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Regime shifts limit the predictability of land-system change

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ABSTRACT

Payment schemes for ecosystem services such as Reducing Emissions from Deforestation and forest Degradation (REDD) rely on the prediction of 'business-as-usual' scenarios to ensure that emission reductions from carbon credits are additional. However, land systems often undergo periods of nonlinear and abrupt change that invalidate predictions calibrated on past trends. Rapid land-system change can occur when critical thresholds in broad-scale underlying drivers such as commodity prices and climate conditions are crossed or when sudden events such as political change or natural disasters punctuate long-term equilibria. As a result, land systems can shift to new regimes with markedly different economic and ecological characteristics. Anticipating the timing and nature of regime shifts of land systems is extremely challenging, as we demonstrate through empirical case studies in four countries in Southeast Asia (China, Laos, Vietnam and Indonesia). The results show how sudden events and gradual changes in underlying drivers caused rapid, surprising and widespread land-system changes, including shifts to different regimes in China, Vietnam and Indonesia, whereas land systems in Laos remained stable in the study period but show recent signs of rapid change. The observed regime shifts were difficult to anticipate, which compromises the validity of predictions of future land-system changes and the assessment of their impact on greenhouse gas emissions, hydrological processes, agriculture, biodiversity and livelihoods. This implies that long-term initiatives such as REDD must account for the substantial uncertainties inherent in future predictions of land-system change. Learning from past regime shifts and identifying early warning signs for future regime shifts are important challenges for land-system science.

1. Introduction

Land systems are the terrestrial component of earth systems and encapsulate the activities and processes related to human use of land as well as the socioecological outcomes of land use. Studying land systems is therefore crucial to understanding the relationships between humans and their environments (GLP, 2005; Verburg et al., 2013). Changes in land systems have been among the most important drivers of global environmental change and have greatly contributed to the emergence of the Anthropocene (Crutzen, 2002; Ellis et al., 2013; Turner et al., 2007). The influence of human action on planetary resources is likely to persist considering the expected increase in demand for land-based products driven by human population growth, diet change and consumption of energy (Haberl et al., 2014; Rockström et al., 2009). Therefore, predictions of the evolution of land systems are important for determining the potential trade-offs between land-system changes and ecosystem services and guiding policy in managing increasingly scarce natural resources (Clark et al., 2001; Davidson et al., 2012).

However, such predictions are notoriously difficult to make because of complex human–environment interactions in land systems (Dearing et al., 2010; Liu et al., 2007). Economic

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globalization further complicates the predictive analyses of land-system change because growing global connectivity, or telecoupling, of land systems poses new conceptual and methodological challenges and may produce unforeseen outcomes (Eakin et al., 2014; Lambin and Meyfroidt, 2011; Liu et al., 2013; Müller and Munroe, 2014). For example, the increasing demand for meat-based diets in emerging and industrial countries has led to an intensification of livestock production, which in turn has caused considerable deforestation in Latin America because of soybean expansion (Fearnside et al., 2013; Morton et al., 2006). One of the challenges of land-system science is to relate underlying global and regional drivers of land-system change to local land-use outcomes and foresee the responses of land-use agents to changes in these drivers (Dearing et al., 2010; Lambin and Geist, 2006; Turner et al., 2007).

The limited understanding of how underlying drivers affect proximate causes of land-system change obscures causality and impairs our ability to forecast change (Veldkamp and Lambin, 2001). Although land-system change often occurs gradually, transitions to alternate states may occur rapidly when critical thresholds are crossed (Dearing et al., 2010; DeFries et al., 2004; Veldkamp and Lambin, 2001). The concept of regime shifts embodies such a transition and has been increasingly used to study sudden changes in ecological systems (Scheffer, 2009). Regime shifts characterize the shift in a system to alternate states that can result from a loss of resilience (Gunderson, 2000), the occurrence of stochastic events (Folke et al., 2004; Scheffer et al., 2001) or positive feedback in synergistic driving forces (Brook et al., 2013). Regime shifts are intrinsic characteristics of complex adaptive systems (Scheffer, 2009), and land systems are complex adaptive human-natural systems. As such, land systems also experience nonlinear and rapid change based on their ability to absorb and adapt to underlying drivers of change (Dearing et al., 2010; Liu et al., 2013). However, the concept of regime shifts has received little attention in land-system science.

Our overall objectives are to examine the occurrence of regime shifts in land systems with four case studies of long-term land-system change in Southeast Asia and to conceptualize and interpret the observed historical changes with the regime shift concept borrowed from ecology. We collected time-series data on land-system change from 1980 to 2012 for four case studies in Southeast Asia (China, Laos, Vietnam and Indonesia). The data allowed us to distinguish periods of linear and nonlinear change and periods of rapid and slow change; therefore, we were able to identify past regime shifts in land systems. Our hypothesis is that these land-system regime shifts were difficult to anticipate, and consequently, the predictability of land-system change and validity of business-as-usual predictions were far from guaranteed. We then discuss the implications of potential occurrence of regime shifts for Reducing Emissions from Deforestation and forest Degradation (REDD) and for governing land-systems in general.

