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Landscape change in the Calakmul Biosphere Reserve, Mexico: Modeling the driving forces of smallholder deforestation in land parcels

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Abstract

This article uses remote sensing and spatial modeling to quantify and analyze land change in Mexico's largest protected area, the Calakmul Biosphere Reserve. Change trajectories are identified within distinct property regimes and between the Reserve's core and buffer zones. A parcel-level spatial econometric model identifies the driving forces of land use change in two communities located along the eastern edge of the Reserve, the locus of increased deforestation in 1987–1996. The study assesses the role of biophysical variables, locational context, household socioeconomics and institutional factors in driving deforestation. The results address the effectiveness of reserves and other state policy instruments in protecting forests.

Keywords: Smallholder decision-making; Deforestation; Mexico; Biosphere Reserves; Spatial modeling

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Introduction

The tropics are critical reservoirs of biodiversity, harboring the world's greatest species richness (Pianka, 1966; Primack, 1993, p. 57). Aside from their biodiversity capital, tropical forests fulfill multiple roles in carbon sequestration, net primary production, and global hydrologic cycles and biogeochemistry (Daily et al., 2000; DeFries, Field, Fung, Collatz, & Bounoua, 1999; Houghton et al., 2000; Myers, 1994; Shukla & Nobre, 1990; Skole & Tucker, 1993; Vitousek, Mooney, Lubchenco, & Melillo, 1997; Wilson, 1988). In recent decades, deforestation has become the leading source of change in global land cover and tropical land use, engendering land degradation, invasion by exotic species and

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the vulnerability of local human populations (Achard et al., 1998; Angelsen & Kaimowitz, 1999; Barrow, 1991; Cincotta & Engelman, 2000; FAO, 1999; Kasperson, Kasperson, & Turner, 1995; Kummer, 1992; Mooney & Hobbs, 2000; Steffen et al., 2003), prompting national and international efforts to monitor and address the loss of ecological diversity. To deal with biodiversity loss worldwide, international research and policy initiatives have adopted a twofold strategy that involves monitoring the ecosystem changes underway, and establishing environmental conservation regimes where possible to stem the changes observed. Protected areas worldwide increased over tenfold between 1970 and 1997 (Zimmerer, Galt, & Buck, 2004).

Beginning with UNESCO's Man and the Biosphere (MAB) Program in the 1960s, conservation practice and policy underwent a sea change when compared to earlier protectionist measures. The Seville strategic action plan prescribes three primary functions for Biosphere Reserves: conservation, ecologically sustainable economic development, and environmental education, research and monitoring (Batisse, 1997; Neumann, 1997). As the decades following MAB and the Seville plan saw a gradual merging, at least in rhetoric, of conservation goals and human development needs (e.g., see Wells & Brandon, 1992), the relationship between people and parks came to be vociferously debated. As desirable as the integration of conservation and development in protected areas has been,[1] critics point out not only how difficult such integration has been to achieve (Wells & McShane, 2004), but also how park establishment and conservation-development policies in protected areas can have socially detrimental impacts, including livestock/wildlife conflicts, displacement of local peoples, armed conflict, strengthening of authoritarian government and distributional inequities generated by development projects in internally differentiated communities (Geisler, 2003; McNeely, 2003; Schelhas, Sherman, Fahey, & Lassoie, 2002; Schmidt-Soltau, 2003; Sharma, 1990; Sundberg, 2002). Other critics highlight the failure of joint conservation-development programs in protecting biodiversity and ecosystems (Brandon, Redford, & Sanderson, 1998; Brosius, Tsing, & Zerner, 1998; Redford & Richter, 1999; Robinson, 1993; Terborgh, 1999). These debates have not faded in recent years, rather, local ecological and social systems in protected areas now face potentially dramatic transformations from globalization and related development policies (Zimmerer et al., 2004).

Against the backdrop of such debates and their implications for management, reserves (and researchers) employ diverse monitoring tools to assess local environmental conditions. Remote sensing and geographic information systems (GIS) constitute what may be the most powerful and prevalent of these monitoring tools, affording timely and comprehensive coverage of protected areas, particularly useful in remote regions of the tropics (Fuller, nd). Large monitoring initiatives such as the TREES project have identified the top 35 global 'hotspots' of biodiversity and vulnerability to habitat loss, among them, the southern Yucatán peninsular region (SYPR) (Achard et al., 1998). Such efforts are necessary in order to rapidly assess the performance of existing protected areas, however, a critical need exists to complement such monitoring efforts with (1) the systematic mapping of landscape change in Biosphere Reserves and (2) an understanding of the underlying driving processes (e.g., see Greenberg, Yeaton, Ustin, Kefauver, & Stimson, 2005; Hayes,

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[1] Specific programs for accomplishing such goals are diverse, including altering/curtailing agricultural activities by promoting agroforestry, ecotourism, sustainable wildlife management, non-timber forest products, conservation education and other initiatives (Hachileka, 2003; Kiss, 1990; Mbile et al., 2005; Nadkarni, 2004; Stone & Wall, 2004).

Sader, & Schwartz, 2002; Luque, 2000; Serneels, Said, & Lambin, 2001; Smith, Horning, & Moore, 1997).

