production. Indeed, some areas have CLUI values reaching up to 200, indicating the practice of perennial or continuous cropping systems. Low to moderate MCI and CII values are observed in the western, central, northern, northwest, and northeastern parts of the RCA.

The moderate to high MCI and CII values in these RCA areas are primarily due to CPS based on Residual Soil Moisture and Belg Rainfall. However, there is significant room for improvement in enhancing VCI in these regions. Despite having moderate to high MCI and CII values, their performance in terms of AYI is low to very low. In approximately 35 and 45% of the RCA with such CPS, the RYI was found to be low and very low, respectively. Higher RYI values are observed in the southern, southwestern, central, and some northern parts of the RCA, where MCI and CII are relatively higher. The VCI assessment indicates that only 1% of the RCA is managed under CPS with very high CI performance. In the remaining parts, cultivated landscape managed under CPS with poor, moderate, and high CI performance cover 19, 18, and 7% of the RCA, respectively (see Figure 10).

5.3 Implications and policy direction

A comparative analysis of the food security index across different CPS shows a significant food gap in the North, Northeast, Central, Central East, East, and parts of the Central RCA. The spatial distribution of GGD and GFDP confirms that the largest nutritional gaps exist in the best-performing landscapes with efficient CPS (see Figure 7 for index values on the map). An important question that needs thorough explanation is why the overall performance of the southern regions is lower compared to other RCA regions, despite the southern and southwest regions having higher MCI and CII values or greater CI potential. There are three main reasons for this discrepancy: (i) The CI analysis weighted all indices equally, resulting in higher values for areas with higher CDI and lower AGD values. (ii) The indicators used in this study did not account for other food sources, such as non-grain foods, or False Banana and fruit crops, which are significant for many populations with different feeding cultures. (iii) These regions are solidly populated, with a high ratio of people to cropland, sometimes exceeding 10 people per hectare. Comparing food supplies to the food-needy population at the district level using secondary sources could help clarify some of the ambiguities (Figure 8).

The performance assessment results suggest that a more efficient CPS alone may not meet food demand or solve problems of landlessness and food security. Consequently, our analysis is not sufficient to fully assess food security and its relationship to CPS. However, the study concludes that high-performing LUS and CPS alone do not ensure food security. In systems with multiple annual harvests, such as perennial or continuous cropping and complex agroforestry systems the MCI is not a good indicator as it only takes into account the area covered and does not differentiate between different crops in a year. In comparison, the CII is a better indicator because it takes into account both the area covered per production season and the frequency of annual grain harvest per unit area. This is evidenced by high CII values in complex agroforestry and perennial/continuous cropping systems where continuous production occurs throughout the year.

