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A conceptual framework for analysing and measuring land-use intensity

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Large knowledge gaps currently exist that limit our ability to understand and characterise dynamics and patterns of land-use intensity: in particular, a comprehensive conceptual framework and a system of measurement are lacking. This situation hampers the development of a sound understanding of the mechanisms, determinants, and constraints underlying changes in land-use intensity. On the basis of a review of approaches for studying land-use intensity, we propose a conceptual framework to quantify and analyse land-use intensity. This framework integrates three dimensions: (a) input intensity, (b) output intensity, and (c) the associated system-level impacts of land-based production (e.g. changes in carbon storage or biodiversity). The systematic development of indicators across these dimensions would provide opportunities for the systematic analyses of the trade-offs, synergies and opportunity costs of land-use intensification strategies.

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Introduction

Future growth in the human population and GDP will increase the demand for food, fibre and fuel over the next decades [1,2,3••]. Most of the related growth in land-based production will have to rely on increases of output per unit area in agriculture and forestry rather than on the expansion of land use: we inhabit a world in which most of the fertile land is already used and only one fifth of the global ice-free surface remains largely untouched by humans [4,5]. There is an urging mandate to safeguard these remaining undisturbed ecosystems, which are often rich in carbon and biodiversity [6•]. Such increased output on currently used land is commonly described by the broadly accepted, but ambiguously defined, notion of 'land-use intensification'.

In the last centuries, increases in agricultural output without the proportional expansion of agricultural land were possible because additional inputs in terms of labour, energy, fertiliser and water were available [7]. However, many of the current techniques of yield enhancement are associated with far-reaching, detrimental ecological and social effects [8–10]. This situation renders an explicit valuation of the benefits and trade-offs of land-use intensification important and calls for innovative ways of measuring and assessing intensification [3••,11]. The development of an operational, consistent monitoring system is particularly important for designing policies to foster sustainable increases in land-based production [12,13•].

The scientific understanding of land-use change, however, is still insufficient to characterise the conditions under which such a 'sustainable intensification' [3••,14••] can and will occur. Many knowledge gaps relate to the underlying processes and determinants of the levels, patterns and dynamics of land-use intensity. First, we lack a commonly shared definition and terminology [15,16•]. Second, the casual use of the term 'intensification' in the scientific literature, often used synonymously with the complex changes related to agricultural industrialisation processes (such as those during the 'green revolution') or with any detrimental socio-ecological effects of landuse, further adds to the ambiguity. Third, traditional approaches often only examine one or a few aspects of land-use intensity while disregarding the multidimensionality of the intensification process in the complex land system [6•,17]. For example, simplified, monodimensional hypotheses on land-use intensification, for example, on the interrelationship between agricultural intensification and area demand, though initially highly intuitive, cannot be substantiated when evaluated against empirical data [18••,19]. Accordingly, simple causal relationships between the individual processes, drivers and impacts of land-use intensification could not be established [20].

We argue that improvements in the scientific understanding of landuse require two, interrelated steps: (1) developing an integrative framework for the analysis of land-use intensity, and (2) generating datasets that allow the systematic study of drivers as well as impacts of changes in land-use intensity. Here, we briefly review the most important scientific approaches concerned with the processes, drivers and consequences of land-use intensity changes. Building on this body of knowledge, we summarise the different dimensions of land-use intensity and systematise the implicitly or explicitly proposed indicators for measuring land-use intensity. Lastly, we propose an integrated conceptual framework for analysis aimed at facilitating the development of datasets for land-use intensity research.

Themes and topics in land-use intensity research

Research has been focussing on different aspects of land-use intensity which can be grouped into four general themes (see supporting online information). (a) The (agricultural) economist perspective, rooted in the seminal works by the 'classic' economists T.R. Malthus, D. Ricardo and J.H. von Thünen, focusses on the interrelation between input factors (land, labour or capital) and outputs (produce) from land, mostly in monetary terms, often entailing a rational choice (utility optimisation) perspective. (b) Another prominent theme focusses on drivers of agricultural change, in particular technology and population growth. This theme gained impetus after the 1960s with the influential rebuttal of E. Boserup [21] to the Malthusian view on the interrelation of population change and technology, and is still vivid in human geography, ecological anthropology and political ecology, with a strong focus on pre-industrial agriculture. (c) A further prominent research strand focusses on potentially detrimental ecological consequences of land-use intensification, including livestock systems [22], in particular on climate and biodiversity, or on essential but non-marketed ecosystem services ([23•], SI for more references). In the light of emerging new demands for land products (e.g. bioenergy), the (d) systemic interrelation between intensification and land expansion (the so-called land-sparing vs. land-sharing debate) (see e.g. Grau *et al.*, in this issue, SI for more references) is another leading theme of land-use intensity research.

