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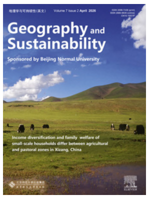

Review Article

Land system science for global environmental change and sustainability: Advances, challenges, and future directions

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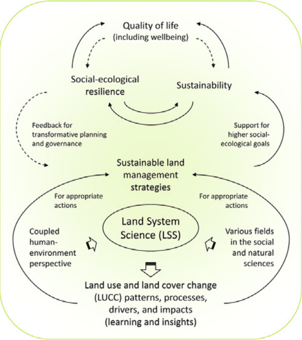
HIGHLIGHTS

- Reviews the evolution of Land System Science (LSS) as a key interdisciplinary field.
- Develops a framework linking LSS to land management and social-ecological goals.
- Explores the contributions of LSS to the Sustainable Development Goals.
- Discusses key challenges and future directions in advancing LSS.

GRAPHICAL ABSTRACT



A conceptual framework illustrating the role of LSS in informing sustainable land management strategies and assessing their impacts on social-ecological goals for transformative planning and governance.

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ABSTRACT

Land System Science (LSS) has evolved as a core interdisciplinary field within human-environment system research, with a particular focus on land use and land cover change (LUCC). This article reviews the emergence of LSS, explores its roles in social-ecological research on global environmental change and sustainability, and discusses its challenges and future directions. We develop a conceptual framework that highlights the role of LSS in informing sustainable land management and assessing its impacts on interrelated social-ecological goals (sustainability, resilience, and quality of life, including wellbeing) for transformative planning and governance. To ensure the continued progress of the field and its ability to address evolving global challenges, LSS needs to better implement a systems-based approach through novel methodological developments, deepen the understanding of LUCC complexities, emphasize strong sustainability, bridge global-local gaps, and enhance the science-policy interface. In addition, while LSS is inherently interdisciplinary, its progress requires further broadening and deepening of collaboration and integration among contributing disciplines.

1. Introduction

The emergence and development of a field of study represent a complex interplay between intellectual inquiry, societal needs, and technological advancements. In its nascent phase, scholars collaboratively identify novel questions or challenges that capture intellectual curiosity, fostering interdisciplinary collaboration reminiscent of Thomas Kuhn's paradigm shifts (Kuhn, 1962). This collective endeavor gives rise to novel conceptual frameworks that define the scope and boundaries of the emerging field (Laudan, 1981). Essentially, this has been the case for land system science (LSS) (Verburg et al., 2013a; Verburg et al., 2015; Turner II et al., 2021), whose emergence was driven by the escalating social-ecological challenges caused by land use and land cover changes (LUCC), alongside advancements in geographic information science, remote sensing, and other related fields. In particular, LSS emerged as a promising interdisciplinary field of study to address the

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growing challenges associated with global environmental change and sustainability.

Since its emergence, LSS has evolved through multiple intellectual and methodological contributions. Foundational work in LSS emphasized the need to understand LUCC as a dynamic process shaped by proximate and underlying drivers, including demographic, economic, technological, and institutional factors (Lambin et al., 2001; Geist and Lambin, 2002). Subsequent work highlighted the conceptual linkages between LUCC, ecosystem services, and human wellbeing (Millennium Ecosystem Assessment, 2005; Crossman et al., 2013; Wu, 2013), building on foundational contributions that established and advanced the concept of ecosystem services (Costanza et al., 1997; Daily, 1997; de Groot et al., 2002). Around the same time, contributions from political ecology perspectives emphasized the importance of power relations, governance, and justice in shaping land systems (Turner II and Robbins, 2008; Brannstrom and Vadjunec, 2013). More recently, studies have underscored the relevance of LSS for sustainability and global frameworks, including the Sustainable Development Goals (SDGs) (Meyfroidt et al., 2022; Zhao et al., 2024), indicating that LSS can inform pathways for integrating environmental, social, and economic objectives.

Earlier reviews and perspectives directly related to LSS have advanced understanding along complementary dimensions: its key challenges and methodological issues (Rindfuss et al., 2004); its role in understanding LUCC, social-ecological dynamics, and sustainability (Turner II et al., 2007); its methodologies for mapping (Lam, 2008) and modeling (National Research Council, 2014) LUCC; its conceptual integration of social-ecological dimensions and sustainability outcomes (Verburg et al., 2015); its framing as an interdisciplinary approach addressing global environmental change and sustainability challenges (Turner II et al., 2021); the key facts about land systems that can help explain the challenges of achieving sustainability in land use (Meyfroidt et al., 2022), and its contributions to the SDGs (Zhao et al., 2024). While these reviews and perspectives have contributed to, and continue to shape, the field, there remains a need to examine how LSS integrates conceptual, empirical, and policy-oriented perspectives to link LUCC dynamics with the broader social-ecological goals (sustainability, resilience, and quality of life, including wellbeing), as well as to explore the emerging challenges and opportunities that may shape its future trajectory.

Addressing these gaps, this paper complements existing reviews and the current science plan of the Global Land Programme (GLP) (Global Land Programme Scientific Steering Committee, 2024) by offering a scholarly synthesis of LSS's emergence, contributions, and evolving role in social-ecological research. The general objective is to provide a comprehensive account of LSS's trajectory and its relevance to contemporary sustainability challenges. More specifically, the paper aims to: (i) trace the historical emergence and intellectual foundations of LSS; (ii) develop a conceptual framework that highlights the role of LSS in linking LUCC dynamics with social-ecological goals, (iii) synthesize the contributions of LSS to social-ecological research and its connections to the SDGs, and (iv) identify and critically discuss the major challenges and opportunities shaping the field's future trajectory.

2. Review approach

This paper adopts a narrative review approach (Sukhera, 2022). This approach synthesizes published literature on a focused topic, employing a flexible, non-quantitative method to construct a narrative of the field's development and current understanding. Examples of narrative reviews are available (Foley et al., 2005; Wu, 2019).

In particular, the literature was selected strategically to align with the manuscript's objectives, focusing on foundational, conceptual, empirical, and policy-oriented contributions that illustrate the emergence, evolution, and current role of LSS in addressing sustainability challenges. Selection criteria were guided by relevance to the key themes of the paper, including LUCC and its drivers and impacts, ecosystem services, human wellbeing, sustainability, and methods and approaches for LUCC monitoring and modeling. While this approach does not aim to be exhaustive, it allows for a focused synthesis that integrates conceptual, methodological, and empirical perspectives, highlighting major advances in the field, together with its challenges and future directions (for its limitations, see Section 6).