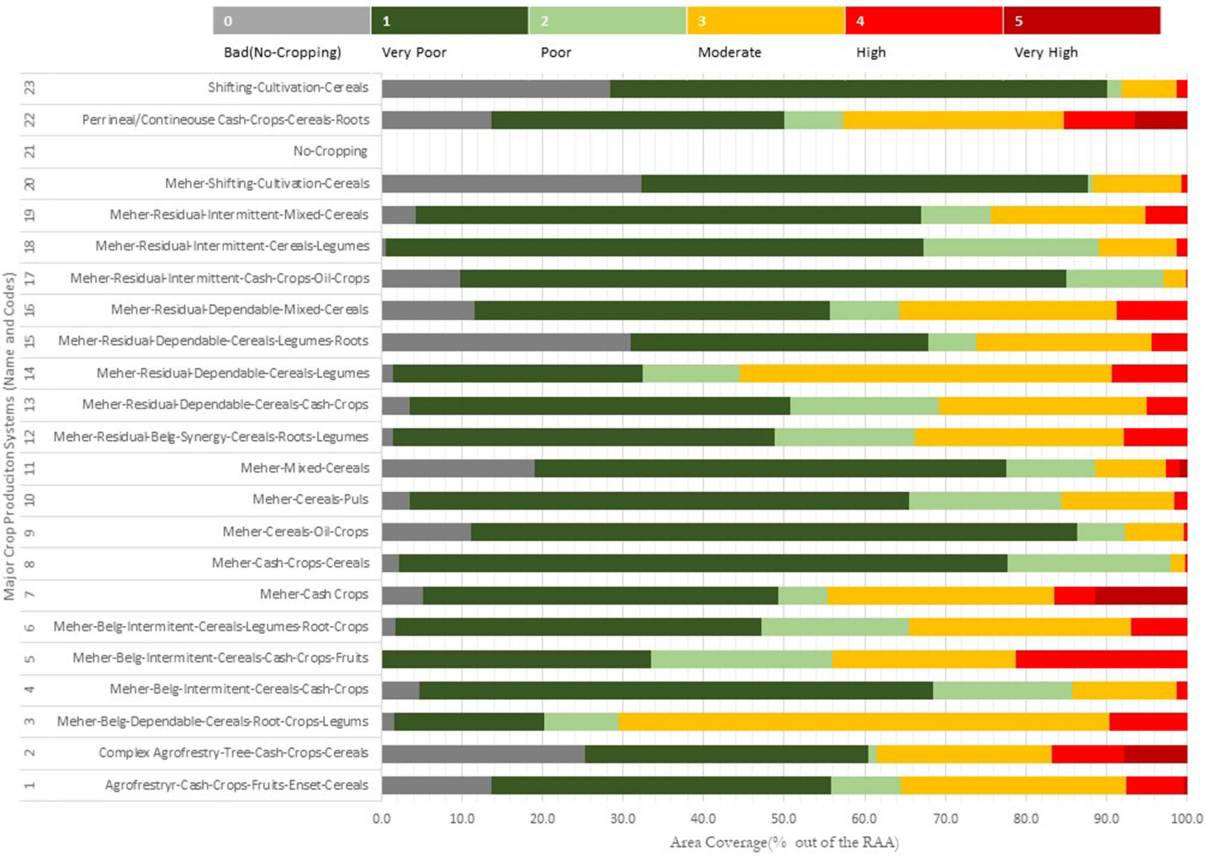

FIGURE 10
Summary of overall performance ranks of major CPS in the RCA.

In addition to knowledge, technology, and land use/management strategies beyond VCI, effective policy solutions are needed to balance natural capital with human needs. In fact, careful interpretation of the data is crucial, as some results of the implemented framework may contradict real-world conditions.

6 Conclusion

This study redefined Ethiopia's Rainfed Cropping Area (RCA) and found it comprises about 60% of the country's land mass. It also assessed the suitability of the uncultivated portion of the RCA for rainfed-based grain production and feed its nation. The results indicate that Ethiopia is currently using only 33% of its RCA for crop cultivation. Out of the remaining 67% of the RCA, only 16% is highly and moderately suitable, which is considered as Potentially Available Cropland (PAC). This study highlights the possible options to use this portion of the RCA. This study confirms that, against the perceived HCI potentials, there is less remaining land in the RCA which is highly suitable (4% of the currently uncultivated portion of the RCA) and can be cultivated without investment than is usually assumed. If land allocation is chosen as a policy option, the highly suitable PAC cannot fully accommodate the current landless households (10% of the total rural household population). However, inclusion of both highly suitable and moderately suitable PAC (109,848 km^2) makes it possible to fully address current landlessness. However, implementation of the identified policy options—land distribution/redistribution, resettlement, and intensification—will face challenges; there is considerable incongruity between densely populated areas, high landlessness, and PAC throughout Ethiopia. Ethiopia's existing highly and moderately suitable (PAC) landscapes are located in sparsely populated areas. In theory, this points to resettlement or rural–rural outmigration as possible options. This implies that land use planners could consider resettling landless people from highly populated regions to the less populated regions. However, policymakers could find these options very difficult to implement under the current ethnic-based political administration; resettling people could continue to foment unrest or ethnic tensions unless handled very carefully. Implementation of such alternative measures also depends on the existence of enabling policy environment across and within the regional governments. Moreover, PAC is largely found in relatively less hospitable environments (particularly regarding temperatures) compared to the cold, humid highlands of the RCA. Considering the options of VCI and/or HCI solutions to landlessness and food insecurity problems, both currently non-cultivated (67%) and cultivated portions (33%) of the RAA have huge potential for non-crop production/farming systems such as Silviculture farming (e.g., timber, wild honey, wild coffee), livestock production (e.g., dairy farming, beef farming, apiary, poultry), eco-tourism, and others. However, the assessments within this study did not consider these farming systems, which is a limitation, and it is recommended that more research is needed in this regard.

