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ARTICLE

Framing the search for a theory of land use

BL Turner II[a,b], Patrick Meyfroidt[c,d], Tobias Kuemmerle[e,f], Daniel Müller[e,f,g] and Rinku Roy Chowdhury[h]

[a]School of Geographical Sciences and Urban Planning, Arizona State University, Tempe, AZ, USA; [b]School of Sustainability, Arizona State University, Tempe, AZ, USA; [c]Georges Lemaître Center for Earth and Climate Research, Earth and Life Institute, Louvain-la-Neuve, Belgium; [d]Earth and Life Institute, UCLouvain, Louvain-la-Neuve, Belgium; [e]Geography Department, Humboldt-Universität Zu Berlin, Berlin, Germany; [f]Integrative Research Institute on Transformations of Human-Environment Systems (IRI THESys), Humboldt-Universität Zu Berlin, Berlin, Germany; [g]Leibniz Institute of Agricultural Development in Transition Economies (IAMO), Halle, Germany; [h]Graduate School of Geography, Clark University, Worcester, MA, USA

ABSTRACT

Land system science and affiliated research linked to sustainability require improved understanding and theorization of land and its change as a social-ecological system (SES). The absence of a general land-use theory, anchored in the social subsystem but with explicit links to the environmental subsystem, hampers this effort. Drawing on land-use explanations, meta-analyses, and associated frameworks, we advance a broad framework structure of eight elements – aggregations of explanatory variables – with links to the biophysical subsystem, for systematic comparisons of extant explanations. Tests and models can be employed to identify which set of variables and their configurations provide robust explanations of across land uses, identifying the potential for theory development. The framework and its application are applicable to both top-down and bottom-up explanatory approaches employed in the social sciences. Links to the environmental subsystem invite future exploration of SES explanations that reach across the different dimensions of global change and sustainability science.

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Search for theory for land system science

Changes in the terrestrial surface of the Earth characterize the history of humankind (McNeill & Engelke, 2016; UNEP [United Nations Environment Programme], 2019). Today, the Earth's landscapes have been largely transformed (Ellis, 2011), restructuring ecosystems and their services in the process of supporting a population approaching eight billion at the highest average level of material consumption in human history. The aggregation of these changes creates environmental impacts that challenge the fundamental structure and function of the earth system (Arbault et al., 2014; Steffen et al., 2011), with cascading effects on biodiversity, biogeochemical cycling, and climate change (De Chazal et al., 2009; IPBES [Intergovernmental Science-Policy Platform on Biodiversity ad Ecosystem Services], 2019; IPCC [Intergovernmental Panel on Climate Change], 2018). For example, agriculture currently contributes up to 29% of anthropogenic greenhouse gases emissions (Vermeulen et al., 2012), and land-use changes at large are responsible for massive losses in biodiversity and environmental (ecosystem) services (IPBES [Intergovernmental Science-Policy Platform on Biodiversity ad Ecosystem Services], 2019; Dirzo et al., 2014).

CONTACT BL Turner Billie.L.Turner@asu.edu School of Geographical Sciences and Urban Planning, Arizona State University, Tempe, AZ, USA

The history of these changes has long been recognized and analyzed (Marsh, 1864; Turner et al., 1990). In the Anthropocene, however, the sheer scope of changes in the Earth system has spawned attention to questions of the sustainability of land systems, emphasizing integrated social-ecological systems (SESs) approaches for understanding the changes and informing solutions (Matson et al., 2016; Steffen et al., 2018).[1] New human-environmental research fields, such as resilience (Biggs et al., 2015), sustainable landscapes (Wu, 2013) and land systems (Verburg et al., 2013), have emerged from those that historically focused on either the environmental or social subsystems. Among these research fields, land system science seeks to improve the observation, monitoring, understanding, modelling, and sustainability of land systems and their change (Verburg et al., 2013; Robinson et al., 2018; Turner et al., 2007; Verburg et al., 2015). Complete assessments of these systems would include ''… all processes and activities related to the human use of land, including socioeconomic, technological and organizational investments and arrangements, as well as the benefits gained from land and the unintended social and ecological outcomes of societal activities' (Verburg et al., 2015, pp. 29–30). Defined in this way, land systems and their dynamics represent SESs as phenomena to understand and explain, pointing to the need for theory (Groeneveld et al., 2017).

A theory of land systems would explain the elements and processes generating land uses and land covers in terms of interactive social and environmental subsystems (Rounsevell et al., 2012).[2] Theories of land systems (i.e., as an SES) remain elusive (Zhou et al., 2019), however, as are those for SESs or human–environmental relationships in general (Roy Chowdhury & Turner, 2019).[3] This situation exists despite the conceptual recognition of environmental (or ecosystem) services as a bi-directional link between the two subsystems (Angelstam, et al., 2019; Bennett et al., 2015; Mace et al., 2012) and the call for integrating environmental feedbacks in land-use theory and models (Lambin & Meyfroidt, 2010; Pongratz et al., 2018). The development of multiple integrated assessment and agent-based models addressing elements operating in either subsystem (Filatova et al., 2013; Verburg et al., 2019) and various frameworks coupling the two subsystems (Aspinall & Staiano, 2017; Barry & Roux, 2012; Bürgi et al., 2005; Hersperger et al., 2010; Vadjunec et al., 2018) have yet to yield the development of a land system theory.

