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Assessing the contribution of land and water management approaches to sustainable land management and achieving land degradation neutrality

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The framework of land degradation neutrality (LDN) and the concept of sustainable land management (SLM) are ways to instigate action required to address land degradation. Although land and water management approaches supporting SLM and the achievement of LDN exist, the transition to sustainable agricultural systems is hindered by various factors and the achievement of LDN is lagging behind. More information on such approaches is needed to sensitize decision-makers for fostering their implementation. This study responds to this need by examining the alignment of the following land and water management approaches with SLM and LDN: agroecology, climate-smart agriculture, conservation agriculture, forest landscape restoration, integrated agriculture, regenerative agriculture, and rewilding. The alignment assessment used a formative methodological approach combining literature review and extensive expert consultations, and is structured along the SLM and LDN pillars of ecosystem health, food security, and human-wellbeing, each comprised by several criteria, as well as selected cross-cutting socioeconomic criteria that span all pillars. The results indicate that each of the approaches contributes to SLM and the achievement of LDN in different ways and to varying degrees, with none of the approaches embracing principles or practices that directly conflict with the criteria of SLM and LDN. A higher degree of alignment was identified for the ecosystem health and food security pillars, while most gaps in alignment concern criteria of the human wellbeing pillar along with certain cross-cutting criteria. The results of the assessment led to the identification of entry points for addressing gaps in alignment via supplementary activities that directly target the gaps during project planning and implementation, as well as through adhering to principles and established guidelines. Importantly, conclusions about the degree of alignment or about gaps in alignment of an approach with SLM and LDN criteria are conceptually indicative, but may change in actual practice depending on where and how projects are implemented. Notwithstanding, clarifying the approaches' contribution to SLM and the achievement of LDN can help overcome the lack of formal intergovernmental recognition of the approaches, prevent misinterpretation, and ensure their strategic inclusion in broader efforts to remedy land degradation.

KEYWORDS

sustainable land and water management, land degradation neutrality, ecosystem health, food security, human wellbeing

1 Introduction

Agricultural systems often rely largely on intensive monocultures with strong soil and vegetation disturbance, high greenhouse gas emissions, chemical inputs and freshwater use, which contribute to climate change and drive the degradation of terrestrial and freshwater ecosystems utilized for the production of food and other goods (United Nations Convention to Combat Desertification, 2022c; Intergovernmental Panel on Climate Change, 2023; Powell et al., 2023). Increasing land use change for agricultural production, including deforestation, have already caused the planetary boundary "land system change" to be transgressed, with continued inappropriate land management further accelerating this trend (Richardson et al., 2023). Such inappropriate management often results in human-induced land degradation, including soil erosion, soil fertility loss and excessive water extraction, contamination and eutrophication of soils, surface and groundwater, while climate change can further aggravate land degradation (Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services, 2018b; United Nations Convention to Combat Desertification, 2022c). Land degradation, which is defined as "the reduction or loss of the biological or economic productivity and complexity of rainfed cropland, irrigated cropland, or range, pasture, forest and woodlands resulting from a combination of pressures, including land use and management practices" (United Nations Convention to Combat Desertification, 2024), erodes future agricultural opportunities, posing a risk to food security and loss of ecosystem services that particularly affects vulnerable groups such as poor rural communities, smallholder farmers, women and indigenous people. Land degradation and climate change also impact high productive agricultural systems, resulting in food insecurity exacerbating also on larger scales (Organisation for Economic Co-operation Development, 2022). To address these multiple adverse impacts, there is the urgent need to accelerate action to avoid, reduce and reverse land degradation and ensure the long-term sustainable management of land resources to secure the capacity of ecosystems to provide services for present and future human wellbeing (Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services, 2018b; United Nations Convention to Combat Desertification, 2022c).

The framework of land degradation neutrality (LDN) and the concept of sustainable land management (SLM) are central to the global intergovernmental response to land degradation. LDN refers to "the state whereby the amount and quality of land resources, necessary to support ecosystem functions and services and enhance food security, remains stable or increases within specified temporal and spatial scales and ecosystems" (Orr et al., 2017, p. 21). It has been endorsed by the signatory parties of the United Nations Convention to Combat Desertification (UNCCD) and is integral to target 15.3 under the UN Sustainable Development Goal (SDG) "Life on Land." SLM refers to "the use of land resources, including soils, water, animals and plants, for the production of goods to meet changing human needs, while simultaneously ensuring the long-term productive potential of these resources and the maintenance of their environmental functions" (World Overview of Conservation Approaches and Technologies, 2024). SLM is globally acknowledged as a land-based solution to address desertification, land degradation and drought and as a means to address the causes and impacts of climate change. The importance of SLM is explicitly recognized by the UNCCD and is embraced by efforts under the United Nations Framework Convention on Climate Change (UNFCCC), the Convention on Biological Diversity (CBD), and the Sendai Framework for Disaster Risk Reduction and the United Nations Environment Assembly (UNEA; Walz et al., 2021).

The Intergovernmental Panel on Climate Change (IPCC) considers the implementation of SLM to have the potential to increase land productivity while being economically viable in different settings (Olsson et al., 2019). There are a multitude of land management approaches that specifically employ practices which contribute to SLM, as well as to the achievement of LDN. They often entail common features, such as the diversity of species to optimize the use of land, recycling of nutrients or the utilization of the micro-environment (Olsson et al., 2019). Although it is known that such sustainable alternatives to commonly employed current agricultural practices exist, the transition to these is often hindered by local biophysical and socioeconomic factors, barriers to establish a fully enabling policy institutional and financial environment, and a lack of appropriate incentives promoting their uptake (Olsson et al., 2019; United Nations Convention to Combat Desertification, 2022c). The IPBES calls for more information on such opportunities to sensitize decision-makers for fostering implementation of approaches that contribute to SLM and achieving LDN, with the long-term goal of improving the stewardship of land and the sustainable use of natural resources

(Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services, 2018b).

This study responds to this need for information by assessing how selected land and water management approaches that have been developed in recent years contribute to SLM and the achievement of LDN. Land and water management approaches are here defined as "the ways and means for organizing human activities on land and for using land resources" (United Nations Economic Commission for Europe, 1996; Walz et al., 2021; based on European Environment Agency, 2024). Clarifying the complementarities these approaches may have with SLM and the achievement of LDN can contribute to overcoming the lack of international recognition that may be hindering their strategic inclusion in broader efforts to remedy land degradation and its consequences. This research builds on an extensive literature review and stakeholder engagement process and considers global conceptual and practical evidence. To our best knowledge, no scientific publication assessed the contribution of multiple approaches to SLM and the achievement to LDN yet. There are publications that elaborate how individual approaches contribute to achieving LDN (Gichuki et al., 2019; Sharma et al., 2022b), however, the identification of criteria to operationalize SLM and LDN and to use these as basis for an assessment is a new contribution of this paper. This study further elaborates on entry points for achieving multiple benefits in land interventions beyond the scope of one individual approach, helping countries enhancing these approaches and integrating them into national plans addressing desertification, land degradation and drought, as well as to climate change mitigation, adaptation and protection of biodiversity in a coordinated way.