2. Regime shifts in land systems

We define a land-system regime as a quasi-equilibrium phase during which a land system remains relatively stable in terms of overall system characteristics and ecosystem functions, such as land area used, land-use intensity, provision of habitats, carbon dynamics and biodiversity. A land-system regime is resilient to perturbation or disturbance when negative feedback and interactions allow the system to recover and maintain its equilibrium state (Fig. 1; cf. Holling, 1973; Walker et al., 2004). Land systems can reside in a regime for a long time; however, they can also undergo abrupt and unexpected state shifts that are persistent and difficult to reverse. During the transitional period between two regimes, feedback and interactions within the land system are reconstructed and reorganized. We define this process as a regime shift in land systems, in analogy with a regime shift in ecosystems (cf. Biggs et al., 2009; Scheffer et al., 2001).

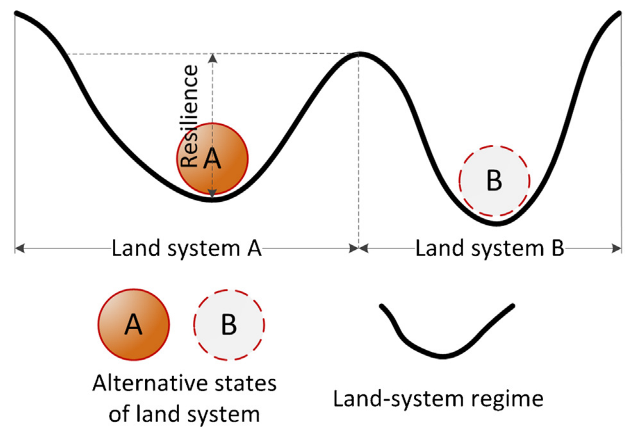

Fig. 1. Regime shifts in land systems. *Note*: The balls represent states of land systems. Land systems can shift from one regime (a stable state confined by a valley) to an alternative regime (another valley), which is illustrated by the ball shifting from A to B. The depth of a valley characterizes the resilience of a land system regime to change. The resilience can be reduced by drivers that push up the valley or improvements of enabling conditions that reduce the height of the hill. Reduced resilience increases the attractiveness of alternative regimes and may facilitate regime shifts.

Regime shifts can be a result of incremental tipping point processes, punctuated changes or the combination of both. In tipping point processes, an accretion of pressure from underlying drivers gradually increases until a threshold is passed; the system then stands at a tipping point wherein a small perturbation can precipitate rapid and large-scale change and push the system to a new state. For example, the Western Sahara suddenly shifted from nearly complete vegetation to the current state of desert approximately 6000 years ago, and the shift was triggered by a gradual variation of summer isolation (deMenocal et al., 2000). Likewise, there is some indication that population growth can build incremental pressure until the system tips over to another state (Ellis et al., 2013). An alternative explanation of systemic change in land systems is provided by the punctuated equilibrium theory in evolutionary biology (Gould and Eldredge, 1977) that postulates that periods of little change may be punctuated by influential events that unleash an episode of drastic change. An example is the formulation of a new state policy that is possibly triggered by incremental, endogenous changes in drivers that exceed a threshold for policy makers and end a longer period of stasis. The policy implementation punctuates the apparent equilibria in the land system (Rudel, 2013).

Similarly, exogenous forces such as natural disasters can lead to punctuated change that often does not have an apparent threshold. A better understanding of regime shifts in land systems is required to inform land-system governance because regime shifts may have substantial impacts on socioecological outcomes, such as land-use intensity, production technology, land-based outputs, livelihoods and ecosystem services. To detect such regime shifts, long-term observational data are required to distinguish linear from nonlinear change and gradual from rapid change to better understand the system dynamics and improve our ability to anticipate critical thresholds (Carpenter and Folke, 2006; Dearing et al., 2010). Predicting regime shifts in land systems necessitates the detection of early warning signs for likely tipping points or potential punctuations that entail rapid or nonlinear change.

Regime shifts can be triggered by socioeconomic, political and environmental changes or, as is often the case, by a combination thereof. The presence of regime shifts in land systems is not new, and such shifts have occurred throughout history. The 'Malthusian technology leap' resulted in a regime shift in agricultural production and technology to ensure food production (Lambin, 2012; Netting, 1993). Other scholars have argued that regime shifts historically occur in areas where population growth has spurred rapid intensification and, ultimately, the transformation of land systems (Boserup, 1965; Ellis et al., 2013; Tiffen and Mortimore, 1994). Regime shifts in land systems can also be caused by rare and essentially unpredictable institutional and political events. For instance, the collapse of the Soviet Union caused rapid and widespread land abandonment in many parts of Eastern Europe (Prishchepov et al., 2012) and land reforms in China and Vietnam resulted in the rapid increase of agricultural productivity and reforestation of former agricultural land (Müller and Zeller, 2002; Xu, 2006).

