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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

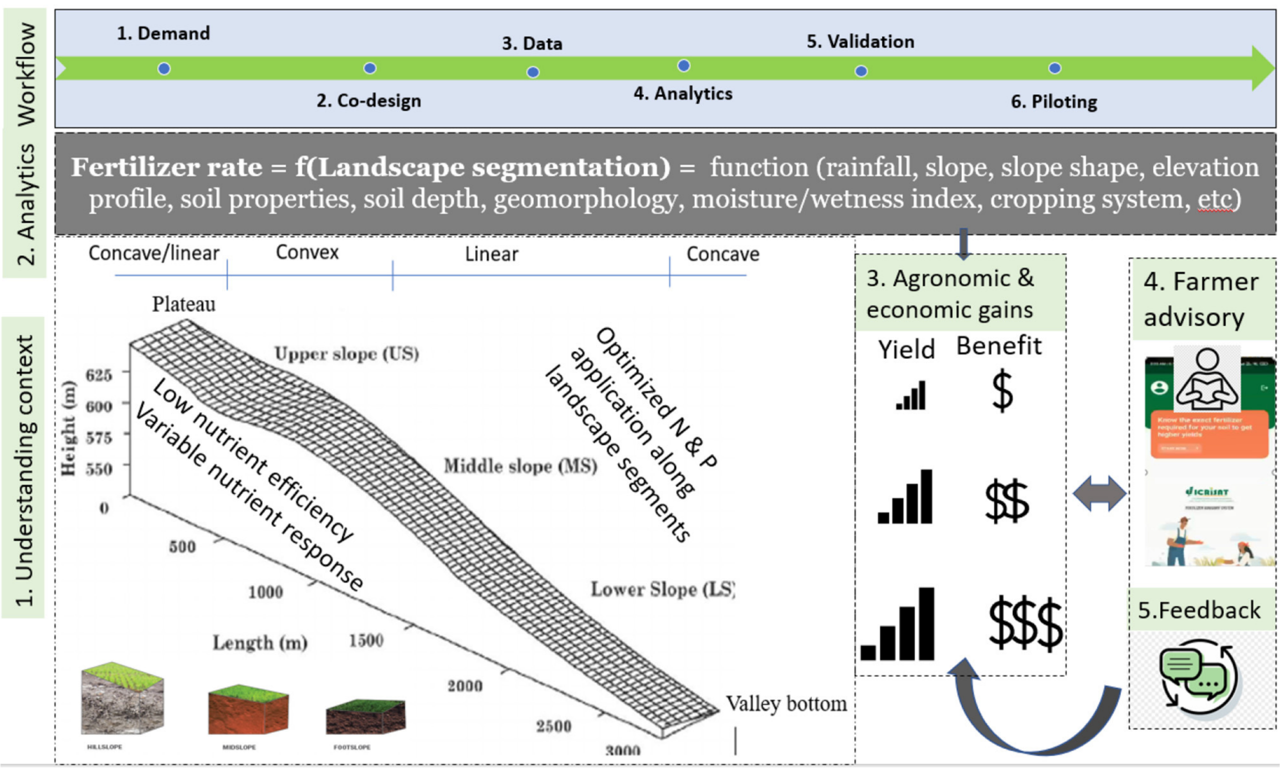
landscape segmentation, site-specific, optimized fertilizer use, agronomic gains, economic gains

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).

