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ORIGINAL ARTICLE

Understanding deforestation in the southern Yucatán: insights from a sub-regional, multi-temporal analysis

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Abstract The southern Yucatán has been identified as a deforestation hot spot. Land-change studies document the extent of forest loss at a regional scale, and case studies provide insights into the drivers of deforestation at the household level. Those studies have paid minimal attention to sub-regional analysis, especially to discrete land-management units above the household level. This analysis of upland forest change addresses the range of variation in deforestation among 96 *ejidos* (communal lands) and the Calakmul Biosphere Reserve, the two dominant land-tenure and land-management units in the region. Satellite imagery, census, and land-tenure data are used to establish the extent and location of deforestation patterns, and multivariate techniques are employed to identify biophysical and socioeconomic variables that explain such patterns. Results show that, for the 1984–1993 period, deforestation in the southern Yucatán was not as prevalent as implied by its hot spot designation. Three clusters of deforestation are identified. A logistic regression analysis establishes that size of forest holdings, population growth, and location in the precipitation gradient correlate with *ejidos* that experienced higher deforestation rates than the rest of the land-tenure units. For the 1993–2000 period, conservation programs and changes in the economic context of this "hollow frontier" contributed to reduce deforestation rates and extent. This analysis illustrates the spatio-temporal heterogeneity of much tropical forest change and caution that it should bring to simple formulations of modeling this change and prescribing policies to control it.

Keywords Deforestation · Southern Yucatán · Logistic regression · Sub-regional analysis

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Introduction

Tropical forests are pivotal to the functioning of the Earth system, global climate, and biotic diversity (Watson et al. 2000). As such, reports of areas with high rates of tropical deforestation worldwide, often labeled "hot spots" (e.g., Myers 1988; Achard et al. 1998), have led the land change and related research communities to focus considerable attention on them (e.g., Rudel 2005; Laurance 1999; Tucker and Townshend 2000). While concern for tropical forests is grounded in a reality of significant deforestation, especially over the last 40 years, the accuracy of global estimates of this land change as well as the precise locations involved have been questioned (Grainger 2008; Waggoner 2009). The challenges are numerous: how to define deforestation; whether to include secondary (re)growth or not, given that much of it may be scheduled for recutting; at what age should secondary vegetation be counted as forest; and how to conciliate discrepancies between estimates derived from country reported data sets and remote sensing assessments, among others (e.g., Kauppi et al. 2006). These concerns have implications far beyond deforestation. They are central to assessments of the forest transition thesis—that economic development leads to reforestation (Mather 1992; Rudel 2005; Rudel et al. 2009), and to the efficacy of proposed programs (e.g., REDD, Reducing Emissions from Deforestation and forest Degradation) to compensate the tropical world for maintaining their forests as carbon sinks (Gibbs et al. 2007).

Often missing from these research topics, but increasingly addressed in land-change science, is the role of the spatial (and temporal) resolution of analysis in determining the rates and relative amount of forest loss or gain observed. Changing the lens of the analysis often changes the outcome and illuminates the variability of the dynamics in question. Researchers working in Amazonia (Brondizio 2006) and Central America (Tucker and Southworth 2006), for example, have found that deforestation rates vary widely when sub-regional analyses are undertaken. Accounting for this variation potentially provides important insights into land-change dynamics, both causes and consequences, including the applicability of such designations as "hot spots" of deforestation. Moreover, the design of conservation policies that aim at reducing deforestation, be they land use surrounding a forest reserve or tied to REDD requires this fine-tuning in targeting land units that exhibit large deforestation, and in tailoring programs according to the characteristics of those units and their managers. Indeed, by zooming in on these hot spots of land-cover change, as well as areas of little change, specific drivers and modifying factors of deforestation may be more clearly discerned, thus improving land policy and land-management strategies (Giri et al. 2003; van Laake and Sanchez Azofeifa 2004; Moran and Ostrom 2006).

These issues apply to Mexico, where forests are disappearing at a rapid pace, regardless of variations in annual figures ranging from 0.4 to 1.4% (FAO 2005; Trejo and Dirzo 2000). Forest losses across the Yucatán Peninsula contribute significantly to the Mexican case (Achard et al. 1998) and generate special attention owing to the Peninsula's pivotal role in the Meso-American Biological Corridor (MBC) (Miller et al. 2001), including the Calakmul Biosphere Reserve (CBR) (Primack et al. 1998). These institutional arrangements seek to protect and facilitate the movement of biota throughout Central America and, in the case of CBR, preserve Mexican carbon stocks. Various definitions and methods of assessing deforestation across the Peninsula generate significantly different estimates of the pace of deforestation (Sohn et al. 1999; Bray et al. 2004; Turner et al. 2004). One study reports a net deforestation annual rate of only 0.1% for the forests of Central Quintana Roo for the years 1984–2000 (Bray et al. 2004), a figure influenced by counting late successional growth (years undefined) in Maya forest *ejidos* as forest, not likely to be recut (Bray and Klepeis 2005). In contrast, the Southern Yucatán Peninsular Region (SYPR) project operating in southwestern Quintana Roo and southeastern Campeche indicates an annual rate of forest loss of 0.29% for 1984–1993, falling to 0.21% for 1987/1988–2000 (Turner et al. 2004; Vester et al. 2007).[1] In this case, successional growth had to register 25 years or more in age to be considered forest.

These and other case studies of deforestation in the Yucatán Peninsula utilizing remote sensing analyses have focused largely on either regional or parcel-level units of assessment, with less attention given to sub-regional analysis, especially to such discrete land-management units as the pervasive *ejidos*—the land-tenure units derived from the collective-rights system instituted by the Mexican government after the Revolution of 1910 (Alix-Garcia 2004)—private properties, and state-controlled lands, in this case the CBR. There are strong reasons to believe that forest-cover change may vary across different institutional arrangements in the southern Yucatán (SY) of Mexico. Not only are some *ejidos* partially located within the CBR, and thus subject to negotiations with reserve officials about land uses, but *ejidos* also differ in age, population density, distance to market, ethnicity, education, and social capital (Haenn 2005; Roy Chowdhury and Turner 2006), hinting that their land uses may differ from one another (see Radel et al., this issue; Gurri, this issue). In addition, the SY crosses two Mexican states that pursue different variants of development strategies affecting land use on *ejidos*.

This research carries out the first sub-regional analysis of upland forest change (i.e. well-drained forests were most forest loss has taken place in the hands of small land holders) in the SY from 1984 to 2000 to assess the range of variation in deforestation characteristics among *ejidos*. It employs land-cover classification and change analysis information generated by the SYPR project, but which to date has been used largely for assessment of forest change within and without the CBR (Lawrence et al. 2004; Vester et al. 2007). Specifically, this study documents the forest changes among 96 individual agricultural *ejidos* during two phases: 1984–1993 and 1993–2000; separates *ejidos* into two categories, according to their deforestation rates (high/low), and employs logistic regression analysis to determine common socioeconomic or environmental characteristics associated with the deforestation patterns found. This analysis by land-tenure units over almost two decades reveals that decisions on land-use and land-cover changes depend on the intrinsic characteristics of the land-tenure units as much as on external pressures. The colonization frontier appears not as a uniform front of deforestation, but as a complex, varied, and ever-changing landscape of forest loss and recovery.