Despite their differences in focus, scope and attention (see SI), a few commonalities among these different strands of land-use intensity research can be identified. First, a focus on agriculture, particularly cropland, prevails, whereas other components of the land system (e.g. urban, forestry) are mostly neglected. Second, unconventional management practices (e.g. fertilisation of intensively managed forests; [24]) and land-system interrelations (e.g. urban-hinterland linkages; Seto *et al.*, in this issue; Meyfroidt *et al.*, in this issue) are largely ignored. Third, monodimensional indicators, mostly agricultural yields or fertiliser application rates, or a data-driven development of indices from the combination of input and output data dominate. Lastly, the stringency of economic approaches, which systematically analyse input-output relationships, is only rarely replicated in non-economic strands of land-use intensity research [25]. Additionally, systemic interrelationships between production and consumption, such as supply-demand linkages, or rebound effects, are rarely taken into account in natural science-based approaches. In contrast, economic approaches rarely consider biophysical constraints or the effects of intensification on non-valued ecosystem services or on biodiversity. Overcoming these shortcomings by developing an integrated framework of analysis appears timely. In the following section, we will review and systematise the proposed measures of land-use intensity to identify the cornerstones of such a framework.

Dimensions of land-use intensity

Given the complexity of land-use intensity, providing a single, unambiguous and encompassing definition or indicator of land-use intensity does not appear to be an adequate target. A comprehensive analytical framework is required that considers the multidimensional nature of land-use intensity. A synthesis of the dimensions of land-use intensity and proposed methods to measure them (Table 1, see also Table S1 in the Supplementary Online Information) allows identification of the core elements of such a comprehensive framework and needs to measure the (a) inputs to the production system, (b) outputs from the production system, and (c) changes in ecosystem properties.

Measuring input intensification

Traditional approaches to measure input intensity can be grouped into four categories. (a) A pivotal input indicator that inspired many authors is provided by Boserup [21,54]. She defines the intensification of agriculture as the increasing frequency of cropping cycles in shifting cultivation systems, that is, increasing inputs of land to the production system. This notion of cropping frequency for measuring land-use intensity is based on the observation that, under pre-industrial conditions, the annual crop yield of a parcel of land can scarcely be enhanced, thus only an increased cropping frequency can increase production. Similarly, rotation length is an important intensity indicator in forestry. The Boserupian notion

Table 1

Summary of dimensions and indicators of land-use intensity

Proposed dimension/indicator	Authors
Inputs	
Cropping frequency, proportion of fallow land, harvest intervals and rotation length in forestry	[21,26,27,28,29,30,31]
Cropping frequency combined with indices for technology	[32,33,15,34]
Indices combining inputs of labour and capital (and skills) per land area	[35,36,37,38,27,39]
Single inputs per land area	[40,41]
Type of forest regeneration (planting, seeding or natural regeneration)	[42]
Outputs	
Agricultural yield (production per area and time)	[25,18••,43,44,45]
Stocking density of livestock[a]	[46]
Felling rates (fellings as percent of net annual increment)	[47]
Inputs and outputs	
Combined indices of inputs and outputs[a]	[14••,48•,49,50]
Changes in system properties	
Biodiversity	[51]
Complexity of ecosystems	[23•]
Net primary production	[52]
Carbon stocks	[53••]
Water and nutrient cycle	[22,51]

[a] Livestock density is classified as output.

was further developed by many authors, for example, by proposing indicators that consider the differences in fallow and cropping period (e.g. [26,28]). (b) Cropping frequency is often complemented by information on applied technology to provide indicators of a wider applicability [15,27,32]. In such approaches, technologies under use are ranked according to their intensity and combined with indices for cropping frequency, an approach criticised due to the proneness to tautologies [55]. (c) The definition by Brookfield [35] places the substitution of capital, labour, and skills against land at the centre of attention of land-use intensity research, a definition followed by many scholars since (see, e.g. [25]), which is stimulating for the development of indices based on combinations of input data. (d) In contrast to this approach, many authors use single production factors as surrogate indicators for input intensification, including the amount of N fertiliser or pesticide applied (e.g. [40,41]). Although studies of this type are able to capture some central aspects of intensification, they cannot account for substitution effects (e.g. changes from mineral fertilisers to manure) or transitions to resource-sparing, intensive high-tech applications (e.g. precision farming). A related approach is the generation of indices by combining input datasets, sometimes also with output data, such as the yield of the dominating cultivars or stocking density of livestock (e.g. [48•]).