The assessment findings revealed that the efforts exerted towards HCI in Ethiopia reach only 33% of the RCA. On the other hand, existing VCI practices cover only 10% of RCA, while in nearly 30% of the RCA, it can be practiced at various levels of suitability. In addition, the performance of existing VCI-oriented CPS is below average, as in only 7% of the practices an acceptable or higher performance is recorded. This confirms that existing efforts made to enhance both HCI and VCI are both insufficient and inefficient.

The study's findings suggest that to fully realize the potential of both intensification practices, it is essential to enhance productivity in marginal areas through sustainable land management practices. Integrating land rehabilitation with intensive agriculture not only benefits farmers to maximize yield, but also to enhance a wide range of benefits that could be obtained from conserved ecosystems. Experiences from the regions of Tigray and eastern Amhara show that investments in marginally suitable lands can bear fruit by generating ecosystem services and creating extra cropland. At the same time, successfully integrating land rehabilitation and VCI requires innovative technologies, improved inputs, effective agronomic practices, and enabling policy options. Various land rehabilitation activities are already being implemented in many parts of the RCA landscapes. In utilizing the full potential of the RCA, the introduction of better land management interventions can help to boost food production and, in turn, contribute to addressing landlessness and food insecurity in Ethiopia. Ensuring sustainable land management and enhancing productivity call for prohibiting undesirable land use shift and enforcing proper land use practices, including making sure any crop cultivation on steep slopes embeds in its soil and water conservation measures. Above all, agricultural research must also be intensified to enable better technological options, such as improved crop varieties, and scaling mechanisms, such as adaptation and upscaling of different crop varieties and cropping practices.

In summary, available options for tacking efforts to address the food insecurity and landlessness issues require: (i) applying efficient and effective land use and land management practices; (ii) developing and implementing strong policy options and strategies that accommodate and/or support sustainable cropping intensifications (resettlement, land distribution, and land use adjustment require spatially explicit datasets and information). We strongly suggest incorporating spatial information in decision-making processes, including land use planning and land administration. Such studies can provide both knowledge and information on the availability of land and alternative options for these lands in addressing landlessness. Therefore, the presented approach and outputs play a considerable role to support scientific and evidence-based decision-making.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

TK: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. MT: Supervision, Validation, Visualization, Writing – review & editing. GD: Resources, Supervision, Validation, Writing – review & editing. AB: Supervision, Validation, Visualization, Writing – review & editing. ET: Data curation, Validation, Visualization, Writing – review & editing. WB: Funding acquisition, Investigation, Project administration, Resources, Supervision, Visualization, Writing – original draft, Writing – review & editing. LA: Data curation, Resources, Software, Writing – review & editing. GZ: Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing. CW: Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing. GO'D: Resources, Software, Supervision, Validation, Visualization, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. This study was supported by the Water Security and Sustainable Development Hub, which is funded by the UK Research and Innovation's Global Challenges Research Fund (GCRF), grant number: ES/S008179/1.

Acknowledgments

The authors express their sincere gratitude to the Water and Land Resource Centre of Addis Ababa University (WLRC-AAU) for the facilitation of the data collection and provision of other required resources to undertake this study.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2024.1393124/full#supplementary-material

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frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 07 January 2025
DOI 10.3389/fsufs.2024.1417400

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OPEN ACCESS

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RECEIVED 14 April 2024
ACCEPTED 01 November 2024
PUBLISHED 07 January 2025

CITATION
Kumar A, Gupta M, Gupta LM, Kour S and Choudhary P (2025) Evaluation of growth, yield attributes, and yield of wheat varieties under *Terminalia chebula* trees.
Front. Sustain. Food Syst. 8:1417400.
doi: 10.3389/fsufs.2024.1417400