[1] The SYPR is a multi-disciplinary and multi-institutional project examining land dynamics in the southern Yucatan operating since 1997. The project joins environmental, social, and GIS/remote sensing sciences to address land-use/cover change in its own right as foundational to a series of forest ecology, socioeconomic development, and coupled systems issues (Turner et al. 2004).

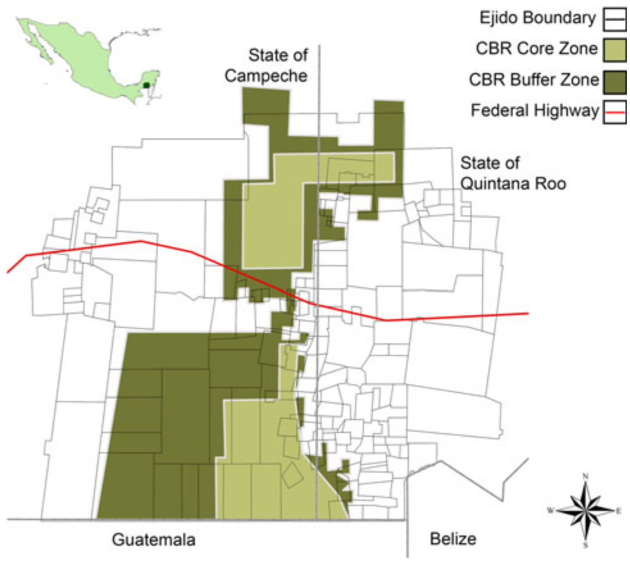


Fig. 1 The study region and site

The study region and site

The SY, described in the introduction to this issue (Turner this issue), is comprised of several types of land-management units and covers nearly 19,000 km^2. These units include 96 agricultural communal lands (*ejidos* cover 9,407 km^2 some of which are located in the CBR) situated fully within its borders, a handful of forest extensions granted to *ejidos* located outside of the study area in which minimal deforestation takes places, private lands (mostly small ranches which long ago cut most of their forests and do not permit secondary vegetation to reach older stages of growth), and the CBR, anchored in the center of the SY. The reserve was established in 1989 and joined the United Nations' Man and Biosphere Reserve Program in 1993. The reserve, which resides fully within the Municipio de Calakmul in Campeche, is composed of a core and a buffer zone of 2,479 and 4,746 km^2, respectively (Fig. 1).

Of the ~19,000 km^2 of the SY considered here, the CBR represents 38%, two-thirds of which constitute the buffer zone and one-third the core.[2] Communal lands owned by the agricultural *ejidos* represent 43% of the area, not including the 1,349 km^2 that lie at the intersection of the communal lands and the reserve (i.e., *ejido* lands over which the boundary of the CBR were demarcated). The remaining 19% is made up of private lands and forestry extension lands granted to *ejidos* that lie outside the study area and are not considered in this assessment for the reasons noted.

Forest cutting and wildlife extraction are prohibited in the core of the reserve (Diario Oficial 1989), while cultivation and some "sustainable" activities focused on forest products extraction are permitted in the buffer zone (Primack et al. 1998; Klepeis and Roy Chowdhury 2004; Haenn 2005; Roy Chowdhury and Turner 2006). At its establishment in 1989, most of the area within the reserve's bounds was public land, but some of it had been previously granted to *ejidos*. Records collected at the reserve's headquarters in Zoh Laguna (Campeche) indicate that *ejidal* rights to at least 4,000 ha were revoked and families from six communities relocated elsewhere with the establishment of the CBR. Nevertheless, 12 *ejidos* (particularly in the northeast and along the reserve's southeastern border) hold some portion of their lands overlapping the reserve's borders. This overlap accounts for <8% of the total CBR core zone and 24% of the buffer zone.

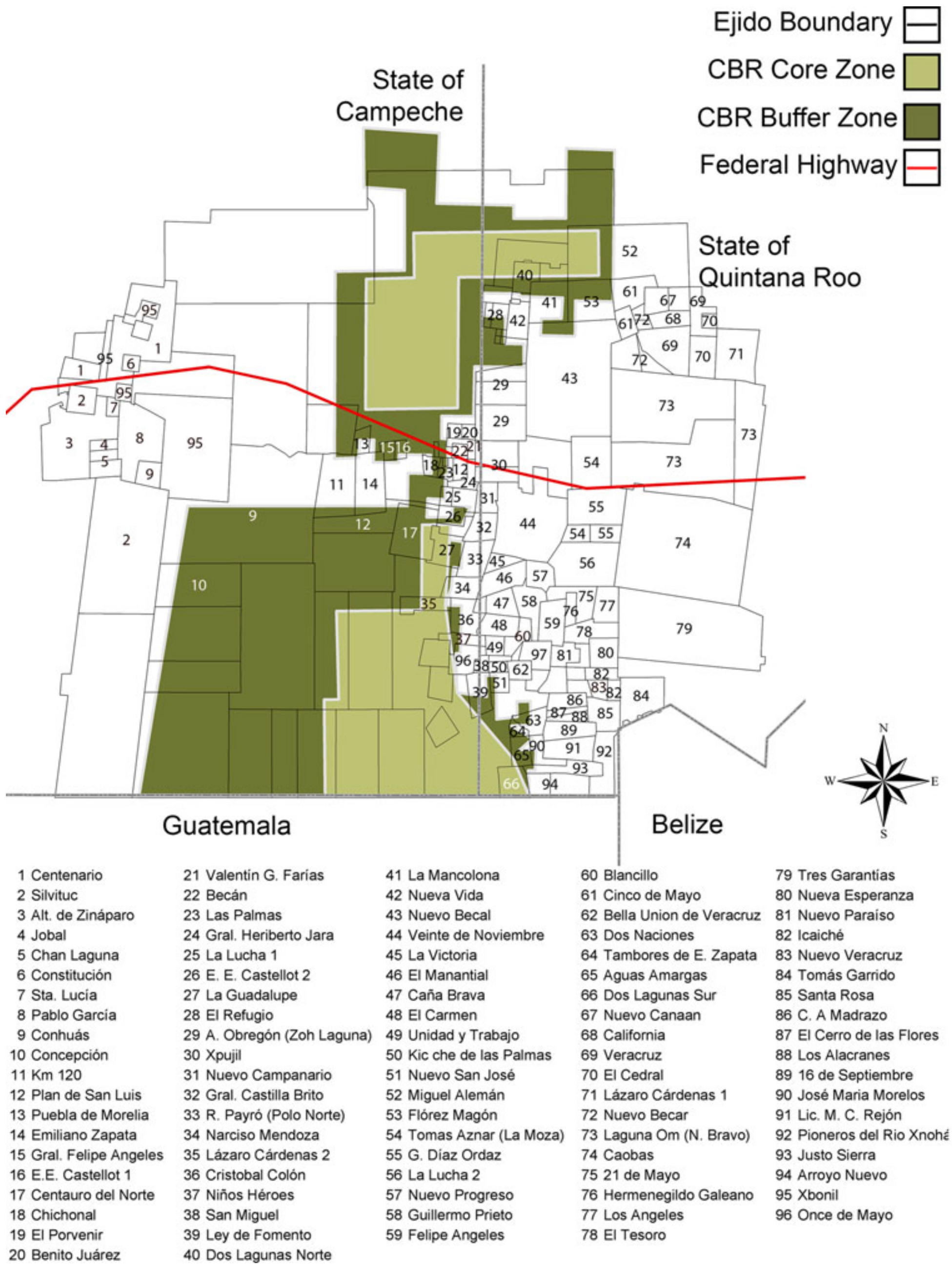
Deforestation rates were sufficiently large between 1990 and 1997 that the SY was categorized by a panel of experts as a hot spot of tropical deforestation (Achard et al. 1998). From 1984/87/88 to 2000, the period for which comparable land-cover classification maps are available (Turner et al. 2004; Schmook et al. 2010), 743 km^2 of deforestation took place, about 4.7% of the original forest of the SY. Between 1984 and 1993 a larger proportion (2.9%) of the original forest was cut (Roy Chowdhury and Schneider 2004), than in the subsequent period, 1993–2000 (1.8%). The initial forest loss included both upland (well-drained soils) and seasonally inundated forests, the last amplified by a few government projects. Subsequently, the majority of deforestation has focused on upland forests (see Turner, this issue), favored by smallholders for most forms of cultivation.

