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Sustainable intensification in land systems: trade-offs, scales, and contexts

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Sustainable intensification of agricultural production is expected to be an important pathway for achieving future food security while protecting the environment. Recognizing that there is no single answer to how different dimensions of intensification can be achieved sustainably, we identify opportunities for research across spatial scales. We focus specifically on research questions around advances in technology and management and suggest that progress on these questions can be made by (i) improving understanding of trade-offs, especially across scales, (ii) recognition of the context-specificity of how agricultural intensification can become more sustainable, and (iii) development, access and wider use of global datasets for integrative research.

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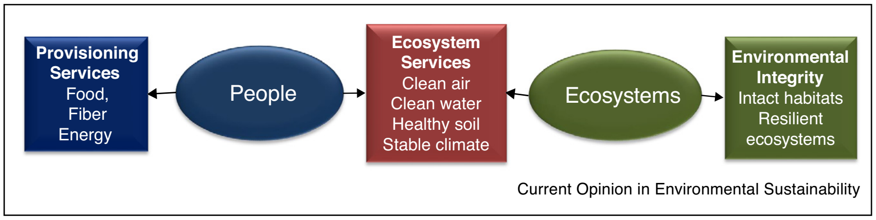
Introduction

A considerable body of research has focused on understanding how future agricultural production can meet the growing demand for agricultural commodities while at the same time reducing environmental impacts [1]. Research in support of this aim is based on the premise that all people require an adequate and nutritious diet, and that producing food and other land-based products should not compromise the ability of land to do so in the future. Likewise, there is consensus that the growing environmental impacts of agriculture, including biodiversity loss, reduction of soil quality (by erosion, chemical use, and nutrient depletion), degradation of water resources, and climate change, must be reduced (Figure 1). Many strategies can contribute toward achieving these goals, including increasing production on existing cropland, identifying management practices that reduce environmental degradation and biodiversity loss, and improving the resilience of production systems to climate and environmental change [2–4].

Research supporting the dual goals of increasing agricultural production while lowering its environmental impact are often framed in the context of 'sustainable intensification'. This term has been defined in multiple ways, focused on the trade-offs between agricultural production and the environment [5], or extended to include the multiple dimensions of food systems, such as food security, access and distribution, food demand, consumption and waste, and socio-economic dimensions such as livelihoods and justice [6–11]. Here, we address where making connections between approaches that focus on different geographic scales is important for advancing research on sustainable intensification. We focus only on the production and environmental impact component of the use of land for primary crop production. While broader food system aspects, including social and economic dimensions are also critical, we refer readers to the previously cited works and Meyfroidt *et al.* (this issue) [12] for broader discussion of those topics.

Sustainable intensification does not refer to any single management practice or system *per se* [3,13]. Trade-offs between agriculture and the environment vary in relation to the diverse modes of intensification, across spatial scales, and against the realities of local environmental conditions (e.g. soils, topography and climate). In addition

Figure 1



Normative dimensions of the requirements from land resources to support people and ecosystems that depend on the sustainability of agricultural production.

to the trade-offs explored here, socio-economic characteristics such as market integration, land tenure, local knowledge, and cultural values will influence how agricultural systems in a region evolve [6,14]. Likewise, the specific field management and production practices that achieve intensification in a sustainable manner depend on regional and local context [15].

Here we further focus in on identifying potential directions for transformative research in sustainable intensification where land system science could make valuable contributions — concepts and tools that can contribute to integrating the social and environmental systems, and strategies for linking research across scales while considering context-specificity [1,16]. We conclude by noting common research dimensions and identifying future research directions for integrative approaches to advance understanding of sustainable intensification.