This article presents an analysis of the rates, patterns and causes of deforestation in the region of the Calakmul Biosphere Reserve (CBR), Mexico's largest protected area. A spatially explicit model of deforestation on smallholder land parcels along the reserve's buffer zone reveals the dominant biophysical, socioeconomic and structural/institutional factors that drive local-scale deforestation.[2] This study collaborates with a wider, interdisciplinary research project investigating local land change (Geoghegan et al., 2001; Turner, Geoghegan, & Foster, 2004), extending previous research in two ways. First, this article presents an initial assessment of specific trajectories of land change in distinct property regimes in the area (state, communal and private lands), and in the core and buffer zones of the reserve. Secondly, in assessing local driving forces of deforestation, this research follows previous approaches incorporating biophysical, locational and household factors, but it adds to the analysis a rich suite of *institutional* variables that are increasingly important in Calakmul's regional economy and ecology. Previous research on parcel land change explored some national policy instruments, most notably a post-NAFTA agricultural subsidy in the Mexican countryside (Klepeis & Vance, 2003). The research presented here broadens the institutional analysis, exploring a richer dataset of variables that capture both structure and agency in land change and encompass a diversity of policies for economic development, social welfare and conservation as well as informal local networks and community organization.

Study site: environmental history and recent political ecology

Until the 1800s, the study region (Fig. 1) was predominantly a forested frontier, a recovering legacy of the ancient Mayan civilization that declined after 900 AD (Turner, 1983; Turner, Klepeis, & Schneider, 2003; Whitmore & Turner, 2001). In the mid nineteenth century, the Mexican government began to facilitate the extraction of timber and *chicle* resin, and by the mid 1900s, began extensive colonization and land grants to *ejidos* (communal lands) in order to defuse land pressures in other parts of the country and address concerns of national security along the country's southern frontier (Klepeis & Roy Chowdhury, 2004).

The establishment and colonization of new *ejidos* from the 1960s onwards triggered an agrarian transformation of the forested landscape driven primarily by *ejidatarios*, smallholder farmers with constitutionally recognized land rights in *ejidos*. Local farmers initially focused on subsistence cultivation of maize swiddens (locally, *milpa*), however, current farm-based activities increasingly reflect a mix of subsistence and commercial crops (Vance, 2004). Ensuing rates of deforestation propelled the region to the top of global lists of hotspots of tropical deforestation (Achard et al., 1998), and the region soon attracted conservation attention. The CBR was established in 1989 and registered with UNESCO-MAB in 1992, placing under federal protection, although not ownership, over 7230 km^2 of

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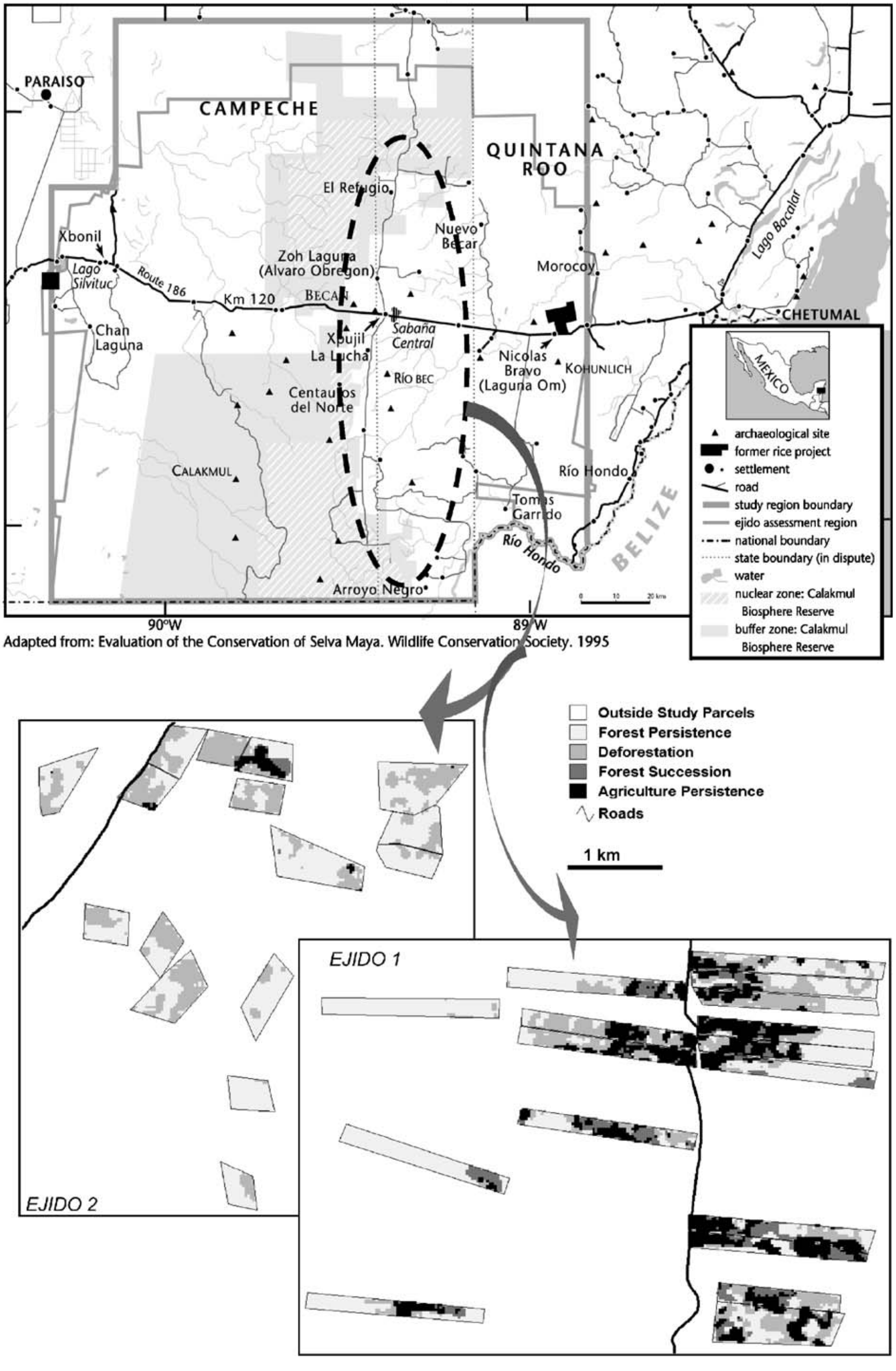
[2] It is important to point out that although this modeling exercise analyzes the driving forces of deforestation, the Calakmul region and the study *ejidos* examined here all encompass large areas of secondary forest succession. Like other successional forests throughout Latin America, these secondary forests hold strong relevance for local management and biodiversity potential (Abizaid & Coomes, 2004; De Jong et al., 2001; Lambert, 1996; Perz & Walker, 2002). An exploration of the spatial dynamics and drivers of secondary succession is beyond the scope of this article, but ecological dimensions of succession in the southern Yucatán are reported by Lawrence and Foster (2002) and Read and Lawrence (2003a, b).