2 Materials and methods

This study was built on five methodological steps, which are presented in the following sections. The research design was formative, through which the different steps were continuously revised to improve the effectiveness and targeted nature of their design (Reigeluth and Frick, 1999).

2.1 Selection of land and water management approaches

The land and water management approaches to be assessed in this study were identified through a selection process which is presented schematically in Figure 1. A more detailed version of this flowchart, including information on which specific options were identified and in- or excluded during the process, can be found in Supplementary material 1.

The starting point of the research process a the statement by the UNCCD Committee on Science and Technology (United Nations Convention to Combat Desertification, 2022b, ICCD/COP(15)/CST/5, section IV, para 56) following COP 15 Decision 19 (United Nations Convention to Combat Desertification, 2022a, Decision 19/COP.15/23/Add.1). It provides a list of land and water management options that could be assessed, including concrete approaches, specific methods, technologies or theoretical management concepts. To identify additional relevant options, UNCCD's Global Land Outlook, Second Edition (United Nations Convention to Combat Desertification, 2022c), as well as other literature was consulted.

Afterwards, Google Trends was used to evaluate global Internet search trends for the land and water management options identified within the last 5 years. This served to identify options that showed the highest public interest (i.e., highest hit rates) as well as increasing public interest (i.e., increasing hit trend). The identification and review of candidate approaches was performed in the English language.

Relevant, English-language literature from the past 5 years concerning each of the options with highest and/or increasing interest was collected through a search of scientific articles and gray literature using the databases ScienceDirect, Scopus, Web of Science, JSTOR and Google Scholar. For this search, the options were entered along with the qualifications "AND" "definition" OR "framework" OR "review" OR "concept." Additionally, a snowball technique was used to identify additional sources that could aid in further characterizing the options. The literature review served to clearly define each of the selected land and water management options and to derive their important and distinguishing characteristics. These characteristics include defining elements, as well as specific goals, principles and implemented techniques and practices that are at the core of each approach.

Lastly, the definitions and key characteristics of the candidate options were reviewed to clarify whether they are framed as a concrete "land and water management approach" as defined earlier, thus as the ways and means for organizing human activities on land and for using land resources, as set out earlier (i.e., instead of being more widely understood as a "method" or a "conceptual framework").

This process led to the selection of seven approaches: agroecology, integrated agriculture, regenerative agriculture, forest landscape restoration, rewilding, conservation agriculture, and climate-smart agriculture.

2.2 Defining SLM and LDN criteria

The seven selected land and water management approaches were assessed for their contribution to SLM and LDN by examining their alignment with SLM and LDN criteria. Alignment refers to the "process of identifying synergies among strategies with common objectives to increase efficiency and effectiveness for improved outcomes" (adapted from Dazé et al., 2018, p. 3). Here, the identification of such synergies between land and water management approaches and SLM and LDN were enabled through investigating how key defining characteristics of each approach, which are specific goals, principles and implemented techniques and practices, relate to criteria of SLM and LDN.

Table 1 displays the 15 criteria used to analyze the alignment of the approaches with SLM. The criteria are derived from the SLM framework developed by Smyth and Dumanski (1995), the definition of SLM by Sanz et al. (2017) as well as the characterization of SLM by Walz et al. (2021). These publications

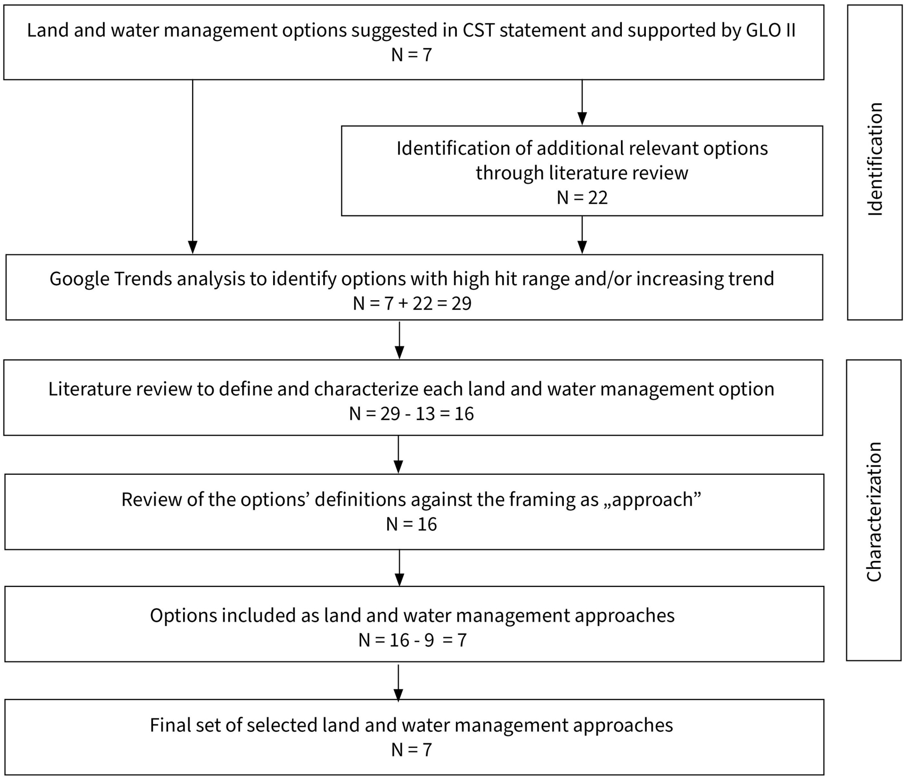

FIGURE 1
Process to select "land and water management approaches" to assess in this study.

TABLE 1 The 15 criteria used to assess the alignment of approaches with SLM.

Pillar	SLM criteria	References
Ecosystem health	Supports biodiversity, ecosystems and ecosystem services and functions	Liniger et al., 2011
	Prevents, mitigates and reverses land degradation	Walz et al., 2021
	Maintains and enhances the quality of land resources	Sanz et al., 2017
	Uses land resources—including soils, water, vegetation and animals—sustainably	Smyth and Dumanski, 1995
Food security	Aims to increase food security and livelihoods	Smyth and Dumanski, 1995; High Level Panel of Experts on Food Security and Nutrition, 2020
	Ensures the long-term productive potential of land resources	Sanz et al., 2017
	Reduces the risks of crop failure or production losses	Based on Sanz et al., 2017
Human wellbeing	Integrates indigenous, local and traditional knowledge	Liniger et al., 2011
	Is land-user driven	Liniger et al., 2011
	Is socially accepted	Based on Smyth and Dumanski, 1995
Cross-cutting	Contributes to progress on policy targets and institutional goals	Sanz et al., 2017
	Integrates biophysical, socio-cultural and economic needs and values	Sanz et al., 2017
	Involves multiple levels of governance and stakeholders	Sanz et al., 2017
	Enables adaptation to climate change and contributes to climate change mitigation	Sanz et al., 2017
	Is economically viable	Based on Smyth and Dumanski, 1995

were identified as key to operationalizing SLM. The SLM criteria are categorized within four categories, or "pillars:" "food security," "human wellbeing," "ecosystem health," and "cross-cutting" socioeconomic criteria that simultaneously address more than one of the other three pillars. In a similar way, criteria where derived to assess alignment with LDN, based on the conceptual framework and principles for LDN implementation (Orr et al., 2017) and the strategic objectives under the vision of achieving LDN formulated in the UNCCD Strategic Framework 2018–2030 (United Nations Convention to Combat Desertification, 2017),

TABLE 2 The 20 criteria used to assess the alignment of approaches with LDN.