3. Emergence of LSS

Like landscape ecology (Troll, 1939; Wu et al., 2024), LSS is said to have developed from *Landschaft,* a German geographic tradition in which the landscape is regarded as the totality of things within a territory, eventually evolving to encompass the significance of human-environment relationships (Turner II and Robbins, 2008) (Fig. 1). The idea of LSS first emerged in the late 1980s, initially articulated as a 'total earth system' study 'in global change' (p. 531) (Kates, 1987) (see also (Brannstrom and Vadjunec, 2013), p. 3). It later evolved into the Land Use and Land Cover Change project (1994–2005), developed within the framework of the International Geosphere-Biosphere Programme (IGBP), which was later joined by the International Human Dimensions Program on Global Environmental Change (IHDP) (Brannstrom and Vadjunec, 2013; Verburg et al., 2013a; Verburg et al., 2015). This project aimed to enhance global environmental change research by uniting natural and social sciences to investigate the roles of individuals and societies in both contributing and adapting to environmental changes (Turner II et al., 1995; Gutman et al., 2004; Brannstrom and Vadjunec, 2013).

During this time, LUCC research matured gradually, becoming more integrative and focused on both the drivers and impacts of land change, in collaboration with other related fields (Verburg et al., 2015). This subsequently led to the emergence of Land Change Science (LCS) (Gutman et al., 2004; Rindfuss et al., 2004; Turner II et al., 2007) as a distinct, interdisciplinary research field that engages scientists across the social, economic, geographical, and natural sciences (Verburg et al., 2013a; Verburg et al., 2015). The scientific literature indicates that the term LCS first appeared in 2002 (Fig. 1), in a 2001 conference paper by Turner II (2002). Recognizing the growing importance of land use and land cover as a coupled human-environment system, LCS has ultimately emerged as a fundamental element in global environmental change and sustainability research (Rindfuss et al., 2004; Turner II et al., 2007).

LCS is defined as an "interdisciplinary field [that] seeks to understand the dynamics of land cover and land use as a coupled human-environment system to address theory, concepts, models, and applications relevant to environmental and societal problems, including the intersection of the two" … It seeks to improve: (i) observation and monitoring of land changes underway throughout the world, (ii) understanding of these changes as a coupled human–environment system, (iii) spatially explicit modeling of land change, and (iv) assessments of system outcomes, such as vulnerability, resilience, or sustainability" (p. 20666) (Turner II et al., 2007).

The progress of LCS largely aligns with the Global Land Project (2006–2015), which succeeded the LUCC project (Fig. 1). In 2016, the Global Land Project was renamed into the Global Land Programme (GLP). The GLP is currently part of the Future Earth, a global initiative to strengthen the interface between policy and science. Launched at the 2012 UN Conference on Sustainable Development (Rio+20), Future Earth is "a network of scientists, researchers, and innovators" that focuses on systems approaches to improving "understanding of complex Earth systems and human dynamics" and promoting "evidence-based policies and strategies for sustainable development" (https://futureearth.org).

In the latter half of the 2000s, the term LSS began appearing more frequently in the scientific literature (Reenberg, 2006, 2009; Turner II et al., 2007; Turner II, 2009), marking the transition from LCS to LSS. According to the scientific literature, the term LSS first appeared in 2006

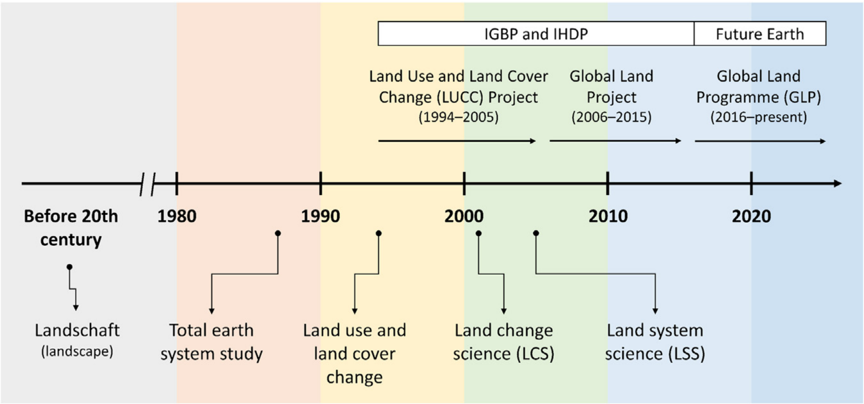

Fig. 1. Overview of the emergence and development of LSS. This approximate timeline was created based on various sources (Turner II and Robbins, 2008; Brannstrom and Vadjunec, 2013; Verburg et al., 2015), including the Global Land Programme (https://glp.earth).

(Fig. 1), in the introductory paper of a Special Issue by Reenberg (2006), stemming from a workshop organized by the Danish Network for Land System Science (LaSyS) in October 2005. In general, the emergence and progress of LSS have been driven by environmental and socioeconomic imperatives and supported by technological and methodological advancements.

At its core, LSS is an interdisciplinary research field that investigates the complex interactions between human societies and land systems, focusing on LUCC as a key process shaping the Earth system (Verburg et al., 2013a; Verburg et al., 2015; Turner II et al., 2021; Meyfroidt et al., 2022). It (i) integrates biophysical, social, economic, and institutional perspectives to analyze the drivers, dynamics, and consequences of land system changes across multiple spatial and temporal scales, and (ii) contributes to understanding and addressing global environmental challenges by linking local land-use realities with broader sustainability goals. The knowledge generated through this integrative analysis is essential for informing sustainable land management, policy development, and governance (Verburg et al., 2013a; Verburg et al., 2015; Turner II et al., 2021; Meyfroidt et al., 2022). Here, land systems are coupled human-environment systems shaped by dynamic interactions among biophysical and socioeconomic processes, which drive LUCC patterns and trajectories across spatial and temporal scales.

4. Role of LSS in social-ecological research

4.1. LSS in a broader context

The pursuit of the three interconnected social-ecological goals, namely sustainability, social-ecological resilience, and quality of life, including wellbeing (Fig. 2), has become essential for human survival, development, and adaptation to environmental and socioeconomic changes (Estoque and Wu, 2024). Critically assessing the dynamic interplay between these goals, along with the factors influencing them, can promote transformative governance and planning. Understanding this multifaceted relationship is essential for empowering planners and decision-makers to navigate the complexities of our rapidly changing world and address the challenges posed by interrelated social and environmental changes (Estoque and Wu, 2024).

In the nexus of social-ecological goals (Fig. 2), sustainability focuses on land management strategies that meet current needs without compromising the ability of future generations to meet their own, integrating environmental integrity, economic prosperity, and social equity (WCED, 1987). Social-ecological resilience encompasses the capacity to adapt or transform in response to unexpected changes while supporting quality of life (Folke et al., 2016). Here, quality of life includes wellbeing and refers to a more comprehensive view of an individual's or a community's overall life experience, encompassing not just mental, emotional and physical states, sense of happiness, life satisfaction, and fulfillment (wellbeing), but also factors like social relationships, economic stability, and environmental conditions (Costanza et al., 2007; Estoque et al., 2019a).

