Middle-range theories of land system change

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Abstract

Land system changes generate many sustainability challenges. Identifying more sustainable land-use alternatives requires solid theoretical foundations on the causes of land-use/cover changes. Land system science is a maturing field that has produced a wealth of methodological innovations and empirical observations on land-cover and land-use change, from patterns and processes to causes. We take stock of this knowledge by reviewing and synthesizing the theories that explain the causal mechanisms of land-use change, including systemic linkages between distant land-use changes, with a focus on agriculture and forestry processes. We first review theories explaining changes in *land-use extent*, such as agricultural expansion, deforestation, frontier development, and land abandonment, and changes in *land-use intensity*, such as agricultural intensification and disintensification. We then synthesize theories of higher-level land system change processes, focusing on: (i) *land-use spillovers*, including land sparing and rebound effects with intensification, leakage, indirect land-use change, and land-use displacement, and (ii) *land-use transitions*, defined as structural non-linear changes in land systems, including forest transitions. Theories focusing on the causes of land system changes span theoretically and epistemologically disparate knowledge domains and build from deductive, abductive, and inductive approaches. A grand, integrated theory of land system change remains elusive. Yet, we show that middle-range theories – defined here as contextual generalizations that describe chains of causal mechanisms explaining a well-bounded range of phenomena, as well as the conditions that trigger, enable, or prevent these causal chains –, provide a path towards generalized knowledge of land systems. This knowledge can support progress towards sustainable social-ecological systems.

Keywords: human-environment systems; box and arrow framework; indirect land-use change; land-use intensification; deforestation; land-use spillover; urban dynamics.

1. Introduction

Change in land use—the purposes and activities through which people interact with land and terrestrial ecosystems— is a key process of global environmental change. Understanding land-use change is central for designing strategies to address sustainability challenges, including climate change, food security, energy transition, and biodiversity loss. Land systems constitute complex, adaptive social-ecological systems (Berkes et al. 1998) shaped by interactions between (i) the different actors and demands that act upon land, (ii) the technologies, institutions, and cultural practices through which societies shape land use, and (iii) feedbacks between land use and environmental dynamics (MA 2003, Verburg et al. 2015). Elementary events of land-use changes that take place at the plot-level over short time periods, such as deforestation or substitution of one crop by another, correspond to changes in the extent and/or intensity of land use. These elementary building blocks combine to form complex, structural processes taking place over broader extents (landscapes, regions, and across countries) and longer time scales, including non-linear transitions (Lambin and Meyfroidt 2010) and spatial reorganization of land uses (Rey Benayas et al. 2007, Kastner et al. 2014, Queiroz et al. 2014, Levers et al. 2018).

Land system science is a maturing field that has produced a wealth of methodological innovations and empirical observations (Lambin et al. 2006, Turner et al. 2007, Verburg et al. 2015). It focuses on monitoring and describing patterns of land-cover change, explaining drivers of land-use change, and understanding linkages between these two. These advances have relied on deductive approaches based on disciplinary frameworks (e.g., neo-classical economics or political ecology), abductive reasoning (i.e., starting from outcomes and retracing these to their likely causes), syntheses based on systematic reviews and meta-analyses of drivers and impacts of land system change (Magliocca et al. 2015, van Vliet et al. 2015), and "box and arrows" conceptual frameworks. The development of land system theories has been lagging due to: (i) a focus on local case studies, favoring *ad hoc* interpretations based on contingent factors; (ii) an emphasis on methodological developments involving improvements in remote sensing and other geospatial analyses; and (iii) the interdisciplinary nature of land system science, which has led to the borrowing of theories from related disciplines including geography, landscape ecology, economics, and anthropology (Meyfroidt 2015, 2016).

Lambin et al. (2001) challenged simplistic notions about the causes of land-use and land-cover change, highlighting complex interactions, multi-causality, and the contextual character of land system processes. Here, we argue that land system dynamics can be apprehended through theoretical generalizations that transcend the place-based specificity of cases, without ignoring their complexity. We consider that theoretical formalization can further the development of: (i) testable hypotheses; (ii) process-based models simulating complex interactions; and (iii) credible knowledge that informs policy and decision-making beyond specific places while remaining sensitive to context. Theories of land systems advance our understanding of the dynamics of social-ecological systems and foster dialogue with other human-environmental sciences.

Here, we take stock of land system science knowledge generated over the last decades, focusing on theories explaining the causes of land-use change and their systemic linkages across places. We focus on middle-range theories, defined as contextual generalizations presenting causal explanations of delimited aspects of reality—events or phenomena (Merton 1968, full definition in Section 2). This stands in contrast to both high-level, unified theories, as well as explanations relying on the singularity of a specific case. While our focus is not on theories relating land-use change to its environmental and human impacts, we account for feedback mechanisms that alter the dynamics of land use. We thus only touch lightly on the normative aspects of land system change. We concentrate on processes in agriculture and forestry, but many theories discussed here have been used for other dynamics, such as urban land uses.

Our objective is to articulate how middle-range theories can contribute to understanding land system change by:

(i) Reviewing the different theories explaining changes in land-use extent and intensity, and
(ii) Synthesizing them into middle-range theories of higher-level processes of land system changes, focusing on land-use spillovers and land-use transitions as non-linear, structural changes.

Section 2 discusses the role of middle-range theories in relation to frameworks, models, and typologies. Section 3 reviews theories of land-use expansion and intensification. Sections 4 and 5 build on these theories to synthesize middle-range theories on structural changes in land systems. We then discuss further theory development on land systems as social-ecological systems.

2. Theories, frameworks, models, and typologies

Different epistemologies have distinct visions of what a “theory” is. Here, a *theory* is defined as a general explanation or stylized facts about events, phenomena, or their attributes (e.g., spatial or temporal patterns), based on a set of factors and their causal relations. The term “*middle-range theory*”, originating from social sciences, describes a process developing from observations and analyses of a specific event or phenomenon, building towards explanations of sets of similar phenomena, which can be progressively expanded to other phenomena presenting similar characteristics or linked to other mechanisms present in other theories (Merton 1968). Here, we define middle-range theories as *contextual generalizations that describe chains of causal mechanisms explaining a well-bounded range of phenomena, as well as the conditions that trigger, enable, or prevent these causal chains* (Meyfroidt 2016). Middle-range theories seek to balance generality, realism, and precision across the breadth of explanatory factors mobilized, to reach a middle ground between ad hoc explanations of singular cases and "grand", universal systems theories that explain all features in a stylized way (Levins 1966, Hedström and Udehn 2009, Hedström and Ylikoski, 2010). In contrast with grand theories, which are posited to apply to a very wide range of phenomena, middle-range theories tend to have a narrower focus and application and should be explicit about the processes it aims to explain and the limits of its reach. Over time, middle-range theories can expand their reach or be combined with each other, as the underlying mechanisms that join them are better understood. Multiple disciplinary and interdisciplinary middle-range theories have been proposed to explain land system changes (SI Appendix A, see Sections 3-4-5).

Middle-range theories can be distinguished from other generalization approaches including conceptual frameworks, models, and typologies. *Frameworks* are a collection of concepts considered as relevant for analyzing a phenomenon, which constitute lenses for looking at reality and boundary objects for inter- and transdisciplinary communication (McGinnis 2011). They provide checklists of variables and components to include in theories, and indicate the assumed structural relations between these building blocks. In contrast with theories, these relations are neither depicted functionally nor their strength hypothesized under different sets of conditions. Prominent frameworks in human-environmental science are the frameworks on proximate causes and underlying drivers of environmental change (Geist and Lambin 2002, MA 2003), the social-ecological systems framework depicting factors of sustainable self-organization of resource-use systems (Ostrom 2009), ecosystem services frameworks linking human well-being and ecosystems (Daily et al. 2009; MA 2003; Fisher et al. 2013, van Zanten et al. 2014), the telecoupling framework on linkages between distant social-ecological systems (Liu et al. 2013, Friis et al. 2016), and others (SI Appendix B). Examples of frameworks specific to land system science include those on major land system components (GLP, 2005), distinction between land-use, land-cover and land-management changes (Pongratz et al. 2018), and land-use intensity (Erb et al. 2013, Kuemmerle et al. 2013). Many social science theories are somewhere between middle-range theories and frameworks.

Frameworks and theories provide bases for constructing dynamic *models* aiming to replicate and enhance system understanding by formalizing and exploring the relations between different variables and their outcomes (National Research Council, 2014, Verburg et al., 2016). Process-based models can rely on theories to inform their assumptions on the structure and type of relations between variables. Models can play an important role in the development and testing of theories, particularly to identify mechanisms and their effects under certain conditions, and to quantify the relations between variables. Constructing a model can be akin to building a theory, by selecting variables, generating hypotheses on their relations, and assessing their influence on outcomes. As social-ecological systems are complex and adaptive, their dynamics are influenced by bottom-up (emergent) and top-down (constraining/enabling) processes and structures. Top-down and bottom-up mechanistic theories can be validated by implementing them in a process-based model, such as agent-based models.

Another generalization approach involves the identification of *typologies*, also referred to as syndromes or archetypes, i.e., recurring patterns or combinations of variables, processes, actors, situations, or outcomes (Schellnhuber et al. 1997, Oberlack et al. 2016, Valbuena et al. 2008, Levers et al. 2018). Typologies can be derived inductively by identifying commonalities within a set of cases, for example using qualitative-comparative analysis (QCA) or other configurational approaches, or deductively via the theoretical identification of key variables that create a typological space. Typologies often lack causal relations, but can be used to build "typological theories" (George and Bennett 2005).