The economic globalization of land use further increases the difficulty of predicting future land-system change (Lambin and Meyfroidt, 2011) and may trigger the crossing of thresholds. For example, the increasing demand for natural rubber led to increased rubber prices and resulted in the rapid conversion of shifting cultivation and rubber agroforestry to monoculture rubber plantations in several Southeast Asian countries (Ziegler et al., 2009). Concurrently, surges in world market prices for palm oil raised incentives for the rapid expansion of both large-scale and smallholder oil palm plantations (Koh and Wilcove, 2007; Mertz et al., 2013).

Climate change may also set off regime shifts in land systems. For example, the projected warmer climate will drive rubber distribution further north and to higher elevations (Zomer et al., 2014). Moreover, gradual changes in regional climate in combination with interacting responses of grazing patterns and vegetation will lead to a loss of resilience of land systems in arid regions and eventually to possibly irreversible desertification (Hughes et al., 2013). A loss of resilience as a result of climate change was also observed in areas of low human population density in the Southern Himalayas, where interactions between anthropogenic forces and increasing temperatures led to rapid shrub encroachment on alpine meadows (Brandt et al., 2013); similarly, on the Qinghai-Tibetan Plateau, rapid winter and spring warming resulted in unexpected phenological changes in alpine grasslands (Yu et al., 2010). Finally, infrequent but extreme climatic events may substantially alter phenology and trigger unpredictable responses from ecosystem properties (Easterling et al., 2000; Thibault and Brown, 2008).

Few of these regime shifts or the scale, spatial distribution and persistence of the responses, which were dependent on specific boundary conditions and internal dynamics in each individual case, were anticipated. In all cases, the nature of the response was determined by thresholds, such as the duration of crises and disasters, scale and persistence of price increases and implementation and control of land policies. The existence of regime shifts makes the prediction of future land-use trajectories extremely challenging; however, prognostic insights are important for planning development and managing tradeoffs. Prominent examples that in part rely on future predictions are land-use policies to mitigate climate change, e.g., initiatives to reduce greenhouse gas emissions compared to business-as-usual developments through climate-smart agriculture or REDD. REDD, if agreed upon in the international climate negotiations, requires reductions in carbon emissions to be additional, and additionality can only be ensured if reliable business-as-usual scenarios of land-use change are produced (Angelsen et al., 2009; Ghazoul et al., 2010).

3. Materials and methods

We conducted fieldwork in four countries of Southeast Asia in two communities each: one inside the park and one in the buffer zone of the Nam Et-Phou Loey National Park in Huaphan Province, Laos; two in Xishuangbanna Prefecture in Southwestern China; two in Con Cuong District, Nghe An Province, near Pu Mat National Park in Vietnam; and two in Kutai Barat District of East Kalimantan Province in Indonesia (Fig. 2). Quantitative and qualitative data were collected at the household and community levels with identical data collection techniques for all sites to ensure comparability. A quantitative household survey was administered in all sites, and questions covered demographic changes, labor allocation, assets and income, agricultural production and the use of forest products. A total of 400 questionnaires were distributed, 50 in each community. The household survey provided statistically representative data at the site-level that were used to triangulate the information collected with the qualitative data elicitation techniques.

We conducted focus group discussions, transect walks and participatory mapping in all of the communities with groups of eight to 15 villagers of different ages, sex and social status. During the participatory land-use mapping, the villagers were asked to sketch the current land-use categories on transparencies overlaid on prints of recent very-high-resolution satellite images (IKONOS, QuickBird). We focused the mapping, subsequent data collection and analysis on five major land-use categories that were identified by the villagers: dense forest, secondary forest, plantation crops, shifting cultivation and arable land. We used the sketch maps as a visual aid and basis for the focus group discussions and to delineate and discuss the changes of land-use categories that had occurred over the past 50 years.

We then reconstructed the historic transitions in the proportions of the major land uses as continuous trend curves in each community. To develop the land-use transition curves, we first estimated the current land-use shares for 2012 based on the participatory maps and estimations by the focus group members. Then, we reconstructed past land-use shares in the focus group discussions. During the discussions, participants identified important landmark events such as policy changes or natural disasters that had occurred in the past 50 years. We then inquired about the approximate share of land use at the particular landmark events, beginning with the most recent event and dominant land-use

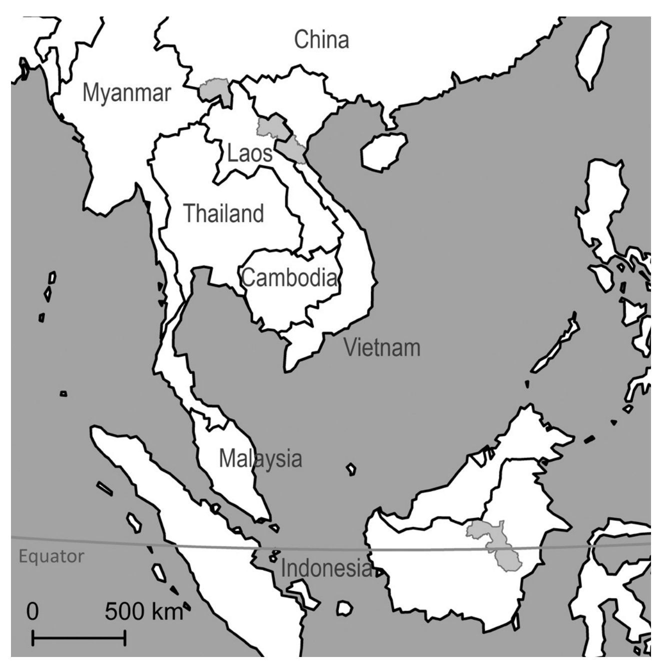

Fig. 2. Study areas in Southeast Asia (location of case study sites indicated in light gray).