Measuring output intensification

Turner and Doolittle [32] and Hunt [56] argue that output indicators would ultimately provide better indicators of land-use intensity because they represent the purpose of agriculture. Netting [25] and Shriar [15] also favour measuring output intensity, as no presumptions about the efficiency of inputs on productivity are made. In biophysical terms, output intensification relates to the increases in production output per unit area and time (e.g. tons of cereals harvested, milk produced or timber removed from forests per unit area and time period).

Many intricacies relate to the measurement of output intensity, referring to (a) the unit of measurement (e.g. in mass, energy, calorific value, monetary value per area) and (b) the methodology used to measure output consistently [56]. Because many land systems are rotational, that is, fields are periodically left fallow to maintain the soil fertility, it is important to relate the outputs to the full production cycle to generate comparable values. Such data, however, are usually not readily available or are highly uncertain ([16•,30], Kuemmerle *et al.*, in this issue).

The large variation in yield resulting from differences in the climate, soil conditions or management history and the specifics of individual cultivars render the use of yield data as surrogates for output intensity problematic. To manage these complexities better, methods have been developed that assess the 'yield gap' between agricultural yields at the plot, farm or regional level to a reference yield that is attained under similar conditions of production (e.g. [57,58,59]) or standardised management [45]. For forestry, an intricacy results from the occurrence of unplanned fellings, for example, following natural fires, pests or storms, which eventually results in naturally induced increases of output per area and year and renders it important to integrate the natural disturbances and harvests [60].

Measuring changes in system properties

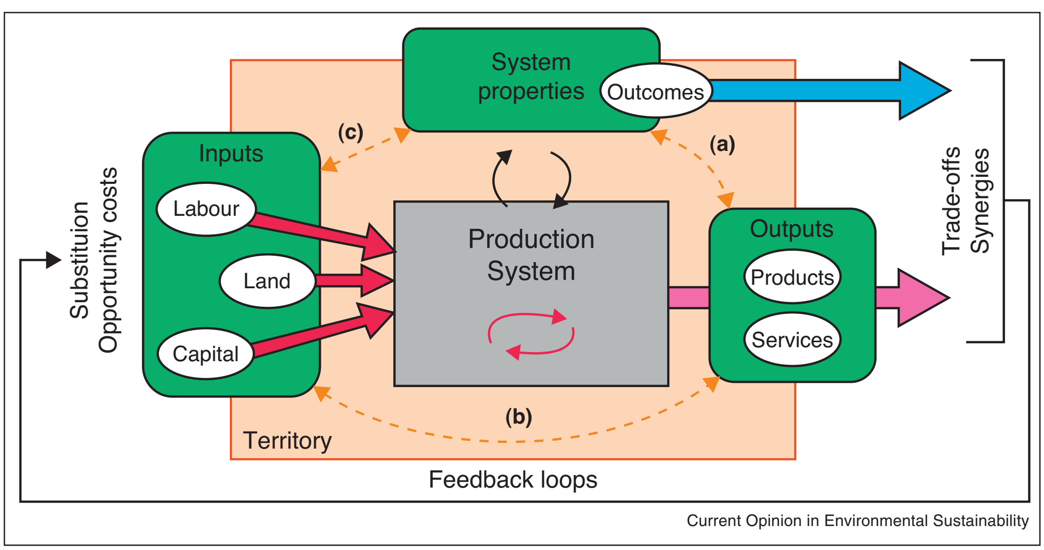
The systematic observation of the effects of land-use intensity on the ecological patterns and processes, such as nutrient cycling, biodiversity, net primary production (NPP), carbon storage, water quality and water retention capacity, is an important component for a comprehensive analytical framework for land-use research. Keys and McConnell [20] and Tscharntke [23•] have placed such alterations of system properties at the centre of their general definitions of land-use intensification. Whereas analyses of the input-output ratio are an established research theme (see SI), the link to altered ecosystem properties is rarely explicit. This is surprising because the alteration of system properties can be decisive for the overall dynamics of the land system ([16•], Seppelt, in this issue).

Considering the effects of changes in the ecosystem parameters and consequential alterations of the provision of ecosystem services appears important to further our understanding of land-use intensity and for developing indicators of system-level outcomes. The measurements of such consequences, for example, the provision of ecosystem services, have proven to be difficult [61,62]. Biophysical approaches exist that quantify these changes at the system level, for example, by quantifying the differences between the actual and potential states of the ecosystem and using the distance between the two states as a proxy for intensity. This notion is closely related to the ecological definition of disturbance [63]. Examples o such approaches include the disturbance assessment by Hannah *et al.* [64], the changes in biodiversity proposed by Matson *et al.* [51], the land use and disturbance intensity index proposed for forestry, as based on the ecological law of self-thinning [53••], or the human appropriation of net primary production (HANPP; in the definition of [52,65]). For further details, see Kuemmerle *et al.* (in this issue).