3. Theories of land-use expansion and intensification

3.1 Land-use expansion and intensification

The increasing global demands that human societies place on land, including for production of goods, nature protection, and ecosystem services, require changes in extent (expansion or contraction) and intensity (intensification or disintensification[1]) of land uses. Land-use expansion occurs into unconverted areas ("wildlands") or over land that is already converted to anthropogenic land cover, such as cropland expanding over pastures as often observed in South America (Baumann et al. 2017). Land-use intensification refers to practices that increase land productivity by (i) increasing inputs per land unit (e.g., labor and capital-based inputs, or technology) or the temporal frequency of land use (e.g., multiple harvests), (ii) increasing output per land unit (i.e., yields), and/or (iii) altering ecosystem properties, as with tree species homogenization in intensive forestry (Erb et al. 2013, Kuemmerle et al. 2013). Considering multiple and growing demands (Haberl et al. 2014, Haberl 2015), intensification is often seen as a path for sustainability, to lessen competition for productive land and mitigate trade-offs such as between food security and environmental conservation (see Section 4.1). However, intensification can produce multiple undesirable environmental and social impacts, such as increasing capital costs to impoverished smallholders (Luyssaert et al. 2014, Kremen 2015, Gossner et al. 2016, Erb et al. 2016a, 2017). The

1 "Extensification" is sometimes also used for disintensification, mainly in the European context, while the same term is frequently used for "expansion" in the North American context. We therefore mainly use disintensification here. Mirroring the multidimensional nature of intensification, disintensification can encompass various realities.

functions assigned to land thus inherently result from social dynamics and conflicting purposes, interacting with biophysical factors. Land-use diversification, or an increase in multifunctionality to produce different goods and ecosystem services on the same land, can be decomposed into the intensification of some land uses and disintensification of others. This distinction is often employed strategically to take advantage of land-use synergies to increase resilience or maintain a basket of outputs per land unit while reducing non-land inputs (Fischer et al. 2017). Expansion and intensification can co-occur, for example intensification through the expansion of a more intensive land use over a less intensive one (Baumann et al. 2017, Meyfroidt et al. 2014).

Theories of changes in land use extent and intensity can be mapped in a two-dimensional space, with places and actors ranked according to their degree of integration in markets on the one hand and to their reliance on labor versus capital inputs on the other (Figure 1). Beyond describing land productivity and its changes, intensification theories frequently predict how the efficiency of other production factors change (Figure 2). These same theories can also explain land-use disintensification and contraction, though legacies and path dependence may challenge their application. For example, the accumulation of landesque capital – i.e., enduring anthropogenic improvements in the productive capacity of land, such as through terraces and irrigation systems – may hinder land abandonment even in the face of unfavorable production conditions (Håkansson and Widgren 2016). We first discuss theories explaining changes in land use extent and intensity in smallholder subsistence contexts, where households are units of decision-making, of production, and of consumption, and directly interact with the environment (Section 3.2, lower-left quadrant of Figure 1). We then consider theories of intensification and expansion dynamics when smallholders progressively integrate into markets for inputs, outputs and consumer goods (Section 3.3, moving right in Figure 1). We then move to land rent theories that are based on the neo-classical economic framework under market conditions (Section 3.4). Section 3.5 incorporates the role of broader institutions and social relations to develop theories of large-scale processes such as frontier development. We end by introducing theories that incorporate non-linear land system dynamics and feedbacks between the human and environmental components of land systems, as a bridge towards Sections 4 and 5 (Section 3.6).

3.2 Theories on smallholder subsistence land use

Some theories describe the behaviors of smallholders or peasants farming for subsistence and relying on labor as their primary input. These theories assume that smallholders pursue a satisficing strategy aimed at maximizing labor productivity and avoiding the drudgery of labor. In the simplest theory, referred to as “full belly”, a households' objective is to reach a certain subsistence target, with minimal labor input (Kaimowitz and Angelsen 1998, Angelsen 1999). In the peasant theory of Chayanov (1966), a household's labor inputs depend on the trade-off between addressing consumption needs, which depend on household size, and the desire for leisure (time away from the drudgery of farm labor), with no or little surplus produced for markets. This theory does not explicitly discuss whether expansion or intensification is preferred to meet growing consumption needs.

In frontier situations, where land and natural resources are abundant but labor and capital are scarce, land-use expansion is expected to best render the satisficing outcome and thus be more likely (Barbier 2010, le Polain de Waroux et al. 2018). In Boserup's theory (1965), intensification arises in response to population pressure (i.e., higher ratio of population per suitable land available for expansion; Erb et al. 2016b). This theory assumes that the technologies required for intensification are available to farmers and explains what causes them to adopt these technologies. Intensification is chosen over expansion only when land becomes scarce, because in non-mechanized systems the marginal productivity gains of labor intensification are postulated to be decreasing—i.e., intensification raises land productivity but decreases labor productivity (Figure 2A, 2B). Output per area and capita are only maintained if land productivity rises faster than labor productivity declines (Figure 2A). Geertz (1963) used the term of "agricultural involution" to describe situations where land productivity stagnates while labor productivity still declines. This involution path may continue up to the point where output per population and area decreases, at which a Malthusian crisis would occur, unless technological or institutional transformation induces a regime shift, returning the system to a path of increasing land productivity (Figure 2A, 2B, Turner and Ali 1996). Netting (1993) built on these theories to emphasize the specificity of smallholder households as being both production and consumption units, allowing for flexible and low-cost family labor inputs. Netting also showed that labor-based, agroecological forms of intensification have higher energy efficiency (energy return per unit of energy invested, EROI) than capital-based forms of intensification (Figure 2B).

3.3. Theories of induced intensification and institutional innovation with market integration

Induced intensification theory (Turner & Ali, 1996) extends Boserup's theory by acknowledging that, firstly, demand per unit area constitutes a necessary but insufficient cause of intensification because it is moderated by technological, institutional, and socioeconomic variables. Institutional constraints on land-use expansion (e.g., land-use policies, tenure, or access rules) also influence land accessibility and intensification possibilities beyond the physical availability of suitable land (Section 3.5). Induced intensification theory also accounts for the role of biophysical attributes in production. The most extremely prime and marginal lands tend to exacerbate intensification, owing to their strong response to inputs on the one hand, or their considerable investments requirements, which tend to be concentrated on small areas and induce path-dependent reinforcement of intensification on the other hand.

Secondly, in addition to subsistence demand linked to population pressure, when land users engage in markets, the demand for agricultural products also comes from other consumers. Households may respond to these demands by separating subsistence from market cultivation, leading to different levels of intensification. These responses depend on the degree of market engagement. Pure subsistence systems are increasingly uncommon, but many land-use agents, particularly in developing countries, face conditions of incomplete or imperfect market integration (de Janvry et al. 1991, Turner et al. 1993). Such conditions are explained by dominant positions of other market actors, risks and transaction costs, and cultural norms, values, and practices (Laney and Turner 2015). Subsistence and commercial sectors can interact through multiple channels, and smallholders' land-use decisions depend not only on their integration with cash crops markets but also with other markets, such as those for buying staple food crops, for labor, and consumer goods and accessing credit (de Janvry et al. 1991, Meyfroidt 2017). In particular, smallholders with limited access to consumer good markets lack incentives to increase production to gain more income, and are thus unlikely to respond to increased opportunities for marketing their surplus production. Subsistence producers, which may not be directly in contact with agricultural products markets, can still be affected by changes in market conditions indirectly through their effects on land and labor demand (Dyer et al. 2012).

The related induced institutional innovation theory (Ruttan and Hayami 1984, Ruttan 1997) embeds the long-term intensification processes within a broader market and institutional environment. Technological innovation, not just its adoption, is an endogenous response to changing scarcity of production factors, as institutions (governments, agribusiness companies) invest in developing innovations that enhance labor or land productivity, determined by the scarcity of either. Over the long term, this process is expected to increase the total factor productivity (TFP), which is the ratio of total output compared to all inputs compounded (Coelli and Rao 2005, Fuglie 2015). TFP reflects knowledge, skills, and technological shifts that enhance the productivity of land, labor, and capital (Figure 2B).

3.4 (Neo)classical economic theories of land rent

(Neo)classical economic theories of land rent formalize expansion and intensification processes by building on the underlying value, or rent, of the land, assuming that land will be used for the activity that generates the largest expected value. In Ricardian theory, rent is a function of land's biophysical characteristics, e.g., soil quality and water availability, and of the scarcity of land with high productivity (Ricardo 1817). In contrast, von Thünen's location theory addresses the spatial organization of land use surrounding a central market (von Thünen 1966). In this theory, land rent is a function of the distance to this central market, which affects transportation costs depending on perishability and bulkiness of the farm goods. This generates patterns where crops with high-value and high transport costs are produced near the market, and less valuable and more easily transportable ones are produced further away, holding farm production costs constant across space. Furthermore, within each land use type, intensity of production declines with increasing distance to market.