Pillar	LDN criteria	References
Ecosystem health	Maintains land-based natural capital	Orr et al., 2017
	Supports biodiversity and the delivery of all land-based ecosystem services	Orr et al., 2017
	Maintains or enhances soil properties	Orr et al., 2017
	Maintains or enhances hydrological features	Based on Orr et al., 2017
	Enhances ecosystem resilience	Orr et al., 2017
Food security	Improves food productivity	Orr et al., 2017
	Aligns with the potential of the land	Orr et al., 2017
	Prioritizes appropriate land-use practices to minimize land degradation	Orr et al., 2017
	Improves adequate access to water	Orr et al., 2017
Human wellbeing	Supports, enhances and diversifies livelihoods	Orr et al., 2017
	Protects all human rights and the right to property	Orr et al., 2017
	Is gender responsive	Orr et al., 2017
	Is inclusive, representative and participatory	Orr et al., 2017
	Enhances community resilience	Orr et al., 2017
Cross-cutting	Leverages existing strategic planning and development processes	Orr et al., 2017
	Balances economic, social and environmental objectives and manages trade-offs	Orr et al., 2017
	Embraces integrated land-use planning	Orr et al., 2017
	Encourages landscape-scale implementation tailored to local contexts	Orr et al., 2017
	Establishes mechanisms for learning and adaptive management	Orr et al., 2017
	Reduces vulnerability to climate variability, drought and other extreme events	Orr et al., 2017

such as increased ecosystem resilience, enhanced land productivity, diversified livelihoods and contribution to the goals the other UN conventions. Based on this framing, 20 criteria were derived to analyze alignment of the selected approaches with LDN, as shown in Table 2. These criteria were categorized within four major "pillars" representing LDN's main objectives and mirroring the "pillars" of the SLM framework. That is, the criteria were categorized as addressing "ecosystem health," "food security," "human wellbeing" or multiples of these pillars as "cross-cutting" socioeconomic criteria. The criteria guide interventions that avoid, reduce and reverse land degradation (i.e., known as "the LDN response hierarchy"), while preventing unintended consequences and contributing to beneficial outcomes (Orr et al., 2017, p. 5).

A number of criteria that appear in both the SLM and LDN conceptual frameworks are similar and can be considered to "overlap." These include, for example, support for biodiversity and ecosystem services and the participatory engagement of multiple stakeholders. This overlap reflects the fact that LDN is envisaged to be achieved through the adoption of SLM. Therefore, the characteristics of SLM as expressed through the criteria are frequently reflected in the LDN criteria as well.

Both SLM and LDN criteria are described in detail in Supplementary material 2.

2.3 Assessing alignment with SLM and LDN criteria

2.3.1 Literature review

More than 400 conceptual documents, case studies and other publications in English language on the seven land and water management approaches were identified through web searches specifically targeting the relation of a certain approach with the 15 SLM and 20 LDN criteria, for example "agroecology" and "support ecosystem services," "land tenure," or "food security." For this purpose, the databases ScienceDirect, Scopus, Web of Science, JSTOR, and Google Scholar as well as Google Search Engine were used. A quantitative summary of the literature review results can be found in Supplementary material 3. An effort was made to include both publications that define and conceptualize the approaches and case studies documenting the actual implementation of the approaches to determine alignment whenever possible. This was done to avoid the tendency of conceptual papers to ignore or gloss over practical, important and on-the-ground characteristics that could be central to SLM or to implementing LDN. When no case studies on the alignment of the approaches with certain criteria were obtainable, conceptual documents on the approaches were decisive for the determination of alignment. This is documented in detail for each approach in Supplementary material 5–11.

Following the identification of pertinent publications, they were reviewed following a qualitative content analysis approach (Cho and Lee, 2014; Kühlmeyer et al., 2020). In the scope of this analysis, the SLM and LDN criteria were applied as deductive codes helping to extract information on how the approaches align with them. This could be when the literature provided *direct* evidence linking an approach and criterion, for example, an approach that fosters multi-stakeholder collaboration aligns *directly* with the SLM criterion to involve multiple levels of stakeholders and governance. In other cases, literature did not explicitly address alignment between the key characteristics and the criteria, but conclusions could be indirectly drawn to that effect. For example, a description of an approach might not explicitly indicate that it is "land-user driven" but includes evidence that farmers are the main actors adopting the approach. This indirect evidence also suggests alignment with the corresponding SLM criterion.

The literature review also looked for evidence on "non-alignment" or "misalignment." Non-alignment was detected when the evidence showed that a criterion is not addressed by an approach. For example, an approach was considered to be non-aligned with LDN criterion requiring gender-responsiveness when it includes no practices or measures to address gender equality in most or all of its implementation contexts. However, non-alignment does not imply misalignment. Misalignment was detected when approaches include measures that might actively undermine SLM or LDN criteria. For example, misalignment could occur when an approach—and the project implementing it—violates land tenure rights in direct contradiction of the LDN criterion to protect all human rights and the right to property.

Evidence of alignment from the literature review was determined to be either "good," "limited," or "no evidence found." For this study, "good evidence" was defined as corroborating evidence regarding alignment from at least three independent sources. "Limited evidence" is evidence from <3 publications. For instances in which no publication provided evidence one way or the other regarding alignment between an approach and a criterion, the alignment evidence was categorized as "no evidence found." The robustness of evidence was used in determining the final alignment assessment.

2.3.2 Expert engagement

We consulted 65 experts from science, policy, and practice working on the selected land and water management approaches to triangulate the findings from the literature review and obtain information on SLM and LDN criteria for which the reviewed literature only provided limited or no evidence on alignment. They were identified as authors of relevant publications as well as through targeted web searches. Information on experts engaged in this study can be found in Supplementary material 4.

The formative approach used in this study consisted of a scoping phase, where experts were invited to bilateral exchanges to get a better understanding of their field of knowledge. In a second step, Focus Group Discussions (FGDs) to discuss the literature-based findings on alignment were conducted with the relevant experts. Overall, seven FGDs were conducted, each addressing one of the seven land and water management approaches. They were hosted in a virtual setting between May and August 2023, with three to six experts joining each discussion.

In the FGDs, the experts were asked:

- whether and why they agree or disagree with the preliminary literature-based assessment of the alignment, lack of alignment or misalignment of the selected land and water management approaches with SLM and LDN criteria, and
- to provide an expert assessment of whether a land and water management approach aligns with a criterion for which no or limited evidence exists.

