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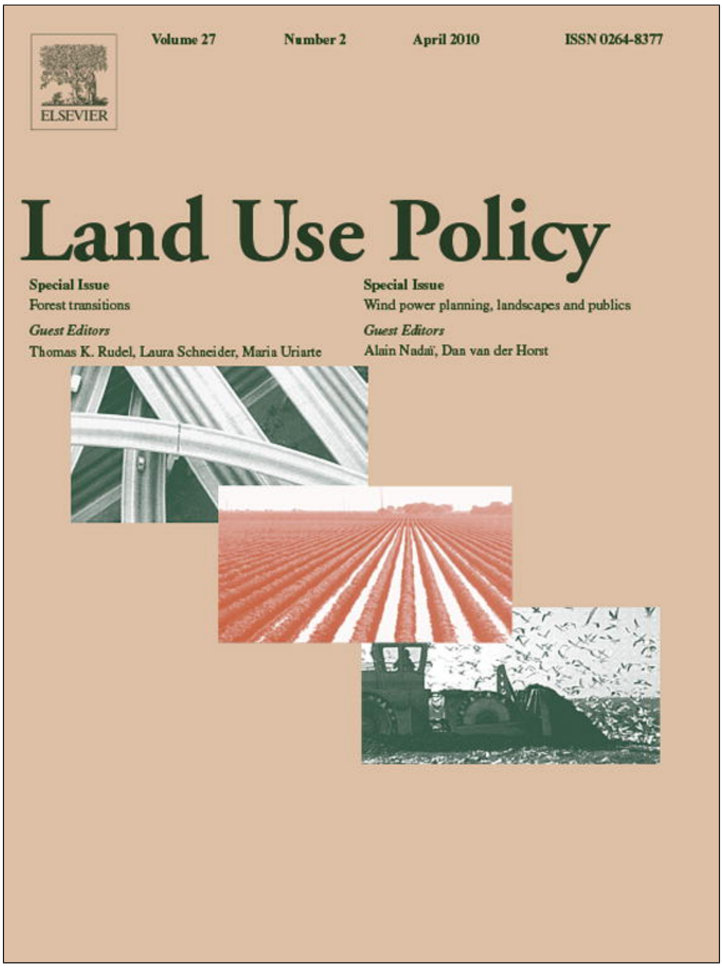

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Sustainability and forest transitions in the southern Yucatán: The land architecture approach

B.L. Turner II *

Arizona State University, School of Geographical Sciences and School of Sustainability, PO Box 875302, Tempe, AZ 85281-5302, United States

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ABSTRACT

Consistent with the challenges of sustainability science, land architecture offers a comprehensive approach to land system dynamics useful for numerous types of assessments, ranging from the vulnerability of coupled human–environment systems to forest transitions. With antecedents in several research communities, land architecture addresses the tradeoffs within and between the human and environmental subsystems of land systems in terms of the kind, magnitude, and pattern of land uses and covers. This approach is especially cogent for changes in tropical forests, given the broad-ranging forces acting on them and the equally broad-ranging consequences of their loss. The rudiments of the land architecture approach are illustrated for changes in seasonal tropical forests in the southern Yucatán of Mexico, the pivot of which is the Calakmul biosphere reserve. Simplifying the dynamics involved, the region-wide land architecture is the collective design of stakeholders with different land-use goals that favor tradeoffs in subsystem outcomes serving better either the reserve and related programs or the smallholder farmers that populate the region. A major tradeoff involves forest cover per se, which holds implications for forest transition theory. Evidence for an incipient transition involves the scale of analysis taken. The dynamics involved hold too much uncertainty to forecast a permanent transition to more forest cover and imply that more complex but robust versions of the theory are required.

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1. Introduction: the challenge

Sustainability science creates new and complex challenges (Holdren, 2008; Kates et al., 2001; Lubchenco, 1998; Raven, 2002). Land systems vulnerable to global environmental change constitutes one of these challenges (GLP, 2005; Gutman et al., 2004; Turner et al., 2007). Vulnerability comprises a well-developed approach in which specific types of hazards (perturbations or stressors) are connected to a subset of their consequences. Until recently, these consequences were treated as biophysical or societal in kind (Brooks et al., 2005; Cutter et al., 2000; Kasperson et al., 2005), an orientation inadequate for addressing the sustainability of land systems, given the breadth of hazards and consequences operating on them (Cutter et al., 2000; Luers et al., 2003; Turner et al., 2003a). Land systems are coupled human–environment systems and require analytical approaches that treat this coupling explicitly (Elmqvist et al., 2003; Folke et al., 2002; Reynolds et al., 2007).[1] Attempts to capture this complexity in vulnerability approaches (Turner et al., 2003a,b) fails to address explicitly the tradeoffs within and between the human and environmental subsystems. Land architecture, in contrast, offers an approach that accounts for these tradeoffs and which can be used to address not only vulnerability but a range of themes and issues of interest to land change science (Turner et al., 2007).

This paper defines land architecture and situates it within several research and practice traditions relevant to land systems, and illustrates the approach through a brief assessment of forest change in the southern Yucatán, linking the outcomes to the forest transition theory—the subject of this special section (Rudel et al., 2009). The tropical forests of SY are part of a Mexican economic frontier in which a period of rapid deforestation appears to have run its course, signaling a transition to more forest cover in a new architecture. But has it? Guided by the objectives of land change science, the Southern Yucatán Peninsular Region (SYPR) project has examined forest change in the region since 1997 (Turner et al., 2004).[2]

* Tel.: +1 480 965 7533; fax: +1 480 965 8313.
E-mail address: Billie.L.Turner@asu.edu.