Land rent manifests itself through the bid rent, or, the maximum amount that any land user would be willing to pay for using that land (Alonso 1964, Peet 1969). Land use extent and intensity change along with bid rent changes, affected by a myriad of factors such as road building, new technologies, climatic change, or market conditions. Such changes move the land-use frontier, usually involving the expansion of the more profitable land use (Walker 2004, Angelsen 2010). Originally, these theories described land use under market conditions where land can be bought or rented, and where goods produced on land are sold on one local, central market. These assumptions are generally relaxed when studying contemporary contexts. Local land uses often responded to distant markets during the colonial era, generating intensive land uses a continent away from the market in question (Peet 1969; Wallerstein 2011). Where land, labor, or products markets are missing or incomplete, concepts of "shadow rents" or "shadow prices" are used (i.e., the value that households put on marginal changes in these variables, Mundlak et al. 2004, Dyer et al. 2006).

Land rent theories underlie many land use simulation models (Irwin 2010, Parker et al. 2012, Filatova 2015), and have been used extensively to explain agricultural change, deforestation (Angelsen 2007, Walker 2004), and urban expansion (Alonso 1964, Sinclair 1967). In urban contexts, further developments include the incorporation of environmental externalities and other amenities into land rent theories (Bockstael and Irwin 2000, Clark et al. 2002), and theories on the role of regulatory institutions such as markets and urban planning policies in shaping different types of land rents (Jager 2003). Higher-level theories of urban land use change posit that cities are "growth machines" organized to intensify land use and thus generate higher land rents (Molotch 1976). Land rent theories may explain broad land use patterns but may fail to explain specific local-level (i.e., parcel) land-use change stemming from individual decision-making (Irwin and Geoghegan 2001).

3.5 Institutional, political ecology and other theories of resource management, access, and appropriation

Another set of theories explains the role of institutions, power, and agent heterogeneity in natural resources management, and in large-scale dynamics of expansion, such as frontiers development or intensification. These theories, drawing from political economy, political ecology, new institutional economics and other sources, focus on the institutions and processes that determine how agents access and use land and other resources needed for agricultural expansion and intensification (e.g., water for irrigation).

The theory of access proposes that technology, capital, markets, knowledge, authority, social identities, and social relations shape how access to land and other resources can be gained, controlled, and maintained (Ribot and Peluso 2003). Access to different resources (land, labor) and capitals (financial, social, cultural) in turn shape the "capabilities" and agency to access additional livelihoods resources and to make land-use decisions (Bebbington 1999). The "environmental entitlements" framework further posits that institutions, defined as regularized patterns of behaviors, mediate the relations between these heterogeneous endowments (assets, capitals) and the entitlements that can be derive from them (Leach et al. 1999, Garrett et al. 2017). Political ecology theories explain that institutions, such as the political and economic systems of the colonial era, shape conflicts over access to environmental resources (Blaikie 1985, Bryant 1998). Other theories also explain how and why farmers diversify towards off-farm activities, with important implications for land use in terms of availability of labor, financial capital, and other resources (Barrett et al. 2001, Rigg 2006, Batterbury 2001).

One prominent institutional theory explains the conditions—called "design principles"—under which different forms of self-governance arrangements of common-pool natural resources can lead to sustainable outcomes. These include clearly defined boundaries of the resource, regulations adapted to local conditions, collective decision-making processes that encompass most resource appropriators, effective and accountable monitoring, graduated sanctions, mechanisms of conflict resolution, and centralized governments that allow local institutions to self-organize (Ostrom 1990, 2005). Institutional theories also discuss the interactions between formal institutions and social organizations (Bebbington 1996).

Theories integrating different insights have been proposed to explain the development of *frontiers*—situations of resource appropriation where land and natural resources are abundant while labor and capital are scarce. The resource frontiers theory expects that, where land is accessible to many potential land users, and with population pressure and increasing affluence, rapid land-use expansion occurs as land-use agents engage in a race for the accumulation of natural resources

(Barbier 2010). Frontier expansion has been described as moving from a populist or pioneer stage, dominated by smallholders whose in-migration is often supported by state policies and infrastructure, toward a capitalized or consolidated stage, where powerful actors consolidate land into large holdings (Pacheco 2005, le Polain de Waroux et al. 2018). In the absence of state planning, these corporate actors produce neoliberal frontiers (Hecht 2005; Brannstrom 2009), where export-oriented farming is motivated more by global demand and deregulated access to land than by government subsidies. The transition from populist to corporate frontiers is associated with two processes. First, declining yields and profitability of pioneer agriculture (due to soil degradation or poor soil quality) with out-migration of smallholders leads to the formation of a "hollow frontier", with depopulation and extensive land uses (Casetti and Gauthier 1977; Hecht 2005; Rudel et al. 2002). Second, a "technology treadmill" occurs when continuing competition leads to intensification and the exclusion of farmers—mostly smallholders—that lag behind due to lack of capital, technology, or knowledge, giving rise to large-scale capitalized agriculture (Levins and Cochrane 1996; Chatalova et al. 2016). Smallholders might sell their land or be displaced, engage in commercial operations as laborers, migrate to cities in a process of "de-agrarianization" (Bryceson and Jamal 1997), or seek cheaper land elsewhere, driving further frontier expansion (Richards 2012, 2015, Section 4.2). Such treadmill occurs in various contexts, not only frontiers. "Commodity frontiers" correspond to contexts dominated by large-scale commodity agriculture in which "abnormal" rents (i.e., land rents much higher than land prices) caused by changes in technology, regulations or other conditions, are maintained through imperfect land market conditions and the heterogeneous capabilities of agents in appropriating these rents. The latter depends on these agents' access to production factors and their information, preferences, and agency (le Polain de Waroux et al. 2018).

Institutional and political ecology theories are also increasingly invoked to explain urban land dynamics at different scales (Roy Chowdhury et al. 2011). Different theories explain that decisions on urban landscapes, from private residential greenspace management to large-scale patterns of urban expansion and densification (i.e., intensification), derive from nested factors at distinct social-hierarchical scales. These factors include (i) household-level characteristics and environmental attitudes (Larsen and Harlan 2006), and social stratification and lifestyle groups (e.g. Ecology of Prestige – Grove et al. 2006); (ii) neighborhood-scale formal and informal institutions (Robbins and Sharp 2003; Heynen et al. 2006) and housing filtering, i.e., the change in status and income of the population of a neighborhood over time (Muth 1969; Bond and Coulson 1989); and (iii) municipal-scale land-use governance such as planning and zoning (Munroe et al. 2005; Irwin and Bockstael 2007) and regional development trends in industrial and transportation infrastructure, and differential diffusion (Geyer and Kontuly 1993). As with other land uses, urban areas can expand but also disintensify and contract. Contemporary processes of recession, de-growth and de- (or post-)industrialization, as well as shifting patterns of urban-rural connectivity and changing public discourses are increasingly theorized to shape urban urban shrinkage and out-migration (Nelle et al. 2017). New, post-industrial economies and governance destabilize industrial urban morphologies by introducing "creative" islands and edges of urban heritage, innovative building design, and new urban open/public spaces and peripheries (Gospodini 2006). Recession landscapes also reflect declining values of residents' willingness to pay for environmental amenities, which affect patterns of urban disintensification (Cho et al. 2011).

3.6 Theories of social-ecological feedbacks

Another set of theories focus on how feedbacks between human and ecological dynamics shape land use. We highlight four influential approaches among a wide variety: regime shifts, resilience dynamics, social-ecological systems, and farmers' adaptation to environmental change.

Regime shifts are large, abrupt, persistent changes in the structure and function of ecosystems (Biggs et al. 2012, Kull et al. 2017). Regime shifts highlight that land systems can experience surprising, non-linear shifts from being around one set of mutually reinforcing structures and processes to another, through the interaction of 'fast', such as weather or market fluctuations, and 'slow' processes, such as erosion of crop diversity (Scheffer et al. 2001, Biggs et al. 2012, Müller et al. 2014, Ramankutty and Coomes 2016). Such theories have focused on economic, bio-cultural, biophysical and health feedbacks mechanisms that can produce 'poverty traps', e.g., through agricultural involution (Lade et al. 2017), as well as on how human-mediated ecological processes such as fire, nutrient cycling, grazing, and water flows regulate regime shifts (Gordon et al. 2008, Bestelmeyer et al. 2015, Jepsen et al. 2015, Rocha et al. 2015). In land systems, the regime shifts perspective helped understand ecological dynamics such as savanna-forest and tundra-forest transitions as influenced by fire and climatic conditions, and herbivory pressure (Rocha et al. 2015). This perspective underlies theories of land-use transitions (Section 5).

Another stream of research focusing on regional environmental management and governance highlights diversity and disturbance as key aspects of the resilience of social-ecological systems (Berkes et al. 2008). Successful intensification usually simplifies ecosystems, reducing their self-regulatory capacity (Holling and Meffe 1996). Societal dependence on land products necessitates increasing investments in artificial regulation to stabilize outputs, which may lead to a 'rigidity trap' in which a large part of the output is absorbed for maintaining production, or to a transition to another land system with new actors and land uses (Allison and Hobbes 2004, Vang Rasmussen and

Reenberg 2012, Goulden et al. 2013). Research on path dependence and sunk costs in land systems, in relation to landesque capital, builds on this perspective (Janssen et al. 2003).