The FGDs generated discussions on alignment between experts, and hence enabled capturing different perspectives and explanations for certain views of experts working on the approaches in different contexts (Nyumba et al., 2017). As in the literature review, the results of these consultations were evaluated through a qualitative content analysis. The experts statements were coded applying the SLM and LDN criteria as deductive codes, so that information on alignment for each criterion could be retrieved (Nyumba et al., 2017; Kühlmeyer et al., 2020).

2.3.3 Final alignment assessment

The final alignment assessment combined evidence from the literature review and from the expert engagement. In this final assessment, two categories of alignment were assigned: *alignment* and *gap in alignment*. **Alignment** between the approaches and the SLM and LDN criteria was determined when all sources of evidence (literature and experts) show agreement on alignment. In contrast, a **gap in alignment** was determined when *any* (i.e., one or more) source of evidence (i.e., from literature and/or experts) indicates an approach is not aligned with a certain criterion. This minimum threshold for determining a gap in alignment reflects the study's rationale that *any* evidence, however slight, suggesting that an approach is not aligned with SLM or LDN criteria means that some additional measures could improve the alignment and could more effectively ensure that an approach advances SLM and helps in achieving LDN. No **misalignment** was detected for any approach with any criterion.

The final step of the formative approach was the identification of entry points to address gaps in alignment. To achieve this, an additional and targeted review of literature was used to develop recommendations for addressing these gaps in alignment. This included publications that specifically provide such recommendations on how certain criteria can be better addressed were searched and analyzed. The experts that participated in the FGDs were reassembled in a final, virtual conference in September 2023 to discuss these and complement them with other entry points for enhancing alignment and thus the contribution of the selected land and water management approaches to SLM and the achievement of LDN.

3 Results of the alignment assessment of land and water management approaches with SLM and LDN pillars and criteria

The assessment demonstrates that all seven selected land and water management approaches align with many, but not all, of the SLM and LDN criteria. Consequently, each of the approaches contributes to SLM and the achievement of LDN in different ways and to varying degrees. The findings of the alignment assessment are summarized in Figure 2. A detailed documentation on evidence and agreement used as basis for the alignment assessment for each approach at the level of individual criteria for SLM and LDN can be found in Supplementary material 5–11.

3.1 Agroecology

Agroecology is defined as "the movement, science and practice of applying ecological concepts, principles and knowledge [...] to the study, design and management of sustainable

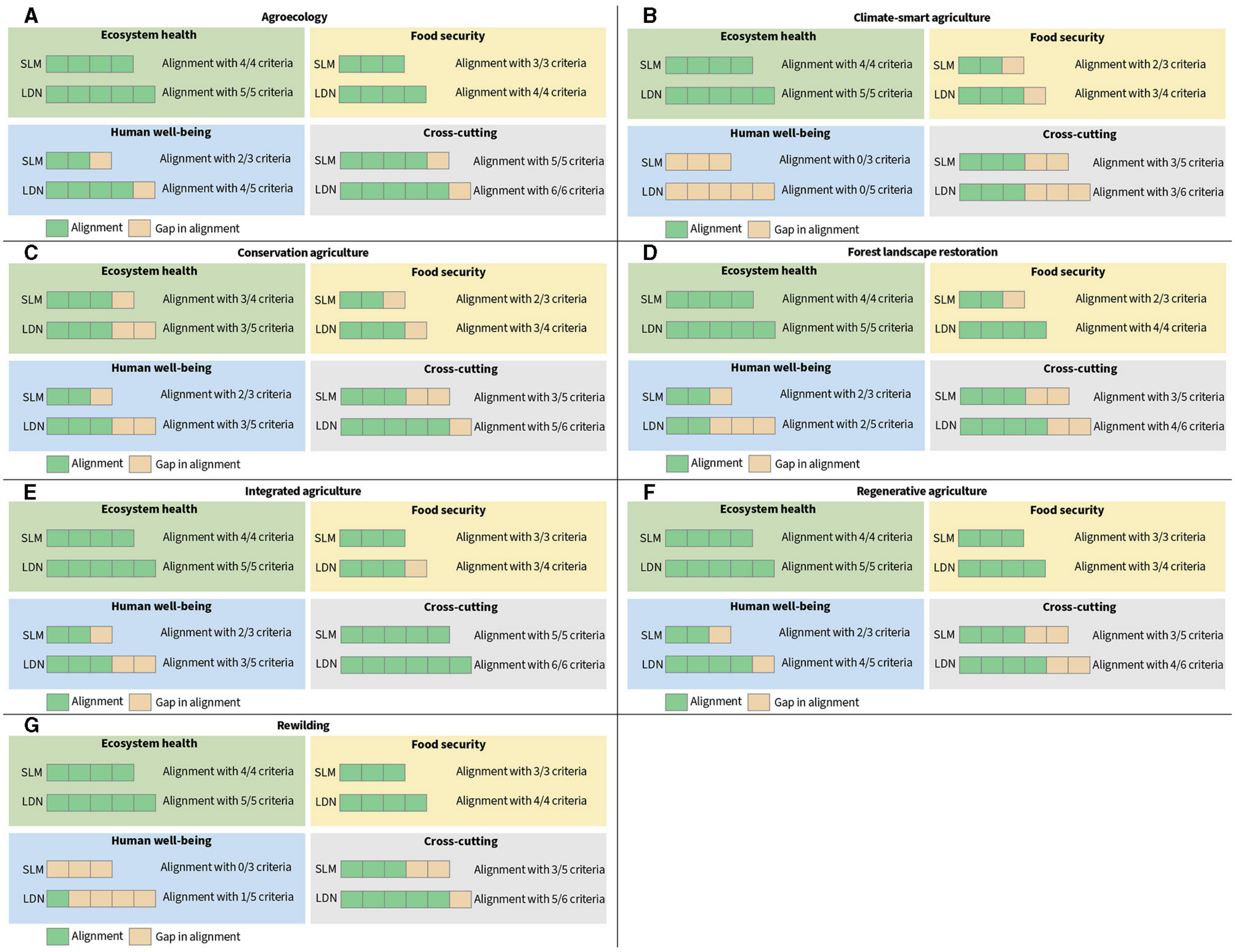

FIGURE 2
Panel summarizing the alignment of each land and water management approach with SLM and LDN pillars and criteria. **(A)** agroecology, **(B)** climate-smart agriculture, **(C)** conservation agriculture, **(D)** forest landscape restorations, **(E)** integrated agriculture, **(F)** regenerative agriculture, and **(G)** rewilding. The details on evidence and agreement that resulted in alignment or gap in alignment per criterion of SLM and LDN is provided in the Supplementary material for each approach (Supplementary material 5–11).