Adapted from: Evaluation of the Conservation of Selva Maya. Wildlife Conservation Society. 1995

Fig. 1. The study region and modeled *ejido* parcels (adapted from Roy Chowdhury, 2003; Turner, Geoghegan, & Foster, 2004).

largely forested lands. As a Biosphere Reserve, Calakmul is charged with the twin tasks of environmental conservation and meeting the livelihood needs of its local communities. In the past two decades, rural development initiatives have proliferated in the region, as have environmental policy interventions and social movements focused on livelihood diversification and (non-timber) forest extraction. Local involvement and perceptions of environment-development projects trace to the initial advent of such programs in the early 1990s, when the local union of *ejidos* successfully brokered communities' negotiations with the state to define conservation in Calakmul in terms of sustainable development, and to establish local control over development aid (see Haenn, 1999). The most recent regional conservation initiative involves the World Bank funded Mesoamerican Biological Corridor to link existing protected areas in southern Mexico and Central America through conservation corridors (Miller, Chang, & Johnson, 2001).

Since the 1990s, Calakmul has undergone significant political–economic and environmental transformations. This article assesses changes in the CBR's core and buffer zones and diverse property regimes, and the effects of the region's main conservation and development policies on the decisions of individual farming households. Variables capturing those policies are used with other biophysical, locational and household factors in modeling deforestation probability on land parcels in two *ejidos*. Both *ejidos* examined are located along the eastern flank of the reserve and were established by the 1980s, however, they reflect different levels of total state investment in conservation-development projects over 1990–1999 (the southern *ejido* receiving more funding). Both communities operate with a parcelized tenure structure involving the allocation of a fixed number of hectares to each *ejido* member in one or more land parcels, which are typically managed individually, as if they were privately owned. Annual regional rainfall is highly variable, ranging from 900 to 1400 mm, with a north–south gradient that brings more rainfall to the southern *ejido*. The region's soils are of two major kinds: lowland, flooding vertisols and well-drained, upland redzinas (mollisols) (Pérez-Salicrup, 2004; Turner et al., 2001); farmers overwhelmingly prefer to farm the latter.

Data sources and overall research methodology

Landsat TM data were classified in collaboration with the Land Cover and Land Use Change (LCLUC) SYPR project (Turner et al., 2004).[3] Bayesian maximum-likelihood classification produced 10 initial land cover classes that were later aggregated for change analysis: water, seasonally inundated, short-statured forest, well-drained, mid-statured upland forest, seasonally inundated savannas, herbaceous wetlands, three stages of upland successional growth, cropland, pasture, and an invasive bracken fern (Roy Chowdhury & Schneider, 2004).

Rates of change were calculated for the entire region, for prevailing tenure regimes and for reserve core vs. buffer zones, using GIS layers delineating the respective boundaries. Estimates of change were derived for 1987–1996, and for the time periods 1987–1992 and 1992–1996 to check for nonlinearities in change over time. Next, deforestation patterns were linked with spatially explicit ancillary data in a binomial logistic regression model to test hypotheses about the role of biophysical, locational and socioeconomic factors in driving deforestation on smallholder land parcels. Biophysical variables were derived from

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[3] LCLUC-SYPR in this article refers to the research project, while SYPR refers to the southern Yucatán peninsular region.

a DEM obtained from Mexico's National Institute for Statistics, Geography and Informatics (INEGI), based upon a digitization of 1:50,000 scale topographic maps, and from a 1:250,000 INEGI soils map digitized by the LCLUC-SYPR project. The household and institutional variables were compiled by the researcher during 2001–2002 through household surveys, land parcel mapping, and interviews and gray literature reviews in Campeche state's environmental, agricultural and social development secretariats. The parcel-scale deforestation model in this article uses survey data from 29 households in the two selected *ejidos* along the CBR buffer zone. Finally, the spatial regression model was validated by comparing sample predictions of deforestation probabilities with observed deforestation locations during the time period modeled. Model validation also revealed the spatial patterns of prediction error, providing initial insight into spatially relevant processes operational on the landscape that were not captured adequately by the model.

Results: land cover changes

Overall land cover change trajectories

While Roy Chowdhury and Schneider (2004) report regional rates of aggregate forest/non-forest transitions and identify sub-regional hotspots of change, the change analysis presented here focuses on three specific land covers and their transitions.[4] Table 1 summarizes the extents of mature and secondary forests and agriculture in 1987, 1992 and 1996, and presents the specific trajectories of transitions among those three land covers for three time periods: 1987–1992, 1992–1996 and 1987–1996.

Mature lowland and upland forests dominate the SYPR, together covering 15,808 km^2 (approximately 91.8% of the region) in 1987. This forest coverage reduced to 15,592 km^2 (90.6% of the region) in 1992 and 15,191 km^2 (88.3% of the region) in 1996. Of the two types of mature forests, upland forests suffered the larger loss during the overall time period 1987–1996, 563 km^2 or 3.3% of its initial extent replaced by other land covers/uses. Both upland and lowland forests shrank by a larger area during the latter part of the time period examined (1992–1996). Secondary forests of 7–15 years of age were reduced by 65 km^2 (0.4%) during the first time period (i.e., 1987–1992), but expanded by over 489 km^2 (3%) during 1992–1996, for a net increase of almost 425 km^2 (2.5%) over the entire time period studied. About 473 km^2 (2.7%) of the region's land was under agricultural use in 1987. Agriculture (including pasture and young fallows under 7 years of age) expanded to over 710 km^2 (4.1%) in 1992, then shrank to 592 km^2 (3.4%) in 1996.