[1] A coupled human–environment system is one in which the societal and biophysical subsystems are so entwined that the system's condition, function, and responses to a hazard (or any external forcing) is predicated on the synergy of the two subsystems. Alternative terms referring to this synergy include social–environmental systems (Folke et al., 2002) and coupled human–natural systems (Liu et al., 2007).

[2] The SYPR project began in 1997 and has involved Clark University, Harvard Forest, University of Virginia, Rutgers University, University of Minnesota, and El Colegio

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The project has developed a sufficient understanding of the land system dynamics to offer the illustration and insights noted.

2. Elaboration of land architecture

2.1. Definition

Land architecture (LA) refers to the structure of land systems, where structure refers to the kind, magnitude, and spatial pattern of land uses and covers in a bounded area. The three attributes of LA largely determine the capacity of the land system to deliver the environmental services expected by society under the prevailing land uses and their impacts on the human subsystem. Environmental (or ecosystem) services are the benefits society gains from nature, classified as provisioning (e.g., water), regulating (e.g., climate control), supporting (e.g., nutrient cycling), preserving (e.g., biotic diversity) and cultural (e.g., recreational space) (MEA, 2005). A sustainable LA delivers the environmental services while maintaining or improving the economic performance of the land uses without threatening the base function of the environmental systems to deliver the services in the first place—the goal of sustainability science (Kates et al., 2001).

The term architecture applies because land systems have structure and are "designed". Their structure is internal to the definition of LA (above). Their design is linked governance. Most of the terrestrial surface of the earth is governed, either *de facto* or *de jure*, facilitating or constraining land uses (e.g., Nagendra, 2007; Vester et al., 2007) directly through policy and zoning and indirectly through the level of enforcement of rules of land access and use, as well as infrastructure development (Watts et al., 2007). In this sense, human action designs the pattern of land systems, if in circuitous and indirect ways.

The approach advocated here seeks foremost to understand the implications of LAs on the operation of land systems treated as coupled human–environment systems. This understanding, of course, holds clues for the design of new architectures.

2.2. Guiding principles

Drawing on the insights gained from global environmental change and sustainability-resilience research, the LA approach recognizes that assessments of land change must move beyond their historical emphasis on resource stocks (provisioning services) to include the full suite of environmental services, especially regulating, supporting, and preserving services (MEA, 2005), and the systemic structures that sustain them. As coupled systems, land systems involve tradeoffs among environmental services and between the outcomes in environmental and human subsystems (DeFries et al., 2004; Rosenzweig, 2003). These tradeoffs follow, in part, from the spatial incongruence of the different land covers (i.e., environmental conditions) required to supply different environmental services (Chan et al., 2006; Nelson et al., 2008), especially as interrupted by human land uses. The complexity generated by treating multiple services and tradeoffs between and among subsystems is further amplified by the scalar dimensions of LAs (Turner, 1989). Land systems are connected locally to globally with important up- and down-scale linkages. For example, a sustainable solution established by a local-level LA may not serve the same functions, if replicated to the regional or watershed scales—a general scalar characteristic (Dark and Bram, 2007; Openshaw and Taylor, 1981; van Gardingen et al., 1997). Despite this recognition (Wu, 2006; Wu et al., 2006), the scalar issues of LA, especially regarding forest change, have focused primarily on global climate issues through modeling exercises (e.g., Henderson-Sellers et al., 1993; O'Brien, 2000). Work on tipping points (Lenton et al., 2008) and regional syndromes of environmental change (Schellnhuber et al., 1997) provide hints of the broader coupled system problems to which these scalar issues can be brought to bear.

2.3. Antecedents to land architecture

LA differs from but has antecedents in landscape architecture, sustainable development, and landscape ecology–conservation biology. Landscape architecture has long examined the design of the land, foremost the built environment, with increasing attention to ecological design and sustainable landscape architecture (e.g., Thompson and Steiner, 1997; Van der Ryn and Cowan, 2007). The overwhelming emphasis within this field of study is planning and design of outdoor space in regard to immediate environmental impacts, such as the urban heat island effect or urban drainage systems in smart growth design (US and SGN, 2006), despite recent calls for a broader environmental approach (Botequilha Leitä and Ahern, 2002; Collinge, 1996). Likewise, LA is implied in environment and development research, especially that overlapping with land change science and seeking sustainable land uses (e.g., Kammerbauer and Ardon, 1999; Laris, 2002; Rao and Pant, 2001). In this case, the non-built environment (e.g., older growth forests, savannas and riparian forests) constitutes a critical facet in the land assessment. Attention overwhelmingly focuses on sustaining provisioning environmental services (e.g., food production).

LA differs from landscape architecture and environment-development in several ways. It aims to consider a full range of environmental services in the land system (above), and considers environmental consequences from the land degradation and ecosystem to the earth system levels. It examines all land covers and uses, not the built or used environment only, and does so to develop a systematic understanding of the land system, rather than focusing foremost on those parts explicitly providing resource production and extraction (provisioning services). Finally, LA considers the critical scalar dimensions of land systems (above)—the impacts on environment services and human outcomes of LAs embedded within or covering other LAs.