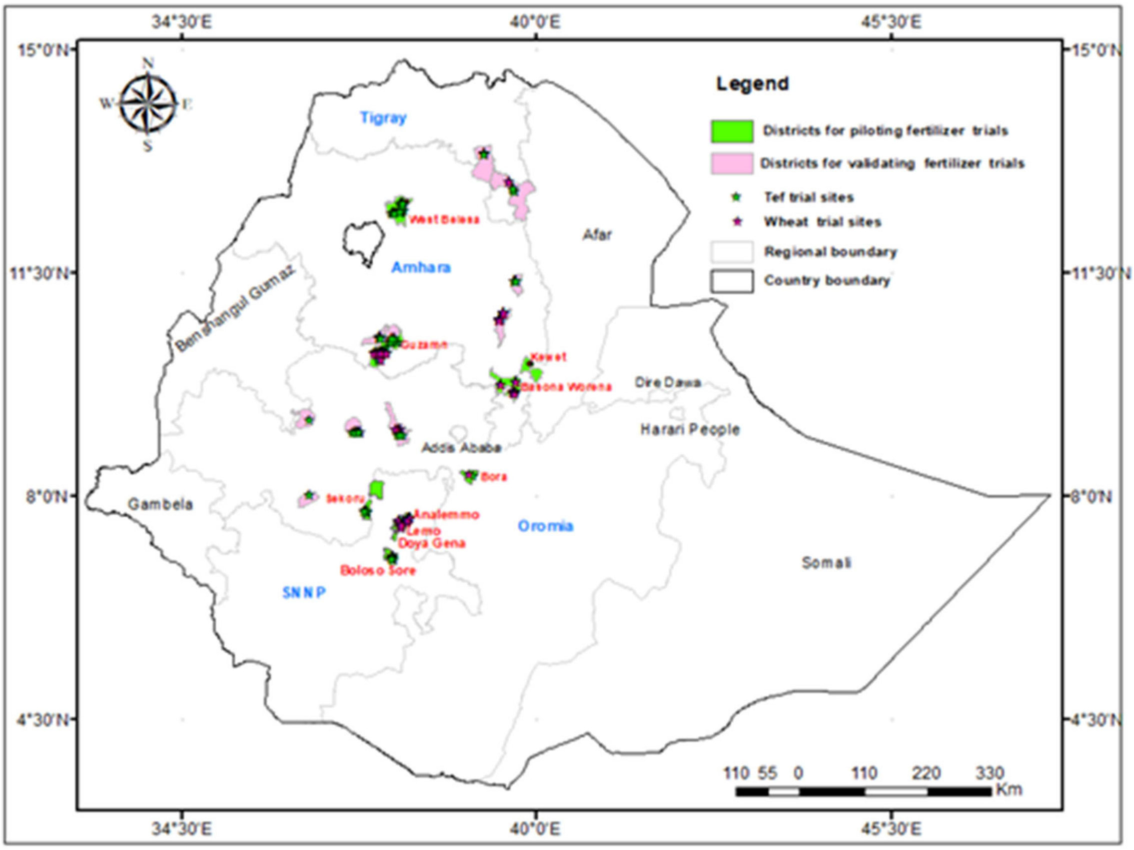


FIGURE 1
Location map of target areas where landscape-specific nutrient application is implemented: teff and wheat on-farm field trails, validation, and piloting trials.

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

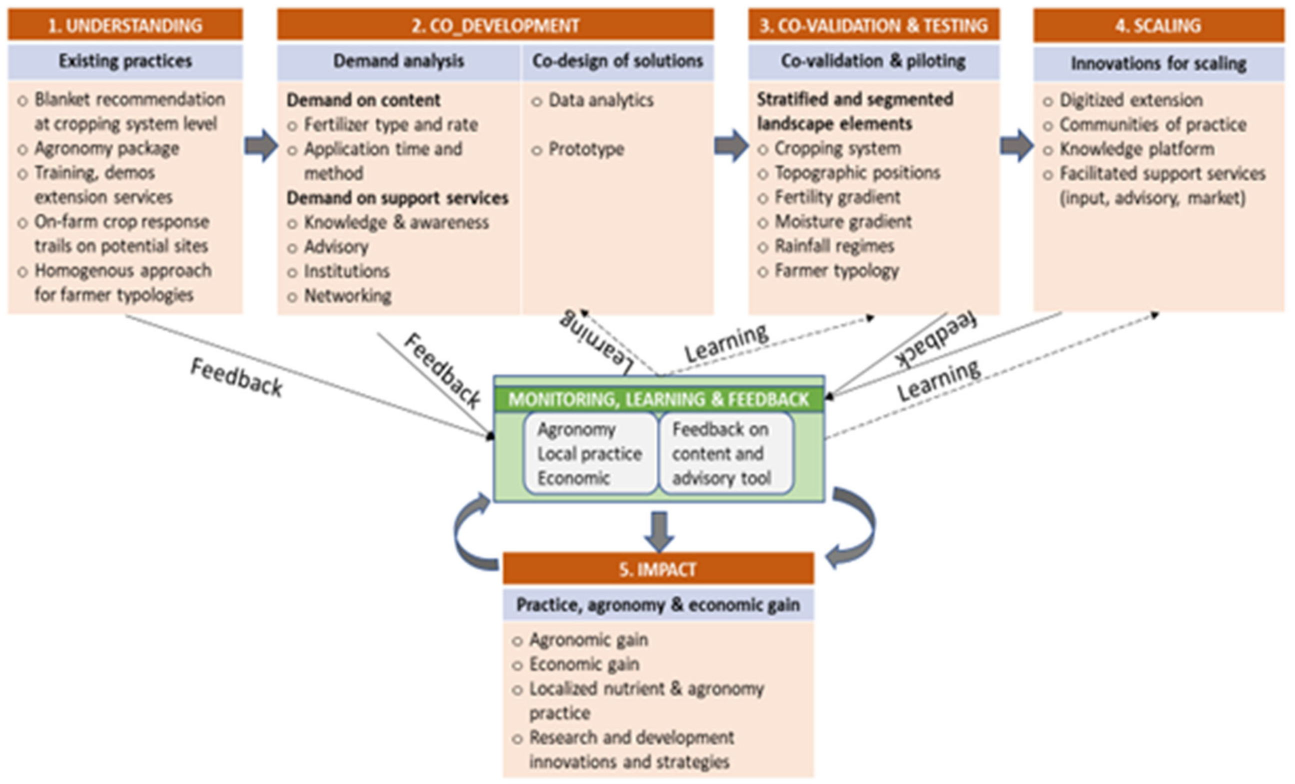


FIGURE 2
A conceptual framework for demand-driven and co-development of farmer and extension agent-centered landscape specific fertilizer application.

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

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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,