category. From there, we traced back the change in area proportion of each land-use category between the landmark events and discussed when changes in land use were particularly rapid. We used the resulting transition curves to discuss rates and processes as well as the underlying drivers and proximate causes of land-use change between landmark events; we also inquired about periods of fast and slow change and used the participatory maps to support the discussions and triangulate the responses. We repeated these steps for all land-use categories and obtained long-term land-use transition curves for all eight sites. We then averaged the changes in the two sites per county because little variation existed within the study sites. We selected the year 1980 as the starting year for the land-use curves because, prior to 1980, subsistence-oriented shifting cultivation was the dominant farming system and land-system changes were slow in all sites.

The land-use transition curves are unique because they provide continuous, long-term land-use data that allow us to determine whether historic land-use changes were linear or nonlinear, if they occurred gradually or abruptly and in which year rapid change occurred. Moreover, the community discussions and household interviews allowed us to derive a level of thematic detail on land-system changes that would not have been possible otherwise.

4. Results

4.1. Land-use trajectories

In 1980, shifting cultivation was the dominant land use in the study sites. Between 1980 and 2012, each site underwent significant transformations away from shifting cultivation toward plantation crops, intensive agriculture and plantation forestry (Fig. 3). In the Lao communities, the area under shifting cultivation decreased gradually from 55% to 30% between 1980 and 2012. Secondary forests replaced the majority of these areas; however, shifting cultivation remained the primary land-use system. The proportion of arable land was constant at approximately 3% of the village territory. Plantation crops emerged in 2000 and accounted for 7% of the land use by 2006, which has remained stable.

In Indonesia, dense forest areas steadily shrank in the study sites, and their share of the total area dropped from approximately 56% in 1980 to 20% in 2012. The dominant proximate causes of this decrease were selective logging (since 1980) and the expansion of plantation crops (mainly oil palm since 1995). Selective logging and the reforestation of shifting cultivation areas led to an increase in secondary forest areas. However, shifting cultivation remains an important land use and occupies 20% of the village territory.

In the communities in China, rubber plantations expanded at an average rate of 4% per year from 1985 until 2006 and have remained stable since then. Shifting cultivation and its associated successional vegetation and forests virtually disappeared, which has substantial implications for ecosystem services and local livelihoods. The coverage of densely forested areas dropped from 40% of the village territories in 1980 to 10% in 2012. Total forest cover (dense and secondary forest combined) declined from almost 60% in 1980 to 17% in 2012.

The major trend in land use in Vietnam was the increase in secondary forests. Most secondary forests regenerated naturally on former shifting cultivation land, but plantation forests (mainly Acacia species) were also established. Selective logging and extraction of non-timber forest products caused significant degradation of dense forests and contributed to the increase in secondary forests. The share of arable land continuously increased from 7% to 20% and expanded particularly fast between 1997 and 2007.

In sum, we can clearly identify periods of rapid land-use change (arrows in Fig. 3) that followed longer periods of gradual change. The onset of the potential regime shifts when the rate of change abruptly increased (circles in Fig. 3) is clearly visible for the sites in Vietnam, Indonesia and China; however, the duration of the periods of rapid change varied substantially between countries. Although this transition period lasted for only three years in Vietnam, the rubber expansion in the Chinese study sites persisted for approximately 20 years and the oil palm expansion in Indonesia that started in 1995 was still ongoing in 2012.