From plants to fields: insights from crop science and agronomic practices

Since the Green Revolution of the mid-20th Century, crop yields in many regions of the world have increased steadily with adoption of higher yielding varieties with expanded use of fertilizers, pesticides and irrigation [17]. More recently, advanced crop breeding and genetic engineering techniques have helped to accelerate the development of new crop varieties and allow farmers to achieve higher yields, reduce pesticide use [18,19], lower costs, and in some cases to reduce the land and environmental footprint of agriculture [20,21]. However, the rate of increase in yields has recently slowed, due to a combination of factors including farmers' lack of resources for intensification, crops approaching maximum achievable yield under field conditions, or because incentives for environmental protection place additional demands on the land [22]. Meanwhile, negative environmental impacts on biota, air and water continue to accumulate owing to increases in fertilizer, pesticides, and irrigation, as well as the emergence of chemical resistance in crop pests and weeds due to greater reliance on a smaller number of pesticides [23]. All of these trends illustrate the urgency of sustainable intensification research, to continue increasing production while recognizing the potential for and developing strategies to reduce negative environmental impacts.

Research at the plant scale includes several emerging trends that are relevant when considering future agricultural systems. For example, research on increasing photosynthetic efficiency is a potentially transformative development that would open up new strategies for sustainable intensification [24,25]. Efforts to improve nitrogen efficiency [26] have been assisted by the discovery of native varieties with novel attributes, such as maize that can fix nitrogen through symbiotic relationships with the soil microbiota [27]. Such developments raise the possibility of high-yielding crops that, if managed appropriately, might require less fertilizer [18,19]. Similarly, the development of locally adapted, high-yielding varieties of perennial grain crops could increase the feasibility of broad-scale agroecological systems, particularly to restore production on degraded or marginal agricultural lands [28]. While the potential of this research has not yet been realized at the scale required for farmer adoption, understanding the implications for land systems of such novel and emerging developments now will reduce the risk of negative environmental or societal consequences resulting from more widespread future adoption of these technologies.

Research on sustainable practices for field-scale management often focuses on specific factors limiting crops from achieving their biological potential [29]. Other approaches have looked to natural ecosystems to design production systems that focus on intensification through production of multiple crops on the same field, relying on the complementarity of different plant functional groups and on ecological functions to maintain soil fertility and reduce losses to pests or weeds [14]. Research into the trade-offs between environmental impact and productivity have found that no one set of practices is ideal for all circumstances, as not all conservation practices (e.g. no-tillage, organic systems) maintain or increase crop yield [23,30,31] or are universally beneficial for the environment (e.g. no-till agriculture requiring pesticide use). Thus, the environmental context and trade-offs must determine how intensification can be achieved sustainably. While our focus here has been on recent technological advances, we should emphasize the crucial contributions of existing management and technologies to sustainable intensification. Indeed, farmers in many parts of the world have adopted management practices that also contribute to sustainable intensification by using context-appropriate technologies, such as smallholder use of terracing and raised-field horticulture in wetlands in developing country contexts of lower financial capacity and sufficient and cheaper labor [32].

The characteristics of crops and how they are managed, especially in terms of tillage and agrochemical inputs, largely determine the environmental impact of agriculture at the local scale. Increasingly, precision agricultural technologies that help target-specific management practices within farm fields show promise to increase input efficiency. As these techniques become more accessible and affordable, precision agriculture can be applied by a broader community of farmers. The management of livestock integrated into crop production systems can also increase the overall food production of lands in certain regions and contexts [33•,34]. Understanding trade-offs of such local management decisions for larger regions is important — for example, perennial grain crops may reduce time and energy required for management and enhance ecosystem services, but if yields remain low will require more land in use to reach the same production level. Assessing how such trade-offs manifest at broader spatial scales requires integrative approaches that connect the relative positive (e.g. increased yield) versus negative (e.g. pollution, water depletion, soil erosion) impacts of different agricultural systems. Understanding the potential cross-scale benefits and challenges of emerging technologies and management practices is a research priority to identify opportunities for sustainable intensification.

From farms to landscapes: insights from landscape ecology and geography

Research at the landscape scale is the fundamental connection between the diverse array of relevant disciplines at the plant to field level and research to inform national and global decision making. Studies are increasingly focusing on the degree of heterogeneity in environmental conditions such as soil quality, water availability, carbon stocks and the degree of endemic species, and how these conditions influence management decisions. For example, conventional agriculture based on the economy of scale associated with a high degree of mechanization and agrochemical use is most feasible where favorable environmental conditions occur homogenously across larger regions (e.g. in temperate or tropical plains). Although local biodiversity might be lost across large areas where industrialized agriculture expands, there will be fewer edge effects (e.g. pesticide drift, isolation of species' populations) than the same agricultural area in an environmentally heterogeneous, fragmented landscape. Conversely, other forms of intensification, such as multi-species cropping or agroforestry systems, could minimize impacts in environmentally heterogeneous regions [35], or restore environmental heterogeneity where it has been lost historically (e.g. due to conventional intensification practices). Thus, environmental heterogeneity determines the scope and intensity of trade-offs associated with land management decisions.