Work underway in landscape ecology and conservation biology, much of it tied to land change science as registered in the Global Land Project (GLP, 2005) and the Resilience Alliance (Berkes et al., 2003), provides foundational elements for LA. This work has begun to examine a full range of environmental services (Daily et al., 2001; MEA, 2005) and the spatial patterns of land covers on those services and the structure and function of ecological systems (Brosi et al., 2008; King, 1991; Moody and Woodcock, 1995; Pejchar et al., 2007; Rosenzweig, 2003; Turner et al., 1989). In addition, it has developed metrics and measures of land patterns, such as those found in FRAGSTATS (Leitão et al., 2006; McGarigal and Marks, 1995) and subsequent variants (McGarigal et al., 2009) that facilitate comparison of different architectures. LA shares these topical interests, goals for science and practice, and methods. Indeed, the use of geographical information science and remote sensing to problem solve is shared as well with landscape architecture and environment-development (e.g., Campagna, 2005; Hanna, 1999). LA, however, attempts to treat the human subsystem more fully than have the eco- and bio-inspired approaches. The latter tend to examine changes in environmental services and extend the implications to the human subsystem or develop generalization largely from the biophysical subsystem and apply them to the coupled system at large. Such efforts tend to place human decision making, societal structures, and such economic principles as substitutability

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– critical elements of the human subsystem – into the background. In those cases where the human subsystem is treated more fully (Daily, 1997; PNAS, 2007; Reynolds et al., 2007), as envisioned by the Global Land Project (2005), LA fuses with ecology-inspired efforts.

2.4. Significance for tropical forests

Developing sustainable land systems is especially important for the tropical world for several obvious reasons: the need for improved human well being throughout most of the tropics; the special role of tropical forests for the functioning of the earth system and maintenance of biotic diversity (Steffen et al., 2004); the magnitude and pace of land changes underway in the tropical world (Achard et al., 2002; Foley et al., 2005, 2007); and the expected negative impacts of climate change in the tropics on both people and environment (e.g., Laurance, 1998; Lobell et al., 2008; Malhi et al., 2007; Parry et al., 2007).

Despite this significance, surprisingly little research has addressed sustainable LA of tropical forest areas, although ecological work has linked the patterning of forests and opened lands to various impacts on environmental services. This patterning, for example, amplifies or attenuates fire impacts on intact forest through edge effects. The more edge exposed to fire, the more damage to intact forests, and the biotic diversity it holds, especially in the first 500 m from the edge (Cochrane, 2001; Laurance and Williamson, 2001). Highly fragmented tropical forests with many irregularly shaped, open patches are apparently much more vulnerable to the impacts of burning than are forests with a few large and geometrically shaped openings. Likewise, tree diversity tends to be higher as the patch size of forest increases (Hill and Curran, 2003), and species diversity for flora and fauna tends to drop dramatically as forest fragments reach critical size-related tipping points (e.g., Dale et al., 1994; also Daily et al., 2001). For example, one study in Amazonia calculates that fragments of 100 ha or less lose one half of the species of birds (Ferraz et al., 2003). Forest fragmentation also affects "...species invasions, forest dynamics, the trophic structure of communities, ... [and] appears to interact synergistically with ecological changes such as hunting, fires, and logging..." (Laurence et al., 2002, p. 605). Fragmentation, depending on its size and resulting land-cover attributes, may even affect climate. Modeling efforts for Amazonia indicate that sufficient pasture placed among forest fragments "increase the mean surface temperature (about 2.5 °C) and decrease annual evapotranspiration (30% reduction), precipitation (25% reduction), and runoff (20% reduction) in the region" (Nobre et al., 1991, p. 957; also Shukla et al., 1990). Specifically, open forest patches less than 100 km^2 and greater than 1000 km^2 may reduce rainfall, while those between these parameters may increase precipitation (Durieux et al., 2003; Li et al., 2006; Malhi et al., 2007).[3]

This important research provides a strong base on which to build a broader understanding of sustainable LAs. It has yet to address the full range of environmental services (but see Dale et al., 1994; MEA, 2005), however, and explicit assessments of the human subsystems are typically lacking. For the most part, eco- and bio-inspired work focuses on the land-cover consequences of land uses, including those spatial dimensions captured in remote sensing and modeling assessments (e.g., Hall et al., 1995). Linkages from environment-development studies to forest fragmentation and the earth system have only begun (e.g., Sayer and Campbell, 2004), but this work need not pay explicit attention to LAs (but see Aldrich et al., 2006; Serrão et al., 1996). Much less attention has been given to reversing the research lens to examine the consequences of the patterning of LAs on income, human wellbeing, social justice, and so forth.

Finally, tropical deforestation has largely been treated as a local- to state-directed activity – at least in regard to the institutions promoting, constraining, or regulating it (e.g., Bray et al., 2004) – although these institutions may be linked to broader socioeconomic dynamics (e.g., Hecht and Cockburn, 1990; Lambin et al., 2001). Increasingly, however, international accords and protocols portend important roles. As an example, international concern about climate change and links to aerosols from landscape burning as well desertification in the Sahel filtered through funding programs to affect land uses in western Africa, including patterns of landscape burning, with impacts on LAs and human well being (e.g., Fairhead and Leach, 1996; Laris, 2002). Similarly, the clean develop mechanisms of the Kyoto protocol and its program aimed at reducing emissions from deforestation and land degradation (REDD) is a pending international accord that will surely affect the LAs of tropical forests. If implemented, REDD will affect the amount, and in some cases, location of forest preservation and restoration within the countries involved, adding yet another factor interacting with local-to-state policies and local-to-global economic forces to shape the LAs of forests.