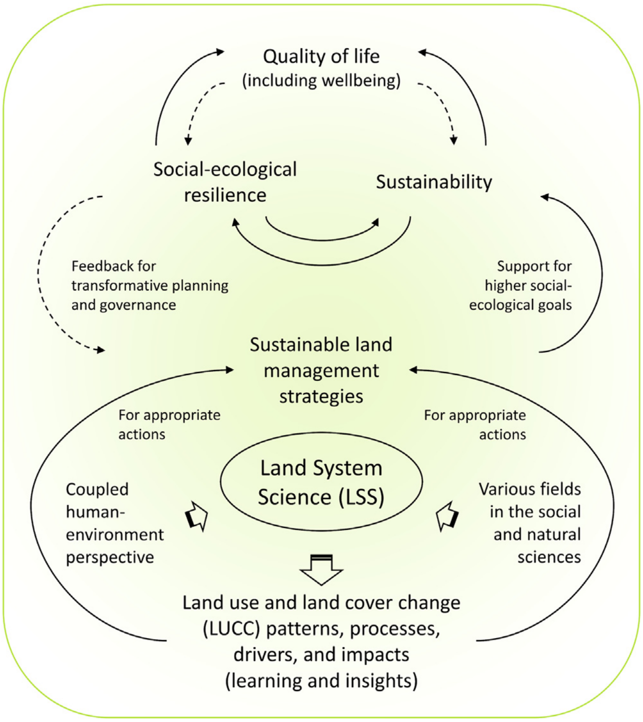

Fig. 2. **A conceptual framework**. The framework illustrates the role of LSS in informing sustainable land management strategies and assessing their impacts on social-ecological goals for transformative planning and governance. The solid lines depict direct influences or inputs, whereas the dashed lines depict feedback. The upper part of the diagram is based from the resilience–sustainability–quality of life nexus (Estoque and Wu, 2024).

Building on this, the framework presented in Fig. 2 integrates insights from resilience theory, sustainability science, and land system literature, reflecting how LSS informs sustainable land management under dynamic feedback conditions. In this framework, land use is fundamental to addressing sustainability challenges, including biodiversity conservation, climate change mitigation and adaptation, health, and food, water and energy security (Meyfroidt et al., 2022; IPBES, 2024). Sustainable land management strategies, such as land use zoning, forest restoration, sustainable agriculture, and sustainable urban development, are essential for achieving the above-mentioned social-ecological goals. LSS plays a crucial role in informing these strategies (Fig. 2). In particular, by focusing on the coupled human-environment system, LSS enables interdisciplinary researchers to identify patterns and processes (such as deforestation, agricultural expansion, and urbanization), drivers (including biophysical and socioeconomic factors), and impacts (including alterations in ecosystem services and biodiversity loss) of LUCC.

The interplay between LSS and social-ecological goals is underscored by a feedback loop, where the outcomes of these goals provide valuable insights for transformative planning and governance aimed at sustainable land management strategies (Fig. 2). In this context, outcomes or impacts also serve as drivers of change. Such insights are critical for informing future scientific inquiries and policy adjustments. To illustrate, alongside the ongoing loss of global tropical forest cover (Vancutsem et al., 2021; Estoque et al., 2022), rapid urbanization in the Global South (Randolph and Storper, 2023), and global forest restoration effort (Chazdon and Brancalion, 2019), the '30 by 30' goal of the Convention on Biological Diversity is shaping the global natural landscape. The Kunming-Montreal Global Biodiversity Framework outlines a suite of targets to conserve biodiversity (www.cbd.int/gbf), acknowledging its multifaceted nature (Díaz et al., 2019). Among these targets, the '30 by 30' goal aims to protect 30% of terrestrial and marine areas by 2030, forming part of a broader, integrated approach that addresses multiple facets of biodiversity. LSS can significantly enhance the implementation of this initiative by assessing the socio-ecological feedbacks and real-world impacts of newly designated protected areas, thereby informing necessary scientific inquiries and policy adjustments. Examples of such feedbacks include critiques on the consequences for vulnerable communities (Schleicher et al., 2019; Venier-Cambron et al., 2024). The socio-ecological systems approach of LSS would aim at the co-design of implementation, accounting for biodiversity benefits and social systems dependent on local land resources.

Such assessments are particularly vital for addressing challenges that emerge when conservation efforts prioritize easily quantifiable targets, such as the percentage of surface area, over equally important, yet less tangible, dimensions of conservation. These include justice, human rights, community inclusion, equitable management, balancing the focus between how much to conserve and how to conserve, and strengthening the protection of existing protected areas (G.D. Li et al., 2024; Oliva and García Frapolli, 2024). By examining these broader dimensions, LSS offers critical insights into the effectiveness of conservation efforts and their alignment with overarching social-ecological goals (Oliva and García Frapolli, 2024; Venier-Cambron et al., 2024). However, while LSS plays an important role in generating knowledge to inform sustainable land management strategies across scales, its actual influence on policy and planning outcomes remains contingent on institutional uptake and context-specific application (more on this in Section 5.4).

The framework presented (Fig. 2) is intended as a heuristic synthesis of key relationships rather than a fully operationalized model. By emphasizing the cyclical and iterative feedbacks between LSS and social-ecological goals, the framework reflects a dynamic environment in which knowledge evolves in response to emerging challenges and conditions. In doing so, it highlights how transformative governance and planning can ensure that land management strategies remain both effective and responsive to societal and ecological needs.

4.2. Connections between LSS and the SDGs

LSS plays a crucial role in the generation and validation of knowledge that underpins efforts to achieve the SDGs. As LUCC lies at the core of LSS, effectively addressing LUCC is key to unlocking the full potential of LSS in advancing sustainability. However, although LUCC is a major driver, its influence on the SDGs is not uniform or straightforward, as it manifests through different pathways, with impacts often cascading through interconnected systems. Conceptually, LUCC can affect the SDGs via three distinct pathways: direct, semi-direct, and indirect (Fig. 3).

Fig. 3. Pathways linking LUCC to the SDGs. This diagram illustrates the three main pathways—direct, semi-direct, and indirect—through which LUCC influences the SDGs. The direct pathway captures immediate social and biophysical effects, the semi-direct pathway highlights socio-ecological and economic interactions, and the indirect pathway reflects long-term systemic and governance-related impacts. *Note*: The classification of the SDGs into these pathways is intended as a heuristic guide rather than a rigid categorization. Because each SDG includes multiple targets and indicators, their links to LUCC may vary in strength and immediacy. The categories should be interpreted as indicative framings to support discussion, not as definitive assignments. Credit for the SDG logos: www.logos.aiesec.org/sdgs.