Evaluation of growth, yield attributes, and yield of wheat varieties under *Terminalia chebula* trees

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Agroforestry plays a key role in the Indian economy in terms of tangible and intangible benefits. Agroforestry can simultaneously satisfy three important objectives, namely, protecting the ecosystems, producing a high-level output of economic goods, and increasing income and basic needs of the rural population, in addition to maintaining the resource base. In the Jammu subtropics, many fruit trees are grown with grasses or as the sole crop. There is not much awareness among farmers about the benefits of agroforestry. To overcome this, we conducted a field trial at the experimental farm of the Division of Agroforestry, Chatha, with the aim of exploring the possibility of growing different wheat varieties as an intercrop under the canopy of harad (*Terminalia chebula* Retz.) trees planted at a spacing of 5 × 4 m^2. Three wheat varieties, namely, JAUW-598, WH-1080, and RSP-561, were grown under the *Terminalia chebula* trees, and growth and yield parameters were recorded at two distances from the base of the tree (0–1 m and 1–2 m). This study investigates the impact of distance from *Terminalia chebula* (harad) trees on the growth and yield of different wheat varieties in the agroclimatic conditions of Jammu and Kashmir. The primary objective was to determine the optimal spacing that minimizes competition for resources between the trees and crops, thereby enhancing wheat productivity. By evaluating key growth parameters and yield at varying distances from the tree base, this research aims to provide actionable insights for optimizing intercropping systems in the region. The growth and yield of varieties were significantly reduced under shade as compared to sole cropping. Maximum spike length (13.91 cm), tillers/plant (7.36), grains/spike (33.62), and grain yield (42.46 qha^{-1}) were recorded in the variety RSP-561 grown in the open conditions. Overall, RSP-561 performed better among all the other varieties with a yield reduction of 47.83 and 12.15% at a distance of 0–1 m and 1–2 m, respectively, under shade as compared to the open conditions. All wheat varieties performed better at a distance of 1–2 m away from the tree base as the amount of shade/competition is less compared to a distance of 0–1 m from the tree base. The study concluded that wheat can be successfully grown at a distance of 1–2 m from the tree base to attain an additional income from the *Terminalia chebula* orchard.

KEYWORDS

competition, growth, intercrop, *Terminalia chebula*, yield attributes

Introduction

Agroforestry has been commonly practiced for many centuries all over the world as a way to increase agricultural sustainability and slow down the negative effects of agriculture, e.g., soil erosion. There are numerous agroforestry systems in use all over the world. Agroforestry aims at combining woody perennials with agricultural crops in such a way that positive ecological and economic interactions between the components could take place. This combination of woody perennials with agricultural crops can be made possible via a spatial arrangement, a rotation of components, or both. Agroforestry provides assets and income from wood energy, diversified crop rotations, improved soil fertility, enhanced local climatic conditions, and ecosystem services and reduces human impacts on natural forests (Chavan and Dhillon, 2019).

Agroforestry creates a micro-climate beneath the crops, which can enhance the productivity and yield of these crops. Productivity in agri–silvi system is comparatively higher than the productivity of sole agriculture (Dhyani et al., 2013). Soil quality and its production capacity can be restored and improved by adopting an agroforestry system such as agri–silvi system, which provides a way to sustain agricultural production (Bijalwan et al., 2020) Integrating trees (forest and fruit) enhances overall productivities and incomes by ameliorating harsh environment of the area (Kumar and Bijalwan, 2021).

Harad or Haritaki botanically known as *Terminalia chebula* Retz. is a medium-to-large deciduous tree. It is one of the multipurpose and medicinal agroforestry tree species, which is found in many states. In Jammu and Kashmir, it was found in sub-tropical forests ranging from 300 m to 1,630 m amsl (Sharma and Thakur, 2015). The dried fruit is also used in Ayurveda as a purported antitussive, cardiotonic, homeostatic, diuretic, and laxative (Priya et al., 2024). In India, production of *T. chebula* fruit is estimated to be 1,00,000 tons of which 20% is exported to countries such as Europe and the United States (World Agroforestry Centre, 2017). In Jammu and Kashmir State, the annual production of harad fruit is approximately 500 tons (as per conversation with a local trader of Jammu).