Works building on the social-ecological systems perspective explored how formal and informal institutions shape and are shaped by social-ecological interactions (Ostrom 2009), and how features of society and ecosystem create fit and misfit between social and ecological dynamics, and enable or impair collective action to address shared environmental problems (Janssen et al. 2007). These studies highlight that institutions regulating natural resources are diverse and include governments, other public institutions, traditional regulations, and cultural norms.

Finally, a large stream of literature proposes theories on how environmental signals are incorporated into decision-making (Verburg 2006, Lambin and Meyfroidt 2010, Meyfroidt 2013). These insights suggest that land use intensification or changing regulations can arise as a response to the degradation of ecosystem services linked to expansion into natural ecosystems under the conditions that this degradation is perceived, interpreted and valued. These perceptions and valuation of environmental change build on cultural backgrounds of what constitute valuable ecosystem services (Daniel et al. 2012). Multiple works have also explored the conditions under which farmers are expected to adopt innovative agricultural practices in response to climate and other environmental change (Prokopy et al. 2008, Niles et al. 2015).

4. Theories of land-use spillovers

We here propose middle-range theories of complex land system processes, such as land-use spillovers and displacement, combining several of the theories discussed above. *Land-use displacement* refers to the separation between places of production and consumption, but has been used in a broader sense to refer to geographic shifts of land use from one place to another (Meyfroidt et al. 2013). *Land-use spillovers*, which can explain some forms of displacement, refer to situations where land-use changes or direct interventions on land use (e.g., policy, program, new technologies) in one place have impacts on land use in another place. With globalization and increasing complexity in land-use change processes, land-use spillovers have constituted a focus for research over the recent years (Lambin and Meyfroidt 2011). Theoretical synthesis on the various forms of land-use spillovers and the mechanisms and conditions under which they occur is thus timely. Various forms of spillovers have been distinguished, including leakage, indirect land-use change, and rebound effects. *Leakage* is a form of spillover caused by a land-use intervention, such as an environmental conservation policy, which triggers land-use change elsewhere that reduces the overall benefit of the local intervention (Meyfroidt and Lambin 2009, Ostwald and Henders 2014).

Indirect land-use change (iLUC) is a land-use change in one place caused by a land-use change in another place (Lapola et al. 2010). Following this definition, all land-use leakage occurs through iLUC. A *rebound effect* is a form of spillover where adoption of intensifying practices stimulates land-use expansion (Angelsen and Kaimowitz 1999, 2001, Lambin and Meyfroidt 2011). Other spillovers have been shown, e.g., between agriculture and forestry through the increased consumption of wood pallets to export agricultural products (Jadin et al. 2016a).

4.1 Land sparing and rebound effect

Intensification is often promoted to fulfill growing societal demands for land-based products, while reducing pressure on land and thus preserving nature, an effect called land sparing or the Borlaug hypothesis (Figure 3). Land sparing can be *absolute*, i.e., resulting in net farmland contraction (Rudel et al. 2009). Globally, intensification of staple crops through the Green Revolution has resulted in *relative* land sparing, i.e., reducing per-capita land demand or the rate of agricultural expansion compared to the counterfactual scenario without intensification, although net agricultural area still increased (Stevenson et al. 2014). The potential impacts of land sparing on biodiversity conservation and livelihoods are debated (Loos et al. 2014, Kremen 2015, Phalan et al. 2016, Fischer et al. 2017). Key assumptions are that intensification spares land and that this land is returned to nature. In reality, intensification can also lead to a rebound effect, i.e., a form of spillover where adoption of intensifying practices stimulates land-use expansion (Angelsen and Kaimowitz 1999, 2001, Lambin and Meyfroidt 2011). Such rebound effect, also known as Jevons' paradox, occurs when intensification increases the profitability of agriculture. Theories identify the conditions under which intensification can spare land – potentially allowing for nature conservation – or is more likely to lead to a rebound effect. Rebound effects include the direct response of the original agents reinvesting an additional income or spared production factors into expansion. It also includes indirect, systemic effects linking increased land-use efficiency to land-use expansion such as through increased consumption of other goods thanks to lower spending on goods produced more efficiently (Greening et al. 2000, Sorrell et al. 2007).

At local scales, land sparing is more likely to occur when intensification increases local production costs per unit, i.e., when intensification requires scarce and thus expensive capital or labor inputs such as irrigated paddy fields (Villoria et al. 2014, Byerlee et al. 2014) (Figure 3, Place A), and when there are strong biophysical, institutional, or other restrictions on accessing land, or high demand for environmental amenities (Rudel et al. 2009, Meyfroidt and Lambin 2011, Phalan et al. 2016). Local land sparing is also more likely when the demand for the product is inelastic to price, i.e., when although intensification makes agriculture more efficient and less costly, this decrease in production costs does not lead to an increase in demand, as in the case of inferior goods (such as staple caloric crops), or when markets are closed (Hertel et al. 2014). In contrast, a rebound effect is more likely to occur at local level when there are low physical or institutional restrictions on land-use expansion and when demand is elastic to price, as is the case for superior goods such as meat, luxury or leisure crops (e.g., cocoa, coffee), feed or bioenergy crops (Lambin and Meyfroidt 2011), or when markets are well-integrated and the intensifying region or producer is large enough to influence prices (e.g., soybean in South America) (Hertel et al. 2014). A rebound effect is also likely when intensification occurs by switching to highly profitable production alternatives with high income elasticity of demand, i.e., products for which demand increases strongly when income rises, such as meat in developing countries. Finally, a local rebound effect is likely when intensification results in increased competitiveness, i.e., the ability and performance of a producer or a region to sell products in a given market compared to the ability of competing regions and producers. Competitiveness increases with intensification when initial yields were low in the intensifying region, and when production costs decrease, as manifested by TFP increases, such as with agglomeration economies (Section 4.3) or low cost of capital and labor (Hertel et al. 2014).

The local land sparing or rebound effect may further affect regional or global land use through markets, depending on the level of market integration (Figure 3, Place B). When local land-sparing intensification is associated with increased local production costs, it may trigger an upward effect on prices when the affected region is large (Hertel et al. 2014, upper part of Figure 3). If the demand on this larger market is elastic to price, demand will reduce, without or with few impacts on land use elsewhere. But if the demand is inelastic to prices and thus stable, the upward shock on price may trigger an intensification or expansion in places that, relatively, gain competitive advantage, and an acceleration of land sparing in the initial place that has lost competitiveness. In the medium or long term, local intensification may promote economic growth and wage increases, and thus cause an indirect rebound effect, locally or globally, by stimulating consumption. Conversely, a rebound effect that makes local land use more competitive may, when happening in a large region, trigger a downward shock on prices in broader markets (Angelsen and Kaimowitz 2001, Villoria et al. 2014, lower part of Figure 3). If demand is inelastic to prices, it may induce land sparing in other regions that have lost competitiveness. When demand is elastic to prices or is increasing because it is elastic to income and wages are rising, the downward effect on prices triggers increased demand and thus further intensification or expansion. When the local and distant effects on land use go in opposite directions, the net balance in area of land being used depends (i) on the relative yields of the place where the initial intensification occurs, versus those where the expansion occurs (Hertel et al. 2014), and (ii) on whether changes in production in distant places occur through changes in area or intensity. An additional condition for absolute land sparing is that productivity increases faster than the demand.

4.2 Leakage and indirect land-use change

Policies aimed at setting aside land or restricting land-use expansion can result in leakage through different pathways, each of which can be explained by a specific middle-range theory (Figure 4). An effective policy may reduce availability of land directly through restricting access or indirectly through set-aside incentives. In turn, increasing the scarcity of land would result in increasing land price, and possibly decreasing the profitability of land use. We identify four leakage mechanisms, which interact in reality: *activity* leakage, *land-market* leakage, *commodity-market* leakage, and *supply-chain* leakage. Leakage is a challenge for example in policies aiming at reducing deforestation, such as through protected areas, the Reducing Emissions from Deforestation and Forest Degradation (REDD+) scheme, or the New York Declaration on Forest and other multi-stakeholders zero-deforestation agreements.

Activity leakage occurs when production factors or inputs are highly mobile such that labor and capital used on the land targeted by the restrictions are reallocated to places with available and accessible land (Atmadja and Verchot 2012, Lim et al. 2017, Pfaff and Robalino 2017). This pathway is akin to the “pollution haven hypothesis” (le Polain de Waroux et al. 2016), according to which polluting companies react to environmental legislation by moving their activities to places with fewer restrictions. Activity leakage is more likely to occur through labor reallocation under conditions of subsistence agriculture, with lack of off-farm alternatives or cultural preferences for land-based activities, and through capital reallocation when sunk costs of capital investments in the initial place are not too large (e.g., extensive cattle ranching which has little fixed assets) (Atmadja and Verchot 2012, Henders and Ostwald 2012). Unfavorable conditions for intensification locally, and growing demand for the affected product reinforce this pathway by creating incentives for producers to continue production elsewhere.

Land-market leakage can also occur, where appreciation of land rent in the affected place spreads through land markets to land situated elsewhere, driving land investments, including deforestation, in these places (Richards 2015). In the region affected by regulations, increase in price of the non-affected land can facilitate activity leakage by providing landowners with financial capital to reinvest elsewhere, as suggested for Brazilian Amazon frontiers (Arima et al. 2018, Richards and Arima 2018). Although in principle this path can occur as leakage from policy restrictions, it is more likely to occur as a form of indirect land use change resulting from an increase in demand of a commodity, as exemplified by soybean demand increasing land prices and driving cattle expansion in the Brazilian Amazon (Arima et al. 2018, Richards and Arima 2018).