The SY can be considered a "hollow" economic frontier (see Busch and Geoghegan, this issue)—one in search of a firm production base. As noted by Turner (this issue), the SY experienced subsistence cultivation, government sponsored programs of several sorts, commercial chili production, labor migration, and pasture-livestock activities (see Radel et al. and Busch and Geoghegan, this issue), all of this in the face of state-sponsored attempts to generate eco-archaeo-tourism. In short, the SY has yet to establish a firm land-based economy capable of supporting the livelihoods of its inhabitants.

The most dynamic change in land cover in the SY takes place within *ejidos*, precisely the smallest unit for which abundant socioeconomic data are collected by the Mexican National Institute of Statistics and Geography (INEGI). The lands of 96 *ejidos* reside fully within the SYPR study region, representing 50% of the total area of analysis by the project (Fig. 2). The reserve and *ejidos*, together, account for 63% of the study area (Table 1). These *ejidos*, the

[2] The SYPR project's original study region approximates 22,000 km^2. If, however, only those land-management units residing fully within the project's bounds are considered (Fig. 1), then the area is reduced to 19,000 km^2.

Fig. 2 The Calakmul Biosphere Reserve and *Ejidos* included in the study



reserve, and the combined *ejido*-reserve land area are the focus of this assessment. Ejidal lands within the study area (forest extensions) belonging to communities who are settled outside the study area are excluded, since the decision-making processes for these lands are linked to populations and territories beyond the study area.

Materials and methods

The land-cover classification undertaken by the SYPR project (Vester et al. 2007) was used to analyze deforestation. The data are derived from Landsat Thematic Mapper TM/ETM+ images for 1984–1987–1988 and 1993–1994–1995 and 2000 (Path 20/Row 47 and 48, Path 19/Row 47 and 48) with a 28.5 m^2 resolution. The satellite images belong to four contiguous zones spanning the study region, and only one image of each year was used for each zone (Vance and Geoghegan 2002). The quality of the Landsat imagery prevented researchers at SYPR from undertaking single-year classifications for the oldest two images used here. This is considerable limitation of the data, particularly for analyzing multi-temporal land-use changes and their underlying causes. Nevertheless, the intervals at which these data were collected and classified allow for comparisons in land-cover changes before and after the CBR was established. Images were prepared for classification using the normal steps of geo-referencing, and haze and noise removal; NDVI information was added, and principal component and texture analyzes were performed. Finally, images were put together for the development of land-cover signatures that involved training sites, ground truthing, and a maximum likelihood supervised classification method (Geoghegan et al. 2001). The land-cover classification rendered 14 different classes.[3] Although ground truthing and validations were undertaken, the overall accuracy of the images is calculated at 86% (Turner et al. 2004; Vester et al. 2007). Classification errors may under- or over-estimate the extent of land change in the area. For this analysis, images were regrouped from 14 to 7 classes to simplify multi-temporal comparison. All secondary vegetation was grouped as one. Pastures and cultivated lands were collapsed in one class, to enable comparisons with the 1983/1987 image where no pasture category was available. Seasonally inundated and adjacent transitional forests and savannas were joined together in one class for simplicity, but they are not the subject of this analysis. All upland forests were also joined in one class, since they tend to have similar species composition (Lundell 1933; Miranda and Hernandez 1963; Pennington and Sarukhan 1968; Perez-Salicrup 2004), and they are the forest of use-choice among the smallholders of the *ejidos*. The remaining three classes, bracken fern (an invasive species), water bodies, and bare surfaces remain ungrouped, as in the original classification. By combining similar classes into one category, errors emerging from misclassification of highly similar cover types are reduced (Pontius and Malitzia 2004).

Upland forests are the focus of attention in this analysis for several reasons. They represent the critical forest types in the regional ecocline between xeric northern and humid southern forests of the Peninsula (Vester et al. 2007). Current deforestation in the SY tends to concentrate on upland forests, which, by definition, occupy well-drained land favored for cultivation by smallholder farmers who dominate *ejidos*. These forests once harbored abundant, valuable hardwood species, two of which, mahogany and Spanish cedar, were logged nearly to extinction by the 1970s and are currently being replanted in some *ejidos* (Klepeis 2003). Finally, upland forests draw the attention of programs for alternative forest uses (Klepeis and Roy Chowdhury 2004). Deforestation was therefore calculated for the whole SY as the net amount of upland forests lost (forest loss minus forest regrowth >25 years in age) to agriculture, secondary growth (<25 years), or bracken fern (Pteridium aquilinum)—an invasive species that thrives in cleared land, especially after burning (Schneider 2004, 2006).