Triticum aestivum, commonly known as wheat, is the most important and staple food crop. It is the most widely grown cereal crop during the *Rabi* season (November–April), which is intercropped with a number of tree species. In Jammu and Kashmir, wheat is grown in an area of 281.87 thousand hectares (Anonymous, 2017). In Jammu, wheat is generally grown as a monocrop and an intercrop in orchards in some places.

Given the potential for competition between trees and crop plants, it is important to maximize complementary interactions and minimize any competitive interactions. In addition to the selection of suitable tree species and crops, another important way to achieve maximization is by understanding parameters such as the minimal distance required between intercropped tree rows and crop plants to avoid significant competition for light and nutrients. Hence, the experiment was aimed to ascertain the influence of distance from the base of the tree (*Terminalia chebula*) on the growth and yield of different wheat varieties.

Materials and methods

This experiment was carried out at an experimental field of the Division of Agroforestry, SKUAST Jammu, to study the growth, yield attributes, and yield under the open and *Terminalia chebula*-based agroforestry system. The experimental site falls under the subtropical zone of the Jammu division of Jammu and Kashmir union territory, India, with a mean annual rainfall of approximately 1,100 mm. The maximum temperature rises up to 45°C during June, and the minimum temperature falls to 1°C during January. The agri-silviculture system is comprised of *Terminalia chebula* trees planted at a spacing of 5 m x 4 m. The plantation was 7 years old, and three wheat (*Triticum aestivum* L.) varieties, *viz.*, WH-1080, JAUW-598, and RSP-561, were sown on 19 November 2018 in between the tree rows and in the open (without trees) to serve as control. The experiment was laid down in a randomized block design with seven treatments and three replications. Two distances from the base of the tree were taken, i.e., D_1—up to 1 m and D_2—from 1 to 2 m. Nine plots of size 10×4 m^2 were prepared under *Terminalia chebula* trees and nine in open. Treatment combinations were allotted to the plots randomly under the canopy and open conditions. Proper fertilization is a critical factor in producing optimum and profitable wheat yields. As per the soil test value, a mixture of 120 kg of nitrogen, 80 kg of phosphorus, and 40 kg of potassium per hectare was applied through urea, DAP, and muriate of potash. While sowing the half dose of nitrogen (N), a full dose of phosphorus (P) and potassium (K) was given as a basal dose while rest of the nitrogen was applied as top dressing at 30–35 days.

Plant population/m^2

The plant population was counted by using a quadrat of 1m^2 from the base of the tree at both distances.

Plant height (cm)

The height of plants was measured from ground level to the tip of the plant with the help of a measuring scale. The plant height was recorded in centimeters.

Number of tillers/plant

Tillers were counted by using the 1m^2 quadrant at a distance of 0–1 and 1–2 m from the sample plot. Tillers were counted at maturity and expressed as tillers per plant.

Spike length (cm)

Length from the neck node to the apex of the spike was measured in centimeters.

Number of grains/spike

From the selected plants, the number of grains was counted and represented as number of grains/spike.

Thousand-grain weight (g)

A total of 1,000 grains were collected from each sample plot, and their weight was measured using electronic balance and expressed in grams.

Grain yield (q/ha)

Harvested crop produced from the selected sample plot was thrashed with a thresher. The grain yield was recorded in kg/sample plot and finally converted into q/ha.

The observations were recorded for plant population/m^2, plant height (cm), tillers/plant, spike length (cm), number of grains/spike, 1,000 grain weight (g), and grain yield (q/ha). The data were analyzed using software O. P. Stat (Sheoran et al., 1998; Figure 1).