3. Land architectures in the southern Yucatán

The land systems in the southern Yucatán (SY) are the outcome of the confluence of state, market, and other socio-cultural forces operating within several governance structures affecting land access and resource use, foremost those set by the Calakmul biosphere reserve (CBR) in cooperation with the MesoAmerican biological corridor (MBC; a United Nations program that aims to facilitate the movement of biota across the peninsula and Central America), and the many *ejidos* or communally owned land units operating within and around and reserve. These structures help shape, intentionally and unintentionally, the kind, amount, and pattern of land uses and covers—the land systems' architectures. In turn, the different architectures have important implications for environmental services and on-land household livelihoods. By exploring as fully as possible these linkages, an expansive range of questions central to land change science are opened to analysis (DeFries et al., 2004).

3.1. The study region

The SY is a project-defined region that surrounds the CBR and covers much of southeastern Quintana Roo and southwestern Campeche (Fig. 1; Turner et al., 2004). It delimits the *meseta* or rolling hill lands that form the spine of the Yucatán peninsula, beginning about 150 m amsl and rising to 350 m amsl, and captures an important ecocline between the xeric forests of the northern peninsula and the humid forests of El Petén, Guatemala (Lawrence et al., 2004; Vester et al., 2007). Much of the SY (ca. 22,000 km^2) was the subject of systematic settlement from the middle of the twentieth century, mostly by smallholder farmers within Mexico's *ejdio* system (communally owned lands).[4] Its population exploded in the

[3] Pielke et al. (1999) demonstrate how land changes, generating a new LA for southern Florida, have had impacts on region precipitation estimated to rival or exceed those associated with global climate change. While this work does not emphasize the pattern of land uses and covers, the architecture is embedded in the assessment, however, demonstrating its potential import.

[4] It is noteworthy that almost all the SY was largely denuded by the Classic Period Maya until their collapse and depopulation of the region between about A.D. 850–950 (Turner et al., 2003). Hurricanes regularly disturb these forests on the century-level scale (Boose et al., 2003), and selective logging took out most of two species of hardwoods during the last century (Klepeis, 2004).

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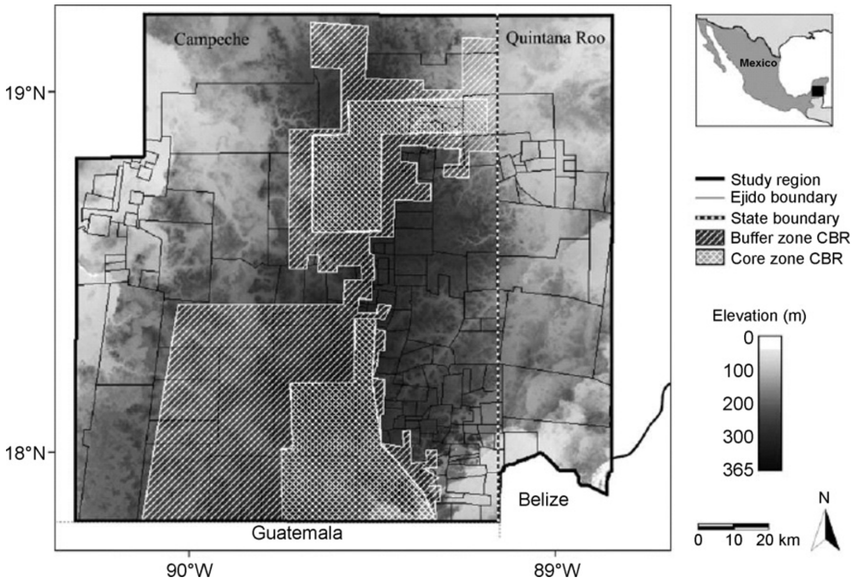

Fig. 1. The southern Yucatán (SY) and Calakmul biosphere reserve (CBR).

last quarter of that century as major highways were developed. About 35,000 legal residents currently reside there.

In this tropical forest and economic frontier, smallholders embarked on major land clearing for cultivation and pasture, in some cases stimulated by state-run, development projects. As much as 12.7% or 2396 km^2 of the forests of the SY had been cut by 2000 (Vester et al., 2007, p. 993), registering the SY as a global "hot spot" of tropical deforestation (Achard et al., 2002).[5] In tandem with the development of the CBR to preserve biotic diversity and carbon storage, the rates of deforestation declined and farmers focused on temporal intensification (decreasing the crop-fallow cycles) of shifting cultivation (Vester et al., 2007) and the diversification of household income. This diversification includes commercial chili cultivation (Keys, 2004, 2005), investment in pasture (Klepeis and Vance, 2003; Schmook and Radel, 2008; Schmook and Vance, 2009), off-farm activities, and in some cases, international male labor migration (Radel and Schmook, 2008). Household economies can be categorized in a number of ways (e.g., Radel and Schmook, 2008), but in regard to on-farm activities two household extremes are useful for analysis: those largely maintaining a subsistence orientation, and those aggressively involved in commercial chili production and investment in pasture (Alayón-Gamboa and Gurri, 2008).