A logistic regression was conducted to determine whether there are significant differences between the socio-economic and ecological characteristics of the *ejidos* responsible for most of the forest loss and the characteristics of the *ejidos* that did not engage in active deforestation. Logistic regression was chosen over linear regression because although information on deforestation figures for each *ejido* exists, classification errors are expected to be larger for individual *ejidos* than for the image as a whole. Heterogeneity and patch size affect classification accuracy (Smith et al. 2002). *Ejidos* tend to have smaller patches of each land-cover type and greater heterogeneity in land-covers than the CBR. Therefore land-cover classification for individual *ejidos* tends to be less accurate. Logistic regression reduces that problem by grouping all *ejidos* into two categories. Logistic regression distinguishes individuals belonging to two or more groups, according to their characteristics. It is employed when the dependent variable is categorical (i.e., good/bad, low/high) and the independent variables are continuous or dichotomous (Hair et al. 1998). Logistic regression transforms the dependent variable into a logit variable (the natural log of the odds of the dependent occurring or not), and then applies maximum likelihood estimation, estimating the probability of a certain event occurring, based on the values of the independent variables. In this case, logistic regression is used to determine which variables are significant in explaining the differences between two groups of *ejidos*, those with high deforestation values and those with small or negative deforestation. For each analysis, *ejidos* were classified in two identical-size groups, taking the median as the criterion for separation. Calculations were also made with polar extreme groups (using only the extreme ends of both groups) to capture the greatest difference between the groups, as has been suggested by some researchers (Hair et al. 1998). Results are presented for both methods. The logistic regression serves also to predict group membership for each case, based on the variables specified, thus allowing for a measurement of the classification error of the model.

The independent variables tested to explain differences between high- and low-deforestation values are those

[3] The 14 classes and their clusters are as follows: (1) Seasonally Inundated Vegetation and Wetland Forests that include *Selva Baja Inundable* (regularly inundated low-statured forest) and *Tulare and Savannas* (variably inundated grasslands and marsh); (2) a Transitional Forest category that includes only one class, *Selva Baja* (irregularly inundated low-statured forest often on edges of seasonal wetlands); (3) Upland Forests that include *Selva Alta and Mediana Perennifolia* (high-stature semi-evergreen upland forest), *Selva Mediana Subperennifolia* (medium-stature semi-evergreen upland forest), and *Selva Baja and Mediana Subcaducifolia* (medium and low-stature semi-deciduous and deciduous upland forest); and (4) Modified Vegetation that includes the *Herbaceous secondary*, *Shrubby secondary*, *and Arboreous secondary vegetation and Bracken Fern* (*an invasive species*, *Pteridium aquilinum*), *Crop cultivation* (milpa/swidden and chili cultivation), *Pasture*, and *Bare Surfaces*. Water bodies were classified as a separate category.

traditionally found in the literature on the drivers of tropical deforestation (Cropper et al. 1999; Geist and Lambin 2002; Geoghegan et al. 2004; Rudel et al. 2005). Typical deforestation models include transaction costs, land assets, land tenure, and ecological characteristics that make conversion to agriculture more feasible as drivers of deforestation (Chomitz and Gray 1995; Kaimowitz and Angelsen 1998). Also, population pressures are included in the literature as direct drivers of deforestation (Rudel et al. 2005). The model explored here uses distance to roads as a proxy for transaction costs, precipitation as a proxy for agricultural potential, and both total *ejidal* land assets and total forested assets. To measure population pressures, the model uses population data derived from the national censuses for 1980, 1990, and 2000 (INEGI 1982, 1992, 2007). Censuses collect information through a household survey but report aggregate results for each locality (i.e., *ejido*), municipality, and state, and for the country as a whole. Data reported for localities are used here, and they have the same level of aggregation as the spatial data that are derived from the imagery. Total *ejidal* land, total *ejidal* forested land, and distance to roads come from the imagery and the subsequent classification (Vester et al. 2007). In this case, only major roads (the east–west and north–south highways) identified in the classification were used. A relatively extensive tarmac road-net connecting *ejidos* exists, especially in the Quintana Roo part of the SY, and many parcels can be accessed by truck over dirt-trails. None of these secondary roads and trails is captured adequately by the SYPR imagery analysis, although new efforts are underway to add the tarmac roads. Lacking reliable information on location, extent, date of construction, and state of those roads from other sources, this article suffers from an under-representation of the importance and magnitude of roads in explaining land change across the region and over time.

Agricultural potential in this rolling landscape was measured using precipitation data as a proxy. A northwest-southeast precipitation gradient exists in the region (Turner et al. 2004), and work by the SYPR project indicates that this gradient, more so than other biophysical factor, affects forests and cultivation (Lawrence et al. 2004).[4] Continuous and accurate precipitation data are missing, however. A few weather stations scattered across the region have produced data since the 1970s. Geoghegan et al. (2004) interpolated this information to produce a precipitation map for the entire SY, which was used for this analysis. Lack of precision and insufficient data for the southern most parts of the area might be affecting the results presented here. Unfortunately, without historic and spatially detailed precipitation data, no improvements in this area are foreseeable.

Additionally, the year of foundation of the *ejido* was included as an explanatory variable because older *ejidos* were established with a clear forest vocation and forest extensions were given to many of them. Newer *ejidos* tended to be smaller and have an agricultural vocation since their establishment. Therefore, this study tries to capture the role of this vocation, as measured by the year of foundation of the *ejido*, in explaining deforestation.

The establishment of the reserve changed the land-tenure configuration of the area. *Ejidal* rights were revoked to at least six communities, and *ejidal* lands belonging to 12 other *ejidos* still overlap with the reserve. The only land-tenure map available takes into account the *ejidal* rights still in place after the establishment of the reserve. A precise delimitation of the *ejidal* rights that were revoked when the reserve was established is not available, and thus the land-tenure configuration before and after the reserve's establishment cannot be included as a variable in the model. Furthermore, some of the large *ejidos* in the region have set-aside land for forest conservation purposes only. In those *ejidos*, deforestation concentrates on the rest of their area (Flachsenberg and Galletti 1999; Radel 2005). Since the extent and location of those 'set-asides' has not been mapped, the values presented here refer to the average forest change experience by the *ejido* and are therefore over-estimating forest-cover change in the 'set-aside' areas and under-estimating forest-cover change in the areas open for exploitation. A more detailed spatial characterization of the intra-*ejidal* land distribution would allow a more precise determination of forest-cover change dynamics in the region.