Results and discussion

The effect of trees on the understory crop is complex. Canopy of trees can exert positive, negative, and neutral effects on the production of plants depending on the local environmental conditions. In the current study, *Terminalia chebula* trees affected various growth and yield parameters such as plant population, plant height, spike length, tillers plant^{-1}, grains spike^{-1}, 1,000 grain weight, and grain yield of all varieties of *T. aestivum* under its canopy (Tables 1, 2). The presence of *Terminalia chebula* trees was

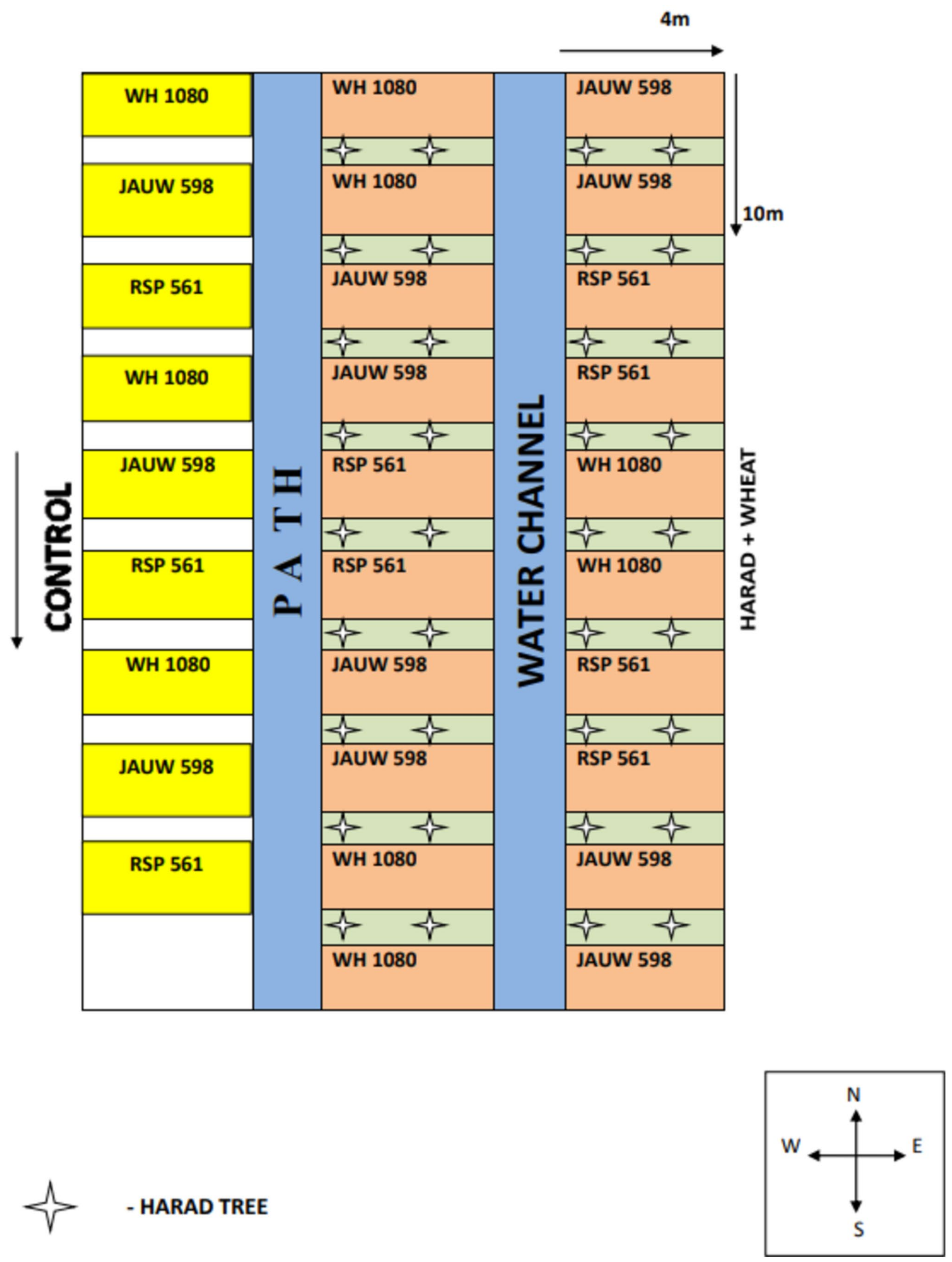

FIGURE 1
Layout plan of the field experiment under open and harad-based agroforestry system.