The initial intervention can result in a decrease in production when land is set aside, regulations are imposed on input use, production costs are increased, or expansion is restricted (le Polain de Waroux et al. 2017, Lim et al. 2017, Pfaff and Robalino, 2016). A large shock on production relative to the size of the product's market—when the affected region is large (Hertel et al. 2014) or in smaller, segmented markets—may trigger a price increase, depending on the degree of market integration and the price transmission for this good. This market shock can be absorbed in three ways. Firstly, the greater the demand-elasticity to price, the more the price increase is absorbed on the demand side through a reduction in consumption of the affected good. Secondly, intensification is likely to occur, locally or distantly, if labor or capital inputs, TFP-enhancing technologies, and production technologies with flexible input-ratios –i.e., which can accommodate diverse combinations of labor and capital-based inputs– are available, and if land supply is restricted (Wunder 2008, Börner et al. 2017). A similar result could be obtained if the affected good can be substituted by another one with lower land demand. Thirdly, if the intervention takes place in a high-yielding region and the conditions for intensification are not met in the different regions where production takes place, the market shock is more likely to be absorbed through *commodity-market leakage*, in which land use expands elsewhere in response to changes in product prices. Examples are the possible restructuring of timber markets in response to policies for Reducing Emissions from Deforestation and Forest Degradation (REDD+) in tropical regions (Jonsson et al. 2012) and of soybean markets under changing environmental governance (le Polain de Waroux et al. 2017). Such leakage may also occur if the affected good is substituted by more land-demanding goods.

The same chain of spillovers can also be triggered when the existing land use is replaced by another land use. The effect is then called indirect land-use change. This pathway can be due to a policy supporting the good derived from the second land use (e.g., a biofuel policy or supply chain intervention that support the production of a "clean" alternative good), or any other process leading to an expansion or increase in demand for that second good. Processes of large-scale land acquisitions (also referred to as "land grabs") and technology treadmill (Section 3.5) can also lead to indirect land-use change, in particular through the *activity* mechanism.

Finally, a supply-chain intervention that excludes a given good or suppliers who do not meet sustainability standards can also result in leakage along the pathways described above (Alix-Garcia and Gibbs, 2017, le Polain de Waroux et al. 2017). But in addition, it can also lead to a *supply-chain leakage*, where producers continue to produce the same good but shift to other buyers, sell their products by "laundering" them through intermediaries that are compliant with the intervention, or switch to producing another good with high environmental impacts (Rausch and Gibbs 2016, Lambin et al. 2018). We propose that this leakage occurs if (i) the incentives to improve production practices are insufficient; (ii) the origin of a product can be easily concealed due to complexity in the life cycle of production, (iii) the stickiness or rigidity in supply chains is low—due to low transaction cost or substitutable goods—, i.e., producers, buyers, and intermediaries can easily shift their activities from one market to another (Villoria and Hertel 2011); and (iv) the affected producers have a competitive advantage against producers elsewhere or can switch to alternative, profitable land uses.

4.3 Other processes of land-use spillovers and displacement

Other spillover effects such as specialization of regions through clustering of specific activities have been explored with economic geography theories of competitive advantage due to technology spillovers (Porter 2000, Fujita et al., 1999). These theories formalize an economic tradeoff between centripetal forces promoting spatial concentration of economic activities, and centrifugal forces triggering their dispersion. The agglomeration factors for a particular activity in each location (i.e., travel costs to markets and jobs, availability of skilled labor, innovation spillovers, and social amenities) are weighted against dispersion factors (i.e., density, land prices, negative spatial environmental externalities). From a business strategy perspective, clustering and intensification of related activities in specific locations lead to path-dependent increasing returns to scale when output increases faster than inputs (Krugman, 1991). The influence of agglomeration economies, or positive externalities associated with the clustering of activities, has been widely used in urban studies to explain how the migration of workers to a city eventually gives rise to an increase in goods and services available, which drives further migration (Fujita and Krugman 1995). The concept of agglomeration economies has also been increasingly integrated into land-use studies in the agricultural and forestry sectors to understand regional variations in land rents that are not explained by Ricardian and Thunian theories (Garrett et al. 2013, Richards 2017).

5. Theories of land-use transitions

Changes in land-use extent and intensity interact to produce non-linear trajectories of land systems. Rapid, non-linear changes in land resource uses are driven by positive feedbacks, where initial interventions or disturbances precipitate a cascade of further changes (Peters et al. 2004, Ramankutty & Coomes, 2016). These dynamics produce land-use transitions, which are structural transformations of land systems from one dynamic equilibrium to another (Lambin and Meyfroidt

2010, Müller et al. 2014), akin to regime shifts in complex systems theory (Scheffer et al. 2001, Biggs et al. 2012, Filatova et al. 2016, Kull et al. 2017, Section 3.6). The development of theories of land-use transition constitute a key achievement of recent land system science, which we synthesize here.

5.1 Forest transition theories

One well-studied type of land-use transition is forest transition, which describes a structural shift from net forest loss to net forest gain through natural regeneration or planted forests (Mather 1992). Forest transitions in the 19th and early 20th centuries occurred mainly in temperate, developed regions, but are increasingly observed in tropical regions as well (Meyfroidt and Lambin 2011).

Three land-use dynamics explain how land is made available for restoration of natural ecosystems and reforestation in one social-ecological system, apart from a decrease in demand (Jadin et al. 2016b) (Figure 5). Firstly, agricultural and forestry intensification can lead to abandonment and reforestation (Green et al. 2005, Section 4.1). Secondly, a spatial redistribution of land use to better match land suitability in increasingly integrated markets may also result in intensification and land sparing (Mather & Needle, 1998, Nanni and Grau, 2017). Thirdly, international trade in land-based products may facilitate forest recovery in one place by displacing pressure on environments elsewhere, as leakage or in response to changes in global markets (Meyfroidt et al. 2010, Section 4.2). Reforestation can arise from natural regeneration on abandoned land, or from tree plantation or assisted nature restoration.

Processes of forest transition have been described through interacting pathways combining these three land-use dynamics and influenced by multiple drivers (Rudel et al., 2005, Meyfroidt and Lambin 2011, Liu et al., 2017; de Jong et al., 2017,). Each of these pathways has been explained by one middle-range theory of forest transition (Figure 5). The *economic development* theory highlights urbanization and industrialization driving labor scarcity in agriculture, and intensifying and concentrating production on the most suitable land, thereby retiring marginal agricultural lands from production (Rudel et al., 2005). Substitution of wood-fuel by fossil and other energy carriers also strongly contributes (Erb et al. 2008). This mechanism is often framed at the national level, ignoring cross-border leakage or international labor migration. The influence of these international processes on national-scale reforestation have been integrated in the *globalization* theory (Mansfield et al., 2010; Meyfroidt and Lambin, 2009; Kull et al., 2007; Hecht and Saatchi, 2007; Li et al., 2017; Jadin et al., 2016b). Trade may correspond to deforestation leakage to countries with less strict environmental regulations (Section 4.2). International trade may also facilitate the concentration of land use on the most suitable lands, possibly relieving pressure on marginal ecosystems in a global-scale land sparing (Section 4.1) (Kastner et al., 2014, Youn et al., 2017). The diffusion of global efforts and ideologies for nature conservation, such as biodiversity protection or carbon sequestration, may also drive reforestation (Hecht and Saatchi, 2007; Kull et al., 2007).

In the *forest scarcity* theory, economic, political, and cultural responses to environmental degradation and the scarcity of forest products and services drive forestry intensification, tree plantation and rehabilitation, land set-asides, and protection of remaining natural habitats (Hyde, Amacher, & Magrath, 1996; Lambin & Meyfroidt, 2010; Rudel et al., 2005, Park and Youn, 2017). This is a form of regime shift characterized by negative feedbacks. Government actions to protect and plant forests may follow various motives beyond forest scarcity, including geopolitics, state consolidation, and prejudices against minority groups (Peluso and Vandergeest, 2001; Hecht et al., 2014, McElwee 2016). These state actions fall under a *state forest policy* theory, which can be considered a variant of the forest scarcity one (Lambin & Meyfroidt, 2010). Governmental support for tree plantation often lies at the intersection of economic development and forest policies (Zhang et al., 2017; Cochard et al., 2017).

The *smallholder, tree-based intensification* theory results from dynamics at the smallholder farm scale that influence planting or maintenance of trees (Rudel et al., 2002; Pokorny and de Jong, 2015). Dynamics of agroforestry, sylvo-pastoral management and gardens can result in a "tree cover transition" that extends beyond forests in the strict sense (van Noordwijk et al. 2014). Other pathways have been suggested, including the "impacts of war and conflict", which ascribe either deforestation or forest recovery to side effects of geopolitical conflict (Hecht et al., 2014, Hecht and Saatchi, 2007; Robert-Charmeteau, 2015; de Bremond, 2013). These theories of forest transition have been formalized through several disciplinary lenses, such as land rent frameworks (Barbier et al., 2010). The different pathways of forest transition lead to distinct ecological impacts and environmental values of returning forests (Kull 2017, Wilson et al. 2017).