Four types of land governing units dominate: state-controlled lands, forest *ejidos*, private ranches, and agricultural *ejidos*. State-owned land is restricted to the center of the reserve; large portions of reserve's periphery are composed of forest extraction and agricultural *ejidos*. Access to *ejido* land is usually through usufruct rights given to member households. A few private ranches are scattered across the SY, most of which have cut their forest at least once and keep their lands in different phases of pasture, shrub, and secondary forest. Together, reserve agents, *ejido* members, and, to a lesser extent in terms of total land area, managers of private, generate different land architectures that lead to a "collective design" for the SY. With the CBR in the center, agricultural *ejidos* and ranches dominate the eastern side of the SY and along the major north–south and east–west highways. Some portion of older growth forest in the *ejidos* is preserved, but otherwise households and ranch managers determine the lands taken to cultivation and pasture, triggering substantial land-cover changes (Vester et al., 2007). Phasing into this century, however, the cutting of older growth forest began to wane and the intensification of uses on extant opened land increased, largely by reducing the period of fallow or age of secondary vegetation cut.

The decision to cut forest – older growth in the past and secondary forest today – takes place in increasingly complex household circumstances predicated on lands controlled or rented; off-farm economic activities, including remittances from migrant male heads; state and NGO programs that have provided subsidies and direct payments for crops and double cropping (taking two harvests from the same field in one calendar year); intensification practices (e.g., disking and fertilizer use) and commercial cultivation; forest use activities[6]; investment in pasture in hopes of populating it with livestock; and for some *ejidos*, CBR rules about forest cutting (Abizaid and Coomes, 2004; Busch, 2006; Haenn, 2005; Keys and Roy Chowdhury, 2006; Klepeis and Vance, 2003; Porter Bolland et al., 2006; Radel and Schmook, 2008; Roy Chowdhury and Turner, 2006; Schmook and Vance, 2009). In addition, this decision involves the type of forest available to the *ejido* and household.

The ecocline of the SY supports three main upland forest types: short stature, deciduous forest; medium stature, semi-deciduous forest; and tall stature, humid forest (Pérez-Salicrup, 2004; Lawrence et al., 2004; Vester et al., 2007). While short deciduous and tall humid forests tend to be distributed to the northwest and south, respectively, medium semi-deciduous forest dominates the central part of the SY, mixed with the other two types, depending on location. The location of *ejidos*, of course, determines the upland forest types available to its members, but lands under medium semi-deciduous and tall humid forests are preferred for cultivation, reflecting superior soil moisture conditions. In

[5] These figures are based on the amount of land controlled by land units totally contained within the demarcation of the SY. The total area of these lands covers 18,900.73 km^2 (Vester et al., 2007, p. 992).

[6] An NGO forestry program (Forestry Pilot Plan) has been implemented in various parts of Quintana Roo, Mexico, including a few *ejidos* in the eastern side of the SY (Bray et al., 2005; Primack et al., 1998; Taylor and Zabin, 2000). Complementary programs to it have not succeeded well within the SY proper, however.

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addition, solution sinks or *bajos* exist throughout the SY. These features infill with thick clays that hold water throughout much of the year. They support a low stature, inundated forest that, for the most part, farmers avoid. The amount of upland forests per household is affected by the proportion of *ejido* land composed of *bajos*.

The different forest types, characterized by the abundance of different species more so than their presence (Pérez-Salicrup, 2004; Ibarra-Manríquez et al., 2002), play important roles in maintaining the biotic diversity along the ecocline, and keystone species within them are affected by human disturbance. The amount of disturbance by forest type, including the connectivity among the types – part of the architecture of disturbance – is foundational to the MBC. The collective architecture of the SY created by the different land managers plays a potentially important role in the function MBC, given that the CBR and the region are centrally located between the drier north of the peninsula and the more humid Petén to the south.

3.2. Results and observations: illustrating land architectures

The illustration offered constitutes a major simplification and idealization of the otherwise complex coupled system of two *ejidos* and their surroundings located in the central SY, an area dominated by medium semi-deciduous forest (above). The land classes are reduced (aggregated) to intact forest (all forest types >25 years in age) and disturbed land (cultivated, pasture, fallowed and invasive-dominated) as they existed in 2000. Fallowed lands are in various stages of successional growth – shrub to secondary forest – or taken over by bracken fern (*Pteridium aquilinum*). This fern is a fire-propagated, invasive species that appears in all opened and burned land. The willingness of farmers “to fight” the invasion tends to be related to how important cultivation is to the household (Schneider, 2004, 2006; Schneider and Geoghegan, 2006). Only direct production from the land is considered in this illustration; excluded are off-farm employment, remittances, and specific types of NGO and state assistance that households may entertain. The environmental and economic data are drawn from different parts of the SYPR project research.

3.2.1. Two ejido comparison

The first *ejido* (Fig. 2) has an architecture based on internal policies that favor preservation of as much intact forest as possible, relying on NGO and other assistance to do so. Recognizing that this *ejido* is large in size, with relatively low land pressures, agriculture is concentrated in a large patch of disturbance in the north, leaving the majority of *ejido* land to the south as one large forest patch in which upland and seasonally inundated forests remain largely undisturbed. The resulting FRAGSTAT measures are indicative of low levels of disturbance: patch density (PD = 0.02), edge density (ED = 2.01), and landscape shape index (LSI = 2.67).[7] This simple LA supports a variety of environmental services. For the CBR and MBC, it maintains biotic diversity, including habitat for top predators, by sustaining large patches of the major forest types with an abundance of slow-maturing, keystone tree species, the fruits of which are essential dry-season food for fauna (Weterings et al., 2008). This LA preserves high levels of above ground biomass (carbon), a goal of the CBR. It captures large amounts of phosphorus (about 1 kg/(ha-year)); Lawrence et al., 2007), the apparent limiting nutrient in the ecosystem, from atmospheric dust and maintains good levels of available phosphorus stocks in the system. This architecture may also assist in sustaining regional rainfall by the amount of water vapor released through evapotranspiration,[8] and reduces the area prone to the invasive bracken fern (Eaton and Lawrence, 2009; Lawrence and Foster, 2002; Lawrence et al., 2004; Read and Lawrence, 2003; Rivera and Calmé, 2006; Schneider, 2006; Vester et al., 2007).