The direct pathway refers to situations where LUCC exerts an immediate and tangible influence on the core targets or indicators of an SDG, typically through processes such as deforestation, land degradation, or land conversion. The semi-direct pathway describes situations where LUCC influences SDGs through interconnected socio-ecological systems, typically mediated by economic activities, institutional arrangements, or biophysical feedbacks such as livelihood shifts and pollution dynamics. The indirect pathway captures how LUCC influences SDGs through long-term, systemic, or governance-related mechanisms, including effects on social equity, education, conflict, or global cooperation, which may not be immediately visible but can have far-reaching consequences. It is important to note, however, that this conceptual classification is not absolute, as each SDG encompasses a broad range of targets and indicators that vary in their sensitivity to LUCC. For example, while the 'water' dimension of SDG 6 is closely linked to LUCC (Fig. 3), its 'sanitation' targets are less directly affected; similarly, although SDG 14 is categorized under indirect impacts, specific targets such as marine pollution from terrestrial runoff could be considered more direct. Our aim is not to provide a definitive mapping but to propose a heuristic framework that highlights typical pathways of influence.

With this classification and its caveats in mind, the SDGs most affected through the direct pathway include SDG 2 (Zero Hunger), SDG 6 (Clean Water and Sanitation), SDG 11 (Sustainable Cities and Communities), SDG 13 (Climate Action), and SDG 15 (Life on Land) (Fig. 3). For example, LUCC is a key contributor to anthropogenic GHG emissions (SDG 13) via deforestation and land degradation (IPCC, 2019, 2022a), while also offering mitigation opportunities through forest conservation and reforestation (Chazdon and Brancalion, 2019; Dinerstein et al., 2019). It undermines biodiversity, ecosystem integrity, and land productivity (IPBES, 2019, 2024) (SDG 15), and directly affects the availability and suitability of land for agriculture, thereby influencing food security (Verburg et al., 2013b; IPBES, 2024) (SDG 2). LUCC also alters water availability and quality (SDG 6) through changes in runoff, infiltration, and pollution (IPBES, 2024; Shadmehri Toosi et al., 2025), and reshapes the spatial structure of cities and affects urban sustainability (Seto et al., 2012; Estoque et al., 2021) (SDG 11).

SDGs primarily affected through the semi-direct pathway include SDG 1 (No Poverty), SDG 3 (Good Health and Well-being), SDG 7 (Affordable and Clean Energy), SDG 8 (Decent Work and Economic Growth), and SDG 12 (Responsible Consumption and Production) (Fig. 3). For instance, LUCC and access to land can either exacerbate or alleviate poverty (SDG 1), depending on how costs and benefits are distributed (Fedele et al., 2021; IPBES, 2024). Access to land and rights to land-based resources are an important determinant of household well-being, and restrictions in access can exacerbate poverty and limit economic opportunities (Fedele et al., 2021). Human health (SDG 3) is influenced by LUCC (IPBES, 2024) through its effects on air (Wong and Geddes, 2021) and water quality (Locke, 2024), the spread of vector-borne diseases (Ferraguti et al., 2023), and vulnerability to natural hazards (Agarwal et al., 2023). Land is also a critical resource in energy transitions (SDG 7), particularly for siting renewable energy infrastructure and bioenergy production, which can intensify land competition (Meyfroidt et al., 2022; Vera et al., 2022). LUCC affects employment and income opportunities in land-based sectors such as agriculture, forestry, and ecotourism (Nahuelhual et al., 2014; Appelt et al., 2022) (SDG 8) and reflects broader patterns in the sustainability of production and consumption systems (SDG 12), especially within global supply chains (Meyfroidt et al., 2010; Lambin et al., 2018).

SDGs primarily impacted through the indirect pathway include SDG 4 (Quality Education), SDG 5 (Gender Equality), SDG 9 (Industry, Innovation, and Infrastructure), SDG 10 (Reduced Inequalities), SDG 14 (Life Below Water), SDG 16 (Peace, Justice, and Strong Institutions), and SDG 17 (Partnerships for the Goals) (Fig. 3). For example, education (SDG 4) may be disrupted when LUCC leads to land loss or displacement, reducing household investment in schooling and negatively affecting student performance (Hua and Li, 2023). LUCC, such as the expansion of commercial agriculture, can deepen gender inequalities (SDG 5) by reducing women's access to land and diminishing their role in land management and decision-making (Chrisendo et al., 2020). LUCC in peri-urban areas can indirectly influence land demand and urban expansion patterns, thereby shaping the planning, provision, and distribution of infrastructure (SDG 9) (Campos et al., 2018). Inequalities (SDG 10) are deepened when LUCC disproportionately affects Indigenous peoples and other marginalized groups (Schleicher et al., 2019). Marine ecosystems (SDG 14) are indirectly influenced by LUCC through long-term alterations in watershed management, coastal land-use policies, and cumulative environmental pressures that affect their resilience and productivity (Sakamaki et al., 2022). Moreover, weak institutions, insecure land tenure, and overlapping land rights are frequently associated with land-use conflicts, which often involve contested LUCC and can affect governance outcomes (SDG 16) (de Jong et al., 2021). Addressing these challenges requires international cooperation and multi-stakeholder governance mechanisms (SDG 17) that support more equitable and sustainable land systems (Verburg et al., 2015; Meyfroidt et al., 2022).

5. Challenges and future directions

The ten facts about land systems (Meyfroidt et al., 2022) provide foundational insights that should guide future research in LSS, offering core principles for scientists, policymakers, and practitioners to address challenges in sustainable land management. Building on these facts and considering the interactions between LSS and social-ecological goals (Fig. 2), we identify five key challenges and directions for advancing LSS: (1) reinforcing the systems lens in LSS, (2) decoding the web of LUCC, (3) embedding strong sustainability in LSS, (4) bridging global-local gaps and enhancing the science-policy interface, and (5) advancing LSS through cross-disciplinary collaboration. These challenges and directions highlight pressing and often underexplored challenges, aiming to stimulate innovative research and support the operationalization of sustainability principles across diverse land system contexts.

5.1. Reinforcing the systems lens in LSS

LSS was initially focused on the drivers of land change and their social-ecological impacts (i.e., LCS), but recent developments have increasingly emphasized land management, governance, and sustainability solutions in a global context (Verburg et al., 2013a; Meyfroidt et al., 2022). Accordingly, the transition from LCS to LSS (Fig. 1) reflects the imperative to adopt an integrated socio-ecological perspective that captures the interplay between drivers and impacts, the interactions between social and ecological systems, and the telecoupling dynamics across areas (Verburg et al., 2013a; Verburg et al., 2015). However, one could argue that this transition reflects a shift in emphasis, from 'change' to 'system,' both of which are already integral to the field. Moreover, recent work appears to place greater emphasis on governance and political aspects of land systems, with relatively less focus on the physical components critical to their functioning.