5.2 Other land-use transition theories

Paralleling forest transition theories, urban theories explain cycles of urban growth, decline and renewal (Clark et al. 2002). Stylized theories of land-use transition, more akin to grand theories, posit that land use in a region follows a series of transitions that accompany socioeconomic development and changes in societal metabolism. Sequences run from wildlands with low human population densities dependent on hunting, foraging, resource extraction, and extensive use of fire, to frontier clearing for subsistence agriculture, and increasingly intensive and commercial agricultural systems, ultimately leading to intensive industrial agriculture supporting large urban populations, and the abandonment of low-suitability agricultural lands (DeFries, Foley, & Asner, 2004; Fischer-Kowalski & Haberl, 2007, Jepsen et al. 2015). These theories aim to explain long-term land-use trajectories, which are presented as a directional modernization process akin to Rostow's stages of growth (Rostow 1960). It also evokes the environmental Kuznets curve, which posits increasing environmental degradation in early stages of economic development and a reversal with higher income, in a trajectory moderated by policies (Barbier, Burgess, & Grainger, 2010). These transitions can be theorized as resource substitution and problem shifting, where adoption of intensive fossil fuel-based land use displaces impacts from land systems towards climate (Erb et al. 2008). In a similar way, sociocultural niche construction theory explains long-term changes in human societal scale and transformation of the biosphere through land use as the product of sociocultural evolution in subsistence regimes based on ecosystem engineering, social specialization, and non-kin exchange (Ellis 2015). Some of these stylized theories have been criticized for being overly deterministic, simplifying the actual complexities of land-use trajectories, and ignoring trade, geopolitics, and other relations between regions (Perz, 2007; Walker, 2008). Yet, they provide a bird's eye perspective and umbrella frameworks under which more specific middle-range theories can be formulated.

6. Directions for further theory development

Middle-range theories of land system change can be formulated to synthesize key processes of land-use change and the conditions under which these processes manifest. Such middle-range theories provide a constructive path towards more generalized knowledge of human-environment systems (Magliocca et al. 2018). These theories remain to be further tested and refined, particularly regarding the conditions leading to different pathways. Several emerging trends in land systems require further theoretical development, including relations between urban and rural areas (Seto et al. 2012), such as central flow theory (Taylor et al. 2010); transnational land acquisition (or "land grabbing") and land speculation, and associated land-use displacement and conflicts (Zomers 2010, McMichael 2012); and new forms of private and hybrid land governance where supply chain actors and consumers promote the adoption of voluntary sustainability standards and sourcing practices (Rueda et al. 2017, Lambin et al. 2018, Lambin and Thorlakson 2018).

Connectivity among distant places is increasing, and globalization plays an increasingly important role in driving land systems dynamics through trade but also via information flows and increased human mobility. Beyond understanding the conditions and mechanisms under which spillovers occur, further theoretical developments are required to explain how connectivity—access to land, markets, technology, information, and financial capital—institutions, and sustainability values shape the susceptibility of different places to receive spillovers. A stronger integration with social theory would allow conceptualizing spillovers as a land use moving across a social as well as physical space, and investigating interactions between these two spaces (Faust et al. 1999).

Theoretical progress will continue to arise from integration with other fields that bring different perspectives on land systems. This encompasses explanations of the emergence of certain spatial patterns of land uses that shape landscape structure and influence social and environmental impacts (Middendorp et al. 2016). Land-use theories incorporate socio-economic and institutional drivers of land system change, but could better account for interactions between biophysical processes and human behaviors at multiple scales (Lade et al. 2017), and the short- and long-term co-evolutionary dynamics between human societies and environments (Gual and Norgaard 2010; Ellis 2015; Waring et al. 2015). Theories could also improve understanding of cross-scale interplays between macro-level phenomena, such as landscape patterns, structures or new functions, and micro-level interactions by building on landscape ecology (Wu, 2013), complex adaptive systems (Page 2015), and sociological approaches on micro-macro interactions (Coleman, 1990). Research on common-pool resources (fisheries, water systems) can also provide insights on cooperation and collective action for sustainable land management. Similarly, research on ecosystem services captures multiple connections between people and nature across landscapes. Theories of land-use spillovers and displacement could better integrate various streams of theories that focus on globalization and telecoupling (Liu et al. 2013, Friis et al. 2016), including: (i) critical sociological theories related to world system theories, such as dependency theory (Frank 1978), core-periphery relations, and (ecological) unequal exchange (Hornborg 1998, Muradian and Martiez-Alier 2001, Moran et al. 2013), (ii) sociological and economic geography theories that analyze the structure and functioning of global production networks and global value chains, and financialization of land uses (Gereffi et al. 2005, Munroe et al. 2014, Isakson 2014), and (iii) anthropological theories of “scapes” that articulate the different types of information and cultural flows that link distant places (Escobar 2001, Tsing 2005, Niewöhner et al., 2016). Spillover theories could also better integrate environmental processes such as Earth system teleconnections from land-use changes to distant regions via changes in rainfall regimes (Keys et al. 2017), spillovers between biodiversity and ecosystem services (Maestre Andrés et al. 2012), or poverty traps linked to land degradation and loss of resilience (Barrett and Bevis 2015, Lade et al. 2017, Haider et al. 2018).

Land system science theories largely rely on the rational actor and expected utility theory as a basis for apprehending human decision-making and behavior. The theories hence assume that agents act purposefully to attain their goals and maximize their well-being according to their expectations (Meyfroidt 2013, Groeneveld et al. 2017). Agent behavior can take the simple form of selfish utility maximization with perfect information, or more refined forms of bounded rationality models

(Simon 1956, Gotts et al. 2003), other-regarding preferences (Fehr and Fischbacher 2002, Sautter et al. 2011), or prospect theory (Ligmann-Zielinska 2009). Land system theories could benefit from incorporating theories of human behavior to address the diversity of motivations and cognitive processes as well as the role of social networks that determine land-use choices, responses to environmental change, and social norms related to land use (Meyfroidt 2013, Schlüter et al. 2017, Groeneveld et al. 2017, van Duinen et al. 2015). For example, empirical studies on smallholder agriculture or ecosystem services are now considering diverse forms of individual and collective relationships to nature that include sense of place and embodiment (Masterson et al. 2017, Raymond et al. 2017), psychological theories of planned behavior (Schwarz and Ernst 2009), and theories from behavioral economics (Nyborg et al. 2016) that account for decisions that deviate from the expected utility theory.

We barely addressed the normative aspects of sustainability and the tradeoffs and synergies between social, economic, and environmental objectives (DeFries et al. 2004, DeFries and Nagendra 2017). Developing interventions to improve the sustainability of land systems first requires solid theoretical foundations on the causes of land-use and land-cover change and how they can be influenced. The discourses on “sustainable intensification”, for example, often rely insufficiently on theoretical knowledge of intensification dynamics and their spillovers and trade-offs (Loos et al. 2014, Rockström et al. 2017).

7. Conclusion

A major challenge in land system theories is that land is simultaneously a biophysical entity, a territory, a commodity, a habitat for nonhuman species, a resource for productive activities, and a buffer for absorbing pollutants. It is allocated, regulated, and administrated by various laws, norms, and rules. It is also a source of meaning and sense of place, a landscape component, and symbolically loaded. Theories of the causes of land system changes cross theoretically and epistemologically disparate knowledge domains, and build on deductive, abductive, and inductive approaches. A grand, integrated theory of land system changes remains elusive. Nevertheless, the past decades have seen the elucidation of chains of causal mechanisms that explain well-bounded phenomena, and the conditions and contexts under which they occur, laying the foundations for middle-range theories on how, why, when, and where land systems change. We have reviewed the major theories of land-use expansion and contraction, intensification and disintensification, and synthesized theories on land-use spillovers including leakage, indirect land-use change, rebound effect, and land-use transitions, with a focus on agriculture and forestry. Middle-range theories come in a nested way, with different degrees of generality: Different pathways leading to a given process each correspond to a theory, but our consolidated account of each of these land system processes is a higher-level middle-range theory. A similar approach articulating chains of causal mechanisms, and the conditions and contexts under which they operate, could be applied to other land and social-ecological systems processes to enrich the portfolio of middle-range theories. Theories of change for sustainability governance would be strengthened by building on causal chains derived from such middle-range theories. Along with basic frameworks, case-specific explanations, and grand theoretical schemes, middle-range theory development constitutes an important endeavor for land system science and for the study of human-environment interactions and sustainability science.

Figures captions

Figure 1. Main theories of land-use expansion and intensification

Theories are mapped by the contexts and agents for which they have been formulated, though they can be used for other contexts. The X-axis distinguishes contexts and agents according to their degree of market integration and commercialization of land use. This axis encompasses the (i) accessibility of markets for inputs (e.g., financial capital, skilled labor, machinery, agrochemicals, but also land); (ii) accessibility and reliability of markets for outputs; and, (iii) share of the farm output which is marketed, or importance of markets for livelihoods. Not all these dimensions necessarily coincide (e.g., large companies in frontiers situations can be fully integrated into global outputs markets but face imperfect land markets; le Polain de Waroux et al. 2018). The Y-axis distinguishes land-use agents (households, farms, companies) in their degree of reliance on labor versus capital-based inputs. Most land uses, e.g., cropland, grazing lands, forestry, agroforestry systems, can fall under various degrees of inputs types and market orientation, depending on the specific context and agents, with different land users operating in the same landscape possibly having different positions in this graph.