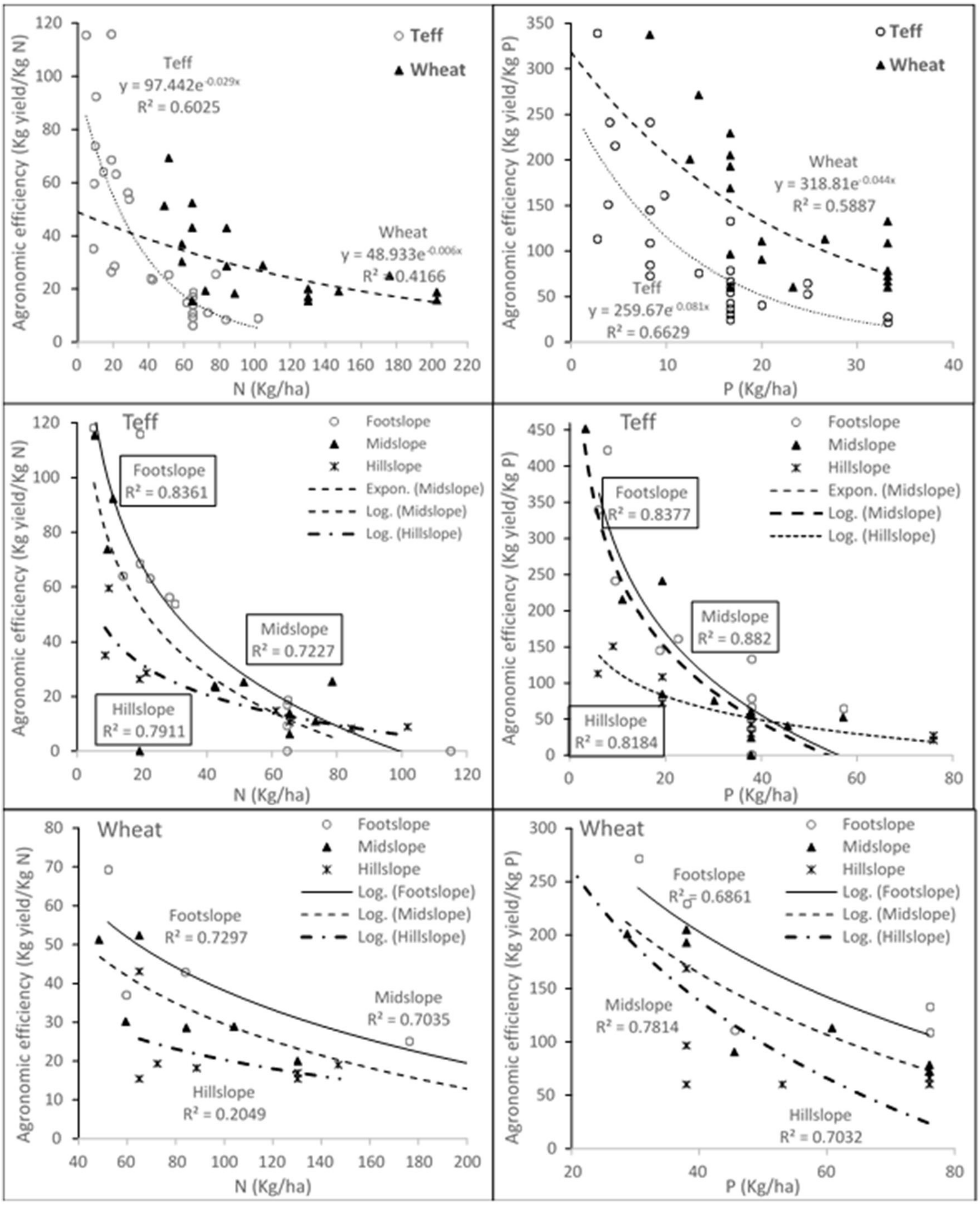

FIGURE 3
Partial factor of productivity of N and P fertilizers for teff and wheat under farmer management practice.

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

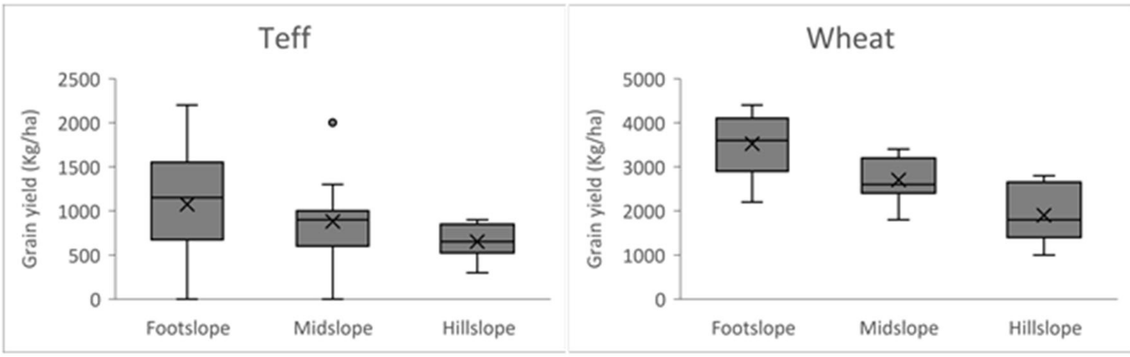

FIGURE 4
Grain yield information on farmers' fields which are generated from farmer focus group discussions.

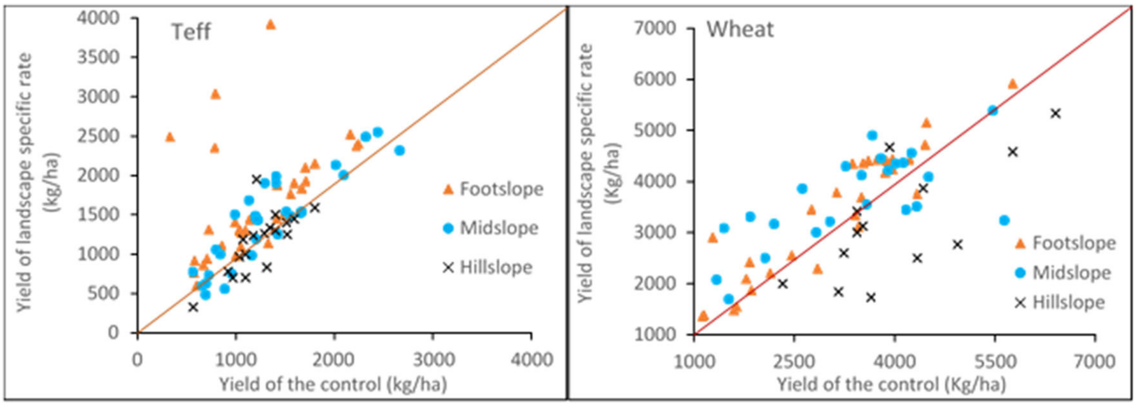

FIGURE 5
The grain yield relationship of the landscape-specific fertilizer application and the control or extension recommendation.