Nevertheless, the systems-based approach recognizes that LUCC is influenced by a complex interplay of ecological, social, economic, and political factors (Verburg et al., 2013a; Verburg et al., 2015; Turner II et al., 2021; Meyfroidt et al., 2022). Over the past decades, the dominance of neo-liberal economic systems has driven continued resource extraction and technological developments that have enabled more intensive use of land, contributing to widespread cropland expansion, urbanization, and deforestation. Yet intensification of land management practices, particularly in arable farming (Pellegrini and Fernández, 2018), has in recent decades contributed more to increases in food production than the expansion of agricultural land (Ritchie, 2022). While such intensification can enhance food supply, it often entails significant negative environmental and socioeconomic consequences (Rasmussen et al., 2018). These subtler changes are more difficult to capture and, as a result, have historically received far less attention than more conspicuous land cover conversions; a systems-based approach can potentially help reveal their complexity.

Building on this recognition of complexity, it is notable that despite numerous global initiatives in recent decades, including the Millennium Development Goals, the Millennium Ecosystem Assessment, the IPCC assessments, the SDGs, the Paris Agreement, and forest conservation and restoration pledges, the issue of tropical deforestation (Gómez-Pompa et al., 1972; Shukla et al., 1990) has persisted and remains inadequately addressed (Vancutsem et al., 2021; Lambin and Furumo, 2023; Smith et al., 2023; Pan et al., 2024). This underscores a persistent challenge of aligning global scientific insights with local governance realities, as further elaborated in Section 5.4. It also reflects a resilient system of tropical deforestation that resists meaningful change and perpetuates high rates of forest loss. The enduring nature of this problem points to deep-rooted structures in socioeconomic systems that sustain it. A systems perspective, particularly through LSS, is therefore crucial for effectively diagnosing the underlying drivers of tropical deforestation. However, even within LSS, fully integrating governance, social, and biophysical factors to capture the resilience of tropical deforestation remains a major challenge.

To provide meaningful insights into the structural dynamics of tropical deforestation, this systems-based approach must engage with deeper societal drivers. These include, for example, behavioral change, power dynamics, market concentration, and even capitalism itself, issues often examined in political ecology and land governance research but not yet fully integrated into the LSS framework. These drivers are illustrative rather than exhaustive and reflect systemic dimensions increasingly emphasized in recent literature. For instance, while preliminary efforts have examined the actors and power dynamics in agri-food networks (Williams et al., 2023, 2025), much remains to be done. Confronting such critical issues is essential for addressing vested interests and institutional failures, such as mismanagement and corruption (Carr et al., 2005; Morpurgo et al., 2023), that underpin unsustainable land use practices. Linking this deeper understanding with the direct drivers and monitoring of LUCC will further enhance a systems-based approach.

5.2. Decoding the web of LUCC

Inherent to the issue about ‘system’, another critical challenge and direction for future research in LSS lies in unraveling the complex processes driving LUCC. This section highlights two complex processes that drive LUCC: the links between land use displacement and trade (both global and regional/local), and the dynamics between urban and rural areas. While existing studies offer valuable insights (Meyfroidt et al., 2010; Pendrill et al., 2019; van Vliet, 2019; Randolph and Storper, 2023), further research is essential to deepen our understanding of these interactions and their implications for sustainable land management.

Land use displacement refers to the shifting of land use activities, such as agriculture or deforestation, from one area to another, often due to restrictions or conservation measures in the original location (Meyfroidt et al., 2010; Weinzettel et al., 2013). At the global level, land use displacement is largely driven by international market demands for commodities like soy, palm oil, or beef. Hence, these global markets can prompt countries to clear forests or convert natural landscapes into farmland to meet export needs. Global trade dynamics often lead to large-scale LUCC, contributing to deforestation, biodiversity loss, and GHG emissions. Forest conservation policies in temperate regions, coupled with local economic conditions such as high prices of timber and related products, can influence international demand for tropical timber and other tropical forest products, resulting in forest loss being displaced to developing countries in the tropics (Meyfroidt et al., 2010; Pendrill et al., 2019; Estoque et al., 2022). This forest loss displacement has important implications, as forest habitat loss in the tropics cannot be compensated ecologically by forest habitat gains in temperate regions (Pereira et al., 2010; Estoque et al., 2022). In other words, the interconnectedness of global supply chains means that LUCC in one part of the world can have far-reaching social-ecological consequences in other places (Meyfroidt et al., 2010; Leijten et al., 2023).

At a regional or local level, land use displacement occurs due to shifts in market dynamics, policy changes, or local governance decisions. Regional trade patterns, domestic market demands, local policy changes, infrastructure development, and the growth of regional markets can drive communities to alter land use practices, for example, transitioning from forested areas to agricultural or urbanized land (Estoque and Murayama, 2016; Appelt et al., 2022). These LUCC often disrupt local livelihoods, particularly in rural and indigenous communities, affecting their cultural landscapes and social fabric (Chrisendo et al., 2020; Appelt et al., 2022). Such LUCC can also result in environmental degradation, such as the loss and deterioration of ecosystem services (Estoque and Murayama, 2016; Hasan et al., 2020).

Many studies have examined land use displacement and its connections to global and local trades. For example, land use displacement has been studied through forest transition, focusing on how deforestation pressures shift to other countries via timber imports and trade using regression techniques (Meyfroidt and Lambin, 2009; Meyfroidt et al., 2010). In another study, spatial and economic flows of land-based resources driven by affluence were traced using global datasets to show how consumption in affluent areas shifts land use to less affluent regions (Weinzettel et al., 2013). Additionally, a land-balance model, trade model, crop attribution model, and deforestation footprint analysis were used to track forest-risk commodity flows, revealing how deforestation driven by consumption in one area shifts to other regions (Pendrill et al., 2019). Another study combined deforestation footprint analysis, input-output modeling, trade flow analysis, and spatial mapping techniques to link nations’ consumption to deforestation in tropical regions, emphasizing how global demand increasingly threatens tropical forest ecosystems (Hoang and Kanemoto, 2021). Several studies have also focused on supply chains (Garrett et al., 2013; Lambin et al., 2018; zu Ermgassen et al., 2020), including the Trase initiative (https://trase.earth).