For the most part, theories, hypotheses, and explanations addressing land dynamics do not fully integrate both the social and environmental dimensions of the SES. Rather, they tend to focus on the structure, processes, and outcomes in one subsystem in much more detail than the other, but do not formalize or fully address the interactions between the two subsystems. As reviewed by Roy Chowdhury and Turner (2019), those focused on the environmental subsystem, for example, tend to treat human activities (e.g., land use) as disturbances to ecosystem functioning or services, with minimal consideration of the interactions within the social subsystem (Wu & Hobbs, 2002). Resilience approaches, emanating from ecosystems research and applied to land-use dynamics (Meerow et al., 2016) call for SES integration but largely focus on the role of redundancy, non-linear relationships, and adaptation in terms of general systems attributes, rather than, for example, land-use and land-cover outcomes. Unsurprisingly, social science approaches to land use tend to prioritize dimensions of the social subsystem (e.g., Rounsevell et al., 2012), including attention to a range of behavioral, structural, and actor-network theories (Dwiartama & Rosin, 2014). Only one or a few environmental factors tend to influence land-use, such as soil quality, or are affected by those uses, such as carbon emissions, biodiversity loss, or soil erosion.[4] For the most part, however, interactions within the environmental subsystem are underemphasized (Roy Chowdhury & Turner, 2019).

For these reasons, the land system science community argues that coupling theories derived from each subsystem remains the most fruitful integrative approach at this time (Filatova et al., 2013; Vadjunec et al., 2018), one that is consistent with SES models on human health and the environment (Galvani et al., 2016) and on the climate, energy-water-land nexus (Kraucunas et al., 2015). In this context, models are particularly useful as focused and purposive instantiations of theory for a particular set of phenomena. Furthermore, quantitative models, as a methodological approach shared between the environmental sciences and land systems science, may offer common ground for scaling up to integrative theory of land as SESs.[5]

Advancing land-use theory

A major impediment to the development of land system theory (i.e., fully SES in kind) is the absence of a general theory or systematic sets of theories of land uses that capture the variables and their dynamics largely within the social subsystem. Various explanations abound that focus on specific facets of land use, such as the intensity of cultivation, the loss or gain in forests, or the spatial arrangement of different uses linked to, for example, economic rent, population pressures, or tenure rules that clarify rights of ownership, use and/or access to land and resources. Several reviews typologize some portion of these explanations, for example, economic and middle range theories (Irwin & Geoghegan 2001; Meyfroidt et al., 2018), but do not attempt to extract a general theory or systematic sets of theories of land uses.[6]

In the following, we present a framework to assist in the search of a general theory or sets of theories of land use. Focused on the social subsystem, such theory should provide a link to the environmental subsystem, but need not attend, at this stage of consideration, to the full SES integration implied for land-system theory (above). Ostrom (2009, 2011) distinguished a framework from a theory, a distinction we also follow here. A framework identifies the elements and general relationships among those elements to be considered in the development of a theory or theories of land uses. Theory, on the other hand, specifies which elements and their interactions explain the existence of a land use or attribute of that use (e.g., use intensity) – it addresses the 'why' question. The elements in our framework constitute aggregations of explanatory variables and their broad linkages drawn from extant land-use theories, hypotheses, and explanations (henceforth these three categories are labeled explanations unless specificity is required).[7] We propose an investigation of the elements to determine which, if any, are statistically robust across a range of explanatory framings applied to land uses and their attributes. This exercise, in turn, should provide insights about potential theory and the generation of linked models and hypotheses.

Land-use frameworks

Numerous models of land use notwithstanding, general theories and generic, conceptual frameworks addressing land use are not abundant. Platt (2014) provided a broad tripartite framing of the environmental and land-use sectors and the legal-political actors influenced by their social context. Raynor et al. (1994) created a land-use and land-cover wiring diagram recognizing eight modules of elements and their interactions, arrayed from local to global in operation. Five of these modules identified elements largely embedded within the social subsystems (e.g., consumption-production to population) and three within the environmental subsystem (e.g., soil and water to carbon cycle). Recently, Aspinall and Staiano (2017) produced a general model framing of land systems as a guide for understanding its SES dimensions, situating how different types of research fit within land system science.

None of these frameworks was developed with the aim of searching for land-use theory per se nor explicitly based on a survey of land-use explanations, although their components and linkages are consistent with a large range of explanations. Given these efforts and the understanding of land use in general, the elements and interactions presented in our framework are not new. Indeed, they exist in different configurations with different specificities in the three frameworks noted above, and in various assessments of specific types of land change or broad-stroke characterizations of them (Angelsen & Kaimowitz, 1999; Geist & Lambin, 2002; Turner et al., 1994). The architecture of our framework differs from the three noted by its focus on land uses, rather than land systems at large and on elements beyond the legal-political sector (Platt's focus), and through a simplification of the dimensions generating those uses. Its design is open to the array of variables employed in land-use explanations and to the exploration of different arrangements of them.

Our combined experiences examining explanatory narratives (case studies), theories, meta-analyses, and models of land use informed the development of our framework. Meyfroidt et al.