The original specification of the model was:

$$\begin{aligned}\text{High deforestation} &= \beta_0 + \beta_1 \text{ Distance to roads}\\ &+ \beta_2 \text{ Precipitation} + \beta_3 \text{ Total land assets}\\ &+ \beta_4 \text{ Percentage of land devoted to agriculture in 1980}\\ &+ \beta_5 \text{ Year of foundation of the } \textit{ejido}\\ &+ \beta_6 \text{ Average annual population growth} + \varepsilon\end{aligned}$$

For the second period of the analysis, another variable was included in the model specification: the deforestation levels of the previous decade, to explore the existence of a potential cyclical component in the deforestation pattern of the *ejidos* of the SY. Therefore, the specification of the model for the 1993–2000 period was:

[4] The precipitation gradient emerges as the critical variable because, in part, other biophysical factors could not be treated in terms of their spatial specificity. The vast majority of the upland forests reside on redzina soils (mollisol order). Soil depth is linked to position on the catena and soil moisture, beyond rainfall characteristics, by slope angle and aspect. These micro-factors are considered here to be distributed relatively evenly throughout the region. See Foster and Turner (2004) for biophysical descriptions of the SY.

$$\text{High deforestation} = \beta_0 + \beta_1 \text{ Distance to roads}$$
$$+ \beta_2 \text{ Precipitation} + \beta_3 \text{ Total land assets}$$
$$+ \beta_4 \text{ Percentage of land devoted to agriculture in 1990}$$
$$+ \beta_5 \text{ Year of foundation of the } \textit{ejido}$$
$$+ \beta_6 \text{ Average annual population growth}$$
$$+ \beta_7 \text{ Deforestation in the previous decade} + \varepsilon$$

A common problem of deforestation models is that of multicolinearity (Kaimowitz et al. 2002). For instance, land assets and year of foundation of the *ejido* tend to be highly correlated, since older *ejidos* are generally larger than newer ones. An effort to keep the model parsimonious has been made and a stepwise procedure has been used, monitoring the impact of including or excluding each variable over both the overall goodness of fit of the model and the variance inflator factor, a common measure of multicolinearity problems (Studenmund 2006).

Results

Forest change trends: 1984–1993

Although *ejidos* represent only half of the total area in question, and 46% of the upland forests in the 1984 images, they made up 75% of the 590 km^2 of forests lost during the 1984–1993 period. For this same period—the early years of the CBR's existence—the core zone lost 55 km^2, just over 3% of its forested uplands, while the buffer zone lost over 114 km^2, near 4% of its forest endowment. *Ejidos* lost more than 8% of their original upland forest endowments. Interestingly, the core and the buffer zones of the CBR that lie in *ejidal* land also saw significant deforestation, 11 and 7%, respectively (Table 1). These changes in forest area lost were significantly heterogeneous throughout the SY (Fig. 3). Twenty-two *ejidos* were responsible for close to 72% of the deforestation that took place in *ejidal* land during 1984–1993, while 48 *ejidos*, roughly half of all the *ejidos* in the area, were responsible for almost 90% of all the deforestation in *ejidal* land for the same period.[5]

A logistic regression reveals differences between the characteristic of the *ejidos* responsible for most of the forest loss ($\geq$3.3 km^2) and those that experienced low

[5] The *ejidos* are as follows: Conhuás (34.9 km^2), Miguel Alemán (22.4 km^2), Nicolás Bravo (20.9 km^2), Tres Garantías (20.5 km^2), Zoh Laguna (13.4 km^2), Nuevo Becal (13.3 km^2), Cristobal Colón (12.3 km^2), Pablo García (12.0 km^2), La Lucha 2 (9.8 km^2), 20 de Noviembre (9.8 km^2), Santa Rosa (9.1 km^2) and Guillermo Prieto (8.0 km^2). Miguel Alemán, Nicolás Bravo and Tres Garantías are all in Quintana Roo and have extensive forest. Conhuás and Zoh Laguna belong to Campeche and they also enjoy large forestry extensions.

Table 1 Upland forest loss for 1984–1993 in the southern Yucatán by type of tenure

	Reserve			*Ejidos*				All study area		
	Core	Buffer	Total	Ejidal land outside of the Reserve	Ejidal land in the core	Ejidal land in the buffer	Total ejidal land	Reserva + *Ejidos*	Other	Total
	(1)	(2)	(3) = (1) + (2)	(4)	(5)	(6)	(7) = (4) + (5) + (6)	(8) = (3) + (4)	(9)	(10) = (8) + (9)
Total area of study (km^2)	2,479	4,746	7,225	8,058	204	1,145	9,407	15,283	3,617	18,900
Upland forest 1984 (km^2)	1,636	3,117	4,753	4,539	117	786	5,442	9,292	2,536	11,828
% Of upland forest	66.0	65.7	65.8	56.3	57.4	68.6	57.9	60.8	70.1	62.6
Upland forest loss 1984–1993 (km^2)	55	114	169	378	13	52	443	547	43	590

Source: Landsat 7 ETM+ imagery 1984–1985–1986 and 1993–1994–1995 (Vester et al. 2007). Calculations by author

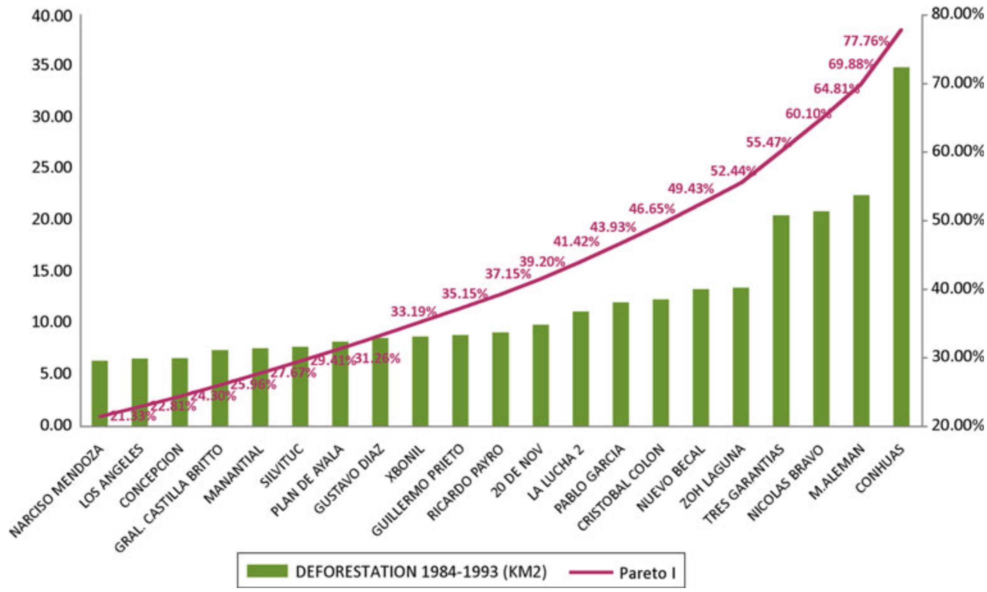


Fig. 3 Twenty-one *Ejidos* responsible for 78% of upland forest loss in the southern Yucatan 1984–1993

Table 2 Logistic regression results for net upland forest loss in the *ejidos* in SY grouped according to net upland forest loss in km^2 between 1984 and 1993, using the median (3.3 km^2) as the criterion for separation

Variables in the equation	Logistic coefficient	Standard error	Wald statistic	Sig.	Exp(*B*)
Forest endowment 1984 (%)	0.033	0.016	4.404	0.036	1.033
Precipitation (mm)	0.2	0.009	4.997	0.025	1.021
Constant	−24.789	10.633	5.435	0.020	0.000

$N = 96$

Nagelkerke $R^2 = 0.454$

Classification error = 20%

deforestation (<3.3 km^2) or even forest recovery (Table 2). Forest loss tended to occur in *ejidos* that have a large share of upland forest as a proportion of their total land holdings—the large *ejidos* of the west—and those located in the more humid regions of the east and south-east (Fig. 4). Both coefficients are significant at the 95% confidence interval. Distance to the two main roads is not a significant variable in explaining differences between *ejidos* with high and low deforestation, a finding consistent with that by Geoghegan et al. (2005). The logistic regression's goodness of fit, measured by the Nagelkerke R^2 statistic, is low, suggesting that missing variables might further explain differences between low- and high-deforestation *ejidos*.