agroecosystems. It includes the roles of human beings as a central organism in agroecology by way of social and economic processes in farming systems. Agroecology examines the roles and interactions among all relevant biophysical, technical and socioeconomic components of farming systems and their surrounding landscapes" (Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services, 2018a, p. 584). As a holistic approach, it pursues multiple objectives, including sustainable (agro-)ecosystems, food security and sovereignty, social justice and economic viability (Wezel et al., 2014; Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services, 2018a; Food and Agriculture Organization, 2024b), which corresponds with a broad range of criteria, covering all pillars of SLM and LDN. Agroecology was found to have the highest degree of alignment among the assessed approaches. The contribution of agroecology to SLM is specifically acknowledged by the IPBES, declaring it—together with conservation agriculture—as viable solutions to address degradation and to improve farmer's livelihood options in the face of climate change (Pandit et al., 2018). Gaps in alignment of agroecology with SLM and LDN criteria concern specific criteria of the human wellbeing pillar as well as cross-cutting criteria. For example, the bottom-up approach builds social acceptance in communities (Food and Agriculture Organization, 2018; Agroecology Experts, 2023). Yet, agroecology often challenges traditional power structures and is frequently associated with social movements. These attributes affect the acceptance of agroecology among some established social and governance institutions (López-García and González De Molina, 2021; Agroecology Experts, 2023). Also, agroecology can be considered to be gender responsive although limitations in its practical application must be considered. Women's participation is essential for agroecology (Food and Agriculture Organization, 2018; Paracchini et al., 2020; Global Alliance for the Future of Food, 2021), however, these essential roles often lack recognition within the implementation of the approach and gender considerations are not always translated into practice (Oteros-Rozas et al., 2019; Agroecology Experts, 2023).

3.2 Climate-smart agriculture

Climate-smart agriculture is defined as "[...) an approach that helps guide actions to transform agri-food systems toward green and climate resilient practices in order to effectively support development and ensure food security in a changing climate. It has three main objectives, which are (i) sustainably increasing agricultural productivity and incomes; (ii) adapting and building resilience to climate change; and (iii) reducing and/or removing greenhouse gas emissions, where possible" (Food and Agriculture Organization, 2017, 2024a). The approach maintains and enhances the productive potential of land and therefore sustains agricultural opportunities in the face of climate change (Alvar-Beltrán et al., 2021), hence it foremost aligns with criteria of the food security and ecosystem health pillars. In addition, the definition shows that the approach implements measures to mitigate and adapt to climate change, which further contributes to international policy goals, specifically the 1.5°C climate change mitigation goal formulated in the Paris Agreement (United Nations Framework Convention on Climate Change, 2015). A major criticism toward climate-smart agriculture is its emphasis on greater productivity, emissions mitigation and adaptation of agricultural systems to climate change, which is said to neglect social considerations. This narrow focus contributes to this approach's gap in alignment with SLM and LDN criteria concerning the human wellbeing pillar as well as related cross-cutting criteria. Karlsson et al. (2018), Taylor (2018), and Autio et al. (2021) argue that there is a lack of participation and inclusion of local and traditional knowledge within climate-smart agriculture. They raise the concern that, by insufficiently considering the situation of smallholders, the approach is not capable of addressing issues of vulnerability and equity in agriculture. Neglecting key stakeholders, such as smallholders, and their needs is further stated to impact their respective livelihoods and to potentially affect the long-term effectiveness and social acceptance of climate-smart agriculture (Fanen and Olalekan, 2014; La Via Compensia, 2014; Karlsson et al., 2018; Taylor, 2018; Autio et al., 2021). Following mostly economic, production-related objectives and missing to account for social needs suggests that climate-smart agriculture does not sufficiently integrate and balance different objectives, as it is requested by the respective cross-cutting SLM and LDN criteria (La Via Compensia, 2014; Coopération Internationale pour le Développement et la Solidarité, 2015; Karlsson et al., 2018; Taylor, 2018).

3.3 Conservation agriculture

The Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services (2019, p. 1,036) defines conservation agriculture as "an approach to managing agroecosystems for improved and sustained productivity, increased profits and food security while preserving and enhancing the resource base and the environment." The approach, which seeks to improve biophysical conditions for and through agricultural production (Lal, 2015), mainly aligns with criteria of the food security and ecosystem health pillars. The alignment assessment also found that the approach's focus on improving soil features (with their cascading social and economic benefits) indicates conservation agriculture's alignment with many criteria within the human wellbeing pillar, as well as some related cross-cutting criteria (Tittonell et al., 2012; Monjardino et al., 2021; Conservation Agriculture Experts, 2023). These may however, not always be evident. Gaps in alignment of conservation agriculture were assessed across all pillars. Despite the evidence on how conservation agriculture is beneficial for the environment, there is a concern regarding the use of glyphosate to remove weeds, which often propagates with no-till, and to prepare for seeding. The United Nations Environment Programme (2018) reports that an increasing number of fields employing a conservation agriculture approach in South America, the United States and Europe are treated with the herbicide, despite growing evidence of its potential negative environmental impacts, including alteration and disruption of soil biodiversity as well as the pollution of plots near water bodies. Consequently, where conservation agriculture comes along with an intensive use of glyphosate, a gap in alignment with certain criteria of the ecosystem health pillar is assessed, as it may alter soil biological features. Further, Chinseu et al. (2019) suggest that—despite the active promotion of conservation agriculture by international donors, advisory bodies, governments and non-governmental organizations— conservation agriculture projects are often not adopted by local smallholders who feel the approach fails to consider co-design and the incorporation of local knowledge leads. These concerns are exacerbated by a lack of technical support for implementing conservation agriculture and by a narrow focus on economic benefits that are often not achieved once donor organizations move out.

3.4 Forest landscape restoration

Forest landscape restoration approach is defined as "a planned process that aims to regain ecological functionality and enhance human wellbeing in deforested or degraded landscapes" (International Institute for Sustainable Development, 2002; Global Partnership on Forest and Landscape Restoration, 2024). The approach promotes forest-related management interventions that align well with criteria of the ecosystem health pillar, while also maximizing environmental, cultural, and economic benefits. For example, forest landscape restoration can sustain soil health through reforestation of local tree species and can improve local and regional water availability as a result of the protective effects of tree cover on watersheds (Mansourian and Vallauri, 2014; Page-Dumroese et al., 2021). Forest landscape restoration also aligns with criteria of the food security pillar, as, for example, the integration of agroforestry practices in projects supports local food production and the satisfaction of nutritional needs (Vira et al., 2015; Guuroh et al., 2021; Ickowitz et al., 2022). In addition, forest landscape restoration is said to be a natural climate adaptation pathway with a high mitigation potential, particularly through carbon sequestration, therefore aligning with cross-cutting criteria concerned with climate change mitigation and adaptation (Beatty et al., 2018; Nave et al., 2018; Garrett et al., 2022). Overall, forest landscape restoration shows a high degree of alignment with SLM and LDN criteria, however with some gaps in alignment mainly with respect to the human wellbeing pillar. This stems from the mixed record of forest landscape restoration projects in contributing to the protection of land-user rights and land ownership, gender-responsiveness and the active inclusion of stakeholders, particularly local farmers. While protecting right to land tenure is essential to the approach, it's enforcement in practice is challenged as tenure relations in forest landscapes are nuanced and often unclear (McLain et al., 2017; Mansourian et al., 2020). Regarding the criterion on gender, although forest landscape restoration purports to consider gender issues and to ensure that stakeholder engagement is gender responsive and addresses power imbalances (Besseau et al., 2018; Chazdon et al., 2020; Global Partnership on Forest and Landscape Restoration, 2020; Djenontin et al., 2021), evidence suggests that women, along with other marginalized groups, are often excluded from REDD+ projects intended to enhance carbon capture in forest landscapes (Sarmiento Bartletti and Larson, 2017). Not properly involving certain groups or communities in project implementation further conflicts with respective SLM and LDN criteria, and with the approach's own principle to engage stakeholders and support participatory governance (Sabogal et al., 2015).