Fig. 2. *Ejido* one land architecture.

Cultivation in the *ejido* is largely classical *milpa* (slash-and-burn maize) modified by a year or two of commercial chili interspersed within each crop-fallow cycle. In this case, only small investments in fertilizers and pesticides are made (Keys, 2004; Roy Chowdhury and Turner, 2006), largely for chili, while the concentrated cultivation involves repeated crop-fallow cycles. This concentration triggers significant declines in available soils phosphorous (Lawrence et al., 2007) and persistent bracken fern problems (Schneider, 2004). To maintain cropping, farmers add labor to weed the fern and, in longer run, must consider replenishing the deplete phosphorus or expand cultivation into the older growth forest. On-farm income for the *ejidos*’ largely subsistence oriented households is only about US $40/ha, not accounting for the value of the consumption crops grown (Keys, 2004). This low level of income suggests that the inputs necessary to sustain the current cultivation system must come with off-farm activities.

The second *ejido*, with much larger land pressures than first, not only employs most of its land in cultivation but is occupied by households of aggressive, commercial-based farmers (Fig. 3). The resulting architecture is a mass of opened and bracken-fern invaded land, with large amounts of secondary forest that will be recut for cultivation and pasture. Small patches of older growth forest are present, the largest in the southwest portion of the *ejido*, but they are not well connected and offer much less habitat for top

[7] Patch density is number of patches in the landscape divided by the area in question. Edge density is the total length of edges in the landscape divided by the area in question. Landscape shape index is the total length of edge in the landscape divided by the minimum total length of edge in the landscape. The larger the LSI, the more complex the shape.

[8] As yet the project has not proven the evapotranspiration observation. Local farmers claim, however, that the more forest cut, the drier the region becomes. Local precipitation data are sparse and temporally incomplete, but suggest a decline in rainfall over the last several decades for those years without a hurricane, a period of major land clearing in the SY and beyond (Lawrence et al., 2004). This decline, if real, may be driven by many factors other than local land changes.

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Fig. 3. *Ejido* two land architecture.

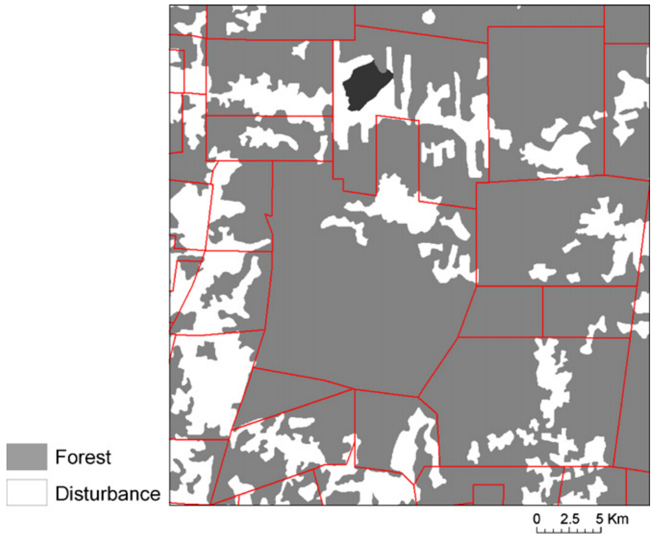

Fig. 4. Multi-*Ejido* land architecture.

predators. PD (0.16), ED (5.91), and LSI (4.20) reflect the high levels of disturbance observed in this *ejido*, with its reduced habitat for top predators. The prevalent secondary forest is dominated by fast growing species, and the keystone species are too immature to fruit. Total biomass and above ground carbon decline significantly (Eaton and Lawrence, 2009); the capture of dust-blown phosphorus is reduced by the amount of secondary growth and the loss of soil phosphorus from cropping is significant; and the secondary forest produces less evapotranspiration, perhaps affecting precipitation (see above).

The more level but non-inundated lands are disked and planted in rows for intensive chili production, with major investments in fertilizers and pesticides to offset the negative consequences of increased crop-fallow cycles (Keys and Roy Chowdhury, 2006). Barring a drought or hurricane, these commercial farmers generate a high farm-based income, reaching more N $100/ha, not accounting for the value of crops directly consumed (Keys, 2004). The income earned is invested in off-farm activities and in planting pasture with eye towards gaining livestock in the future (Schmook and Radel, 2008).

The differences in the LAs of these idealized *ejidos* reflect much more than the different aspirations and land uses of their members. They have major implications for the tradeoffs between environment services and human outcomes, and thus the sustainability of the land systems for the farmers and the CBR and MBC. The first case provides a LA consistent with the needs of the reserve and corridor, scoring well in most of the environmental services considered, but does not perform well in regard to on-farm food and income generation. The second case improves on-farm income, barring a major natural hazard or failure in the chili market, but does so by significantly reducing environmental services, especially those that the reserve and corridor seek to maintain.