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

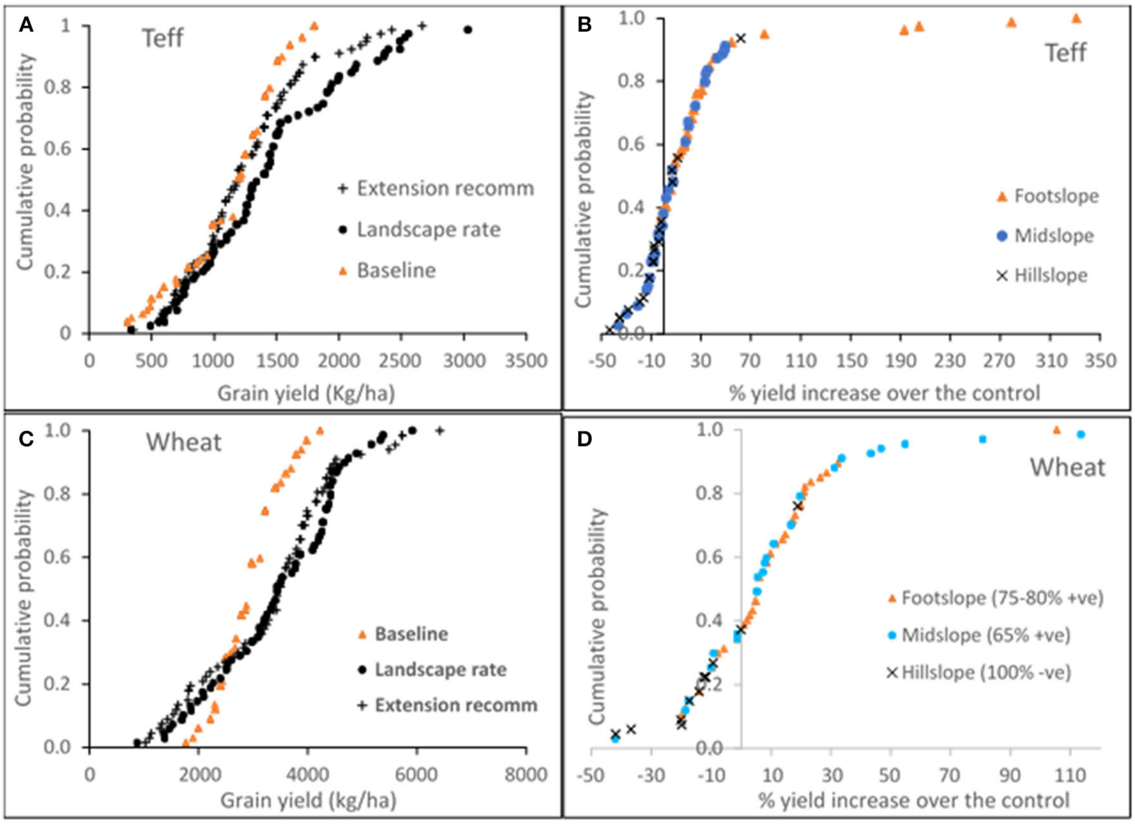

FIGURE 6
Comparison of cumulative probability of yield response from landscape-specific rate and extension recommendations for teff **(A)** and wheat **(C)** and percent yield increase over the control yield of teff **(B)** and wheat **(D)** at the validation stage.

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

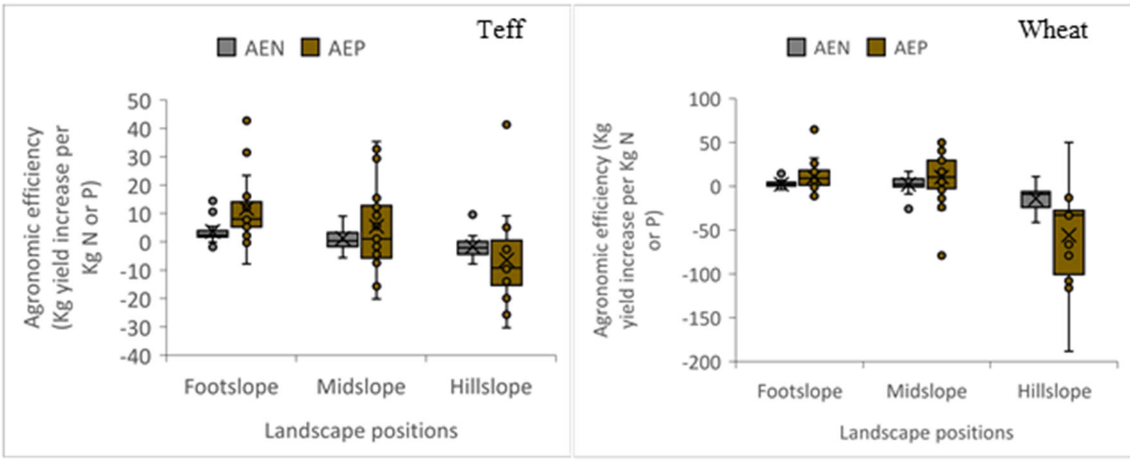

FIGURE 7
Agronomic efficiency of N and P (change in yield over the control per N and P fertilizer applied) for teff and wheat along landscape positions.