Focusing on actual transitions rather than individual land covers in the three dates reveals some interesting trends (Table 1, Fig. 2). Regionwide agriculture-related deforestation claimed 272 km^2 of mature forests and 149 km^2 of secondary forests over the whole time period 1987–1996.[5] Both mature (369 km^2) and secondary forests (160 km^2)

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[4] Roy Chowdhury and Schneider (2004) calculated a 0.4% annual rate of deforestation for the 18,700 km^2 LCLUC-SYPR region for 1987–1996, using an aggregate mature forest/non-forest change analysis. Adjusting for the region's extensive secondary succession, especially that ranging in age from 7 to 15 years, annual deforestation rates recalculate to 0.12% over 1987–1996.

[5] The extent of agricultural deforestation in 1987–1992 and 1992–1996 cannot be simply summed to derive the net extent for 1987–1996, since this would exclude agricultural areas that have reverted to other land use/covers (such as secondary succession). The net 1987–1996 trajectories are instead independently derived from cross-classifications of the first (1987) and last (1996) image dates.

Table 1
Regional land cover and its change

Land cover extent (km^2) Percent of region covered in parentheses	1987	1992	1996
Mature forest (*baja* and *mediana* forest)	15808 (91.8)	15592 (90.6)	15191 (88.3)
Secondary forest (7–15 years)	846 (4.9)	782 (4.5)	1271 (7.4)
Agriculture (including pasture and young fallows of 1–6 years)	473 (2.7)	710 (4.1)	592 (3.4)
Change trajectory extent (km^2) Percent of cover class in date 1 that transitioned (or not) in date 2 in parentheses	**1987–1992**	**1992–1996**	**1987–1996**
Mature forest–mature forest	15044 (95.2)	14734 (94.5)	14630 (96.3)
Secondary forest–secondary forest	254 (30.04)	325 (41.59)	278 (21.86)
Agriculture–agriculture	180 (38.0)	325 (45.8)	166 (28.0)
Mature forest–agriculture	370 (2.3)	136 (0.9)	272 (1.8)
Secondary forest–agriculture	161 (18.9)	103 (13.2)	149 (11.7)
Secondary forest–mature forest	399 (47.12)	323 (41.36)	380 (29.92)
Agriculture–secondary forest	133 (28.01)	224 (31.54)	117 (19.76)

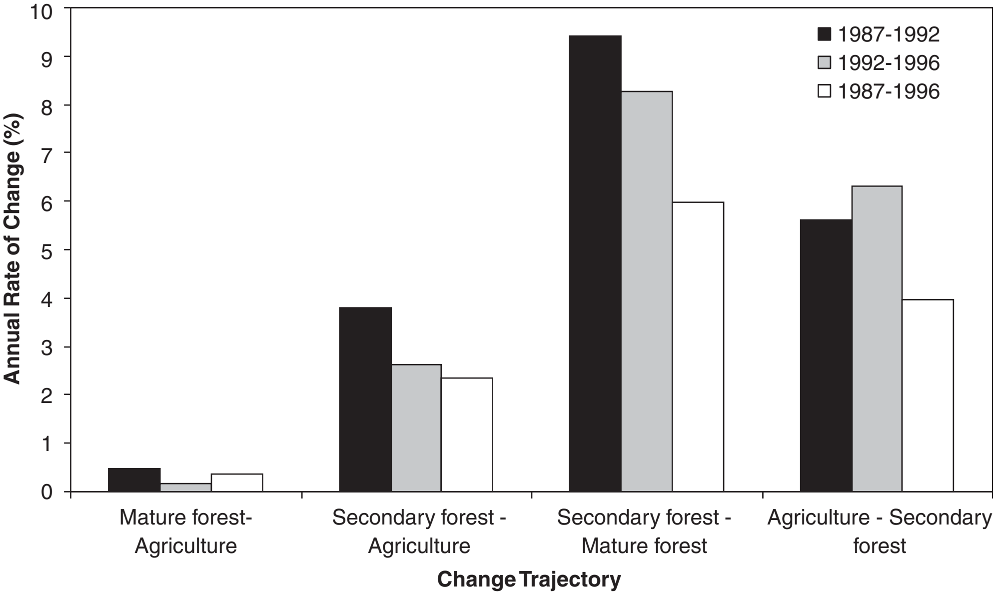

Fig. 2. Proportional rates of dominant change trajectories in the region.

underwent greater losses to agriculture during the earlier period (1987–1992), possibly reflecting greater rates of *ejido* colonization and land clearance, earlier household life-cycles, and/or weaker forest protection in the then fledgling CBR. During 1987–1992, 132 km^2 of former agricultural lands underwent successional regrowth as they were fallowed, increasing to 224 km^2 in 1992–1996.[6] Even larger extents of late successional forests reached the spectral and structural properties of mature forests during the time periods studied—an area of 399 km^2 (47%) of older successions were replaced by mature forest pixels in 1987–1992, and a similar extent of 323 km^2 (41%) in 1992–1996. Fig. 2 depicts the annual rates of selected change trajectories over the two time periods in question as well as over the entire decade examined. For the entire time period, the highest annual rates of change are observed for the succession of older secondary forest to mature forest (5.98%), followed by secondary succession on agricultural lands (3.95%), clearing of secondary forest for agriculture (2.34%), and the clearing of mature forests for agriculture (0.36%).