3.2.2. Scalar comparisons

The variants of the two LAs (above) among the many *ejidos* and other land units in the SY provide a measure of architectural heterogeneity that differentially serve the goals of CBR and MBC, and the smallholder farmers. If the LA of the second or deforested *ejido* (Fig. 3) were replicated throughout the SY (Fig. 1) and chili markets remain strong, on-farm income across the region would rise, at least initially. The environmental services required for the reserve, corridor, and ecocline would, of course, decline. Over the long haul, economical substitutes for soil phosphorus and other lost nutrients would be required to maintain on-farm income, all other factors being equal, and rainfall might be reduced regionally. Alternatively, if the LA of first or forest preservation *ejido* (Fig. 2) were replicated across the SY, the aims of the CBR and MBC would be well served but at the cost of the on-farm livelihoods that smallholders would generate.

Similarly, the sustainability of any *ejidos*' LA involves the dynamics generated by the totality of the individual *ejido* architectures in which it is embedded. Consider, for example, the forest preservation *ejido* that renders the biophysical outcomes sought by the CBR and MBC. This *ejido* is surrounded by others (Fig. 4) maintaining fundamentally different LAs weighted to outcomes more favorable to the human subsystem, as in the case of the second *ejido*. The *ejido* set thus maintains a LA more similar to the aggressively cultivated *ejido* (Fig. 3). Indeed, ED (8.26) and the LSI (10.33) actually increase for the *ejido* set, compared to that *ejido*. Even the large patch of older growth upland forest in that *ejido* is isolated, cutoff from other large patches of upland forest, raising questions about biotic diversity and the ecocline functions.

4. Implications for forest transition

Despite its simplification, the illustration above indicates that different LAs present different implications for sustainability by individual land management units and by those units taken as a whole. Currently, the LAs generated by agricultural *ejidos* outside the CBR are not necessarily compatible with the preservation of forest cover and environmental services that the reserve seeks. The thin soils and markets in this frontier economy, in turn, raise serious questions about the capacity of all *ejidos*, but especially those in the reserve with restrictions on forest–land use, to sustain improved livelihoods by way of on-farm activities alone. A compromise architecture of the land systems that fulfills the needs of the two principal stakeholders – farmers/*ejidos* and agents/reserve – may evolve, but it too will involve tradeoffs that must be considered carefully. Among these tradeoffs is the amount of forest cover for the full set of forest types in the SY, apparently critical for the maintenance of biotic diversity as well as carbon storage. The answer holds insights for forest transition theory.

Forest transition theory developed from assessments of large-scale and "permanent" reforestation in the western world, linked to major shifts in the base economy of the area in question from extractive and agricultural activities to industrial production and

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service economies (e.g., Mather, 1992; for details see Rudel et al., 2009). The population formerly engaged in extractive activities follows these changes because of the enhanced material livelihoods gained by doing so; thus the demand for extractive uses of forest lands declines and long-term forest land-cover returns (i.e., Granger, 1995; Walker, 2008). Perz (2007) links the theory to modernization principles, which, he claims, have not succeeded well in the tropical word (for a critique, Walker, 2008). Lambin et al. (2001), however, note the variance and complexity of land dynamics in tropical forests suggestive of multiple pathways towards forest recovery, and Rudel et al. (2005) point to at least one such pathway—forest product scarcity leading to replanting trees.[9] Given that successional forest growth may be identified as a sign of a forest transition or the incipient stages of it, the number of potential pathways enlarges.[10] For example, an arrested first phase of the forest transition can be detected throughout the tropical world. This reduced pace of deforestation and regeneration of forest cover occurs not because the local-to-regional economy "develops" or forest products become scarce. Rather, economic conditions are such that extractive land uses, including agriculture, fail to yield livelihood expectations. Land managers seek alternative livelihoods, reducing pressures on use of forested or cleared lands, in some cases assisted by NGO and state agencies which subsidize or directly pay for non-timber, forest extraction programs (e.g., Bray et al., 2004). Such conditions, a variant of which may be linked to the creation of parks and reserves with their rules about forest use, have been framed by Rudel et al. (2002) as a hollow frontier.

Portions of the SY may be witnessing a forest transition associated with an arrested first phase: rapid deforestation has halted for various reasons and some formerly denuded lands are in various stages of forest recovery. This recovery has little to do with the two recognized pathways to forest transition (above), either tangible economic development or forest scarcity replanting, given the large tracts of older growth in the region. Rather, the forest dynamics underway are attributable to at least three interactive factors that affect the collective design of land systems in the SY: changes in the Mexican agrarian economy, part of its neoliberalization program that de-emphasizes support (direct payments and subsidies) of the *ejido* system (de Janvry et al., 1997; Liverman and Vilas, 2006; Randall, 1996); the creation of the CBR and MBC with their emphasis on forest preservation, including rules that restrict forest cutting among *ejidos* residing within the reserve (Primack et al., 1998); and the SY's status as an economic frontier in which land managers search for, but have not found low-risk, good profit land uses (Busch, 2006; Schmook and Vance, 2009).[11]

The first factor and indirectly, the second are partially consistent with forest transition theory. While the Mexican and SY regional economy have not yet entered the stages of economic development that triggered forest recovery in Western Europe and the United States, the actions of the Mexican state have been taken with economic development in mind. The decline in support for *ejidos* is part of state-led initiatives to modernize the economy of Mexico by de-emphasizing "marginal" agriculture, while attempting to increase non-farm alternatives to the affected land users.[12] The CBR and MBC, in turn, have been implemented partly because Mexico believes it can improve the SY and state economies through archaeo-eco-tourism, with spinoffs assisting local people, while preserving and enlarging the area of forest as part of Mexico's commitment to international environmental concerns (Primack et al., 1998). In this reality, policy has shifted to push the regional economy beyond extractive activities, which in turn has pushed households to explore ways to diversify their income-generating portfolios, including illegal international migration (Radel and Schmook, 2008).