3.5 Integrated agriculture

Integrated agriculture refers to agricultural production systems characterized by the operational integration of multiple separate, interconnected enterprises, resulting in synergistic interactions and resource transfers among them (Hendrickson et al., 2008). The most common practical expression of an integrated agriculture approach is an integrated crop-livestock system (ICLS). ICLS is characterized by the operational integration of plants and animals in agriculture (Food and Agriculture Organization, 2010a; Sekaran et al., 2021). ICLS is multi-scalar and can occur within a farm, between farms or at a regional or landscape level. Integrated agriculture was assessed to have a high degree of alignment with SLM and LDN criteria. Given the approach's emphasis on the synergistic and sustainable use of resources to preserve the natural resource base, it most clearly aligns with criteria of the food security as well as the ecosystem health pillar. Integrated agriculture projects implement, for example, integrated soil fertility management, which integrates multiple organic (i.e., mainly from animal sources) and inorganic fertilizers, contributes to food security by ensuring the long-term viability of soils and the long-term productive potential of land resources (Vanlauwe et al., 2010; Adams et al., 2020). Integrated agriculture—which focuses on agricultural systems and farmers as a whole—was also found to align with cross cutting criteria and criteria of the human wellbeing pillar. For example, integrated agriculture was assessed to be economically viable and therefore to enhance livelihoods, as the land management approach is capable of boosting employment and income, for example through dairy-crop collectives, as well as integrated agriculture implementation supporting local livelihoods (Regan et al., 2017; Amede et al., 2023). Still, the assessment revealed few gaps in alignment concerning criteria of the human wellbeing and food security pillars. The gaps reflect the fact that human rights and gender considerations are beyond the scope of most IA projects. Further, it is unclear how the approach improves adequate access to water since consulted experts argue that improving water access generally lies outside the scope of integrated agriculture (Integrated Agriculture Experts, 2023).

3.6 Regenerative agriculture

Regenerative Agriculture Initiative and The Carbon Underground (2017) define the approach as a "holistic land management practice" that aims to improve soil health, nutrient availability and the resilience of crops, while supporting climate change mitigation and adaptation through improved soil carbon sequestration, water retention, and the restoration of degraded soil biodiversity. Regenerative agriculture actively contributes to regenerating ecosystems and their services while addressing social and economic aspects of sustainable food production, with soil conservation as a key entry point (Schreefel et al., 2020). Therefore, the approach aligns well with criteria of the ecosystem health and food security pillars. The approach uses targeted practices, such as no-till or cover crops, to sustain the natural resource base and the land's potential for higher crop yields in the short-term and more stable yields in the long-term. Thus, regenerative agriculture projects support the production of sufficient food of high nutritional quality. Rather than improving food productivity only by increasing yields, regenerative agriculture also improves productive efficiency and stability—although this depends on the local context and may require a significant transition time (i.e., years) to achieve (Newton et al., 2020; Schreefel et al., 2020; Giller et al., 2021; Land Water Management Approaches Experts, 2023a). Considering the human wellbeing pillar, the inclusion of multiple stakeholders in the implementation of regenerative agriculture is described as a key principle of the approach by Giller et al. (2021). How this principle is implemented in practice is not always clear. However, regenerative agriculture is known to actively build on and integrate local and indigenous farming techniques (Sharma et al., 2022a; Wilson et al., 2022). Overall, a high degree of alignment of regenerative agriculture with SLM and LDN criteria is assessed. However, there are also particular cases in which regenerative agriculture did not align with some of these criteria, resulting in gaps in alignment, mainly concerning certain cross-cutting criteria. Although the approach is said to promote the holistic integration of soil and ecosystem health, community wellbeing and agricultural productivity, social and economic considerations are not always included in regenerative agriculture projects. Regenerative agriculture's strong focus on the use of conservation agriculture and agroforestry practices and its focus on soil and ecosystem functioning suggests an imbalance favoring environmental objectives over social and economic ones (Regenerative Agriculture Initiative and The Carbon Underground, 2017; Giller et al., 2021; Kenny and Castilla-Rho, 2022), and may affect the economic viability and social acceptance of the approach. It has to be noted that the assessment of these gaps results from the fact that regenerative agriculture is a relatively new approach and that there are different ways of defining it, causing only limited evidence on how it generates benefits beyond environmental sustainability yet (Newton et al., 2020; Kenny and Castilla-Rho, 2022; Tittonell et al., 2022; Khangura et al., 2023).

3.7 Rewilding

Rewilding is defined as "the process of rebuilding, following major human disturbance, a natural ecosystem by restoring natural processes and the complete or near-complete food web at all trophic levels as a self-sustaining and resilient ecosystem with biota that would have been present had the disturbance not occurred" (Carver et al., 2021, p. 1,888). The rewilding approach was found to show the greatest alignment with SLM criteria related to the ecosystem health pillar and its goals to recover ecological processes and establish self-maintaining natural ecosystems. It has also been found that rewilding significantly contributes to global ecosystem services, such as water management, climate change mitigation, protection against coastal erosion and protection of biodiversity (Svenning, 2020; Harvey et al., 2023; Schmitz and Sylvén, 2023; Hughes et al., 2024). Positive effects on biodiversity and ecosystem services instigated through restoration activities under the approach further contribute to carbon storage and sequestration and stimulate progress on policy targets and institutional goals related to biodiversity loss and climate change, such as the UN Decade on Ecosystem Restoration, as well as CBD's Kunming-Montreal Global Biodiversity Framework (Carver et al., 2021; Hawkins, 2023; Land Water Management Approaches Experts, 2023a). Moreover, rewilding is a direct response to meeting the global objective of creating "ecological integrity," which is one of the founding principles of the 1992 Rio Earth Summit declaration on environment and development, to guide countries toward sustainable development (11th World Wilderness Congress, 2020). Alignment was also found for criteria of the food security and human wellbeing pillars. While food security is not a specified goal of rewilding, the approach can nevertheless improve food productivity if rewilding and agriculture are integrated at a landscape scale (Corson et al., 2022; Fraanje and Garnett, 2022; Mikołajczak et al., 2022; Wang et al., 2023). If this understanding is applied, the enhancement of natural processes and ecological functions can have beneficial influences on land resources utilized for agricultural uses, hence generating alignment with criteria of the food security and human wellbeing pillar, which increases the degree of alignment. Gaps in alignment were found to mainly concern criteria of the human wellbeing pillar. Some case studies from the United Kingdom demonstrate how rewilding projects do not properly involve local communities, neglect land property and land user rights and cause land-holder displacement and therefore a lack of social acceptance of the approach (Wynne-Jones et al., 2018; Jones, 2022; Martin et al., 2023). In contrast, however, numerous examples across the globe show that many existing rewilding projects have a strong human dimension (Land Water Management Approaches Experts, 2023a). These examples include projects where indigenous and communities are actively engaged to link rewilding efforts with sustainable agriculture and grazing management (Bush Heritage Australia, 2024; Enonkishu Conservancy, 2024; Peace Parks Foundation, 2024).