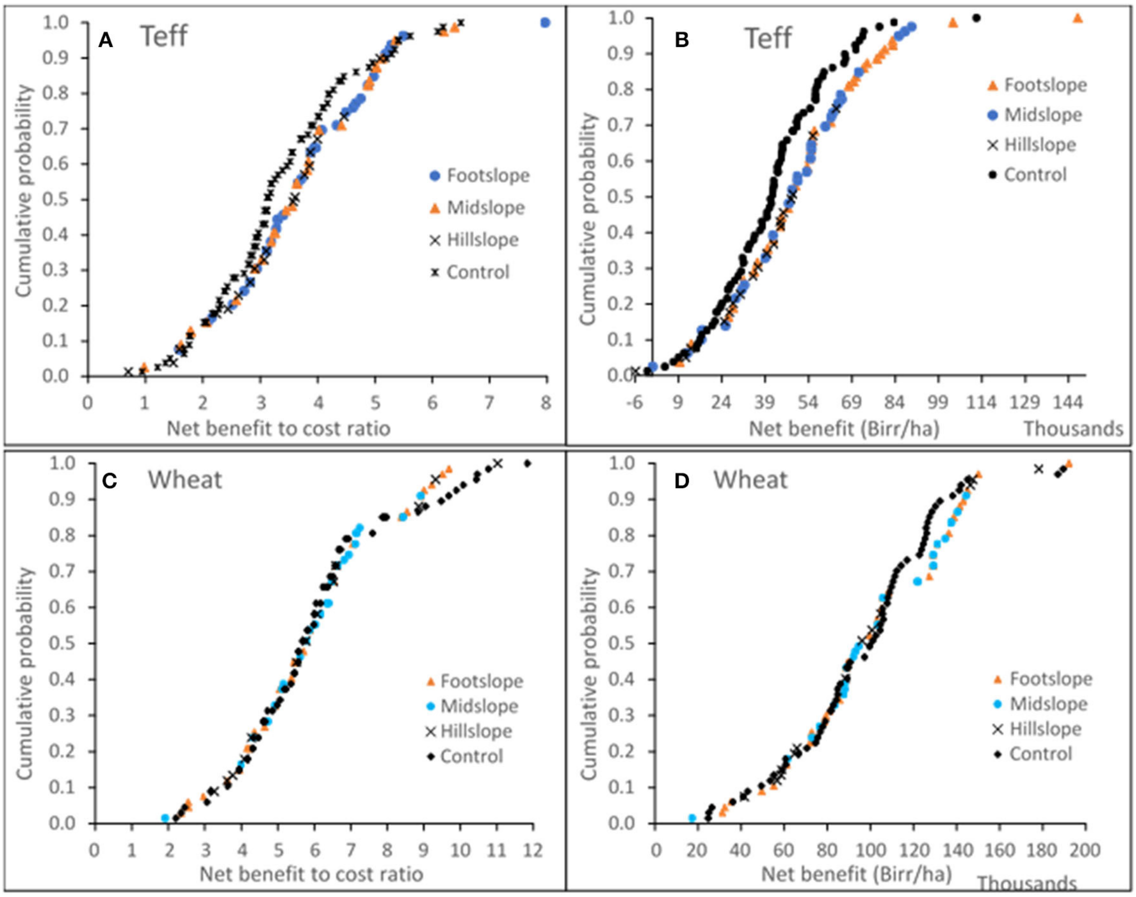

FIGURE 8
Comparison of economic responses using the cumulative probability of net benefits and net benefit to cost ratio (BCR) from landscape-specific rate and extension recommendations for teff **(A, B)** and wheat **(C, D)** measured at the validation stage.

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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.

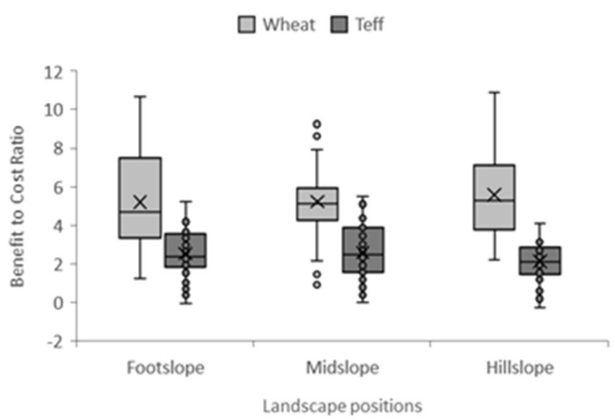

FIGURE 9
Net benefit to cost ratio (BCR) at the three landscape positions for wheat and teff measured in the validation trials.