Overall land cover change by property regime and reserve zones

The regional trends noted above vary significantly when analyzed by property regime, or by zones in the core, buffer or outside the reserve boundaries. Fig. 3 details the land tenure composition of the SYPR and the CBR.

Over half of SYPR lands are dominated by *ejidos*, the main locus of land transformations. The remainder of the region is comprised mainly of federal lands or forest extensions granted to *ejidos* that are often from other municipalities. About 3% of the region's lands are privately owned, usually with cattle ranches, and some land (1%) remains under unresolved tenure. As Fig. 3 indicates, all the above property regimes of the larger SYPR are represented in both the core and buffer zones of the reserve as well. It is important to note that although *ejidos* officially comprise 49.6% of the reserve, only 19% of the reserve is actually owned by *ejidos* local to Calakmul; the remaining *ejidal* lands are in the aforementioned remote *ejidal* forest extensions.

Most mature forests are located on *ejido* lands (Table 2), and *ejidos* accounted for over 49% of all mature forests that persisted over the 9-year period under study (Table 3). Older secondary forests, a frequently overlooked yet important category of land cover in studies of tropical forests, cover 1062 km^2 or 11.4% of total *ejidal* lands, holding rich potential for biodiversity and carbon sequestration. Almost three-quarters of all succession from secondary to mature forests occurred on *ejidos*. Agriculture covers 525 km^2 in *ejidos*, 35.3 km^2 in national/forest extension lands, and 24.3 km^2 in private lands. Approximately 91% of all agricultural deforestation of mature forests occurred on *ejidal* lands, followed by 4.4% on federal lands and 3% on private property. The recycling of older forest fallows for agriculture followed similar trends.

The CBR represents the best hope for forest conservation in the region, yet an analysis of the spatial patterns and trajectories of land change underscores the environmental importance of *ejidos* that lie outside the reserve's boundaries. All land change trajectories over 1987–1996, including the persistence of mature (62%) and secondary forests (89%), occurred predominantly outside the reserve's boundaries (Table 3), partly a reflection of the relative size of the reserve to the overall region (40%). Reserve management personnel recognize the ecological importance of surrounding communities and include them in land and forest conservation initiatives and environmental education programs. On the other hand, the reserve seems to have had some measure of success in stemming deforestation.

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[6] For the reasons noted in the preceding footnote, the individual extents for 1987–1992 and 1992–1996 do not sum to the 1987–1996 aggregate.

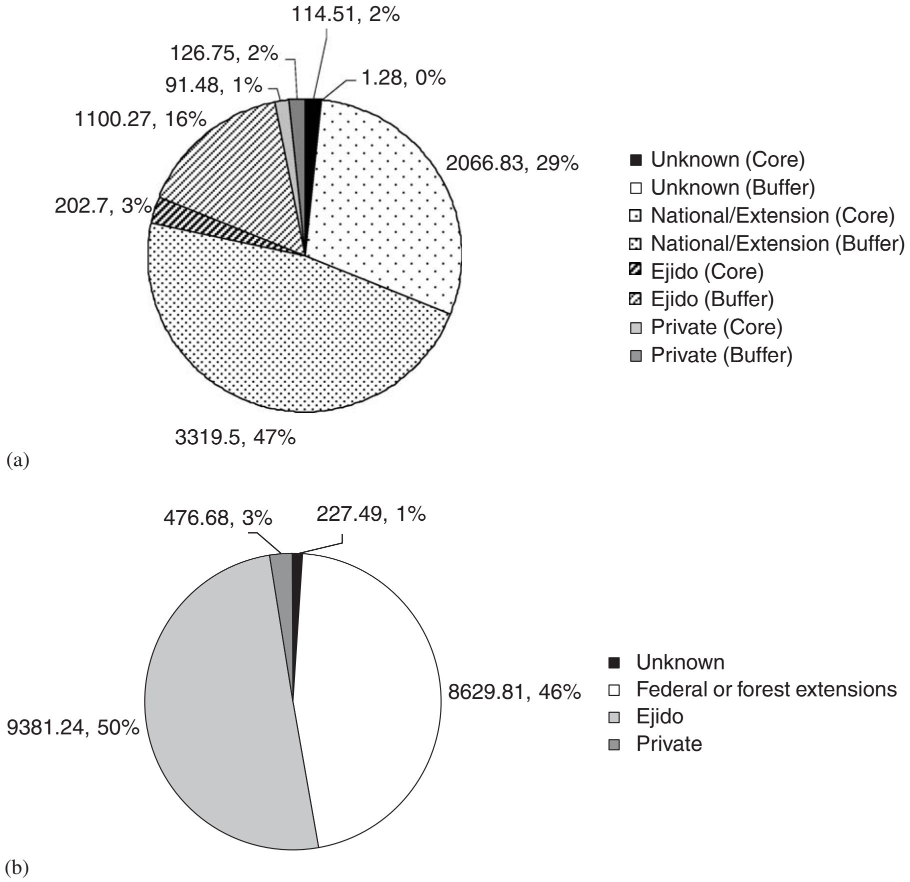

Fig. 3. Land tenure in sq. km. and percentages of (a) the region and (b) within the reserve (adapted from Roy Chowdhury, 2003).

Of the 421 km^2 of mature and secondary forests deforested over 1987–1996, only 7% occurred in the reserve's buffer zone, and 3% in its core. In addition, almost 15% of all succession from agricultural lands to older fallows occurred on reserve lands, mostly in the reserves' southeastern buffer area *ejidos*.

The significance of land changes in the CBR and especially in its surrounding communities begs an understanding of the fundamental driving forces of land use decision-making in *ejido* land parcels. The following section details an econometric model of parcel-scale deforestation in two *ejidos* adjacent to the CBR, with particular attention to national policies and emerging local institutions for conservation-based development.