3.8 Synthesis of the alignment assessment

The assessment generated a detailed understanding of how each of the selected land and water management approaches aligns with the defined criteria, therefore how they contribute to SLM and the achievement of LDN, and where gaps exist.

3.8.1 Greatest alignment of land and water management approaches with SLM and LDN

Among the 15 SLM criteria and 20 LDN criteria against which the alignment of the seven approaches was assessed, almost all approaches were found to show the greatest alignment with those criteria relevant to the pillar food security (i.e., criteria for maintaining and enhancing land quality and potential) and all were found to align with LDN and SLM criteria of the ecosystem health pillar. All approaches assessed were found to align with SLM and LDN criteria pertaining to ecosystem health because of their emphasis on minimizing land degradation and on employing practices that improve ecological conditions, which are common goals of many land resources management approaches, methods and tools. Importantly, this alignment suggests most of the selected approaches also contribute to the LDN response hierarchy that seeks to avoid, reduce and reverse land degradation. Five of the approaches directly embrace responses central to LDN, while the remaining two contribute to LDN by reducing land degradation (i.e., integrated agriculture and climate-smart agriculture; see International Tropical Timber Organization, 2020; Jiban et al., 2020; Schreefel et al., 2020; Alvar-Beltrán et al., 2021; Carver et al., 2021; Amede et al., 2023).

Nearly all approaches were found to align with the SLM and LDN cross-cutting criteria on climate change adaptation and the contribution to policy targets. Through their practices, the approaches mostly promote carbon capture and sequestration, which support LDN targets for maintaining and enhancing soil organic carbon as well as similar targets under the United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement. Further, many approaches employ practices that contribute to one or more of the SDGs and to the aim of the UN Decade on Ecosystem Restoration (see Rhodes, 2012; Lipper et al., 2014; Stanturf et al., 2015; Kassam et al., 2019; Sinclair et al., 2019; United Nations Environment Programme, 2021; Schmitz et al., 2023).

3.8.2 Gaps in alignment of land and water management approaches with SLM and LDN

While none of the approaches embrace principles or practices that directly conflict with the criteria of SLM and LDN, some gaps in alignment were identified where the specific objectives and methodologies of the approaches did not address particular environmental, social and economic criteria. This study considered gaps in alignment to occur where approaches were said to be *not* aligned with criteria by one or more sources from literature and by experts consulted for this study and in cases. This allowed the study to identify both unanimously identified gaps and gaps identified by only a few sources as requiring attention to improve alignment.

Gaps in alignment identified mostly relate to specific criteria comprising the human wellbeing pillar of SLM and LDN, as well as certain cross-cutting criteria. The most common gap in alignment concerns the protection of land tenure rights. The results also suggest that several approaches are not set up to address land tenure, or in practice may fail to deliver on this criterion (e.g., climate-smart agriculture, rewilding, or integrated agriculture). In some instances, an approach may suggest it is dedicated to secure land tenure rights in general, but it fails to do so in specific projects. Reasons for this varied in practice, but some projects are situated in locations where tenure is unclear or where existing land use agreements are not accessible (see Mansourian et al., 2020; Jones, 2022; Sharma et al., 2022b).

Other common gaps in alignment relate to the inclusive and representative participation of relevant stakeholders. These gaps mostly reflect a lack of assessment, during the design and implementation of projects based on the approach, of the needs and livelihoods of local communities, smallholders and/or vulnerable groups, such as women, leading to negative impacts on their livelihoods (see Taylor, 2018; Chinseu et al., 2019; Martin et al., 2023). For many approaches, challenges exist in systematically identifying and bringing together all relevant actors and in accommodating individual interests and perspectives, which results in a lack of project focus on participatory design and the involvement of multiple stakeholders. Insufficiently integrating or prioritizing context-specific social and economic needs further commonly results in projects implementing the approaches to not sufficiently integrating and balance different objectives.

Gender responsiveness was identified as fundamental to project design and implementation for nearly all the approaches assessed. Nevertheless, experts consistently cautioned that despite its formal recognition by the approaches, gender responsiveness is not always translated into practice (Agroecology Experts, 2023; Conservation Agriculture Experts, 2023; Regenerative Agriculture Experts, 2023; Rewilding Experts, 2023).

4 Entry points to enhance alignment of land and water management approaches with SLM and LDN

Gaps in alignment with SLM and LDN among many of the selected approaches could be addressed in the following ways: First, identified gaps could be filled by including *supplementary, relevant remedial activities* in the project design and implementation. For example, integrated agriculture may not explicitly address gender responsiveness, but this criterion can be embraced by integrated agriculture projects by embedding gender equality and empowerment efforts within project design, implementation, and monitoring. These efforts may include a well-designed gender assessment that identifies existing structures of gender inequality and actions to overcome it, such as helping women access resources or organizing capacity training specifically for women (Integrated Agriculture Experts, 2023). This would contribute to the gender-responsiveness of integrated agriculture and align the approach more with SLM and LDN criteria. Similarly, projects implementing crop-centered approaches, such as conservation agriculture and climate-smart agriculture, could assess social needs during the project planning phase to determine uncertainty in land tenure, limited access to knowledge, unequal access to water and power imbalances in the food market.

Second, simultaneously *incorporating multiple site-specific but nevertheless complementary land and water management approaches at landscape scale* can also help address the identified gaps in alignment, synergizing their multiple strengths. Combining the practices from different approaches acknowledges that there is no one-size-fits-all approach (Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services, 2018b). Integrating regenerative agriculture practices within rewilding contexts, for example, can ensure the objective to restore natural ecological processes can be achieved while contributing to livelihoods and food security (Fraanje and Garnett, 2022; Mikołajczak et al., 2022). Similarly, embedding climate-smart agriculture in landscapes shared with natural or rewilded ecosystems can promote the adaptation of agriculture to climate change while also promoting nature conservation and the provision of ecosystem services (Harvey et al., 2014; Land Water Management Approaches Experts, 2023b). In dryland ecosystems, rewilding can slow desertification and provide ecosystem services, such as recharged aquifers, cleaner air, and stabilized soils, to nearby farms and communities (Butterfield et al., 2021). Meanwhile, agroecology, water harvesting and water cycle management practices could be adopted by other approaches (e.g., climate-smart agriculture or integrated agriculture) to foster availability and access to water. Such synergies exist between the selected approaches but also with any other approach or practice that addresses gaps in alignment with relevant criteria, such as those related to food security, biodiversity, economic viability and livelihoods. This, in turn, can promote a greater contribution to SLM and to achieving LDN.