(2018) provide an extensive review of theories addressing land-use extent, intensification, spillovers, and transitions, which we do not reiterate here.[8] Example explanations, however, include induced agricultural intensification and innovation (Muyanga & Jayne, 2014; Turner & Ali, 1996), forest transitions (Barbier et al., 2010; Meyfroidt & Lambin, 2011; Rudel et al., 2009), land rents and land-use zones around cities and protected areas (Brun et al., 2015; Chakir & Lungarska, 2017); urban expansion (Poelmans & Van Rompaey, 2010; Seto et al., 2011); telecoupling and land grabbing (Franco, 2012; Rulli et al., 2013); and spatial polarization and reorganization of land use (Kuemmerle et al., 2015; Stürck et al., 2018). We also considered explanations that have been under-emphasized in land system science, such as those addressing the social and political embeddedness of markets or variations in actors' decision-making (Munroe et al., 2014; Turner & Robbins, 2008). The meta-analyses examined included those addressing the intensification of cultivation (Keys & McConnell, 2005), tropical deforestation (Angelsen & Kaimowitz, 1999; Geist & Lambin, 2002), mangrove degradation (Roy Chowdhury et al., 2017), dryland degradation (Geist & Lambin, 2004), shifting cultivation (Heinimann et al., 2017; Van Vliet et al., 2015), and drivers and impacts of land-use change at large (Van Vliet et al., 2016). Finally, recognizing elements of the biophysical world, we drew on various models focused on ecological consequences of land use (Lawler et al., 2014; NRC [National Research Council], 2014).

From these works, we traced the explanatory variables of land uses (e.g., urban residential or agriculture) or their attributes (e.g., intensity of cultivation), the aggregation of which constitute the elements of the framework. For example, induced intensification theory addresses the intensity of cultivation and its change. The original theory (Boserup, 1965) identified population pressures (i.e., increase in the ratio of population of the farming units per area cultivated) as the major cause of the demand for subsistence production and the level of labor and technology employed to enhance land productivity (i.e., yield and output per unit area and time) to fulfill that demand. Subsequently, the theory was expanded to account for the ambient conditions of the environment (Turner & Ali, 1996) generating land pressures in tandem with population as well as links to how land-labor dynamics affect technological development (Binswanger & Pingali, 1984; Ruttan & Hayami, 1984). We followed the specified causal and other independent variables to land use across a large range of explanations to identify those consistently employed in the explanation, clustering them into the elements in our framework.

Proposed framework

As noted, land-use explanations employ different initial causes entertained in various explanatory structures operating in exogenous or endogenous relationships (Lambin & Meyfroidt, 2010), or some combination thereof (Le Polain de Waroux et al., 2018). The elements in our framework (Figure 1) constitute the aggregation of virtually all of the variables found in land system explanations, be they initial or mediating in kind. The arrows connecting the elements constitute the explicated relationships among the variables that have been or can be tested.

Many initial causal variables in land-use explanations explicitly identify or infer an influence on *demand* (e.g., Angelsen & Kaimowitz, 1999) – land users' desire for land owing to its location (e.g., convenience for urban expansion), environmental conditions (e.g., soil fertility), or its inherent resources and products (e.g., minerals, timber).[9] Through a series of variables, demand operates on *land use* or the purpose for which the land is employed, be it housing, commercial cultivation, or conservation grasslands, or the attributes of a type of use, such as the intensity of cultivation or grazing.

Historically, many land-use explanations focused on land users (e.g., individuals, households, managers, corporations, states) as independent actors, guided by behaviors associated with market, command, and subsistence economies (Huber et al., 2018; Meyfroidt, 2013) or some variation thereof (e.g., mixed market-subsistence economies) (Schipmann & Qaim, 2010; Roy Chowdhury, 2010; Roy Chowdhury & Turner, 2006), captured in the element of actors' attributes. Subsequently, however,

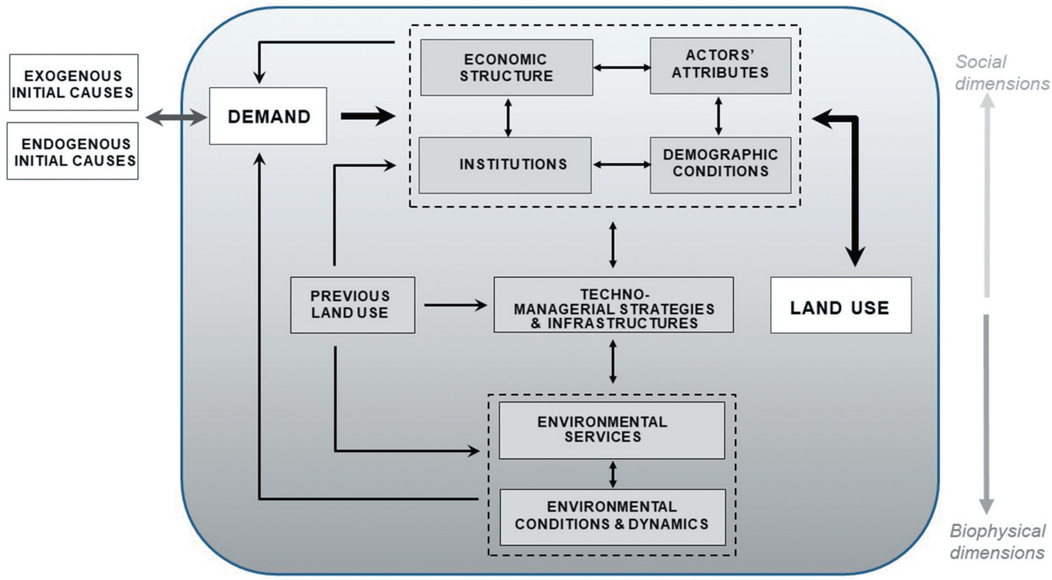

Figure 1. Framework Elements and their Relationships (explanation in text).

explanations have accounted for the opportunities and constraints on behaviors by the socio- or politico-economic structures in which actors exist, such as imperfect markets or 'hollow frontiers' (Barbier, 2012; Busch & Vance, 2011; Harrison, 2017), and by the variations among actors based on capital assets, gender, social capital, or norms and values (De Krom, 2017).