Results: driving forces of deforestation on land parcels

Spatial econometric models are now widely used to understand processes of land use change and link to behavioral themes, i.e., the factors that influence the decisions of the agent of the changes in question (Chomitz & Gray, 1996; Cropper, Griffiths, & Mani,

Table 2
Land covers in km^2 by property regime and by the reserve zones (percentages, in parentheses, sum to 100 for each column)

	Federal/Ext.	*Ejido*	Private	Unknown	Core of CBR	Buffer of CBR	Outside CBR
Wetland forest	1455.82 (20.31)	1628.23 (17.45)	18.44 (3.87)	70.12 (30.83)	421.73 (20.82)	658.43 (16.92)	2093.77 (18.53)
Upland forest	5530.47 (77.16)	5973.57 (64.03)	380.52 (79.83)	123.65 (54.35)	1510.50 (74.59)	3067.15 (78.84)	7439.89 (65.86)
Secondary forest (7–15 yrs)	137.71 (1.92)	1062.47 (11.39)	45.29 (9.5)	24.76 (10.88)	74.90 (3.70)	126.36 (3.25)	1069.68 (9.47)
Agriculture	35.29 (0.49)	524.90 (5.63)	24.26 (5.09)	7.08 (3.11)	16.70 (0.82)	36.95 (0.95)	538.13 (4.76)
Bracken fern	0.93 (0.01)	86.96 (0.93)	0.95 (0.20)	1.86 (0.82)	0.41 (0.02)	1.12 (0.03)	89.23 (0.79)
Inundated savannas	1.62 (0.02)	38.48 (0.41)	7.16 (1.50)	0.01 (0.00)	0.37 (0.02)	0.16 (0.00)	46.88 (0.41)
Water	5.44 (0.08)	14.66 (0.16)	0.06 (0.01)	0.00 (0.00)	0.51 (0.03)	0.16 (0.00)	19.50 (0.17)

Table 3

Dominant trajectories of land-cover persistence and change in the study area (in km^2), with percentages in parentheses

	Federal/Ext. regionwide	*Ejidos* regionwide	Private regionwide	Unknown regionwide	Core CBR	Buffer CBR	Outside CBR
Persisting mature forest	6875.75 (47.03)	7194.02 (49.21)	363.55 (2.49)	186.63 (1.28)	1906.17 (13.03)	3656.30 (24.99)	9067.86 (61.98)
Persisting secondary forest	22.37 (8.06)	238.49 (85.90)	12.18 (4.39)	4.60 (1.66)	12.79 (4.60)	17.15 (6.17)	247.88 (89.23)
Persisting agriculture	19.19 (11.58)	136.26 (82.20)	9.60 (5.79)	0.72 (0.43)	3.64 (2.20)	12.86 (7.75)	149.35 (90.05)
Mature forest to agriculture	11.86 (4.36)	246.62 (90.70)	8.16 (3.00)	5.26 (1.93)	7.48 (2.75)	19.74 (7.26)	244.80 (89.99)
Secondary forest to agriculture	4.17 (2.81)	136.83 (92.10)	6.47 (4.35)	1.11 (0.74)	5.57 (3.75)	4.34 (2.92)	138.71 (93.33)
Secondary forest to mature forest	75.28 (19.80)	277.79 (73.07)	22.55 (5.93)	4.53 (1.19)	15.64 (4.11)	44.80 (11.78)	319.86 (84.11)
Agriculture to secondary forest	13.63 (11.66)	95.58 (81.76)	5.17 (4.42)	2.52 (2.16)	6.41 (5.48)	10.87 (9.30)	99.67 (85.22)

For each transition (row), the four regionwide land tenure column percentages sum to 100, as do the three Reserve zone column percentages.

Table 4
Deforestation on household land parcels, binomial logistic regression model for 1987–1996, $n = 9861$ pixels on land parcels belonging to 29 households (adapted from Roy Chowdhury, 2003)

Suite of factors	Variable	Coeff.	Z
Biophysical factors	Elevation (meters)	0.013	4.06****
	Slope (degrees)	0.005	0.47
	Upland soil (dummy)	0.846	7.61****
	Initial land cover as upland forest (dummy)	2.182	5.74****
	Rain (millimeters)	0.027	5.07****
Landscape context and accessibility	Fragmentation index in 1987	1.530	0.36
	Diversity index in 1987	−0.977	−1.12
	Dominance index in 1987	−1.152	−1.34
	Frequency of agricultural pixels in neighborhood in 1987	0.099	4.73****
	Distance to roads	−0.004	−5.49****
	Distance to market (Xpujíl)	−0.007	−8.72****
	Distance to nearest agriculture in 1987	−0.035	−14.53****
Internal household characteristics and strategies	Native speaker of Spanish (Mestizo)	−3.193	−7.08****
	Tenancy (number of years held land parcel)	0.130	0.4
	Tenancy (squared)	−0.014	−1.77*
	Entitlement (total ha available as land right)	−0.010	−0.85
	Total land parcel area (ha)	0.006	0.74
	Family size	−1.192	−5.95****
	Number of active students	0.932	3.37****
	Quality of life index	0.742	6.09****
	Receive funds/remittances (dummy)	−0.560	−1.02
	Both send and receive funds (dummy)	−0.579	−0.75
	Neither send nor receive funds (dummy)	−2.473	−3.48****
	Sell labor (dummy)	−2.232	−9.02****
	Both sell and purchase labor (dummy)	0.244	0.93
	Net worth of livestock holdings (Mexican $)	0.00005	4.29****
	Income from chili in past year (2001)	−0.0001	−11.6****
	Number of off-farm wage income sources	−0.413	−8.29****
	Intensity of forest use index	−0.334	−3.77****
Structural and institutional factors	Area inscribed in summer PROCAMPO (ha)	0.297	1.3
	Area inscribed in winter PROCAMPO (ha)	−0.044	−0.3
	Area inscribed in *Roza-pica-siembra* (ha)	0.666	2.31**
	Area inscribed in assisted mechanization (ha)	−0.867	−2.63***
	Area inscribed in improved fallows (ha)	0.753	5.62****
	Quality of life improvement subsidies (Mexican pesos)	−0.0001	−1.81*
	Total PRONASOL loans received during 1990–1999 (Mexican $)	−0.001	−6.03****
	Access to extension services	0.521	4.95****