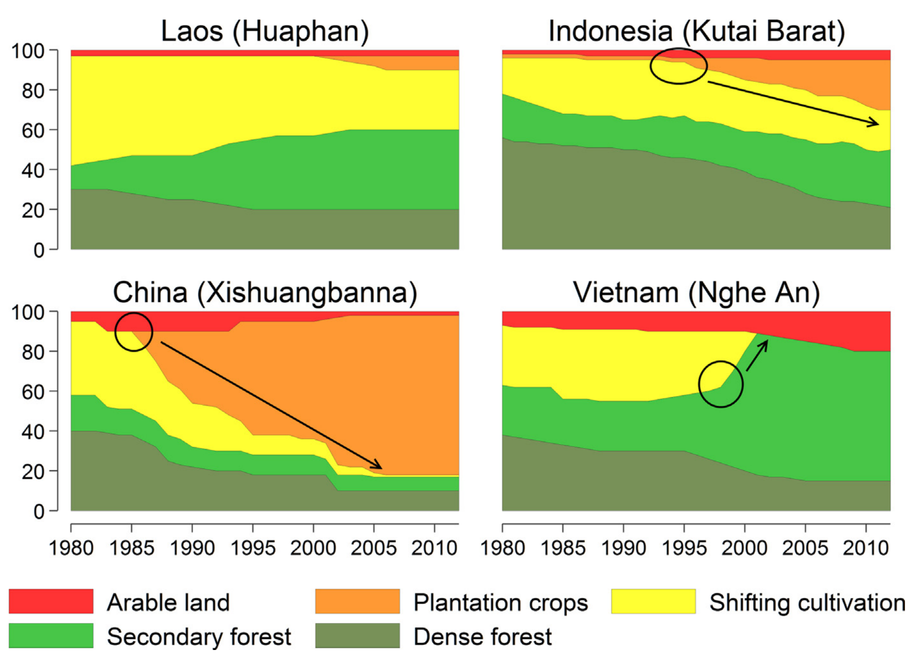

Fig. 3. Land-use transitions from 1980 to 2012. *Note*: Shares of land-use types from 1980 to 2012 aggregated for all communities within each study site. Circles indicate the onset of regime shifts and arrows indicate the rapid shift to a new regime. Data are from fieldwork in all sites (see Section 3).

4.2. Observed regime shifts

We use the graphs from Fig. 3 together with our qualitative knowledge and quantitative data for all of the sites (see Section 3) to categorize the land systems in the study sites into different regimes, i.e., into quasi-equilibrium states with gradual linear changes in land-use inputs, outputs and outcomes. Comparisons over time reveal regime shifts in land systems to alternative stable states and allow for the disentangling of the causal mechanisms leading to the observed shifts.

For all sites, the initial land-system regimes in the early 1980s were dominated by shifting cultivation with subsistence-oriented production (Fig. 4). Since then, land systems have embarked on distinct pathways governed by diverse underlying drivers that have resulted in different agricultural production strategies and divergent outcomes in terms of livelihoods and ecosystem services. In the Lao communities, no regime shifts were detected despite high population growth. However, agricultural and forest land allocation and conservation policies have led to a gradual reduction in the fallow periods of shifting cultivation (Fig. 4). Concurrently, improvements in the local infrastructure, access to capital and new crop varieties provided favorable conditions for these changes. At the time of writing, a shift to commercially oriented cash crop production such as permanent cropping of hybrid maize is occurring in the Lao case study areas (Vongvisouk et al., 2014). Moreover, the rubber boom in China is spreading to other areas in Laos (Mann, 2009), although this development had not yet reached our study sites in Laos.

The Indonesian sites are not in an equilibrium state; instead, they appear to transition from a subsistence-oriented regime to a market-oriented regime. At one site, land systems remained in a regime of smallholder production for long periods until the sudden onset of the oil palm expansion led to the partial commercialization of land systems; however, households continued the largely subsistence-oriented shifting cultivation on part of their territory. The main driver behind the oil palm expansion was the rising commodity price for palm oil (upward-pointing arrow in Fig. 4), in part driven by the increasing demand that resulted from biofuel mandates (Deininger, 2011), combined with improvements of infrastructural conditions (downward-pointing arrow in Fig. 4), both of which increased agricultural land rents and reduced land-system resilience. Eventually, local authorities granted land concessions to commercial oil palm companies, which marked the commencement of the regime shift to highly capital-intensive plantations and accompanying rampant deforestation. As a result, traditional shifting cultivation areas remain in a process of conversion to commercial oil palm plantations. In the other Indonesian site, small-scale rubber plantations are expanding; however, the planned construction of a connecting road from the district capital may also allow for the expansion of commercial oil palm plantations.

In Xishuangbanna, China, the replacement of shifting cultivation and forests with rubber plantations (Fig. 4) represented a regime shift toward highly capital-intensive and purely market-oriented production. While the expansion of rubber was foreseeable, its pace and extent was not. The maximum rubber production was expected to hit a ceiling at 100,000 tons (Chapman, 1991), yet the current production is already 200,000 tons per year (China Statistical Yearbook, 2011), and many rubber trees have not reached their full production capacity yet. This rapid rise of rubber plantations was driven by steadily increasing world market prices as a result of the growing demand for latex (Fox and Castella, 2013;