Figure 2. Theoretical trajectories of land-use intensification and changes in productivity

Fig. 2A. Classic trajectories of land-use intensification articulating the theories of Boserup, Malthus, and Geertz (adapted from Ellis et al. 2013, inspired by Turner and Ali 1996). Fig. 2B. Intensification trajectories expressed in terms of labor, energetic and economic efficiency versus land productivity. Labor productivity is expected to decline under Boserupian intensification without mechanization or higher capital intensity (e.g., more fertilizers applications per unit area) (Section 3.2). Energetic efficiency (measured as energy return per unit of energy invested, EROI) is expected to decline under most forms of intensification, though it declines more strongly under capital-based, industrial intensification than under agroecological intensification. With decreasing labor productivity under Boserupian intensification, or lower energy efficiency under industrial intensification, total factor productivity (TFP) may decline unless new technologies or institutional arrangements allow a structural transformation of the land-use system towards higher TFP, until reaching again a point of decreasing marginal returns and possible decline (inspired by Stone (2001).

Figure 3. Theory of land sparing and rebound effect with intensification

The causal chain starts from the left with an intensification event, which can be induced by pressure on land, new technologies, or other factors (Section 3). Each arrow describes a causal link between two events, under the conditions indicated in the boxes overlaid on the arrows. The left panel (Place A, dark green) describes the effects on the place where this initial intensification occurs. The right panel (Place B, light green) describes potential effects on the broader market (or local market if the initial place is disconnected from broader markets), and possible feedbacks to the initial place.

Figure 4. Theory of leakage and indirect land-use change (iLUC)

The causal chain starts from the left with an intervention restricting land use in one place (Place A, dark green box). Each arrow describes a causal link between two events, under the conditions indicated in the boxes overlaid on the arrows. The leakage pathways on the right panel (Place B, light green box) can take place locally or distantly, depending on conditions that make local or distant places more susceptible to receive leakage. The three triggers on the top-left give rise to the same land-use processes, but these are then called iLUC. Leakage pathways can also be triggered by a supply chain intervention that bans a given good or production method (e.g., if its production entails deforestation).

Figure 5. Theories of forest transition

The central panel, starting from the left, describes the processes within a given area (e.g., country) for which forest transition is observed. Each arrow describes a causal link between two events, under the conditions indicated in the boxes overlaid on the arrows. The upper and lower horizontal panels describe exogenous drivers linked to globalization. Background colors indicate the different pathways (i.e., middle-range theories) of forest transition.

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Figures

Figure 1. Main theories of land-use expansion and intensification

Figure 2. Theoretical trajectories of land-use intensification and changes in productivity

Figure 3. Theory of land sparing and rebound effect with intensification

Figure 4. Theory of leakage and indirect land-use change (iLUC)

Figure 5. Theories of forest transition

FIGURE 1 | Main theories of land use expansion and intensification

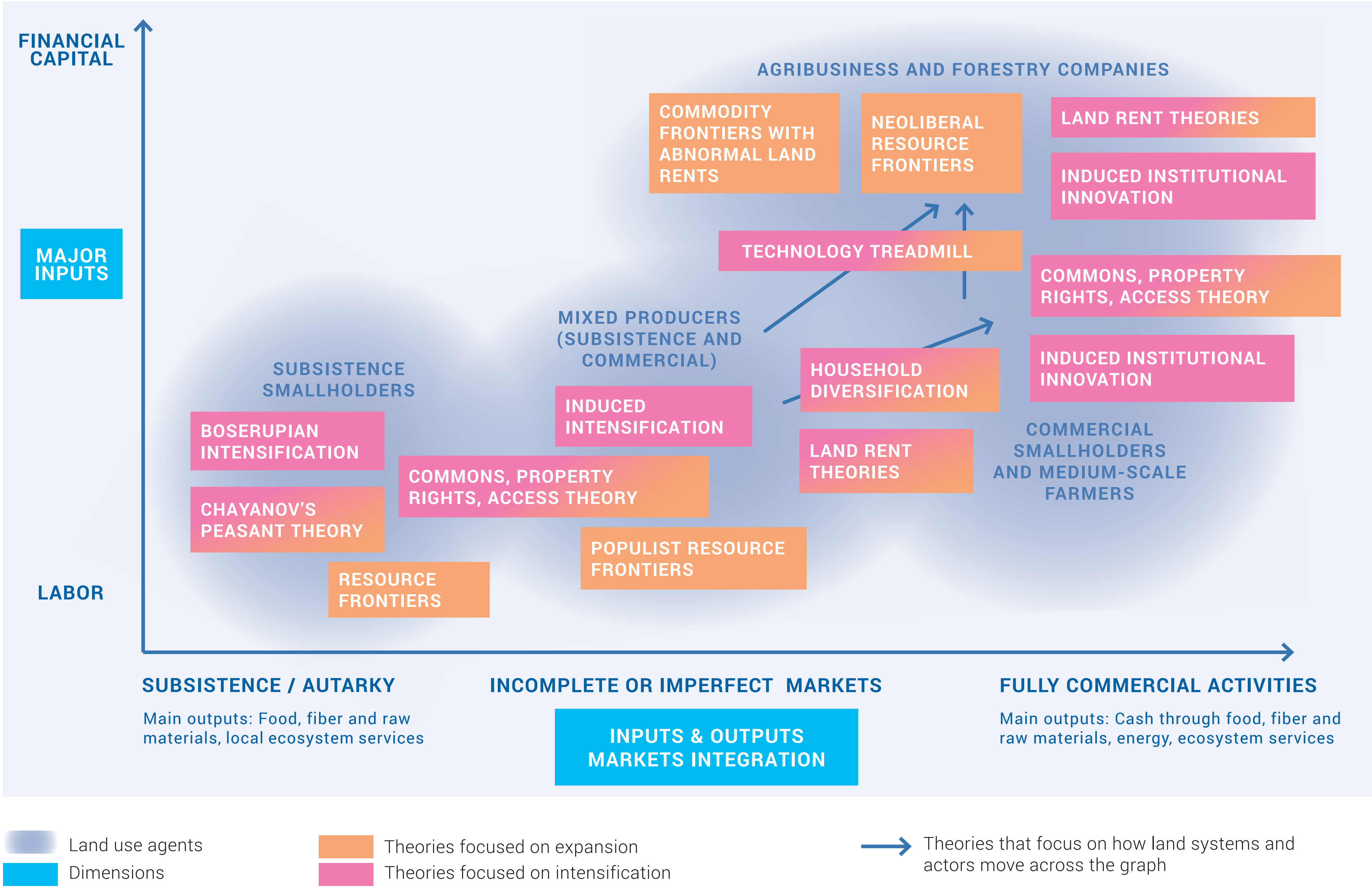

FIGURE 2 | Theoretical trajectories of land-use intensification and changes in productivity