Increasing attention has also been given to 'telecouplings' and 'spillovers' including 'leakages' (Meyfroidt et al., 2020). Telecouplings constitute distal drivers on land use (Liu et al., 2016), such as long-distance acquisition of land by foreign corporations or governments, referred to as land grabs in much of the literature (e.g., Franco, 2012; Rulli et al., 2013). Such couplings could involve factors within almost all of the elements. Leakages, in contrast, follow from land-use policies in a country or region that generate new or expanded land uses elsewhere to recover the lost land-based production (Lambin & Meyfroidt, 2010). More recently, and commonly linked to policy, illicit and clandestine activities on land uses have drawn attention, such as tropical deforestation following narco-trafficking and its land uses for money laundering (Munroe et al., 2014; Tellman et al., 2020).

Beyond the variations in explanations focused on decision-making, a major variable through which economic structures account for land uses is the economic rent for land, be it agricultural zonation relative to markets (Colantoni et al., 2017) or residential housing relative to the central business district (Thrall, 2017). Transportation patterns and, in some explanations, environmental factors influencing transportation, affect the zonation in question (Miranda et al., 2019). Likewise, land quality has long been used to determine economic rent, or the advantage of one parcel of land over another (Bowman et al., 2012).

Numerous land-use explanations involve *institutions*, in this case, the rules and norms that govern social interaction applied to land systems, both formal and informal.[10] These institutions commonly address access to land (e.g., tenure) and hence its relative supply, its resources (e.g., timber), and the various inputs required for the use at issue (e.g., irrigation water). Both formal *de jure* rules and informal *de facto* community rules, social norms, and societal expectations are addressed. Examples of the former are state laws concerning tenure and mineral rights. Those for the latter are rules or claims on common property (Garrett et al., 2013; Kronenburg García & van Dijk, 2020; Osabuohien, 2014), gender distinctions applied to input access (Radel et al., 2012), or expectations about loaning or renting land to extended family members (Laney & Turner, 2015). The absence of rules and/or attempts to circumnavigate rules through clandestine activities or during times of violent conflict also fall within the institution element (e.g., Baumann & Kuemmerle, 2016; Chiodelli & Moroni, 2015; Sesnie et al., 2017), although land-use theory and models have been slow to incorporate explanations of such processes (Tellman et al., 2020). In addition, less attention has been given to complex and cascading factors changing land uses, such as international organizations demanding changes in landscape strategies (e.g., landscape burning) to halt desertification in parts of western Africa (Archibald, 2016).

Importantly, institutions and economic structure are intertwined, with broad associations existing between them, such that a shift or change in one may affect the other, with various consequences. For example, usufruct land tenure commonly shifts to private property with liberalization of economies and market penetration, varying by place-specific social conditions (Farley et al., 2012), whereas the changes in land tenure may facilitate land uses to adjust to markets (Holden & Otsuka, 2014). Policy changes, in some cases conflicting with one another, affect land-use decisions and the intensity of cultivation (Dobler-Morales et al., 2019). In addition, changes in the socioeconomic elements may feed back on demand by changing the sources creating it, as in cases where improved market performance move land managers to devote more production to commercial cropping or to resist that production (Laney & Turner, 2015).

Actors' attributes – the characteristics of the immediate or proximate decision-making unit (e.g., individual farmer, urban developer, company) shaping land-use behavior – are central to almost all land-use explanations, often embedded within or reduced to economic structure. These attributes are more complex, however, involving shared values, beliefs and norms, commonly registered through the concept of culture (Holloway, 2002; Stern, 2000; Stern et al., 1995), and individual or household characteristics encompassing, for example, economic status, gender, educational levels, social capital, power dynamics, and controlling institutions (Brannstrom & Vadjunec, 2014; Holtan et al., 2015). In many cases, an actor's decision is influenced by interactions with other actors, as in the case of land uses under collective usufruct, or other formal or informal associations of land users (Turner & Stiller, 2020; Wentz et al., 2016). The distinctions among these attributes tend to influence access to land and the inputs for land use, affecting the relative supply of land among different land users. Individual, community, and cultural attitudes and values also influence land-use decisions, including the perception of what land is used and how. Taken as a whole, actors' attributes may culminate in community visions of 'a way of life' or culture that influences land use (Alesina & Giuliano, 2015; Laney & Turner, 2015; Meyfroidt, 2013).[11]

Actors not only respond to the other social elements in our framework but also change them in some cases (Raymond & Robinson, 2013). Community actors may alter informal institutions, commonly through interactions with economic structure or demographic conditions, as in the case of adjustments in grazing practices and/or (re)allocations of grazing rights on grassland commons owing to the loss or gain of critical resources (Meyfroidt et al., 2016). The experimentation of a few farmers pioneering new, risky land uses may subsequently flip the entire community to the new practices (Junquera & Grêt-Regamey, 2019). Or, actors may expand an existing land use where intensification would be more profitable (Piquer-Rodríguez et al., 2018).