However, the issue of land-use displacement at both global and local levels remains insufficiently addressed. LUCCs are inherently complex and span multiple scales, making it difficult to capture their drivers, trajectories, and feedbacks comprehensively. Furthermore, scientific results are often not communicated in accessible or actionable formats, creating a gap between knowledge and policy application (more on this in Section 5.4). A recent review also highlights persistent gaps in land-use spillover research, in which land-use spillover is defined as unintended land-use changes in one area resulting from policy interventions or decisions made elsewhere, including inconsistent definitions and measurement methods, weak integration into policy frameworks, insufficient multi-scale analysis, and limited geographic and sectoral coverage (Ramírez-Mejía et al., 2025). Hence, a crucial avenue for future research is to leverage LSS to deepen understanding of land-use displacement, including spillover effects, to better inform sustainable land management strategies.

Urban-rural relationships also create complex LUCC dynamics through resource flows, population movement, and economic activities. Urban areas depend on rural regions for essential resources like food, raw materials, and land for expansion (Gebre and Gebremedhin, 2019; Estoque et al., 2021). This demand can lead to LUCC in rural areas, such as deforestation, agricultural land expansion, farmland conversion or infrastructure development. While urban growth brings benefits like improved infrastructure, education, and market access, it also places pressure on rural ecosystems and can lead to loss of natural area (Estoque and Murayama, 2016; van Vliet, 2019) and drive biodiversity loss and land degradation (Seto et al., 2012; Estoque et al., 2021), erosion of cultural traditions and local ecological knowledge (Rangel et al., 2024), and have large ecological footprints (Wackernagel et al., 2006; Wu, 2010). Rural areas may also experience depopulation as people migrate to cities in search of better opportunities (Estoque et al., 2019b; Santos and Fernández Fernández, 2023), further reshaping local economies and cultures.

Addressing these interlinkages between urban and rural areas, along with governance mechanisms to mitigate their impacts (Gebre and Gebremedhin, 2019; Ros-Tonen et al., 2021; Huang et al., 2024), is crucial for designing effective, sustainable land management strategies that promote balanced development and enhance social-ecological resilience. Furthermore, land policies are often site-specific due to geographic, cultural, and socio-political factors, and may not be directly transferable to other locations (Ostrom, 2011; Ros-Tonen et al., 2021). This reinforces the importance of linking global knowledge with local conditions and realities (see also section 5.4) to design land use policies and land management strategies that are responsive to specific geographies, cultures, and socio-political realities (Verburg et al., 2013a; Sievers et al., 2024).

Up to now, urban and rural dynamics have often been investigated by different research groups, focusing mostly on their respective domain of interest. However, in many cases, we are talking about a gradient between urban and rural land systems that cannot be separated. In this regard, LSS can play a vital role in analyzing urban-rural dynamics and their effects. For example, by examining resource flows, migration patterns, and socioeconomic activities between urban and rural areas, LSS can help reveal the socio-ecological impacts of urbanization (Seto et al., 2012; Estoque and Murayama, 2016), including farmland loss, rural depopulation, and ecosystem degradation. It can also help identify opportunities to enhance rural infrastructure, improve market access, and support sustainable urban expansion. By addressing these dynamics holistically, LSS, through new forms of land use planning such as land system architecture (Turner II, 2016; Frazier et al., 2019) and geodesign (Goodchild, 2010; Huang et al., 2024), for example, can potentially enable the formulation of policies that balance urban and rural needs, protect rural environments, and foster sustainable development and enhance resilience and wellbeing across interconnected landscapes.

5.3. Embedding strong sustainability in LSS

Weak sustainability assumes that human-made capital can substitute for natural capital, whereas strong sustainability recognizes that many essential aspects of nature and its services (i.e., the critical natural capital) are irreplaceable and must be preserved (Daly, 1995; Ekins et al., 2003; Wu, 2013). Consequently, weak sustainability provides an attractive pathway for policy makers as it does not require transformative change in underlying structures and behaviors. However, weak sustainability is not viable in the long run (Daly, 1995). Strong sustainability requires a deep understanding of the relationship between biodiversity, ecosystems, and human wellbeing under global environmental change. LSS is, therefore, key to advancing from weak to strong sustainability. Focusing more on strong sustainability entails maintaining irreplaceable critical natural capital, which requires respecting biophysical limits and protecting biodiversity and ecosystem integrity in dynamic landscapes constantly altered by human activities.

Recent advancements in strong sustainability have focused on embedding environmental limits within policy frameworks and decision-making processes. A key development has been the conceptualization of planetary boundaries (Rockström et al., 2009, 2024) and the more recent safe and just Earth-system boundaries (Rockström et al., 2023; Gupta et al., 2024), which represent, respectively, primarily biophysical limits to keep Earth stable and an integration of planetary boundaries with justice considerations to aim for a safe and just future for both people and planet. Environmental accounting practices are also gaining momentum, aiming to enable governments and corporations to track the depletion of natural capital (Sundarasen et al., 2024). However, land systems are often depicted by forest area, net primary productivity, and other broad-scale metrics of land condition; hence, a more comprehensive representation of the complexity and functioning of land systems in a socio-ecological context is needed. At regional and urban scales, landscape sustainability science (also abbreviated as LSS) has emerged as a strong sustainability approach for linking landscape pattern, biodiversity, ecosystem function, ecosystem services, and human wellbeing, while closing the loop through landscape planning and governance (Wu, 2013, 2021; Opdam et al., 2018; Fang et al., 2024).

The SDGs are important initiatives that contribute to strong sustainability by promoting sustainable land management, biodiversity conservation, and guiding climate action for mitigation and adaptation. The resurgence of nexus thinking is another important development in the field, ensuring that land system policies consider cross-sectoral synergies and trade-offs, creating more holistic solutions for long-term sustainability (Estoque, 2023; IPBES, 2024). Achieving strong sustainability through LSS requires an integrated approach such as this one, but one that explicitly encompasses ecological limits, governance systems, and human values. One critical implication of this perspective is the need to better understand how local places and regions can contribute to keeping the world system within planetary or safe and just boundaries and how local actions add up to global sustainability (Rockström et al., 2009, 2023, 2024; Gupta et al., 2024), or how global boundaries scale back to local and regional commitments (Dearing et al., 2014; McLaughlin, 2018; Bai et al., 2024).

Another key focus is considering land as a commons, challenging the dominant private ownership model and emphasizing community-driven land management (Creutzig, 2017). Within LSS, this necessitates the development of models that treat land as a shared resource, promoting cooperative stewardship and equitable governance frameworks. Equally important is understanding reciprocal contributions between people and nature, which strengthen positive feedback loops that enhance ecosystem integrity and human wellbeing (Ojeda et al., 2022). This perspective extends beyond what nature provides to people, emphasizing what people can contribute to nature, thereby supporting transformation pathways that recognize humans as integral to ecological systems and aligning with the concept of social-ecological systems (Ostrom, 2009).