Table 4 (*continued*)

Suite of factors	Variable	Coeff.	Z
	Links to intra/inter *ejidal* unions, municipality	0.513	2.27**
	Links to NTFP cooperatives	−1.234	−6.58****
	Ejido-level state investment, 1991–1999 (Mexican $)	−0.00002	−9.17****
	Constant term	5.906862	0.77
	Pseudo-R^2	0.25	

$p > 0.10$ (NS).
$^{*}p = 0.10$.
$^{**}p = 0.05$.
$^{***}p = 0.01$.
$^{****}p = 0.001$.

1999; Geoghegan et al., 2001; Munroe, Southworth, & Tucker, 2004; Nelson, Harris, & Stone, 2001; Pfaff, 1999; Walker, 2004). In analyzing land cover change in Honduras, Munroe et al. (2004) found that binomial logit specifications of overall land cover transitions (e.g., deforestation over a given time period) yielded better model fit compared to multinomial logit specifications exploring the detailed permutations of past change trajectories. This study applies their lessons in using binomial logistic regression to model land use/cover change over the overall time period 1987–1996 to understand parcel-scale deforestation decisions. It is important to point out that many of the explanatory variables discussed hold significantly different implications for land cover when modeled at the regional scale, a function of scalar dynamics that will be taken up elsewhere. The ensuing discussion and Table 4 detail the model formulation, variables and results.

Decisions about deforestation on parcels in Calakmul are informed by considerations of (1) the local biophysical environment and surrounding landscape structure, (2) infrastructure conditions including access to transportation and markets, (3) household-specific characteristics and strategies, and increasingly (4) institutional and political–economic structures. Following Geoghegan et al. (2001), if farmers' expected returns to deforestation are positive, then the outcome of their decisions can be viewed in the remotely sensed data (land cover change map) as deforested pixels on their parcels. For the classification derived-dependent variable ($y = 0$ if forest persists, and 1 if a forested pixel in 1987 becomes agriculture in 1996), the probability of deforestation at a pixel can be given as

$$Pr(y_j = 1|x_j) = \frac{e^{\beta_0+\beta_1 x_1+\beta_2 x_2\ldots}}{1 + e^{\beta_0+\beta_1 x_1+\beta_2 x_2\ldots}},$$

where the x's are the independent (explanatory) variable values at that pixel, and the β's are coefficients that can be estimated using a binomial logit specification (Maddala, 1983). The model assumes random errors (u's) whose cumulative frequency distribution approximates a logistic function, and can be summarized as

$$y_i = \beta_i x_i + u_i.$$

Biophysical factors, landscape context and accessibility

Deforestation was hypothesized to be less likely on high elevations and slopes, since such terrain may increase site preparation costs and reduce returns to land cleared for agriculture. Slope is found not to be significant in the parcel deforestation model, but the estimated coefficient for elevation is positive and significant, indicating that over the time period modeled, higher elevations were more likely to be deforested (Table 4). This may partly reflect parcel-level variations in micro-topography not accounted for in the coarse, regionwide DEM. Upland soils and medium-statured upland forests are preferentially felled for agriculture, as expected. Average rainfall ranges from 1032 to 1142 mm in the parcels studied, and, as mentioned earlier, follows a strong north–south gradient. Rainfall can influence productivity and therefore expected returns to land clearance: it was hypothesized that higher rainfall would be linked to higher productivity and indirectly to higher deforestation probability, a relationship that the model results confirm.

Unlike results obtained elsewhere and at regional scales of analysis (e.g., Geoghegan et al., 2001; Mertens & Lambin, 2000; Roy Chowdhury, nd), indices of landscape structure are not significant predictors of parcel-scale deforestation. The process of agricultural expansion does, however, unfold in a spatially contiguous manner, as supported by the strong and positive link between parcel deforestation and the frequency of agricultural pixels in the neighborhood, and the negative relationship between deforestation and distance to existing agricultural pixels in 1987. A parcel's accessibility with respect to roads and markets (the municipality seat Xpujíl) is a clearly significant consideration in its deforestation as higher travel costs reduce returns from agriculture for both subsistence and market farmers, making far-lying forests more likely to remain preserved.

Socioeconomic factors: internal household characteristics and overall economic strategy

The socioeconomic variables used in the model were chosen based on their relevance to various theories of smallholder land use, including the induced-intensification thesis, institutional theory and political ecology (Bassett, 1988; Laney, 2002; Ostrom, 1990; Robbins, 2004; Turner & Ali, 1996; Turner & Brush, 1987; Zimmerer & Bassett, 2003).

Calakmul's *ejidos* are home to over 16 ethnic groups from 23 Mexican states (Campeche State Government, 1997). Ethnicity was hypothesized to be one determinant of land use decision-making since some research has claimed that some indigenous (Mayan) communities may foster better forest stewardship given appropriate institutional support (e.g., Bray, Ellis, Armijo-Canto, & Beck, 2004), while others have implied that indigenous communities cause higher deforestation owing to factors related to demography and/or off-farm wage income skills (Geoghegan, Schneider, & Vance, 2004). The parcel model results presented here indicate that Mayan household parcels were more likely to be deforested than Mestizo parcels in the time period modeled. However, this may be due to the fact that the *ejido* with the majority of non-Mayan households also happened to be the longer-established land grant; therefore, much of its initial deforestation was already in progress before the time period studied.