The third factor, which involves the concentration of agricultural activity on extant opened lands, has yet to reveal land uses that, alone, can lead to sustained and improved household livelihoods. Commercial chili production is a boom-bust proposition (Keys, 2004); livestock ventures in past have proven difficult in large part due to the paucity of water during the extended winter dry season; and smallholder farmers do not have the assets to undertake large-scale farming akin to Mennonites just beyond the SY borders (in Campeche and Belize). Diversifying the household economy, which in some cases appears to reduce forest clearing and increase the area of successional growth, is a safety measure that *ejido* members employ given the precarious economic performance of the land systems.

It is noteworthy that the first and third factors are especially dynamic compared to the second, and they have the potential to change dramatically the collective design of the LA of the region. For example, households have not relinquished claims to the land (e.g., Abizaid and Coomes, 2004), which is retained as a safety net or with an eye towards projected, higher reward uses. Off-farm income, including state payments intended for other purposes, is commonly directed to expanding pasture, especially among *ejidos* surrounding the CBR that do not have formal constraints on forest–land uses (Busch, 2006; Klepeis and Vance, 2003; Schmook and Radel, 2008; Schmook and Vance, 2009). This response leads to conditions akin to the hollow frontier. Should livestock production ultimately prove sufficiently rewarding, deforestation rates for the SY are likely to rise again with shifts in LAs.

The appearance of an incipient forest transition in the SY is also determined by the scale of analysis employed. The CBR and its rules about cutting forest lands, which has halted deforestation within the reserve, provide a region-wide outcome indicative of forest restoration (Rueda, 2007). In contrast, *ejidos* to east and west of the CBR either continue to deforest, if at modest rates, or show little sign of permitting opened lands to return to older growth status (Rueda, 2007). If these trends hold, the SY will maintain a bifurcated LA consistent. Enforced policies of the CBR will induce substantial stands of old growth forest within the reserve, although not a result of the modernization of the regional economy in which smallholders voluntarily move into other economic sectors or of forest scarcity. Outside the reserve, however, deforestation will continue depending of the circumstances, creating a highly fragmented and open landscape on all but the south side of reserve which abuts the Maya biosphere reserve in Guatemala. Such a bifurcated, general LA not only raises questions about forest transition but about the capacity of the CBR to function adequately (Vester et al., 2007). Alternatively, if no acceptable agricultural alternatives emerge in the region and economic opportunities elsewhere in the Mexico or abroad draw

[9] Transition theory must resolve the role of successional versus planted and managed regrowth. Much of the transition in the western world, on which they theory is based, involved successional processes of forest regrowth, leading to functioning, if altered, forest ecosystems. Identification of forest transition in the tropics includes planted trees, as in plantations (e.g., Rudel et al., 2005), which need not provide a full array of environmental services expected from forest cover (see Chazdon, 2008; Kauppi et al., 2006).

[10] Bray et al. (2004), for instance, refer to a more forested, sustainable land systems to the north of the SY, an interpretation predicated on including successional growth are more or less permanent forest cover that will move into old growth phases.

[11] It is noteworthy that large-scale, mechanized cultivation takes place to the northwest of the SY region among high-capital investing, Mennonite farmers. These developments are sufficiently recent that the longer-term economic viability of the land system cannot be determined.

[12] NGO-sponsored programs focused on non-timber, forest extraction, such as the Forestry Pilot Plan, are also challenged by the macro-economic changes underway in Mexico (Bray et al., 2005; Taylor and Zabin, 2000).

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away much of the population, reducing land pressures, the lands surrounding the CBR will cease being deforested and successional growth may be permitted to reach older growth stages.

Which of these situations, or some other, prevails will provide insights about forest transition theory. It is clear, however, the pace of deforestation and reforestation observed for the region depends on lens taken. The variations observed are differentially linked to forest transition theory, suggesting that the base concept requires elaboration and modification (Mather, 2007), that reduces its elegance but provides greater explanatory power. Among these modifications is the role of direct government intervention (Mather, 2007), as in the case of establishing parks and reserves, as well as macro-policies guiding the rural economy.

5. Conclusions

The search is underway to develop tropical forest lands in a more sustainable ways, foremost with an eye towards preserving and conserving, as much as possible, the critical roles of tropical forests in the maintenance of the earth system and biotic diversity. To date, this search has not systematically addressed a full array of environmental and human tradeoffs inherent in different land systems and amplified by the consideration of the architecture of those systems. The land architecture approach appears to be especially cogent for questions of the coupled systems consequences of land change and such themes and theories as forest transition. The SY example illustrates how the collective design of regional LA yields tradeoffs supporting differing land-use goals with different implications for the functioning of CBR and MBC and for household livelihoods. The recent changes in the land architecture hints of a possible forest transition, but one only ephemerally embedded in the rationale of forest transition theory. The current arrested phase of initial deforestation, if it should prevail, suggests possible alterations of or additions to the formal theory. Given sociopolitical uncertainties in the Mexican and SY regional economies, the transitions of forest cover in SY cannot be forecasted adequately. Regardless, the LAs for the region will continue to affect the interactions and the outcomes of the coupled (human–environment) land systems.

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