Ranging from urban settlements to frontier settings, the impacts of *demographic conditions* – defined here as number, density, and movement of people – on land uses have a long research history (Bren d'Amour et al., 2017). Population pressures, for example, constitute the initial causal variable for the intensity of cultivation within subsistence and mixed subsistence-market economies (Boserup, 1965). Changes in population-land ratios increase or decrease the pressures to produce more or less from land. These changes, in turn, affect the amount of capital and labor invested in cultivation (i.e., cropping intensity), and in some cases, influence the shift from subsistence to market cultivation (Headey et al., 2014; Muyanga & Jayne, 2014), changing actors' attributes with feedbacks affecting household size as well as migration. In turn, changing population pressures may require shifts in the rules of access to land or resources for production (Boserup et al., 2013), whereas extant institutions may deny sufficient land access, triggering migration (Herrero et al., 2014; Turner & Ali, 1996). These pressures, in turn, depend on land supply (absolute availability and relative access), which is also affected by environmental conditions and techno-managerial strategies (below) to manipulate those conditions (Holden & Otsuka, 2014). Declines in population by emigration or loss of labor owing to seasonal or temporary migration can reduce land pressures, with consequences for local governance and techno-managerial strategies that, respectively, may prove inappropriate to continue or cannot be maintained (Kuemmerle et al., 2016; Schmook & Radel, 2008; Tarolli et al., 2014). International and national policies also affect local land pressures by shifting access to land or production from subsistence to commercial cultivation (Jayne et al., 2014; Osabuohien, 2014). In such cases, the rules governing land use or inputs for that use may generate land conflicts (Lambin & Meyfroidt, 2010). For example, state restrictions on the use of marginal land in order to increase forestation in China have generated controversy among farmers (Wang & Maclaren, 2012).

Demographic conditions also affect technological development for agriculture. The supplies of land and labor interact to determine the focus on investments for production (Binswanger & Pingali, 1984). Land or labor scarcity induces technological innovation and change that saves land or labor, respectively, demonstrated largely through state and commercial investments at the country level (Ruttan & Hayami, 1984). The induced intensification thesis applied to smallholder subsistence cultivation, however, indicates that land scarcities drive the use of technologies and strategies to enhance land productivity, consistent with the innovation thesis.

The remaining four elements – *previous land uses, techno-managerial strategies and infrastructure, environmental services*, and *environmental conditions and dynamics* – cascade from the intersection of the social and biophysical subsystems to the biophysical alone (Figure 1). Given their role in determining the supply of land and, in many cases, the strategies of land uses, exploration of these elements is pivotal for land-use theory, our aim here, and the future development of land systems theory.

The eight interrelated elements link demand to land use: *structure of the economy, institutions, actors' attributes, demographic conditions, techno-managerial strategies and infrastructure, environmental services, environmental conditions and dynamics*, and *previous land uses*. The dashed boxes refer to the social and environmental subset of elements. Techno-managerial strategies and infrastructure, and previous land uses reside between the two subsets. The specific variables employed in land-use explanations are grouped here as eight framework elements, arrayed according to their position within or between the social and biophysical subsystems.[12] Recall that these elements are consistent with those found in other frameworks, although the level of variable aggregations among the frameworks leads to different numbers of elements, including attention to the biophysical link of land use. Focusing on the social subsystem, these elements are *structure of the economy, institutions, actors' attributes* and *demographic conditions*. The *structure of the economy* is the context in which economic and related decisions are made.

Techno-managerial strategies and infrastructure that include various technological inputs, management methods, and permanent landscape alterations manipulate land for use. Using agriculture as an example, hybrid crops, organic cultivation, and wetland drainage capture the terms 'techno', managerial, and infrastructure, respectively. These strategies and infrastructure are human innovations, but the base environment shapes which types of strategies and infrastructures are suitable for specific land uses. As such, the element resides at the interaction of the social and biophysical subsystems.

Techno-managerial strategies and infrastructure are endogenous in some explanations, either through on-farm innovations or borrowed from other land systems (Jayne et al., 2014). They may be exogenous if introduced into land systems from afar. For example, the global diffusion of hybrid or genetically modified crops has changed managerial requirements that, in turn, influence the environment and its services, generating legacy effects for future use (Bürgi et al., 2017). Green revolution crops in the developing world increased food significantly but raised the capital investments required for farming, with strongly negative consequences for marginal smallholders and long-term environmental impacts (Dawson et al., 2016; Pingali, 2012).

The ambient biophysical setting – from soil qualities to ecological communities to climate – and its functioning constitute *environmental conditions and dynamics*. A multitude of associations has long been made between this element and land use, generally at the aggregate level (e.g., ecosystem, landscape, climate). As well, integrated assessment models and agent-based models of land use commonly incorporate some facet of this element (Rosenzweig et al., 2014; USGCRP [U.S. Global Change Research Program], 2018). Some explanations, however, firmly address land use-climate interactions, such as that between urbanization and precipitation in southern Florida (Pielke, 2005), climatic zones and land uses (Piquer-Rodríguez et al., 2018), and urban to regional heat island effects from built-up impervious surfaces (Peng et al., 2012). The dynamics of the ambient environment, such as global climate changes, generates regional differences in the 'fertilization effect' from increasing levels of atmospheric CO_2, changes in extreme weather events such as droughts or severe storms, and the length of growing seasons (Rosenzweig et al., 2014). These and other impacts are expected to increasingly alter the conditions for many land uses.