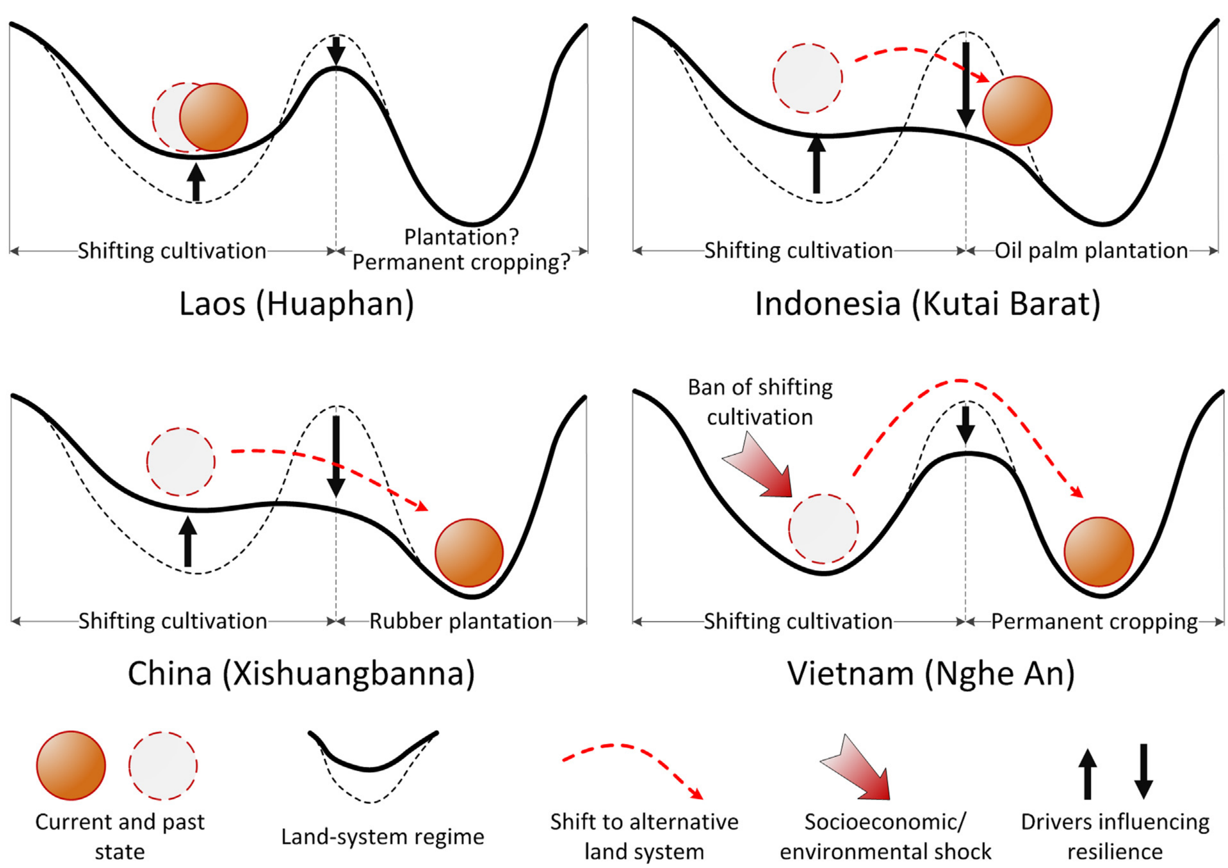

Fig. 4. Regime shifts in land systems. *Note*: Ball-and-valley diagrams of land-system regimes and observed regime shifts. Light gray balls and red balls characterize the state of land systems in 1980 and 2012, respectively. Upward-pointing arrows designate the pressure from underlying drivers (e.g., population growth and rising commodity prices) and downward-pointing arrows designate the improvements in enabling conditions (e.g., road upgrading). The red arrow symbolizes the external policy shock in Vietnam.

Li et al., 2008) and supported by policies that fostered rubber plantations and discouraged shifting cultivation (Ziegler et al., 2009).

The land-system regime in Vietnam abruptly changed to a regime characterized by small farms with a mix of subsistence and market-oriented permanent cropping. The Vietnamese regime shift was the result of significant policy punctuation as the government zoned off areas for protection and enacted land allocation policies that induced land scarcity, which effectively banned shifting cultivation (Fig. 4; cf. Meyfroidt, 2013a). In the Vietnamese and Chinese cases, there is little evidence of reversibility of the regime shifts because government policies discouraging shifting cultivation and favoring permanent agriculture will likely persist (van Vliet et al., 2012).

In summary, we have disclosed how regime shifts of land systems can be induced by two distinct pathways. One pathway consists of a sudden and significant external shock that punctuates a period of stasis and pushes the land system to an alternative stable state. This pathway is largely in line with the punctuated equilibrium theory, as observed in our Vietnam sites. The other pathway is a systemic shift to a new regime that can be triggered by subtle perturbations, which pass a critical, previously unknown threshold in a key driver. The original equilibrium can no longer be sustained, and the land system rapidly tips over to an alternative equilibrium state. The sites in China largely follow this tipping point pathway. However, regime shifts may often be caused by a combination of the two pathways. For example, multiple conjunctural causes may have been responsible for the impending regime shift in Indonesia wherein increased commodity prices and improved infrastructure reduced the resilience of the land system and the granting of concessions provided the decisive punctuation for the regime shift.

5. Discussion

5.1. Confirmation of observed changes and underlying drivers

The land-system changes in the four study sites largely followed the patterns observed in other regional studies in Southeast Asia. The historical dominance of shifting cultivation systems in Xishuangbanna is well known (Xu et al., 2005), as is the ongoing transition to rubber (Mann, 2009; Xu et al., 2014; Ziegler et al., 2009). In Vietnam, policies discouraging shifting cultivation and the labor intensification of land use in the lowlands led to the emergence of secondary forests and forest plantations on former shifting cultivation plots (Müller and Zeller, 2002; Sikor, 2001). Much of contemporary rural Laos is dominated by shifting cultivation landscapes, although fallow lengths are declining and permanent agriculture is slowly increasing at the expense of areas under traditional forms of shifting cultivation of upland rice (Hurni et al., 2013; Müller et al., 2013). Finally, the oil palm boom in Indonesia is well documented in the literature (Carlson et al., 2012; Koh et al., 2011) and has replaced traditional land systems such as rubber agroforestry. However, few studies successfully anticipated the drastic land-system changes, and the large majority of studies were published after tipping points had already been reached in many locales. In general, the literature shows little evidence of the successful anticipation of regime shifts in land systems for any of the observed processes in any of the target countries.