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

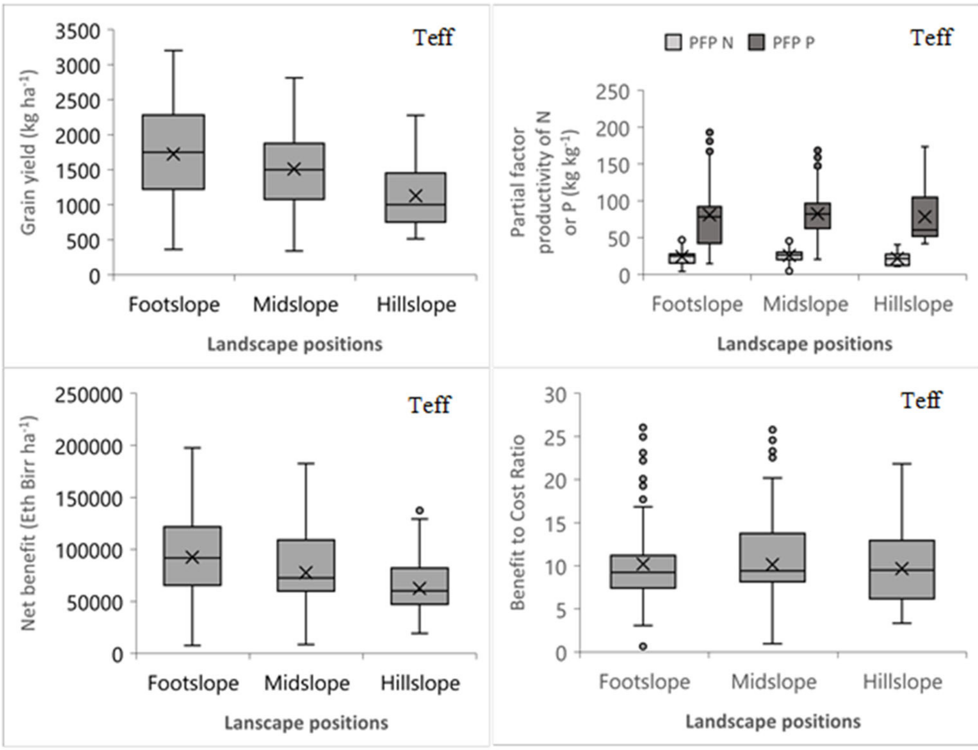

FIGURE 10
Agronomic and economic benefits of a validated landscape-specific fertilizer application using the digital advisory tool for teff at the piloting stage.

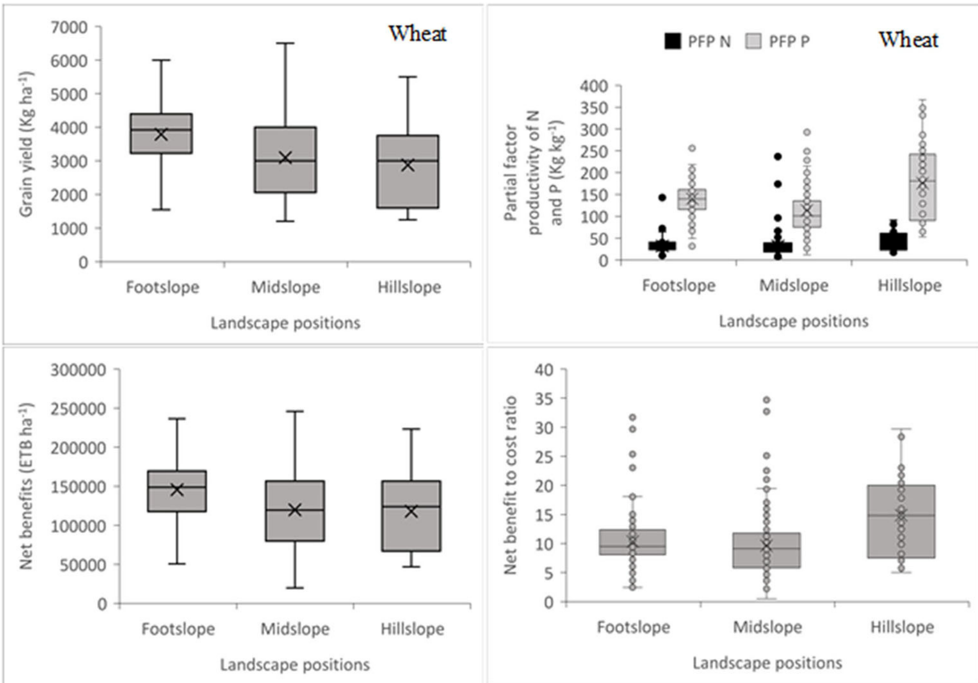

FIGURE 11
Agronomic and economic benefits of a validated landscape-specific fertilizer application using the digital advisory tool for wheat at the piloting stage.

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.

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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.

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

References

Abay, K. A., Abay, M. H., Amare, M., Berhane, G., and Aynekulu, E. (2021). Mismatch between soil nutrient deficiencies and fertilizer applications: implications for yield responses in Ethiopia. *Agric. Econ.* 53, 215–230. doi: 10.1111/agec.12689

Abera, T., Debele, T., and Wegary, D. (2017). Effects of varieties and nitrogen fertilizer on yield and yield components of maize on farmers field in mid altitude areas of Western Ethiopia. *Int. J. Agron.* 2017, 1–13. doi: 10.1155/2017/4253917

Agegnehu, G., and Amede, T. (2017). Integrated soil fertility and plant nutrient management in tropical agro-ecosystems: a review. *Pedosphere* 27, 662–680. doi: 10.1016/S1002-0160(17)60382-5

Alemu, L. B., Tekalign, M. A., Wassie, H. W., and Hailu, S. D. (2016). Soil micronutrient status assessment, mapping, and spatial distribution of Damboya, Kedida Gamela, and Kecha Bira Districts, Kambata Tambaro zone, Southern Ethiopia. *Afr. J. Agric. Res.* 11, 4504–4516. doi: 10.5897/AJAR2016.11494

Amede, T., Gashaw, T., Legesse, G., Tamene, L., Mekonen, K., Thorne, P., et al. (2020). Landscape positions dictating crop fertilizer responses in wheat-based farming systems of East African highlands. *Renew.Agric. Food Syst.* 37, S4–S16. doi: 10.1017/S1742170519000504

Blesh, J., Isaac, M. E., Schipanski, M. E., and Vanek, S. J. (2022). Editorial: ecological nutrient management as a pathway to zero hunger. *Front. Sustain. Food Syst*. 6, 1079973. doi: 10.3389/fsufs.2022.1079973

Bufebo, B., Elias, E., and Agegnehu, G. (2021). Effects of landscape positions on soil physicochemical properties at Shenkolla Watershed, South Central Ethiopia. *Environ. Syst. Res.* 10, 1–8. doi: 10.1186/s40068-021-00222-8

Central Statistical Agency (2021). *Agricultural Sample Survey 2020/21(2013 E.C.) (September – December 2020). Report on Farm Management Practices, Vol. III.* Statistical Bulletin, May 2021, Addis Ababa.