It is noteworthy that some land-use explanations have explicitly accounted for broadly defined conditions of the environment, such as Ricardian theory accounting for the impacts of land quality (e.g., suitability for agriculture) on economic rent, which have been adapted to include future climate change impacts (Severen et al., 2018). Variations in the theory of the isolated state account for transportation impacts, which in turn can be affected by environmental conditions, such as the role of major waterways disrupting the zonation of land-uses surrounding cities.

These notable examples notwithstanding, land-use explanations underplay the role of the environment, largely reducing the environment to a few factors that affect land use, and none truly engages the social and biophysical subsystems interactively. Assuming that attention to these interactions will improve land-use explanations as they do in modeling assessment (Goldstein et al., 2012), and given the larger goal of developing land systems theory, *environmental (or ecosystem) services* is also added as an element that connects environmental conditions and dynamics to land uses.

These services constitute the material and nonmaterial benefits that the environment provides to land users (Larigauderie et al., 2012), such as food and fiber provisioning, or pollination, soil fertility, climate and hydrological regulation, including drainage (Bateman et al., 2013; Raudsepp-Hearne et al., 2010), whereas disservices are the negative externalities or loss of services (Zhang et al., 2007).[13] *Environmental conditions and dynamics* and *techno-managerial strategies and infrastructure* determine the supply of these services and disservices, affecting the supply of land for particular uses. Accounting for environmental services and their change provides various insights into land uses that might otherwise be missed, such as the cost to maintain or increase a service (e.g., purchasing itinerant pollinators), which may limit land-use options. Foremost, environmental services offer an important bridge to the biophysical subsystem for future development beyond land-use theory to land systems (or SES) theory (Angelsen, 2007).

Finally, current and future land uses can be strongly shaped by the *environmental services* rendered by former uses, typically linked to the accumulation of past *techno-managerial strategies and infrastructure* (Perring et al., 2016). This shaping by *previous land uses* (our element label) may create legacy effects affecting other elements (Munteanu et al., 2015).[14] In some cases, previous land uses create path-dependent outcomes or 'lock ins' by facilitating certain land uses and inhibiting others (Bürgi et al., 2017; Müller et al., 2014), in some cases generating co-evolved social structures-land use lock ins (Gual & Norgaard, 2008). Legacy effects range from irrigation infrastructures generating sunk (i.e., past and non-recoverable) costs that make their replacement by another land use economically irrational (Balmann et al., 2006) to degraded or abandoned environments proving too costly to rehabilitate or reactivate (Kuemmerle et al., 2015; Prishchepov et al., 2013) or flipped into a new, unwanted state (Thompson et al., 2016). Importantly, legacy effects can also influence the social elements directly. For example, land-use policies may contribute to the immobility of production factors and impede structural change by favoring certain land uses, as in the case of the production quota for milk in the European Union's common agricultural policy, which favored existing producers while posing barriers for new entrants (Grant, 2010).

In addition to these relationships, the social and environmental elements feed back on demand as identified in the discussion above. Any combination of economic structure, institutions, actors' attributes, and demographic conditions may affect the demand for land and its resources, as exemplified by changes in economic conditions and institutions in Eastern Europe and Russia (Meyfroidt et al., 2016). Land availability itself, especially land possessing certain environmental conditions, may generate demand for its use. For example, tropical environments are required for oil palm production, leading to more than 14 m ha of tropical lands worldwide to be taken to oil palm plantations (Kongsager & Reenberg, 2020).

In sum, the demand for land provides a broad and necessary, but insufficient explanation of why a certain land use emerges. It operates through and, in some cases, is generated by variables within our eight elements (Figure 1). Together the variables in these elements specify why land use exists or changes, with attention to who may use the land and the resources required for that use, the decision-making fabric of the users, and the environmental conditions encountered. In addition, they explain situations where the demand for land changes without changes in land-uses, for instance, due to institutional barriers or actor motivations linked to their social attributes. The variables within the elements explicate the supply of land and how land is used by illuminating the provisioning, mobilization, and maintenance required for accessible services and output.

Use of the framework

The many variables found in land-use explanations and their configuration (linkages from demand to land use) are not predetermined in our framework. Rather, the framework notes eight elements for which selected variables should be examined through multiple explanatory pathways, perhaps organized somewhat similarly to processes articulated for formulating, testing and consolidating 'generalized knowledge claims' (Magliocca et al., 2018). In the induced intensification case noted above, for instance, demand related to population (*demographic conditions*) in subsistence economies (*economic structure*) create the intensity of cultivation (land-use attribute). Subsequent testing of this explanation (induced intensification theory) enlarged the economic structure to mixed subsistence-market conditions, registering various parts of *actors' attributes*, and added general environmental elements (i.e., environmental conditionsand their contributed *environmental services*). Our framework indicates that in this broader context, existing *institutions*, available *techno-managerial strategies*, and *previous land uses* should be added to the analysis. Different variables within the elements and different configurations of the relationships can then be tested iteratively to determine which provide robust explanations of cultivation intensity. Approaches similar to the stepwise procedure identifying the variables and relationships used to address Ostrom's SES framework (Ostrom, 2009, 2011) constitute methods to be investigated (Schlüter et al., 2014). This exploration would be followed for different land-use explanations, ideally generating theory sets. These sets in turn should provide clues about the derivation and usefulness of merging the sets for increasingly general levels of land-use theory.