The current empirical evidence suggests that global-scale underlying drivers such as rapid economic growth in emerging economies and increasing commodity prices for agricultural and forestry products concurrently affected all sites. However, land-system responses diverged, conditioned by particular local biophysical and socioeconomic conditions, which eventually resulted in varying land-system outcomes. The increasing global commodity prices for rubber and palm oil were the principal underlying drivers of monocultural cash crop expansion in China and Indonesia, respectively. For example, the oil palm sector began to grow rapidly in the 1990s following national policies favoring the dietary use of palm oil (Jacquemard and Jannot, 1999), and market expansion since 2000 was driven by international demand and increasing palm oil prices (World Bank, 2013). However, neither the policy change in the 1990s nor the subsequent rise in the global commodity price for palm oil were anticipated. In general, the scope and extent of global megatrends and their effects on land-system change in Southeast Asia were rarely foreseen, and thresholds were typically only detected in hindsight.

It is equally challenging to foresee the effects of national policy changes that punctuate long periods of business-as-usual and usher in a period of accelerated land-system change (Rudel, 2013). Our prime example here is Vietnam, where traditional shifting cultivation systems were virtually banned by government policies and produced profound impacts on local land-use patterns (Fig. 3). The land titling program, implemented from 1993 onwards, secured land ownership for paddy and rainfed areas. Furthermore, the forest allocation that began in 1994 was aimed at securing rights to forested land (Sikor, 2001). These land-use policies, coupled with strong law enforcement, were paramount for the land-system changes in Vietnam but difficult to foresee in Vietnam's dynamic political environment.

Finally, infrastructure developments, especially road construction, are prominent drivers of land-system change and particularly of tropical deforestation (Pfaff et al., 2007). Indeed, roads improve accessibility and may open up new areas for development. A rich body of literature has analyzed the *ex-post-facto* impact of road construction and road improvements on subsequent changes in land use or the simulated impacts of planned roads on future land use (Soares-Filho et al., 2004). Transportation networks are also important for changes in land systems in Southeast Asia. Improvements in the transportation network at the Chinese sites (upward-pointing arrow in Fig. 4) and government investments in processing facilities for latex (downward-pointing arrow in Fig. 4) were crucial in enabling the rubber boom. Similarly, harvested palm oil fruits must be rapidly processed; therefore, the enlargement of oil palm plantations in Indonesia was dependent on the improvement of transportation networks to processing facilities (downward-pointing arrow in Fig. 4). Currently in Laos, a rapid shift from the current system dominated by shifting cultivation of upland rice to market-oriented hybrid maize cultivation to be used as feed in Vietnamese pig production appears to be occurring. At the moment, it seems as if a booming hybrid maize sector is driving the construction of roads to transport the agricultural products more quickly to the market. Land systems in Laos hence seem to loose resilience (Fig. 4). However, despite an in-depth knowledge of local conditions, the impact of road improvements on the behavior of land-use agents (both smallholders and commercial companies) in the study sites of Vietnam and Laos and the probability of road upgrades triggering potential regime shifts in land systems toward commercial plantations or input-intensive annual cropping remain unknown.

5.2. The challenge of predicting regime shifts in land systems

Pressures on land systems accumulated in the majority of the study sites through one or a combination of underlying drivers that led to a reduction of land-system resilience and eventually pushed the land systems into another regime. In Vietnam, for example, a change in land-use policy triggered the regime shift. While a change in land-use policy can sometimes be foreseen, anticipating policy-driven regime shifts requires knowledge about the timing of policy enactments and site-specific land-use responses. Such predictions are challenging because both the timing as well as the magnitude of the policies' effects are unknown a priori. As a result, land-use models often fail to anticipate policy-driven regime shifts.

More generally, the inability to anticipate regime shifts in land systems is arguably a result of the intrinsic complexity of forecasting underlying drivers, their effects on proximate causes and the resulting nonlinear land-system changes (Smith et al., 2010; Turner et al., 2007). Although statistical or simulation models are often successful at predicting gradual changes based on observed historical changes, the anticipation of abrupt, nonlinear change remains extremely challenging because thresholds are typically unknown and difficult to anticipate or model (Meyfroidt, 2013b).

Moreover, models rely on drivers that are hypothesized to shape land change, and the emergence of new, previously unknown drivers or the occurrence of surprises can invalidate model outcomes. As shown, business is often unusual in land-system change because land use can respond to changes in exogenous underlying drivers or to the emergence of new drivers in various unexpected ways. Therefore, additional emphasis is required on the exploratory analyses that anticipate possible thresholds of incremental and punctuated change of land systems and identifying salient future drivers. Moreover, the inherent uncertainty of future predictions must be made explicit because outcome variability is crucial for the potential consequences on ecosystem and livelihoods and because outcome variability increases with longer prediction periods.