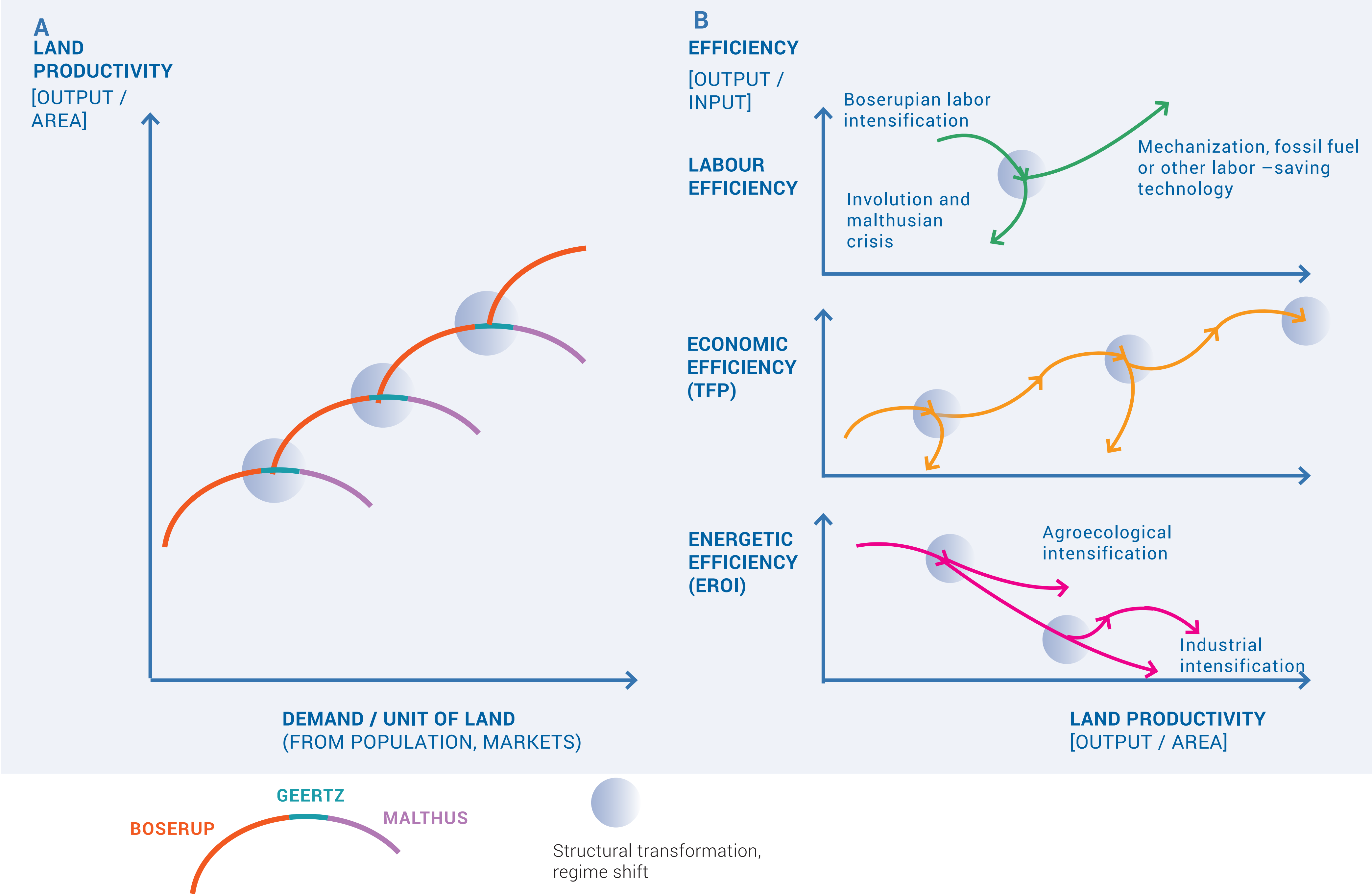

FIGURE 3 | Theory of land sparing and rebound effect with intensification

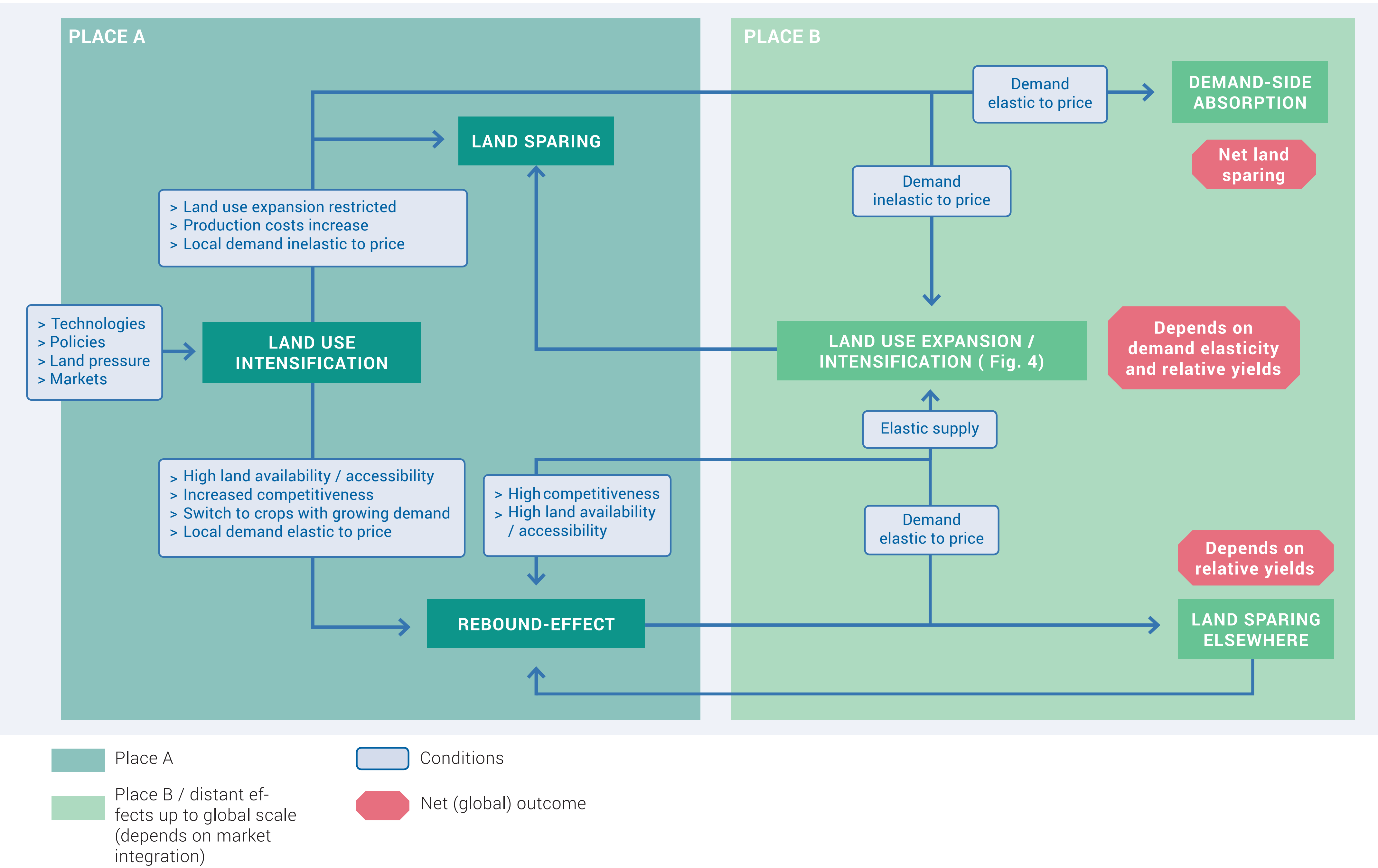

FIGURE 4 | Theories of leakage and indirect land use change (iLUC)

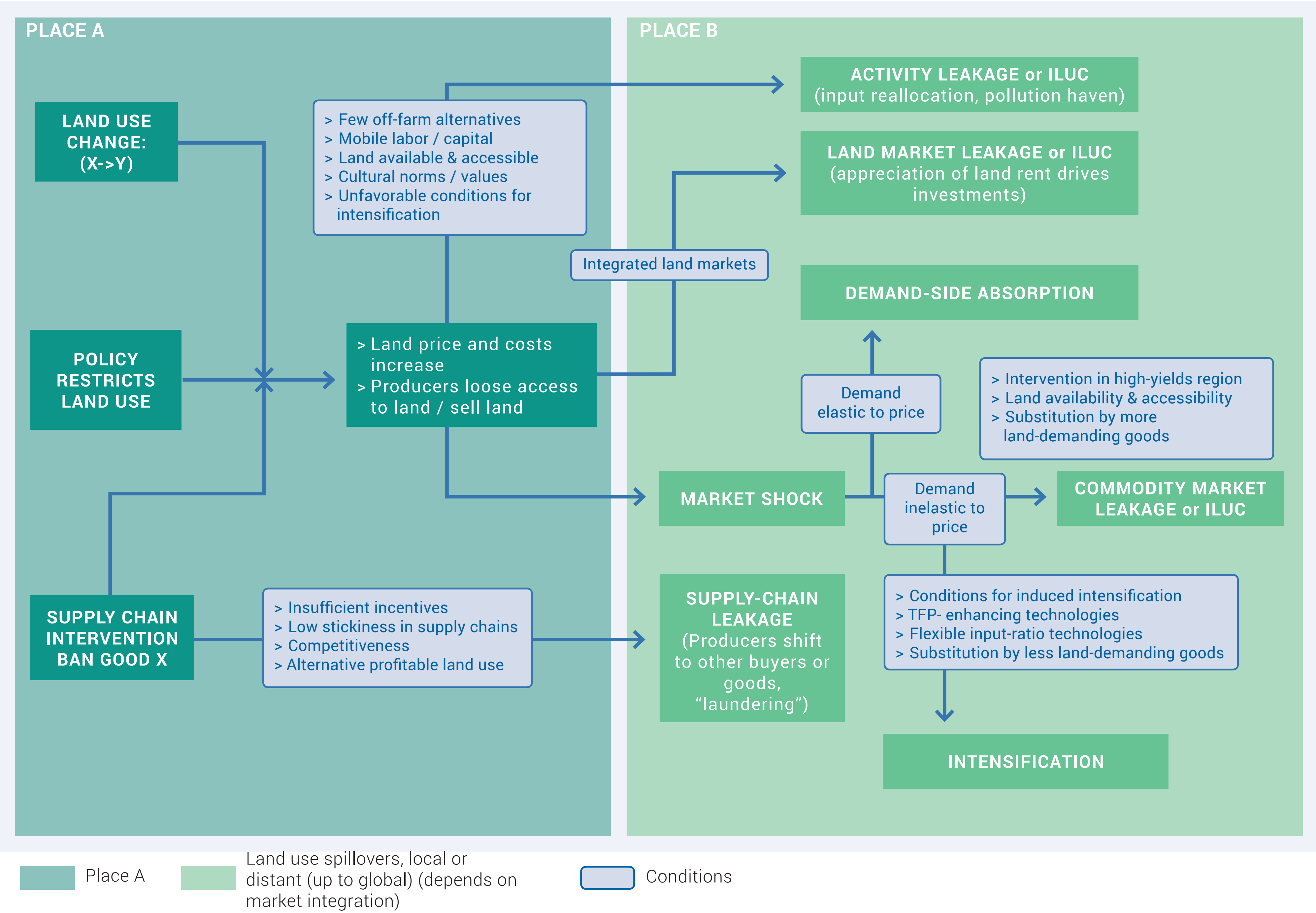

FIGURE 5 | Theories of forest transition