A debate in landscape research is to what extent accepting strong local trade-offs (e.g. intensifying agriculture maximally) can lead to lower environmental impact at broader scales (e.g. because less area is needed for production) [4,10,33•]. In some contexts, landscape configuration [37•,38•] can be used to understand how local trade-offs aggregate at the landscape level. For example, carbon emissions resulting from forest conversion to agriculture scale linearly with the amount of forest converted. Conversely, ecosystem functions such as water retention, rainfall recycling or biodiversity loss, may respond in highly non-linear ways, with potential tipping points at critical levels of deforestation [39]. At the same time, minor landscape interventions (e.g. devoting less than five percent of a farmed landscape to grass or forest), can have substantial environmental benefits [40]. In addition, specific landscape arrangements can maintain and restore ecosystem services, such as pest control, which often underpin or contribute to agricultural production [41,42].

Further exploring the common contexts that reduce trade-offs at the landscape level will contribute to developing research priorities at both local scales (e.g. what crop characteristics and management systems to further study and develop) and larger national to global scales (e.g. what scenarios and planning are necessary to reduce trade-offs across diverse landscapes). For example, land-use planning can be used to identify land system architectures that lessen trade-offs with the environment [43,44]. Emerging approaches based on multi-criteria optimization can identify configurations of land uses that maximize agricultural production while minimizing environmental impacts at the landscape scale [45]. Designing agricultural landscapes to maintain connectivity among natural areas can lower biodiversity impact substantially [46,47]. While such 'optimized' landscapes can in practice be difficult to achieve, such research can be insightful as to which landscape configurations are more advantageous than others, thus leading to concrete policy and management suggestions. For example, maintaining crop heterogeneity or restoring landscape elements such as hedgerows and single trees is effective at reducing negative impacts on biodiversity at the farm level [48]. Recent work increasingly suggests that optimal landscapes for biodiversity consist of a mix of land-use intensities and differ from pure sparing or sharing landscapes [49,50•,51].

These insights and methodologies can be valuable to examine how developments in research at the plant to field scale might scale up, and to identify potential trade-offs of emerging management systems and technologies in advance of widespread adoption.

From national and regional to global scale: insights from integrative and scenario research

Research at broader geographic extents encompasses a wide range of approaches, from data observations and frameworks to spatial optimization and scenario assessments. Here, multi-disciplinary approaches contribute to understanding of global challenges, such as the role of land systems in achieving sustainable development, climate mitigation, and protection of biodiversity. Pathways to sustainability are strongly influenced by national-level decisions that set the legal framework and influence the level of adoption of global principles and of international flows of agricultural products. Thus, this research is often considered under a governance scale framework, to provide key framing conditions for consideration of such trade-offs, such as institutions and planning contexts [52].

Research to integrate across scales can contribute insights into where crops achieve their highest potential yield and to where agricultural production can be maximized with optimization of water and nutrient inputs [53], pest and disease control. Kehoe *et al.* [54], for example, identified regions where potential agricultural expansion and intensification coincide spatially with unique biodiversity, and therefore locations where decisions about the diverging trade-offs of these land-use strategies are most important to consider. Assessing the relative global value of land for agricultural use versus protected areas, and their integration in multifunctional landscape planning at local, regional and global scales, is an important consideration for global conservation planning, including the Half Earth proposal [55•; Ellis *et al.* this issue).

Building from such insights, scenario research has been applied to understand trade-offs at the global scale while considering specific objectives, such as how to increase agricultural output to meet world food demand in the future. Erb *et al.* [33•] found more feasible scenarios for achieving future food security with zero deforestation when high yields are assumed compared to when lower yields are assumed, and when comparatively land-inefficient livestock production systems (e.g. cattle ranching) are minimized. Mehrabi *et al.* [56] and Egli *et al.* [57•] found that the spatial organization of agricultural lands could strongly alter the trade-offs between agricultural production and biodiversity conservation.