The logistic regression was used to predict group membership. Eighty percent of the cases were correctly classified (Table 2). Classification errors are high, reinforcing the poor performance of the model in explaining differences between the two patterns of deforestation.

When only the polar extremes (68 cases) were included, the logistic regression's goodness of fit increased, as measured by the Nagelkerke R^2 statistic, from 0.454 to 0.673. In addition to forest holdings and position in the precipitation gradient, average annual population growth between 1980 and 1990 becomes a significant explanatory variable in predicting cases belonging to a group of *ejidos*

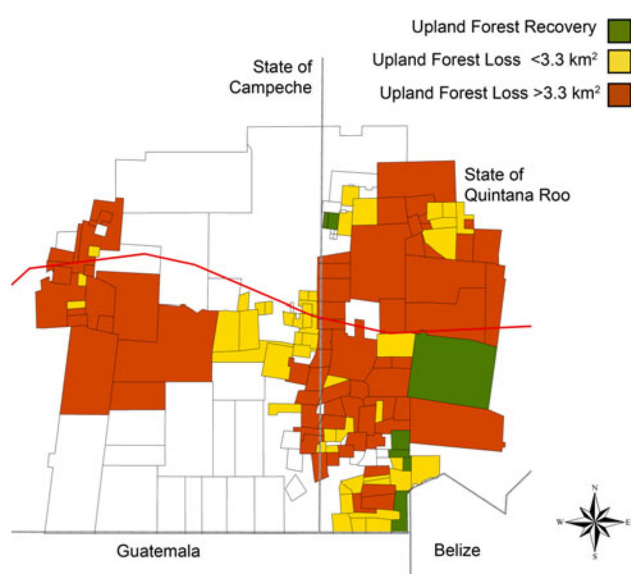


Fig. 4 Upland forest loss and recovery in the *Ejidos* of the southern Yucatan 1984–1993

Table 3 Logistic regression results for net upland forest loss in the *ejidos* in SY grouped according to net upland forest loss in km^2 between 1984 and 1993, using the median (3.3 km^2) as the criterion for separation and only polar extremes

Variables in the equation	Logistic coefficient	Standard error	Wald statistic	Sig.	Exp(*B*)
Forest endowment 1984 (%)	0.079	0.037	4.506	0.034	1.082
Precipitation (mm)	0.020	0.01	3.933	0.047	1.02
Average annual population growth rate (%)	11.086	5.827	3.619	0.057	65,222
Constant	−38.095	15.311	6.191	0.013	0.000

$N = 68$

Nagelkerte $R^2 = 0.673$

Classification error = 17.1%

with high deforestation. The sign of the three coefficients is positive, and they are significant at the 90% confidence interval. The model correctly predicted 83% of the cases (see Table 3).

Forest change trends: 1993–2000

The decade of the 1990s saw a slowing in the rates deforestation throughout the SY (Vester et al. 2007). A little over 0.5% of the upland forests were lost, down from almost 5% in the previous decade. The reserve's forests remained virtually unchanged between 1993 and 2000. The *ejidos* in the region also saw reduced deforestation, and even some forest recovery, particularly in the areas of intersection with the reserve. Even *ejidos* that do not share land with the reserve experienced reductions in their deforestation levels to 0.5%, down from 8% in the previous decade (Table 4).

The distribution of this slower pace in deforestation was again not homogenous across the region. Two concentrations of forest recovery emerged: one in the large, old *ejidos* in the far west and the other in the smaller and newer *ejidos* of the *zona chilera*, along the southern highway. A total of 58 *ejidos* saw their forests recover, while the remaining 38 experienced a reduction in their forests due to conversion to agriculture, secondary growth, and bracken fern invasion. Figure 5 presents a summary of the deforestation/reforestation picture, were 28 *ejidos* had low upland forest loss (under 3.3 km^2), while ten *ejidos* cut over 3.3 km^2 (all of them in the west).

A logistic regression for the period indicates that forest loss tended to accelerate in *ejidos* that had experienced low deforestation in the previous decade, measured as a percentage of their forest holdings. The sign of the coefficient is negative and significance at 90% confidence interval. Forest loss also occurred in those *ejidos* that had larger populations in 1990 (Table 5). The sign of the coefficient is positive and significant at the 90% interval. The overall goodness of fit, measured by the Nagelkerke R^2 is 0.421. The model predicts group membership correctly in more than 83% of all cases. All 58 *ejidos* that experienced forest growth in the 1993–2000 had lost part of their forest in the 1984–1993 period. Forest increase resulted from secondary growth but also from a reduction in agricultural lands of about 2%. Eighty-two percent of the *ejidos* that increased their forest holdings reduced the amount of land devoted to cultivation and pasture. Among the *ejidos* that cut part of their forests, the same reduction in agricultural lands holds.

The logistic regression analysis for polar extremes (78 cases) was calculated eliminating cases for which relative upland forest change was below 2% and absolute forest change was below 1 km^2 (Table 6). In this case, relative upland deforestation between 1984 and 1993 continues to be the most significant explanatory variable, and the sign is again negative. The coefficient is significant at the 95% confidence level. Population in 1990 is no longer significant, but total forest holdings, as a proportion of total land holdings, become significant in explaining forest loss in the 1993–200 period. The sign of the coefficient is negative, and it is significant at the 95% confidence level. The overall goodness of fit, as measured by the Nagelkerke R^2 increases to 0.534, as does the ability to correctly predict case membership that increases to 88%.

Although upland deforestation in the SY from agricultural expansion seemed to have come to a halt in the 1990s, with an increase in older secondary vegetation and a reduction in agricultural land and pastures, the forests were more fragmented than before (Vester et al. 2007), fallow cycles seem to have shortened (Schmook, this issue), and bracken fern, an invasive species associated with fire episodes and profound land changes (Schneider 2004, 2006), was more prevalent in 2000 than it was in 1984. Bracken fern increased 2.5 times between 1984 and 2000 from 8,981 to 22,314 ha, affecting all 96 *ejidos*. Even the *ejidos* that reduced upland deforestation experienced increases in bracken fern. Only 14 *ejidos* saw both bracken fern reduction and forest recovery.