Chivenge, P., Saito, K., Bunquin, M. A., Sharma, S., and Dobermann, A. (2021). Co-benefits of nutrient management tailored to smallholder agriculture. *Glob. Food Secur.* 30, 100570. doi: 10.1016/j.gfs.2021.100570

Chivenge, P., Vanlauwe, B., and Six, J. (2010). Does the combined application of organic and mineral nutrient sources influence maize productivity? A meta-analysis. *Plant Soil*, 342, 1–30. doi: 10.1007/s11104-010-0626-5

Degefie and Tamene. (2017). "Trends and challenges of fertilizer use in Ethiopia," in *A Review of Soil Fertility Management and Crop Response to Fertilizer Application in Ethiopia: Towards Development of site- and Context-Specific Fertilizer Recommendation. CIAT Publication No. 443*, eds L. Tamene, T. Amede, and J. Kihara (Addis Ababa: International Center for Tropical Agriculture (CIAT)).

Desta, B. T., and Almayehu, Y. (2020). Optimizing blended (NPSB) and N fertilizer rates for the productivity of Durum wheat (Triticum turgidum L.var. *durum) in the central highlands of Ethiopia. Cogent Food Agric.* 6, 1766733. doi: 10.1080/23311932.2020.1766733

Desta, G., Amede, T., Gashaw, T., Legesse, G., Agegnehu, G., Mekonnen, K., et al. (2022). Sorghum yield response to NPKS and NPZn nutrients along sorghum-growing landscapes. *Exp. Agric.* 58, 72. doi: 10.1017/S0014479722000072

Drinkwater, L. E., and Snapp, S. S. (2022) Advancing the science and practice of ecological nutrient management for smallholder farmers. *Front. Sustain. Food Syst*. 6, 921216. doi: 10.3389/fsufs.2022.921216

Elias, E., Okoth, P., and Smaling, E. (2019). Explaining bread wheat (*Triticum aestivum*) yield differences by soil properties and fertilizer rates in the highlands of Ethiopia. *Geoderma* 339, 126–133. doi: 10.1016/j.geoderma.2018.12.020

Elias, E., Teklu, B., and Tefera, T. (2020). Effect of blended fertilizer application on bread wheat yield, agronomic efficiency and profitability on Nitisols of Southern Ethiopia. *South Afr. J. Plant Soil*, 37, 292–299. doi: 10.1080/02571862.2020.1791982

Erb, K. H., Haberl, H., Jepsen, M. R., Kuemmerle, T., Lindner, M., Müller, D., et al. (2013). A conceptual framework for analyzing and measuring land-use intensity. *Curr. Opin. Environ. Sustain.* 5, 464–470. doi: 10.1016/j.cosust.2013.07.010

FAO (1997). *National fertilizer and Inputs Unit Ethiopia: Project Findings and Recommendations. Report Prepared for the Government of Ethiopia by the Food and Agriculture Organization of the United Nations. Rome: FAO.*

García-Martín, M., Torralba, M., Quintas-Soriano, C., Kahl, J., and Plieninger, T. (2021). Linking food systems and landscape sustainability in the Mediterranean region. *Landscape Ecol.* 36, 2259–2275. doi: 10.1007/s10980-020-01168-5

Gebremaria, G., and Assefa, D. (2014). Nitrogen Fertilization effect on grain sorghum (*Sorghum bicolor L. Moench) yield, yield components and witchweed (Striga hermonthica (Del.) Benth) Infestation in Northern Ethiopia. Int. J. Agric. Res.* 10, 14–23. doi: 10.3923/ijar.2015.14.23

Haileslassie, A., Priess, J., Veldkamp, E., Teketay, D., and Lesschen, J. P. (2005). Assessment of soil nutrient depletion and its spatial variability on smallholders' mixed farming systems in Ethiopia using partial versus full nutrient balances. *Agric. Ecosys. Environ.* 108, 1–16. doi: 10.1016/j.agee.2004.12.010

Haneklaus, S., and Schnug, E. (2000). Decision-making strategies for the variable-rate application of compound fertilizers. *Commun. Soil Sci. Plant Anal.* 31, 1863–1873. doi: 10.1080/00103620009370543

He, X., Hou, E., Liu, Y., and Wen, D. (2016). Altitudinal patterns and controls of plant and soil nutrient concentrations and stoichiometry in subtropical China. *Sci. Rep.* 6, 2461. doi: 10.1038/srep24261

Jowkin, V., and Schoenau, J. J. (1998). Impact of tillage and landscape position on nitrogen availability and yield of spring wheat in the Brown soil zone in southwestern Saskatchewan. *Can. J. Soil Sci.* 78, 563–572. doi: 10.4141/S97-065

Karaca, S., Gülser, F., and Selçuk, R. (2018). Relationships between soil properties, topography, and land use in the Van Lake Basin, Turkey. *EJSS* 7, 115–120. doi: 10.18393/ejss.348412