found to influence the growth parameters of wheat crops grown at two different distances in all three varieties. Reduction in these parameters was observed when wheat was grown in association with the tree at different distances as compared to the sole crop (control). This is probably attributed to the intense competition for resources such as water, nutrients, and solar radiation, especially at the tree–crop interface. A marked reduction in plant population was recorded in the wheat grown under tree canopy as compared to the wheat grown in open conditions (control). The maximum average plant population was recorded in control (47.00) and minimum (21.66) in T_5 (RSP-561, 0–1 m), which was statistically at par with treatments T_6 and T_7. It might be due to the immediate leaf shedding of trees after crop sowing, which leads to the reduced germination and the poor development of germinating seedlings. Leaf fall after the sowing acts as a barrier to germination and affects the availability of light and nutrition to developing seedlings; thus, their survival is affected. The plant population of wheat gradually increased with an increase in distance from the tree, which is clearly depicted in Table 1. The findings are in accordance with the findings reported by Chauhan et al. (2012) and Gawali et al. (2015) on wheat grown under different tree species. Reduction in plant height was mainly found at the closer distance of crop from the tree base (0–1 m) because at closer distance shading effect and competition for resources were more significant than the other distance D_2 (1–2 m) as well as in control. Maximum height (105.22 cm) was found in the variety WH-1080 (T_7) in an open condition whereas minimum (74.08 cm) in RSP-561 (T_5). Similar results were specified by Hossain et al. (2006) and Chauhan et al. (2012) in wheat grown under trees as well as in open conditions.

In the present study, tillers per plant were not affected by the shading effect of the tree. The maximum (7.36) tillers per plant were recorded in control treatment T_9 (RSP-561), and the minimum (6.49) was recorded in treatment T_4 (JAUW-598 at 1–2 m). Khan and Ehrenreich (1994) have also reported that the number of tillers per plant in wheat was not significantly affected when grown under *Acacia nilotica* trees. The environment has a significant effect on spike length; i.e., spike length was lower under trees than open. The maximum (13.91 cm) average spike length was recorded in treatment T_9, which was statistically at par with treatments T_5 (12.33 cm) and T_6 (13.04 cm). The minimum (10.12 cm) average spike length was recorded in treatment T_1. It might be due to lower production of photosynthates under low light conditions as the light intensity decreased under trees. Similarly, Gill et al. (2009), Dufour et al. (2013), Gawali et al. (2015), and Artru et al. (2017) have also reported that spike length was increased with an increase in distance from the tree base. On the other hand, the number of grains per spike was not affected by the presence of trees in all three varieties at both distances. These results are in accordance with the findings reported by Satyawali et al. (2018).

During the present study, we found that 1,000 grain weight of wheat varieties was significantly affected by the distance of the crop from the tree base. Maximum 1,000 grain weight was found in control as compared to the crop grown under tree canopy at two different distances. Some of the grains at closer distances

TABLE 1 Soil status of the experimental site.

Parameter	Test values	Method used
pH	7.90	1:2.5 soil water suspension electrode pH meter (Jackson, 1967)
EC(ds/m)	0.15	1:2.5 soil water suspensions with a systronic conductivity meter (Jackson, 1973)
Available Nitrogen (kg/ha)	251.30	Alkaline potassium permanganate method (Subbiah and Asija, 1956)
Available Phosphorus (kg/ha)	16.10	Olsen et al. (1954)
Available Potassium (kg/ha)	162.70	Ammonium acetate method (Jackson, 1967)

TABLE 2 Effect of *Terminalia chebula* trees on various growth parameters of wheat.