Collecting data in line with our framework is critical to its use for theory development. The most systematic option would involve a research program in which a standardized set of causes and explanatory chains (below) commensurate with the elements in question are examined anew across a range of land uses and their attributes, akin to the extensive, systematic data collections on common property regimes (Ostrom, 2010) and Ostrom's SES framework. Such an option was considered in the deliberations of the original, international science program on land use and land cover (Aspinall & Staiano, 2017; Turner et al., 1994) but was never instituted. A less systematic option would group the range of extant theories and explanations (e.g., by type of use or by context) and re-examine them by adding the missing elements or specific variables within the elements. This effort would likely confront the problem of incomplete data in the original research collection, requiring the use of proxies, interpolations, or data derived from different scales of analysis to engage our framework. In this case, increases in the uncertainties of the results will require attention.

Assuming that the required data can be gathered, various statistical models can be used to explore different formulations of elements or the variables comprising them, determining their robustness for different land-use outcomes (Magliocca et al., 2018). These formulations may rearrange the linkages presented in Figure 1, the ordering of the elements, or omit some elements and, perhaps, add new ones. The exercise, even if it fails to achieve the theory(ies) in question, should prove significant for land system science and affiliated research communities, establishing the explanatory specificity at which land use may be cast and the potential fit of the social dimensions with the environmental subsystem.

Addressing explanatory chains

The use of explanatory or causal chains, in which sets of cause–consequence relationships are linked hierarchically or interact with one another, is common in land-use research. Both top-down and bottom-up approaches are employed in the identification of causal chains and are applicable in our framework assessment.

Top-down formulations are commonly associated with ‘grand theory’ that provide the overarching rationale from which cascading causal connections link to the land use. For instance, the global political economy (a guiding grand narrative) creates regional inequities, which, through various processes, foster land appropriations in frontier economies by powerful actors (e.g., companies) to produce commodities, and generate ‘telecouplings’ of otherwise spatially distant producing and consuming lands (Friis & Nielsen, 2019). In this process, tropical deforestation occurs and smallholders are displaced elsewhere, spurring additional deforestation for cultivation. Such structural approaches addressing various facets of land systems are common in political ecology (Brannstrom & Vadjunec, 2014; Peet & Watts, 2004) but have not been examined with the aim of advancing a comprehensive theory of land use.

Bottom-up approaches, especially as associated with abductive approaches, begin with a specific land condition or change and explore plausible immediate or direct causes (Walters, 2017; Walters & Vayda, 2009).[15] Once the first-order explanation is established, the cause becomes the phenomenon to be explained, and an exploration for its explanation is undertaken. For example, the loss of a community-maintained mangrove forest results from the expansion of shrimp aquaculture. This expansion followed from technological advances in the production process, state-support for infrastructure development, increasing presence of international markets, and new international trade agreements. In this approach, commonly used in land system science, related anthropological studies, and some versions of political ecology, immediate land change is traced to an ever-widening set of events and processes (Meyfroidt, 2016). The array of variables and relationships found in such bottom-up approaches tend to be directed to specific cases and case studies, however, and not to land-use theory per se.

Regardless of the approach employed, the search for an inclusive land-use theory requires: (1) a clear delimitation of the land-use elements and processes that are covered by the explanation; (2) a chain of causal relationships among the elements derived from any combination of the approaches in question; and (3) a specification of the conditions and contextual factors under which the different steps in the explanation are expected to operate.

Summary

Despite considerable advances in land system science and related research fields, an inclusive theory of land use or sets of theories have not emerged. A major step toward their development involves our ability to assess and compare systematically how configurations of explanatory variables affect different land-use explanations. We provide a framework, consisting of eight elements comprising sets of explanatory variables, to structure such comparisons. A variety of approaches can be used to explore the relative strength and significance of the explanatory variables across the range of land-use explanations, searching for configurations of the variables within and across our elements that provide robust explanations land-uses that can link to the biophysical subsystem. The exercise, even if it fails to achieve the theories in question, should prove significant for land system science and affiliated research communities, establishing the explanatory specificity at which land use may be cast and the potential fit of the social dimensions with the environmental subsystem. Pursuit of the exploration should also enhance LSS and its connections to global environmental change, resilience, and sustainability research, perhaps providing insights concerning the development of SES theory at large.