Additionally, examining the impacts of digital economy (Liu et al., 2024), such as land changes, energy demands, pollution and biodiversity loss, can help incorporate indirect consequences of technological advancements into sustainability efforts. Similarly, further integrating cultural values and human behavior into land system models can foster transformative governance approaches that address not only empirical but also ethical and ontological questions associated with sustainability (Olausson, 2024). Cultural values, particularly those embedded in indigenous and local knowledge systems, alongside human behaviors such as a deep sense of care (Olausson, 2024), can provide alternative models to economic-centric governance, reinforcing pathways toward strong sustainability. Foresight of this kind has to go beyond exploring large-scale policy options and consider more transformative scenarios. Current foresight processes are said to suffer from a continuity bias (Raskin and Swart, 2020; Rothman et al., 2023), which tends to overlook not only potential discontinuities but also transformative changes, such as shifts in land governance arrangements, that could contribute to achieving strong sustainability.

Overall, the transition from weak to strong sustainability requires a paradigm shift in how we perceive natural resources and ecosystems. Advancing strong sustainability in LSS entails integrating ecological and social limits, governance systems, and human values, while adopting strategies that account for environmental, social, and economic dynamics. Through such an integrated approach, as emphasized by the safe and just Earth-system boundaries framework (Rockström et al., 2023; Gupta et al., 2024), we can better support the preservation of irreplaceable natural systems and the pursuit of long-term sustainability.

5.4. Bridging global-local gaps and enhancing the science-policy interface

A persistent and increasingly critical challenge in LSS lies in the disconnect between global-scale knowledge production and the local-scale contexts where land-use decisions are most often made. While LSS has advanced in developing spatially explicit models (Mas et al., 2014; National Research Council, 2014; Verburg et al., 2019), identifying land change drivers (Lambin et al., 2001; Meyfroidt et al., 2022), and producing globally relevant scenarios (Kubiszewski et al., 2017; Popp et al., 2017), more efforts are needed to ensure that these outputs effectively inform meaningful, context-sensitive local policies or practices. Progress has been made in several areas, including downscaling strategies that translate broad insights into local narratives and generate spatial data at finer resolutions (Verburg et al., 2006; Kubiszewski et al., 2017; Estoque et al., 2019c), participatory scenario modeling and co-design frameworks that involve stakeholders in envisioning future land-use trajectories (Suchá et al., 2022; Neuhoff et al., 2023), including modeling that consider spatial planning and policies (Liang et al., 2018; Domingo et al., 2021), and the integration of land use and spatial data with institutional and cultural contexts (Siqueira-Gay et al., 2019; Ros-Tonen et al., 2021).

Despite these advances, persistent challenges remain in addressing scale-dependent patterns and processes, institutional frameworks, and political priorities (Turner II and Robbins, 2008; Verburg et al., 2013a; Meyfroidt et al., 2022). Scientific knowledge generated at global or regional levels is also often perceived as too abstract, distant, or temporally misaligned to meet the urgent, place-specific concerns of local planners and communities (Verburg et al., 2013a; Sievers et al., 2024). At the same time, local practices and values remain underrepresented in global assessments and modeling frameworks (Brondizio et al., 2016; Frazier, 2024). Bridging this global-local divide requires methodological innovation and careful attention to the alignment of knowledge with decision-making contexts. In particular, downscaling approaches need further development, addressing challenges not only related to data resolution and scale, but also to regional adaptability.

Strengthening the science-policy interface is critical for enhancing the societal relevance of LSS. Scientific outputs are not always communicated in ways that are accessible or actionable for decision-makers (Turnhout et al., 2016; Beier et al., 2017). At the same time, policymakers, particularly at higher levels, often face technical complexity, time constraints, or misalignment of policy cycles (Turnhout et al., 2016; Beier et al., 2017). To address this, LSS should further emphasize knowledge translation through policy-relevant briefs, scenario visualizations, spatial dashboards, decision support systems, and the use of boundary organizations or knowledge brokers (Beier et al., 2017; Rodela et al., 2017; Wiegleb and Bruns, 2023). Science can also play a proactive role in shaping and establishing boundary organizations, such as IPCC and IPBES, whose global assessments serve as pathways for linking research and policy (Wesselink and Hoppe, 2020; Wiegleb and Bruns, 2023). Similar efforts are needed at national and regional scales to better account for contextual factors and translate generic scientific insights into actionable interventions.

To realize its transformative potential, LSS must embrace a dual ambition: generating rigorous knowledge while fostering action-oriented engagement. This requires a shift from producing knowledge about land systems to producing knowledge for land sustainability transformations. In the same time, it also calls for greater reflexivity among researchers regarding their roles as active participants in co-producing solutions (Anguelovski et al., 2025; Kallergi and Landeweerd, 2025).

Finally, contextualizing global insights locally is further complicated by fragmented, contested land governance systems shaped by unequal power dynamics (Brondizio et al., 2009; Ostrom, 2011). Integrating institutional analysis and critical perspectives, such as the institutional analysis and development framework (Ostrom, 2011) and the governance network theory (Klijn and Koppenjan, 2012), can help uncover structural conditions shaping land use decisions. By embedding these dimensions with attention to power, equity, and historical legacies, LSS can extend its relevance to a broader array of actors and foster more inclusive and just land system transformations.

5.5. Advancing LSS through cross-disciplinary collaboration

The LSS community is primarily composed of geographers, many of whom work at the intersection of social and environmental issues and are informally referred to as ‘betweeners’ or ‘tweeners’. This ‘tweener’ perspective bridges disciplines and can help develop solutions that consider the broader implications of spatially explicit social and environmental processes, addressing challenges such as urbanization, deforestation, and biodiversity loss. To advance strong sustainability, LSS should deepen collaboration with ecology, including landscape ecology, conservation biology, and restoration ecology, and integrate insights from hydrology, climatology, and other environmental sciences. Without these environmental insights, assessing and understanding the ecological impacts of LUCC becomes difficult.

To further strengthen this holistic perspective, LSS should also embed systems thinking deeply into land change research, particularly integrating the functioning of social and institutional systems within land systems. Advances in this area have largely been led by social scientists, but differing research approaches and methodologies across disciplines, including tensions between theory, context specificity, and generalization, often hinder genuine integrative analysis. As a result, efforts across disciplines often coexist without genuine integration, limiting the potential for achieving true conceptual synthesis. LSS should prioritize the co-evolution of fields to illuminate dynamic interactions, spatiotemporal relations, and feedback between environmental, social, and economic systems. Methodological innovation is crucial to enhancing collaboration and is foundational to all aspects of LSS, including reinforcing systems thinking (Section 5.1), capturing LUCC complexity (Section 5.2), advancing strong sustainability (Section 5.3), and addressing global-local gaps and improving science-policy interface (Section 5.4). Across these areas, developing and refining transdisciplinary tools, participatory approaches, and spatially explicit modeling techniques remain essential for operationalizing LSS’s transformative potential.