Treatments	Parameters			
	Plant population/m^2	Plant height (cm)	Tillers/plant	Spike length (cm)
	Mean values	Mean values	Mean values	Mean values
T_1 (WH-1080, 0–1 m)	24.66	78.22	7.06	10.12
T_2 (WH-1080, 1–2 m)	25.66	84.23	7.22	11.02
T_3 (JAUW-598, 0–1 m)	27.33	79.80	6.91	10.32
T_4 (JAUW-598, 1–2 m)	35.33	82.44	6.49	11.14
T_5 (RSP-561, 0–1 m)	21.66	74.08	7.13	12.33
T_6 (RSP-561, 1–2 m)	38.66	80.18	7.17	13.04
T_7 (Sole WH-1080)	39.33	105.22	7.01	11.48
T_8 (Sole JAUW-598)	47.00	97.56	7.12	12.02
T_9 (Sole RSP-561)	42.00	94.08	7.36	13.91
$C.D_{0.05}$	15.54	10.32	NS	2.01
SE(m)±	5.14	3.41	0.33	0.66

TABLE 3 Effect of *Terminalia chebula* trees on various yield parameters of wheat.

Treatments	Parameters		
	Number of grains/spike	1,000 grain weight (g)	Grain yield (q/ha)
	Mean values	Mean values	Mean values
T_1 (WH-1080, 0–1 m)	29.36	34.73	24.72
T_2 (WH-1080, 1–2 m)	31.01	35.02	30.23
T_3 (JAUW-598, 0–1 m)	29.69	30.34	22.69
T_4 (JAUW-598, 1–2 m)	32.03	34.29	32.24
T_5 (RSP-561, 0–1 m)	29.25	35.57	22.15
T_6 (RSP-561, 1–2 m)	30.90	38.79	37.30
T_7 (Sole WH-1080)	32.80	39.82	35.72
T_8 (Sole JAUW-598)	30.48	39.04	40.25
T_9 (Sole RSP-561)	33.62	41.25	42.46
$C.D_{0.05}$	NS	4.63	8.31
SE(m)±	1.51	1.53	2.74

were shriveled and smaller in size. The possible reason could be the lesser availability of moisture, light, and nutrients for proper growth and development of the wheat crop; in addition, shading results in an appreciable decrease in a number of grains per spike and grain weight. Similar results were reported by Gill et al. (2009), Chauhan et al. (2012), Dufour et al. (2013), and Artru et al. (2017).

The yield of the wheat varieties was better in the open than under the *Terminalia chebula* trees. Maximum (42.46 q ha^{-1}) grain yield was recorded in treatment T_9, which was at par with treatment T_8 (40.25 q ha^{-1}), T_6 (37.30 q ha^{-1}), and T_7 (35.72 qha^{-1}). Minimum (22.15 qha^{-1}) grain yield was recorded in treatment T_5. The effect of distance and shade on the yield parameters was significant and absolutely clear. The maximum reduction in grain yield was obtained at a distance of 0–1 m (D_1) as compared to a distance of 1–2 m (D_2) from the tree base, and maximum yield was recorded in open conditions. It might be due to the effect of shade on the crop. The grain yield was lowest near the trees and gradually increased with distance from the trees. The reduction in the yield of intercrop due to the presence of trees may be attributed to the pattern of canopy spread resulting in variation in light interception and competition of the tree roots for nutrients and moisture (Table 3). Reduction in the grain yield of wheat in all the varieties at different distances is well supported by the findings reported by Hossain et al. (2006), Gill et al. (2009), Chauhan et al. (2012), Dufour et al. (2013), Gawali et al. (2015), Artru et al. (2017), Bisht et al. (2017), Satyawali et al. (2018), Yadav et al. (2018), and Kumar et al. (2019).

Conclusion

From the present study, it is concluded that wheat can be grown successfully at a distance of 1–2 m from the base of *Terminalia chebula* trees. RSP-561 is the suitable wheat variety for intercropping in the harad orchard on the basis of a minimum yield reduction of 12.15% at a distance of 1–2 m from the tree base compared to WH-1080 and JAUW-598.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

AK: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing. MG: Project administration, Supervision, Validation, Writing – review & editing. LG: Project administration, Validation, Writing – review & editing. SK: Project administration, Supervision, Validation, Writing – review & editing. PC: Project administration, Supervision, Validation, Writing – review & editing.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Conflict of interest

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