Notes

1. The social-ecological system or SES term originated in ecological-oriented research, especially that within resilience studies (Folke, 2006). Ostrom (2009) developed a SES framework designed with resilience questions in mind, focused on actors and institutions, and their dynamics with the environment, especially drawn upon in studies of common property regimes. Subsequently, the Ostrom framework has become much more expansive in terms of the socio-economic considerations it entertains (McGinnis & Ostrom, 2014; Partelow, 2018). Other parts of sustainability and human-environmental science reference SESs as social-environmental systems because the biophysical dynamics in question range beyond that historically examined in ecology (Eakin & Luers, 2006; Matson et al., 2016). In this usage, tightly linked social and environmental subsystems constitute an SES in which various parts of either subsystem are addressed; institutional dynamics or governance need not be considered. We use the term 'social-ecological system' and 'environmental subsystem' here because they are common to the land system science literature, regardless of references to Ostrom. It is noteworthy that a recent review of sustainability (Clark & Harley, 2020) drops both SES terms and uses, instead, nature-society interactions, which along with human-environment relationships, are terms long used in geographical and anthropological research.
2. The origins of land system science are linked to the former international program of Land-Use and Land-Cover Change or LUCC (Turner et al., 2007), which morphed into the Global Land Programme (Verburg et al., 2013). In the original LUCC lexicon, land use referenced the social subsystem and land cover, the ecological or environmental subsystem. Subsequently, land cover inferred a link to the biophysical subsystem, and ecosystem services as the link feeding back to the land use.
3. Several research fields have long-standing traditions examining human-environmental (or social-environmental, nature-society) relationships (e.g., Barrows, 1923; Moran, 2016; Platt, 2004; Sauer, 1925; Turner, 2002). With the exception of the geographical factor or environmental determinism, these fields and the various explanatory perspectives crossing them maintain broad conceptual themes that underpin the relationships in question, but do not constitute theory – general explanations of specific types or sets of phenomena within these relationships. An initial theoretical foray advanced from the landscape morphology school of geography (Wagner 1960) was abandoned, and contemporary cultural and political ecology and land system science have yet to achieve human-environmental theory (Turner & Robbins, 2008).
4. Interestingly, even work focused on resilience, institutions and SESs, following Ostrom (2009), has been lacking or has inadequate explicit attention to the environmental subsystem (Epstein et al., 2013; Vogt et al., 2015).
5. We recognize that sustainability science, to which land system science links in various ways, draws on SES approaches but has a strong place-based dimension (Clark & Harley, 2020; Kates, 2001). Social and environmental factors vary considerably across places and situations, suggesting that there are no panaceas for sustainability problems. This recognition should not to be confused with the commonalties of phenomena and processes involved in the problem, and the value of theory to understand those commonalities.
6. Middle range theories are empirically grounded, general (nomothetic) explanations of phenomena, consistent with hypothetico-deductive approaches used in the sciences at large (Meyfroidt et al., 2018). Parts of the social sciences use the middle range label in juxtaposition to 'grand theories' in social science – those abstract concepts covering all social structures common to critical and social theory and structuralism.
7. Ostrom (2011, p. 8) also notes that models are 'precise assumptions about a limited set of variables and parameters [to advance] predictions about the results of combining variables using a particular theory [or coupled theories for SES problems].' This interpretation is consistent with our use of models as well. Tests are analytical assessments (including that of specific hypotheses linked to models) of the characteristics and relationships examined in a theory or a more specific model.

8. The Supplemental Information in Meyfroidt et al. (2018) provides a detailed list of explanations and frameworks addressing different facets of land-uses and the theories thereof.
9. Macroeconomics commonly approach land uses through demand and supply. In one sense, absolute land supply is fixed and typically cannot be enlarged, save in a few instances of land reclamation. In another sense, the supply of land for different land users is relative, determined by access to the land. This access is the product of different configurations of the variables in the elements in our framework that maintain, increase, or decrease access to land.
10. The meaning of institutions differs among research communities (Ménard & Shirley, 2014). We use the term in reference to rules, including norms, of social interactions (Hodgson, 2015) as articulated in Ostrom (2011). This definition is more restrictive than those that include, for example, culture and economic structures as institutions of social interaction. Recognizing the relationships among culture, economic structures, and social interactions (e.g., Alesina & Giuliano, 2015), land-use explanations tend not to render such breadth of meaning to institutions. To be consistent with land-use explanations and for clarity in our framework, we separate institutions from culture and economic structures.
11. We recognize the distinctions that different scholarship employs through the concept of culture (Baldwin et al., 2006), and that a case can be made that culture should constitute its own 'box' in our framework. In its broadest and perhaps simplest meaning, culture refers to any set of ideas, beliefs, values and practices that are socially learned and transmitted, creating shared patterns of behavior and norms and the meanings given to them (e.g., Henrich, 2016). Culture may also shape various dimensions of the other elements in our framework. Our actors' attributes element captures the array of values and norms affecting land-use behavior not specified in the other elements. This array is composed of interactive cultural and individual dimensions that we cluster as actors' attributes. Use of the framework may prove the need to separate these dimensions in the future.
12. These eight elements, variously labeled and linked, are also found in different parts of the 'conceptual model of land system as a coupled human-environment system' presented by Aspinall and Staiano (2017). Their 'holistic framework' presents an array of phenomena, processes and research interests beyond the eight elements on which we focus.
13. 'Nature's contributions to people' constitutes a possible relabeling of environmental (ecosystem) services (Díaz et al., 2018). We use services because it dominates the literature to date.
14. Our framework is designed for examination of extant land-use and its change. As such, previous land uses reside outside our timeframe, but affect the current conditions of the other elements. In long-term or time series assessments, the relationships of elements with previous land uses would be interactive.
15. In contrast to deduction and induction in which the outcome phenomenon or event is derived from causal factor (i.e., logical inference), abduction reverses the sequencing, searching for a cause to link to the outcome (e.g., Walton, 2014).

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No potential conflict of interest was reported by the authors.

ORCID

Patrick Meyfroidt http://orcid.org/0000-0002-1047-9794

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