Furthermore, while LSS incorporates knowledge from diverse fields, including geography, remote sensing, landscape ecology, landscape architecture, political ecology, and sustainability science, constraints within research project review and funding systems often hinder deeper interdisciplinary integration. In practice, funding and publication pressures often steer disciplines back toward their core domains, constraining the collaborative potential of LSS. Addressing these systemic barriers is crucial to fostering innovative interdisciplinary approaches that move beyond disciplinary silos and enable holistic solutions to land change challenges.

Turning to a major application domain, LSS is particularly relevant to addressing climate change, as LUCC is a key contributor to GHG emissions, making it important for mitigation efforts (IPCC, 2022a), while land use and land cover, through nature-based solutions, also play crucial roles in helping humans adapt to the impacts of climate change (IPCC, 2022b). Additionally, LSS provides critical insights into how LUCC affects local and regional climate processes. For example, deforestation can alter precipitation patterns (Smith et al., 2023), while urban expansion can intensify urban heat island effects (Estoque et al., 2017). In turn, climate change impacts natural ecosystems (IPCC, 2019). The LSS community, therefore, should also enhance collaboration with the climate science community.

The well-known Shared Socioeconomic Pathways (SSPs) (Popp et al., 2017) that dominate the climate science community have been featured in major global assessment reports, including the 2018 Special Report on Global Warming of 1.5 °C and the 2023 Sixth Assessment Report by the IPCC (www.ipcc.ch), as well as the 2019 Global Assessment Report on Biodiversity and Ecosystem Services by the IPBES (www.ipbes.net). These SSPs were developed primarily using coarse integrated assessment models, which simulate broad socioeconomic and environmental futures, including land-use change. However, the SSPs have been criticized for being overly narrow, focusing primarily on climate mitigation and adaptation while insufficiently addressing key sustainability challenges, such as biodiversity loss (Lazurko et al., 2025), as well as human-nature relationships, particularly those affecting ecosystems and biodiversity (Alexander et al., 2023). Critics have also pointed out that the SSP portfolio lacks critical indicators such as income distribution, spatial population dynamics, human health, and governance (van Ruijven et al., 2014). Additionally, it assumes economic convergence and the absence of major growth disruptions in the developing world, resulting in an overly optimistic lower band of growth projections, which may lead to impact assessments that underestimate the full human and material costs of climate change, particularly for the poorest and most vulnerable societies (Buhaug and Vestby, 2019). The SSPs’ projections of future land use (and land use change) are also limited, as they lack a spatial dimension and therefore need to be spatialized or downscaled (Fujimori et al., 2018; Estoque et al., 2019c; Gao and Pesaresi, 2021). The projections also address only net changes, without reflecting the gross losses and gains across land use classes (Chen et al., 2020; Estoque et al., 2020). At the same time, such projections focus only on broad changes without addressing the more complex changes in land systems, including changes in management and landscape configuration.

In LSS, various modeling techniques have been developed (Mas et al., 2014; National Research Council, 2014) to simulate spatially explicit land changes and assess their impacts under different scenarios. These tools employ classified historical land use and land cover data and various methods for quantifying and spatially allocating LUCC to project land dynamics and guide decision-making. Emerging technologies, such as deep learning and large language models, are increasingly being explored to enhance data-driven analysis, improve prediction accuracy, and support scenario development (C.Q. Li et al., 2024; Zeng et al., 2025). In this regard, LSS can complement coarse integrated assessment models and extend their capabilities to enhance socioeconomic scenarios by integrating additional dimensions and providing a more spatially explicit and holistic understanding of land system dynamics, encompassing both social and ecological systems. While land use is not exclusive to the LSS domain, the LSS community appears to have had limited, if any, involvement in the development of the global future land-use scenarios under the SSPs.

6. Limitations

As a narrative review, this paper does not provide an exhaustive or systematic account of all contributions to LSS. Literature was purposefully selected to align with the paper's objectives, which may introduce biases in coverage and emphasis. Despite efforts to include diverse perspectives, certain fields and knowledge systems may be underrepresented. The framework presented, which links LSS in general, and LUCC dynamics and sustainable land management in particular, to social-ecological goals such as resilience, sustainability, and quality of life, has yet to be empirically tested. These limitations mean the synthesis should be viewed as a critical overview rather than a definitive account, while still offering a transparent foundation for future research and debate. Similarly, the classification of the SDGs as direct, semi-direct, or indirect in terms of how they are impacted by LUCC is heuristic, as the links between specific SDG targets/indicators and LUCC may vary.

7. Conclusions

This article reviews the emergence of LSS, examines its roles in social-ecological research, and discusses its challenges and future directions. Rooted in the integration of human-environment systems, LSS has matured into a vital interdisciplinary field, addressing the complexities of LUCC in the context of sustainability and global environmental challenges. Its progress has been driven by socioeconomic and ecological imperatives and supported by technological and methodological advancements. The transition from LCS to LSS represents a significant shift in emphasis from a 'change' (LCS) to a broader 'system' perspective (LSS), both of which are intrinsic to the field, emphasizing the intricate interactions within social-ecological systems. LSS has become instrumental in advancing social-ecological research, particularly in identifying and promoting sustainable land management strategies that are essential for achieving sustainability, fostering social-ecological resilience, and enhancing quality of life, including human wellbeing.

For LSS to continue progressing and contributing meaningfully to these goals, future research should prioritize the following: (1) embracing a systems-based approach that captures the complexity, feedbacks, and emergent properties of land systems; (2) deepening the understanding of LUCC across scales and sectors; (3) grounding research more firmly in the principles of strong sustainability, particularly by recognizing the non-substitutability of critical natural capital; (4) bridging global-local gaps through context-sensitive analysis, multiscale integration, and an enhanced science-policy interface to ensure knowledge is actionable and timely; and (5) promoting more deliberate and genuine integration across disciplines, moving beyond parallel contributions toward intellectual synthesis and co-production. Advancing LSS requires a sustained commitment to systems thinking, transdisciplinary integration, and context-sensitive knowledge co-production. By bridging epistemological divides, linking global and local perspectives, and aligning research with societal needs, LSS can more effectively guide land system transformations toward sustainability and resilience, ultimately enhancing quality of life, including human wellbeing.

Hence, LSS carries direct practical and policy implications by providing an evidence base for designing context-sensitive policies, guiding sustainable land management, and informing transformative planning. The framework presented operationalizes this role by structuring how integrated LSS insights on LUCC are translated into actionable knowledge. This approach enables the effective integration of scientific evidence into sustainable land management to advance social-ecological resilience, sustainability, and quality of life, including wellbeing.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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