Discussion

Forest change in the SY has not been uniform in terms of its spatial and temporal dimensions and trajectory. Major

Table 4 Upland forest loss for 1993–2000 in the Southern Yucatán by tenure regime

	Reserve			*Ejidos*				All study area		
	Core	Buffer	Total	Ejidal land outside of the Reserve	Ejidal land in the core	Ejidal land in the buffer	Total ejidal land	Reserva + *Ejidos*	Other	Total
	(1)	(2)	(3) = (1) + (2)	(4)	(5)	(6)	(7) = (4) + (5) + (6)	(8) = (3) + (4)	(9)	(10) = (8) + (9)
Total area of study (km^2)	2,479	4,746	7,225	8,058	204	1,145	9,407	15,283	3,617	18,900
Upland forest 1993 (km^2)	1,629	3,059	4,688	4,149	106	744	4,998	8,837	2,493	11,376
% Of upland forest	65.7	64.4	64.9	51.5	51.9	64.9	53.1	57.8	68.9	60.2
Upland forest loss 1993–2000 (km^2)	6.9	−4.8	2.1	19.7	1.0	−13.4	7.3	22	39.5	61.3

Source: Landsat 7 ETM+ imagery for 1993–1994–1995 and 2000 (Vester et al. 2007). Calculations by author

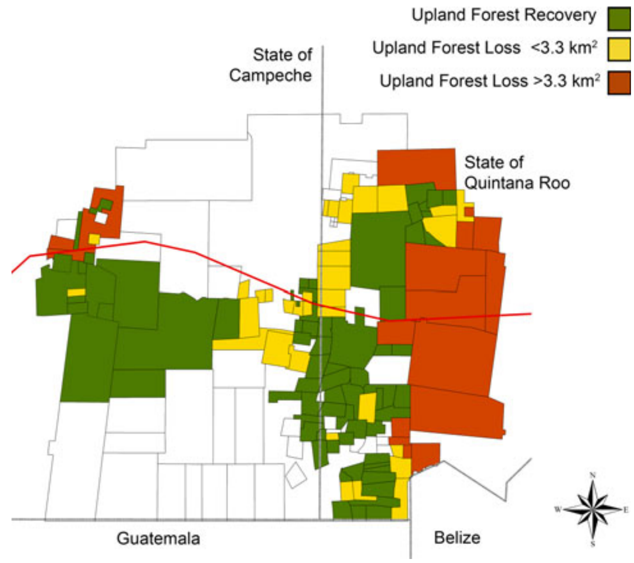


Fig. 5 Upland forest loss and recovery in the *Ejidos* of the southern Yucatan 1993–2000

deforestation was underway between 1984 and 1990, a product of a two-decade phase of experiments with agricultural development in the region (World Bank 1990) during which the number of agricultural *ejidos* and households increased significantly (INEGI 1982, 1992, 2007). Previous to and during this time, cultivated lands and pasture expanded into older growth forest, creating a highly fragmented landscape of open lands, bracken fern, and successional growth (Lawrence et al. 2004). Cultivation exceeded subsistence in response to government programs that purchased surplus maize (Lustig 1998), and local farmers experimented with commercial chili production, including the disking of the thin redzina soils with an eye toward more intensive cultivation than the traditional *milpa* or swidden agriculture that had dominated the region. Despite the creation of the CBR in 1989, both the core and buffer zones of the reserve experienced forest loss where the boundaries of the reserve overlapped *ejidos*. Indeed, the very creation of the reserve likely triggered deforestation as smallholders sought to lay claim to lands with their *ejidos*, as suggested by Abizaid and Coomes (2004).

Deforestation was especially acute in three locations: on the older and larger *ejidos* on far eastern and western reaches of the SY, and among the smaller and newer *ejidos* along the southern road skirting the southeastern borders of the CBR. The first two clusters of *ejidos* lost large pieces of forest but, given their sheer size, they were able to preserve a significant proportion of their forest holdings. The third cluster lost smaller patches of forest, but given the small size of the *ejidos*, these losses are very significant in relative terms. The eastern and western clusters of

Table 5 Logistic regression results for net upland forest loss in the *ejidos* in SY grouped according to whether they lost or gained upland forest between 1993 and 2000

Variables in the equation	Logistic coefficient	Standard error	Wald statistic	Sig.	Exp(*B*)
Deforestation 1984–1993 (%)	−0.149	0.084	3.125	0.077	0.861
Population 1990	0.002	0.001	3.628	0.057	1.002
Constant	−0.588	0.890	0.437	0.509	0.555

$N = 96$

Nagelkerte $R^2 = 0.421$

Classification error = 16.7%

Table 6 Logistic regression results for net upland forest loss in the *ejidos* in SY grouped according to whether they lost or gained upland forest between 1993 and 2000, using only polar extremes

Variables in the equation	Logistic coefficient	Standard error	Wald statistic	Sig.	Exp(*B*)
Deforestation 1984–1993 (%)	−0.299	0.14	4.534	0.033	0.742
Forest endowment 1993 (%)	−6.126	3.084	3.947	0.047	0.002
Constant	4.321	2.140	4.079	0.043	75.265

$N = 78$

Nagelkerte $R^2 = 0.534$

Classification error = 13.1%

deforestation coincided with *ejidos* (Miguel Alemán, Conhuás and Nuevo Becal on the Campeche western side, and Nicolás Bravo, Pablo García, and Tres Garantías, on the Quintana Roo eastern side) situated on the edge of the *meseta* (about 150 m amsl). The western cluster is made up of those *ejidos* that had been the object of failed, large-scale, wet-rice experiments in the late 1970s and early 1980s. Although those projects failed, the investments left significant numbers of people and infrastructure (Turner et al. 2004). For the most part, households in these *ejidos* had large amounts of land (up to 80 ha/hh), and they tended to abandon land invaded by bracken fern, expanding the once forested parcels for cultivation. The larger *ejidos* of Conhuás and Zoh Laguna in Campeche, and Tres Garantías in Quintana Roo were established on land previously granted to timber concessions (Klepeis 2000), and many of the occupants of these *ejidos* continue to log, if less intensively than in the past. They took advantage of the acquired know-how, machinery and roads left by the timber companies (Galletti 1999) and overexploited the forests until the mid-1990s (Flachsenberg and Galletti 1999). These *ejidos* also had significant population growth and agricultural production, which might explain why deforestation was so high during the 1980s. In contrast, the newer *ejidos* in the South had much less land per household (commonly $\leq$20 ha). The migrants settling them had experience with chili cultivation elsewhere in Mexico. They invested in commercial jalapeño production (Keys 2004, 2005), which in concert with subsistence maize cultivation led to large percentages of their upland forests being cut. Several years of good profits inspired the *ejidos* in question and their neighbors to invest significantly in chili, becoming the *zona chilera*. These three clusters of deforestation are located beyond the northwestern xeric zone where, on average, annual rainfall increases.