5.3. Regime shifts and implications for REDD

The difficulty in predicting regime shifts has considerable implications for initiatives and mechanisms that rely on the trajectories of future land use. One such initiative is REDD, whose successful implementation depends on ensuring the additionality of reductions in carbon emissions beyond business-as-usual developments (Angelsen, 2008). The anticipation of business-as-usual development serves as the baseline for compensating emission reductions below what would have occurred in the absence of compensation. The establishment of such baselines requires the prediction of future forest-related carbon fluxes, and such predictions are marred with uncertainties because land systems may shift in unexpected ways. For this reason, deterministic future predictions of forest carbon change are unlikely to convince potential REDD investors that their investments are truly additional, particularly in dynamically changing regions such as Southeast Asia.

Another related challenge of REDD schemes is to ensure the permanency of emission reductions induced by carbon credits beyond the compensation baseline. If the opportunity costs of emission reductions rise (for example, as a result of increases in commodity prices, improvements in accessibility or changes in policy), then investments might be put in jeopardy because considerably higher payments would be required to compensate land users for foregone future income opportunities (Phelps et al., 2013). This poses some intriguing questions for REDD initiatives. Should opportunity costs for conservation in semi-subsistence smallholder systems be compared to current prevailing land systems or to the profits that can potentially be obtained by suitable cash crops such as rubber or oil palm? Will the past trends of deforestation in China and Vietnam and the currently rampant forest degradation in Vietnam soon reach the more traditional farming systems in Laos? Our results suggest that we can potentially draw lessons from past regime shifts in land systems to formulate future scenarios for biophysically similar locations; however, predicting their timing and the extent of change remains extremely challenging.

The simple idea of REDD-type approaches that provide financial compensation for successful efforts to reduce carbon emissions or enhance the sequestration of forest carbon will be extremely difficult to enact because the possibility of regime shifts in land systems threatens both the additionality and permanence of emission reductions. Payments for the absolute amount of carbon stored in a landscape and monetary incentives for the provision of other forest-based ecosystem services are a more direct compensation; therefore, they will possibly be more effective and easier to implement than rewarding lower reduction or faster accumulation of carbon sinks compared to the unknown business-as-usual. Other options for improving carbon stocks such as investments in sustainable forest management, zoning polices or moratoria on forest clearing may also be more successful at improving forest carbon stocks and securing co-benefits such as biodiversity conservation and watershed functions; however, they may potentially be at the cost of economic development and export earnings.

5.4. Implications for land-system science

Land-system science must place increasing emphasis on the complex, telecoupled and often nonlinear nature of land-system changes by anticipating a range of outcomes that could occur and explicitly acknowledging uncertainties associated with projections. Land-system projections in dynamic landscapes are particularly likely to have a high degree of uncertainty because it is impossible to control for and predict potentially important and fast changing covariates. Therefore, being aware of potentially substantial misjudgments inherent in future projections is crucial for scientists and decision-makers alike; one option is to steer land use toward desirable regimes with active landscape design (Koh et al., 2009) or landscape architecture (Turner et al., 2013) by means of regulatory measures and market-based instruments while recognizing the resilience of the regimes to changes in external framework conditions. Of course, this will depend on the capacity of governments to engage in these exercises.

One way to improve predictive capacity is to *ex ante* identify warning signals for tipping points of land-system regime shifts (Dearing et al., 2010) by learning from the history of land-system regularities and irregularities in sites with similar biophysical conditions. This may be particularly valuable for an improved understanding of the telecoupled land systems in Southeast Asia. A historic example is the expansion of oil palm production in Indonesia and Malaysia that displaced rubber plantations further north into mainland Southeast Asia (Fox and Castella, 2013). Likewise, the rubber boom in Southwestern China may be replicated across northern Laos and in neighboring Myanmar once political and economic boundary conditions are in place. Similarly, oil palm plantations may outpace the forest conservation action in rural areas of Cambodia and southern Vietnam. Although many developments may seem specific to particular locales, they may carry important messages for other sites as well.

6. Conclusion

Predictions calibrated on historic data are extremely valuable for forecasting gradual land-system change in response to foreseeable developments. However, predictive analysis is less successful in anticipating regime shifts that are characterized by abrupt, nonlinear and often surprising change. We have demonstrated the occurrence of regime shifts in land systems in Southeast Asia, and our results support a paradigm shift in analyzing the dynamics of increasingly complex land systems. Failing to recognize the intrinsic characteristics of complex system change (such as regime shifts) can cause inefficient and ineffective outcomes for well-intended efforts such as REDD.

Forecasts of land-system change should acknowledge the substantial uncertainties inherent in future predictions and place increasing efforts on anticipating systemic change and learning from past triggers of regime shifts. One challenge for land system scientists will be finding better ways of integrating uncertainty and potential regime shifts into scenario building. Moreover, identifying early warning signs of regime shifts and identifying system characteristics that maintain land systems within preferred regimes can assist policy makers in guiding land systems toward desirable futures.

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