A conceptual framework for measuring land-use intensity

On the basis of our review, we suggest that the research aimed at studying land-use intensity or change therein over time will have to integrate the three dimensions outlined above systematically in a conceptual framework (Figure 1). The land-based production system embedded within a territory should be at the centre of the research on land-use intensity. The indicators for land-use intensity should then systematically integrate the inputs to the production systems (e.g. land, labour and capital) with the outputs (i.e. products). This view, consistent with economic principles, allows the study of the input-output relationships, such as the effects of diminishing returns or substitution effects of labour, skills and capital [35]. The framework is also compatible with the pivotal Boserupian notion of cropping frequency as a measure for land-use intensity and allows analysing the dynamic relationships of intensification and land expansion.

Figure 1



A conceptual framework of land-use intensity (green: dimensions of land-use intensity). We propose a new perspective on land-use intensity that systematically links three dimensions (green fields): inputs, outputs, and the associated system level outcomes of land-based production resulting from alterations of the system properties (e.g. biodiversity change, carbon loss, or loss of cultural heritage). This allows one to (a) integrate trade-offs and synergies between land-based production and its associated unintended outcomes; (b) systematically link inputs and outputs; and (c) relate the substitution effects at the input side to changes in the system properties and their socio-ecological effects (dashed orange arrows). These relationships are key in understanding the feedback loops between production and consumption and to identify the conditions under which sustainable intensification can occur.

On the basis of biophysical indicators, much can be gained from such an integration: beyond the agricultural yield, which already represents the ratio between output (production per year) and input (land area), other ratios could be calculated in analogy to the production function in economics. A few such biophysical indicators already exist and reinforce the power of such approaches. The indicator 'energy return on investment' (EROI;[66]), for example, balances energetic inputs and outputs to and from land and can illustrate the net-effects of intensification strategies. Time series analyses reveal that, during industrialisation, the tremendous gains in labour efficiency come at the expense of a deteriorating energy balance, which, in certain cases, even falls below one [67].

It is important, however, to move beyond simply assessing inputs and outputs and to also consider the outcomes of land-based production, which are the result of (frequently) unintended alterations of the system properties but are decisive for the dynamics of the coupled socio-ecological system. Quantifying the trajectories of the ratios between inputs, outputs and changes in ecosystem properties can provide deep insights into society-nature interactions and would allow the opportunity to balance the costs and benefits of land-based production while explicitly acknowledging and internalising the unintended outcomes of land-use intensification strategies. Only a few empirical examples of such integrative perspectives exist: at the level of agricultural products, approaches based on life cycle assessments (LCA) have been developed to systematically assess the environmental impacts of production chains (for a review see [68•]). At the land system level, the HANPP framework allows the calculation of HANPP efficiencies of final biomass products (e.g. the amount of HANPP per final product in tC/yr; [69]) and can, thus, evaluate the environmental pressure associated with biomass products. A similar approach is the carbon footprint concept [70], which aims to quantify the carbon emission related to the final consumption of products (e.g. food). Similarly, the local or global biodiversity loss 'embodied' in every unit of input or output could be a compelling indicator for evaluating land-use options and to identify sustainable land systems [71]. Such accounting schemes would also allow to address a growing challenge of land systems science, that is, the growing teleconnections of land systems (see Meyfroidt, in this issue; Güneralp, in this issue) and their relation to land-use intensification pathways.

Ultimately, the further development of indicators that explicitly address all three dimensions would allow consistent and systematic integration of the intended socio-ecological outcomes or land-based production with the associated direct, indirect and opportunity costs. This would enhance our analytical capacity to explore trade-offs, synergies and feedback loops systematically, and, thereby, inform decision making for a sustainable future land use.

Conclusions

Satisfying the growing human demand for land-based production without compromising the natural resource base requires sustainable land-use intensification. The formulation of strategies to foster sustainable intensification, however, requires a better conceptualisation of the land-use intensity itself, in addition to improved monitoring systems that provide a solid basis for decision making. Unfortunately, to date, neither conceptualisations nor datasets are available of sufficient quality and quantity (Kuemmerle *et al.*, in this issue) to allow for consistent analyses of land-use intensity.

In this article, we suggest that the analysis and monitoring of land-use intensity should follow an integrative conceptual framework that focuses on three dimensions of land-use intensity: inputs to the land, outputs from the land, and the human-induced, but unintended outcomes of land-use intensification that are best measured at the system level.

The development of such a monitoring system is a great challenge that requires the concerted effort of multiple disciplines. However, such an effort would contribute substantially to advance our analytical capacity for understanding land-use changes and, thus, ultimately provide a basis for forging sustainable land-use strategies.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cosust.2013.07.010.

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