Third, some of the gaps identified could be addressed by *more rigorous adherence to the principles* of each approach by project designers and practitioners. While some approaches (e.g., agroecology, forest landscape restoration and rewilding) have defined principles that closely align with SLM and LDN criteria, results show that these are not always translated into practice. Rewilding and forest landscape restoration projects, for example, have been criticized for not being participatory, with cascading impacts on other social aspects and the SLM criteria on integration of indigenous, local and traditional knowledge and on social acceptance of the approaches (Basnett et al., 2017; Oteros-Rozas et al., 2019; Martin et al., 2023). Disregarding an approach's principles can result not only in less effective interventions, but it may also fail to meet the environmental, economic, and social standards demanded under SLM and LDN. Project monitoring and evaluation for these approaches should track whether these principles are observed in each context. Other approaches, such as integrated agriculture and climate-smart agriculture, lack principles that align with social criteria (climate-smart agriculture in particular, has been criticized for not protecting human rights; Sharma and Suppan, 2011; Land Water Management Approaches Experts, 2023b), but this shortcoming can be addressed by adopting appropriate social safeguards when implementing projects.

Finally, *established guidelines* for ensuring better alignment of approaches with SLM and LDN have already been vetted by the international community and can help to address the alignment gaps. These include the *Voluntary Guidelines on the Responsible Governance of Tenure* (Food and Agriculture Organization, 2019) and the *Gender and Land Rights Database* (Food and Agriculture Organization, 2010b). These guidelines have to be actively applied to ensure they contribute to SLM and to achieving LDN. Further, case studies document how projects successfully address gaps in alignment. For example, the Terai Arc project in Nepal (Ministry of

Forests and Soil Conservation, 2015) illustrates a rewilding project that has been designed to be gender-responsive, serving as a model for other rewilding efforts.[1] In some cases, specific assessment tools can help evaluate the performance of an approach with regard to environmental, economic, and social objectives. These tools, such as the Sustainability Assessment of Food and Agriculture Systems (SAFA; Food and Agriculture Organization, 2013), identify benefits and trade-offs for each approach, revealing where changes are needed to align more with corresponding SLM and LDN criteria.

Importantly, the results of the alignment assessments for each approach were found to depend on its context of implementation. While a case study in one geographical context might show that practices of a land and water management approach align with certain SLM and LDN criteria, one in another context might provide evidence that these criteria are not addressed. Thus, the alignment assessment conclusions of this study should not be considered universally applicable. Considering the context when implementing approaches can avoid unintended outcomes that arise when efforts try to better align an approach with certain SLM or LDN criteria. Certain practices that contribute to SLM and LDN in one context may be unsuitable in another and even increase land degradation. None of the approaches provides a one-size-fits-all solution. Instead, the effective application of each approach ultimately depends on high-quality, site-specific spatially explicit data on environmental, economic, and social factors to ensure the evidence-based design and implementation to achieve multiple benefits.

5 Limitations of the study

Importantly, though every effort was made to be comprehensive in the literature review, the authors of this paper recognize that research on the approaches is extensive and involves many more sources and experts than could be incorporated in this study. Further, although efforts were made to ensure gender and geographic balance among the experts consulted, male experts (66%) and those from Europe and North America (60%) comprised the majority of experts. This can result in the limited reflection of perspectives from different geographic regions and different genders. A potential reason for the predominance of experts from Europe and North America could be the exclusive use of English language research in this study. Also, the identification and review of candidate approaches was performed in English language, and thus excluded foreign language references to those approaches in the Google Trends analysis initiating this study. Although it has to be assumed that current mainstream literature is predominantly written in English and thus more results are available in that language, future research should also consider diversity of languages used for land and water management research in order to more comprehensively integrate multiple perspectives on approaches at the global scale. Lastly, the assessed land and water management approaches focus mainly on the management of croplands, forest landscapes and other natural ecosystems and none specifically addresses water management *per se*. However, all of the approaches include the water dimension of land and water management as an integral part of their agriculture and natural ecosystems management practices. For example, water management is addressed through specific practices such as water harvesting in agroecology (Altieri et al., 2015), through enhancement of soil water conservation through mulching and other techniques in conservation agriculture (Mugandani et al., 2021) and through the promotion of water-related ecosystem services during the restoration of natural ecological process required for rewilding and forest landscape restoration projects (Beatty et al., 2018; Carver et al., 2021). Thus, the seven selected approaches can all be considered as management approaches addressing both land and water. Nevertheless, a similar assessment to the one conducted could be performed for approaches with a more specific water management focus to understand how these contribute to minimizing land degradation and to the multiple environmental, social and economic goals relevant to achieving LDN and to contribute to SLM. Likewise, further research could consider approaches that target specific land use systems (e.g., sustainable rangeland management). Lastly, this study does not discuss indicators that could be used to monitor and evaluate the contribution of an approach to certain SLM and LDN criteria during the implementation process. Proposals of such indicators are available. Bouma (2002), for example, elaborate on a land quality indicator for SLM. For LDN, three biophysical indicators to measure progress toward neutrality already exist: land cover, land productivity and soil organic carbon (Orr et al., 2017). The collection of such indicators to concretely measure an approach's alignment with the SLM and LDN criteria during the implementation process could be collected as a follow-up to this research. This could enhance guidance for project design and implementation on how to monitor and evaluate the contribution of an approach to SLM and to achieving LDN.

6 Conclusion

This study investigated how selected land and water management approaches contribute to SLM and the achievement of LDN. It shows that all the approaches align with many SLM and LDN criteria, particularly those on ecosystem health and food security. Gaps in alignment chiefly concern criteria on human wellbeing and cross-cutting socioeconomic criteria that span the pillars of ecosystem health, food security, and human-wellbeing. The gaps can be addressed to improve alignment and the contribution of the selected approaches to SLM and the achievement of LDN through the uptake of supplementary activities in project planning and implementation, synergetic use of different approaches within one project, more rigorous adherence to defined principles, and applying established guidelines. Importantly, the context of implementation influences alignment with SLM and LDN criteria and must be considered when interpreting the findings of this study.

Demonstrating the alignment of selected land and water management approaches with SLM and LDN and by identifying entry points for addressing gaps in alignment can guide practitioners in planning and evaluating land and water

1 Supplementary material 12 provides examples on databases and case study collection for each approach.

management projects that leverage policy and donor support to increase the potential to advance SLM and to achieve LDN.

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

LH: Conceptualization, Data curation, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. YW: Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Visualization, Writing – review & editing. JH: Conceptualization, Data curation, Investigation, Methodology, Writing – original draft, Writing – review & editing. LD: Conceptualization, Data curation, Investigation, Methodology, Visualization, Writing – review & editing. EW: Conceptualization, Data curation, Investigation, Methodology, Visualization, Writing – review & editing. OA: Writing – review & editing. NH: Writing – review & editing. JH: Writing – review & editing. IK: Writing – review & editing. JP: Writing – review & editing. DR: Writing – review & editing. MS: Writing – review & editing. CT: Writing – review & editing. JV: Writing – review & editing. BO: Conceptualization, Funding acquisition, Methodology, Supervision, Writing – review & editing.

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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.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsrma.2024.1423078/full#supplementary-material

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