Kenea, W. B., Reidsma, P., Descheemaeker, K., Rurinda, J., Balemi, T., van Ittersum, M. K., et al. (2021). Variability in yield responses, physiological use efficiencies, and recovery fractions of fertilizer use in maize in Ethiopia. *Eur. J. Agron.*, 124, 126228. doi: 10.1016/j.eja.2020.126228

Lelago, A. (2016). Assessment and Mapping of status and spatial distribution of soil macronutrients in kambata tembaro Zone, Southern Ethiopia. *Adv. Plants Agric. Res.* 4, 144. doi: 10.15406/apar.2016.04.00144

Manzeke-Kangara, M. G., Amede, T., Bailey, E. H., Wilson, L., Mossa, A. W., Tirfessa, D., et al. (2023). Landscape and micronutrient fertilizer effect on agro-fortified wheat and teff grain nutrient concentration in Western Amhara. *AgriRxiv* 2023, 176. doi: 10.31220/agriRxiv.2023.00176

Martinez-Feria, R. A., and Basso, B. (2020). Unstable crop yields reveal opportunities for site-specific adaptations to climate variability. *Sci. Rep.* 10, 1–2. doi: 10.1038/s41598-020-59494-2

Mzuku, M., Khosla, R., Reich, R., Inman, D., Smith, F., MacDonald, L., et al. (2005). Spatial Variability of Measured Soil Properties across Site-Specific Management Zones. *Soil Sci. Soc. Am. J.* 69, 1572–1579. doi: 10.2136/sssaj2005.0062

Njoroge, S., and Zingore, S. (2022). Variability in yield response strongly affects maize productivity and nutrient requirements. *Growing Africa* 1, 2–5. doi: 10.55693/ga12.EWJD1663

Pircher, T., Nertinger, M., Goss, L., Hilger, T., Karungi-Tumutegyereize, J., Waswa, L., et al. (2022). Farmer-centered and structural perspectives on innovation and scaling: a study on sustainable agriculture and nutrition in East Africa. *J. Agric. Educ. Ext.* 12, 1–22. doi: 10.1080/1389224X.2022.2156894

Raghubanshi, A. (1992). Effect of topography on selected soil properties and nitrogen mineralization in a dry tropical forest. *Soil Biol. Biochem.* 24, 145–150. doi: 10.1016/0038-0717(92)90270-8

Sartas, M., Schut, M., Proietti, C., Thiele, G., and Leeuwis, C. (2020). Scaling Readiness: Science and practice of an approach to enhance the impact of research for development. *Agric. Syst.* 183, 102874. doi: 10.1016/j.agsy.2020.102874

Seifu, W., Elias, E., and Gebresamuel, G. (2020). The effects of land use and landscape position on soil physicochemical properties in a semiarid watershed, northern Ethiopia. *Applied and Environ. Soil Sci.* 2020, 1–20. doi: 10.1155/2020/8816248

Smaling, E. M. A., Stoorvogel, J. J., and Windmeijer, P. N. (1993). Calculating soil nutrient balances in Africa at different scales. *Fertilizer Res.* 35, 237–250. doi: 10.1007/BF00750642

Spielman, D. J., Kelemwork, D., and Alemu, D. (2011). *Seed, Fertilizer and Agricultural Extension in Ethiopia (ESSP II Working Paper 020).* Washington, DC: IFPRI.

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., et al. (2015). Planetary boundaries: guiding human development on a changing planet. *Science* 347, 1259855. doi: 10.1126/science.1 259855

Stoorvogel, J. J., Smaling, E. M. A., and Janssen, B. H. (1993). Calculating soil nutrient balances in Africa at different scales. *Fertilizer Res.*, 35, 227–235. doi: 10.1007/BF00750641

Turner, M. D., and Hiernaux, P. (2015). The effects of management history and landscape position on inter-field variation in soil fertility and millet yields in southwestern Niger. *Agric. Ecosyst. Environ.* 211, 73–83. doi: 10.1016/j.agee.2015.05.010

Yadav, T. C., Singh, Y. P., Yadav, S. S., and Singh, A. Subhash, and Patle, T. (2023). Spatial variability in soil properties, delineation site-specific management division based on soil fertility using fuzzy clustering in gwalior, Madhya Pradesh, India. *Int. J. Plant Soil Sci.* 35, 49–78. doi: 10.9734/ijpss/2023/v35 i62840

Yasrebi, J., Saffari, M., Fathi, H., Karimian, N., Emadi, M., Bagherneja, M., et al. (2008). Spatial variability of soil fertility properties for precision agriculture in southern Iran. *J. Appl. Sci.* 8, 1642–1650. doi: 10.3923/jas.2008.1642.1650

Yimer, F. (2017). Effect of landscape positions on soil properties in agricultural land: a transect study in the Rift Valley area of Ethiopia. *J. Sci. Dev.* 5, 21–31.

Yokamo, S., Jiao, X., Jasper, K., Gurmu, F., Jahan, M. S., Jiang, R., et al. (2022). Grain yield and nitrogen use efficiency vary with cereal crop type and nitrogen fertilizer rate in ethiopia: a meta-analysis. *Agric. Sci.* 13, 612–631. doi: 10.4236/as.2022.134041

Yoo, K., Amundson, R., Heimsath, A. M., and Dietrich, W. E. (2006). Spatial patterns of soil organic carbon on hillslopes: Integrating geomorphic processes and the biological C cycle. *Geoderma* 130, 47–65. doi: 10.1016/j.geoderma.2005.01.008