The 1990s witnessed a significant reduction in the rate of deforestation across the SY as cultivation practices appear to have intensified, focusing on already open lands and successional growth (Schmook, this issue). Forest loss declined in the CBR, and secondary vegetation in the buffer zone grew older, making it undistinguishable from old-growth forest, perhaps reflecting improved implementation of reserve rules about deforestation and cultivation (Primack et al. 1998). Deforestation continued in older, large, and more populated *ejidos*, but in reduced amounts and rates, especially in the far west, suggesting that their location within the Municipio de Calakmul, aspiring to be the "green municipio" of Mexico, may have played some role through the attention given to rules and incentives about forest conservation within the core and buffer zones of the CBR (Roy Chowdhury and Turner 2006). There was, however, an increase in the diversification of household income portfolios during the 1990s, in which many longer established households invested in off-farm activities associated with the emergence of Nicolás Bravo (east), Xpujil (center), and the villages around Laguna Silvituc, as modest-sized settlements of multiple services, and the incipient increase in tourism services associated with the initial development of El Mundo Maya (IADB 2003). Targeted subsidies to families in poverty emerged as the preferred form of government intervention (Harvey 1996; Lustig 1998), providing families with cash income not tied to cultivation.

The small, newer *ejidos* of the *zona chilera*, which witnessed significant deforestation proportionate to their size in the previous decade, gained older growth from late successional vegetation. Two possible reasons for this shift in trajectory seem apparent. Here and in other *ejidos* with lands neighboring and overlapping with the CBR, the reserve's rules against cutting older growth and the various community-based conservation programs, such as the Parks in Peril Program (TNC 2006) and the government sponsored Empleo Temporal, intended to intensify cultivation and diversify sources of income appear to have had an impact on land-use decisions. This claim is made conditionally, however, because of a more obvious economic phenomenon. Increasing numbers of households in the small *ejidos*, especially in the *zona chilera* used their profits from chili to support the migration of males, particularly to the United States (Radel and Schmook 2008). While households retain subsistence production, the amount of chili production appears to be decreasing, particularly among households with migrating members. Households appear to be opting for larger and more secure incomes gained elsewhere off the farm (Schmook and Radel 2008).

An analysis of land-cover data posterior to 2000 would be needed to assess whether trends observed by 2000 will remain in a somewhat steady state, continue toward reforestation, or make an abrupt change in trajectory as they did during the 1990s. Progress in this area has been hindered by difficulties with Landsat 7, but is being addressed by the SYPR project. Regardless, several observations are noteworthy. First, the initial cycle of forest change identified here is not unique to the SY. Localized or sub-regional cycles have been documented for Amazonia, for example, related to household lifecycles (Brondizio 2006). The period in question for the SY captures various parts of this lifecycle for the older and newer communities (Radel et al., this issue). Second, the hollow frontier thesis (Busch and Geoghegan, this issue) appears to be consistent with the land dynamics and household rationales displayed in the SY. Lacking a secure land-production base from firm markets and with shifting policy agendas for the region, households and communities explore multiple avenues to secure and improve their livelihoods, leading to shifts, if not cycles, in forest use. Indeed, Busch and Geoghegan (this issue) point to a possible return to deforestation as livestock development increases in the region, another exploration in land economy.

Much of the dynamics of land use in tropical forests is marked by strong spatio-temporal variation. Spatial homogeneity of deforestation, perhaps erroneously interpreted from observations of hot spots, may not be the rule throughout the tropics. Strong heterogeneity often prevails, and in such cases, the spatial scale of analysis employed will provide different outcomes. The permanency of deforestation in the tropics is also not necessarily the rule, especially where hollow frontiers prevail, coupled with community and household lifecycles. This spatio-temporal variance holds significance for REDD and other programs seeking to preserve tropical forest lands via payments and other policy options. It is not always clear how much expansion of permanently opened land (i.e., regrowth not permitted to reach older growth stages) will take place. Land change and related research (Ostrom et al. 2007) suggest that panaceas do not exist relative to simple mechanisms designed to limit the spread of deforestation, other than the strong enforcement of set-aside or conservation areas, or focus production activities on extant open lands, especially for hollow frontiers. After all, various assessments suggest that where a demand for forest resources (e.g., timber and land) and entitlement (formal or not) to them exist, forests will fall (e.g., Kaimowitz and Angelsen 1998), and that the intensification of cultivation on some extant open lands does not necessarily foster reforestation on other such lands (Rudel et al. 2009).

Conclusions

The two-phased, sub-regional analysis of land change in the SY has illuminated several phenomena that were not previously apparent form a regional perspective. Although the SY, including the CBR, experienced a high upland deforestation rate during the 1984–1993 period (0.5% annual), this phenomenon was localized in three nodes: the large *ejidos* of the west and east, and the smaller *ejidos* of the south and southeast, along the main north–south road. It is noteworthy that the clusters of *ejidos* in the east, south, and south east occupy those sections of the SY that typically receive more total and reliable rainfall. That the *ejidos* in question cross the state boundaries of Campeche and Quintana Roo and that upland forests located within the CBR were lost, suggests that impacts of the CBR and the eco-friendly design of the Municipio de Calakmul had no yet developed. Rather, *ejidos* everywhere, but especially those in the three clusters, were expanding agriculture, especially the older *ejidos* that lost parcels to bracken fern invasion. The overall changes raised serious concerns for the CBR.

During the 1990s the pace of deforestation slowed, and for more than 20% of the *ejidos* it came to a halt. Again, reforestation and the decline in deforestation were not registered evenly across the SY. Forest recovery occurred in the *ejidos* that had experienced large deforestation rates in the previous decade, particularly among the larger, older *ejidos* in the west and the smaller, newer *ejidos* in the *zona chilera*. Both nodes reside in the Muncipio de Calakmul, created in part to serve the CBR, and thus there is reason to speculate that the various rules and incentives set in place to reduce deforestation there may be having an effect (Rueda 2007). Alternatively or in concert with the CBR, households increasingly appear to be diversifying their income portfolios. Older households in the older *ejidos* seem to be investing in local service activities, while households in the *zona chilera* are engaging in male labor migration (Radel and Schmook 2008).

That the temporal dynamics of forest cover reported here—forest losses in the 1980s followed by reforestation in the 1990s—points to the emergence of a cyclical component in forest-cover change in the SY has not yet been established. More recent imagery will be needed to assess the stability or not of the current trajectories of upland forest gain-loss, and data at a finer scale are required to address empirically the causes. Regardless, the forest that is currently coming back is highly fragmented and displays a somewhat disturbed mosaic. As agriculture recedes, not only the forest but also bracken fern take over. With less interest in agriculture, it is difficult to anticipate effective control of this invasive.

The spatio-temporal heterogeneity of deforestation in the SY is not surprising and is consistent with deforestation dynamics throughout much of the tropics. Whatever its cause (e.g., household lifecycles, hollow frontier, or something else), this heterogeneity looms large in modeling projections of future forest cover and for policies seeking to reduce the rates of forest loss or to preserve large stands of older growth forests.

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