Research at the national to global scale is highly integrative — findings from landscape scale analyses can lead to broader insights when connections between them are made. Looked at regionally, individual land-use changes can be seen as land-use redistribution, such as when agriculture is abandoned in mountainous areas but intensified and expanded in flatland areas [58]. While the local change may have specific environmental implications, the broader scale impact is that by agricultural land use adjustment to the most productive areas, overall outcomes for the environment are more sustainable [59]. A key question emerging from this research is whether globalized trade has the potential to enhance the extent of natural ecosystems, lead to lower greenhouse gas emissions and food prices by optimizing the distribution of land uses [60] or if it leads to increasing displacement of environmental impacts toward the most sensitive and vulnerable regions [61].

One limitation of research at this scale is the necessity of making generalizations from the complex field to landscape research findings discussed earlier. Novel approaches to fully consider how landscape heterogeneity and local trade-offs scale could lead to new insights on what decisions lead to sustainable intensification at global scales. Advancing such global scale studies depends on the availability of consistent and reliable data sources. Recent improvements in spatially detailed, globally consistent datasets on land management practices allow for systematic, cross-scale analyzes of how trade-offs between intensification and environmental impacts vary across both spatial and temporal scales [62,63]. In cases where data are limited, new research designing frameworks for extrapolating from known data across landscapes are beginning to help address gaps by enabling rapid scaling of local research findings on environmental conditions and agronomic practices [64•]. Such data resources can be mined for insights and further inform regional and global economic scenario models that consider the environmental and societal trade-offs associated with different potential realizations of future agricultural systems.

Conclusions

Sustainable intensification encompasses specific disciplinary research in subjects ranging from crop science to agronomy, ecology, economics, rural studies, and more. Sustainable intensification thus requires research integrating across multiple disciplines. Some common dimensions of sustainable intensification across multiple disciplines that are helpful in the design of integrative research approaches include:

i increase input efficiency of energy, nutrients and water,
ii minimize nutrient and agrochemical loss to the environment,
iii maintain the long-term productive capacity of the soil and land,
iv minimize natural habitat conversion and disturbance,

v maximize the environmental value of agricultural lands,
vi understand spatial patterns of land use that optimize trade-offs at different scales,
vii accelerate the rate of change toward more sustainable systems.

Emerging technology and agricultural management strategies are changing how these seven common dimensions may need to be considered in future research. Changing social and environmental context, meanwhile, increases the urgency for continued research into the design of agriculture systems that support sufficient food production for achieving global demand while supporting local livelihoods [11,12]. Research is needed to understand how to embed sustainable intensification within socioecological systems that are resilient and adaptive to cope with rapidly changing climate and socioeconomic conditions.

In accordance with these considerations, we identify three integrative priorities to advance sustainable intensification research:

1) How do emerging advances in technologies and practices at the field scale influence sustainable intensification at regional to global scales?
2) How do trade-offs between intensification and environmental impacts vary across geographic scales, and how can that be accounted for both conceptually and from a land governance perspective?
3) What global datasets of land management, environmental characteristics, and socio-economics are needed to help advance scenario research that can inform analysis of trade-offs across scales?

One avenue that can contribute to addressing these priorities is a systems perspective that integrates across ecological characteristics that considers diverse levels of environmental homogeneity or heterogeneity, and that considers trade-offs across geographic scales. Land system science approaches can contribute to understanding the contextual basis and to linking the environmental impacts considerations to the social and economic considerations. In particular, improving our understanding of the distant impacts of local to national actions on ecosystems and communities in other regions helps bridge the scales between local actions and global consequences. By including social, governance, and economic considerations, researchers can explore the motivations of actors who drive land use change, the trade-offs considered and how those evolve over time.

Looking forward into the future, careful assessment of environmental impacts of emerging technology and management across scales is needed to achieve sustainable intensification. By considering research relevant for sustainable intensification across scales, land system science in collaboration with other disciplines can contribute to identify appropriate combinations of intensification and sustainability to address global scale food security and environmental challenges.

Conflict of interest statement

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