The length of time a household had been present in the *ejido* was hypothesized to influence deforestation probability, since longer-established households may already have more land cleared and under cultivation that they could continue to farm. Model results indicate only weak support for this hypothesis, and only when non-linearities are taken into account through the tenancy-squared variable. Total *ejidal* entitlements (guaranteed in the *ejidal* rights document, but possibly not yet assigned) and assigned land parcel area appear not to significantly influence parcel deforestation. Official entitlements are partly offset by extended access to other land parcels through kinship networks and reciprocal labor-sharing arrangements that are extremely difficult to capture in spatially explicit models. Family size was hypothesized to increase deforestation probability due to subsistence demand. In contrast with earlier LCLUC-SYPR results (see Geoghegan et al., 2001), larger families appear to be linked to lower probabilities of deforestation in the land parcels studied here. Larger households in the *ejidos* studied may farm the same area for longer periods of time, and/or be further along in their lifecycle. Amazonian research reflects that lifecycle phase relates to land clearing activities (Moran, 2000).

Education can be an important influence on land use, non-farm wage income-earning skills, expectations about quality of life (QOL) and household finances. In Mexico, the federal PROGRESA program (now *Oportunidades* under the Fox administration) allocates funds for school-going children and their mothers, assisting family finances. On the other hand, students in a family also require critical financial resources that might otherwise be invested in land parcels. Although village-level indicators of education may lower deforestation probabilities at the regional scale in Calakmul (see Roy Chowdhury, nd), household-specific education (specifically, number of school or college-going students in the family) appears to increase the likelihood of deforestation at the scale of the household parcel. While school-going children may cause a (temporary) reduction in local labor supply for farm management, consumption demand continues to drive deforestation on parcels. Families with larger numbers of active students may also be in earlier stage lifecycles, linked to higher deforestation in their lands. A composite indicator variable captured aspects of households' QOL, including the quality of house construction, access to running water and electricity, and the consumption/ownership of vehicles and various appliances. Such QOL/wealth indicators appear to be linked to increased probability of deforestation, indicating that improvements in living standards do not necessarily reduce agricultural extensification.

Variables capturing a household's overall economic strategy record whether they send/receive monetary remittances, or both/neither[7]; whether they buy or sell labor, or both/neither[8]; the number of off-farm wage income sources they tapped over the time period examined; the net worth of their livestock holdings; their income from market chili cultivation as an indicator of their market orientation, and an index of their use of standing primary and secondary forests. Model results show that compared to household that had to send monies to family members (typically students) living outside their community, households that only received remittances, both sent/received monies, or neither sent nor received monies were less likely to undertake deforestation on their land parcels. This indicates that households met such additional financial responsibilities by increased expansion through deforestation during 1987–1996, possibly for increased production for sale. Households that sell their labor for wages had significantly lower probabilities of parcel deforestation, possibly using labor sales as a strategy for meeting their subsistence needs. Farmers that both purchase and sell farm-based labor (the majority) are associated with higher deforestation probabilities, though this relationship is not significant.

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[7] One or more of these four dummy variables capturing remittances were dropped to avoid multicollinearity.

[8] One or more of these four dummy variables capturing labor strategies were dropped to avoid multicollinearity.

Over the time period modeled, farming households that had higher livestock holdings (and therefore higher feed demand and/or need for pasture clearance) also had higher deforestation probabilities. Lower deforestation probabilities are observed during 1987–1996 for households with larger incomes derived from market chili sales during 2000—an imperfect explanatory variable since it would be more appropriate to use chili figures for past years. Reliable figures for past years' incomes are difficult to obtain, however, and when analyzing deforestation over 1987–1996, the 2000 chili estimates are at best a weak proxy for future market orientation. The 2000 chili data will be put to better use to investigate more recent deforestation and forest succession patterns (year 2000 and later) in future studies. Off-farm wage jobs tapped by a household reduce parcel-level deforestation probability, indicating that such income opportunities enable a shift away from extensive agriculture. Finally, a household's economic strategy also includes their reliance on standing primary and secondary forests for timber and non-timber forest products, including fuel wood, medicines, fruits, raw materials for fencing and house construction, forest-based apiculture, etc. The intensity of forest dependence is negatively linked to deforestation likelihood, indicating that households that rely more on forest extraction do not undertake large agricultural extensification on their land parcels.

Socioeconomic factors: household links to structural and institutional factors

As mentioned before, one contribution of this study is the analysis of a rich suite of structural and institutional factors not before considered for their effects on Calakmul's land use and/or spatially explicit land change probabilities. These factors include (1) planted hectare-based agricultural subsidies (PROCAMPO), (2) subsidies for land use intensification and commercialization (specifically, local *roza-pica-siembra* or RPS zero-burn program inscriptions for green fertilizers, state government and municipal assistance for mechanization, and improved fallows through NGO-initiated agroforestry and reforestation programs), (3) state programs for improvements in local QOL standards (specifically, the PROGRESA program providing educational assistance for school-going children and their mothers, the Alianza para el Campo—Rural Alliance program providing basic home and agricultural tools and appliances, and food aid), (4) rural credit program *Credito a la Palabra* through PRONASOL (Programa Nacional de Solidaridad—National Solidarity Program), (5) state-sponsored seasonal employment programs (Programa de Empleo Temporal—Temporary Employment Program), (6) access to extension and information networks (household participation in workshops, seeds, capital and other inputs, agronomic orientation and technical assessment/advice), and (7) access to local and regional social capital (through intra/inter-*ejido* unions, local NTFP cooperatives and networks, and state investment in *ejido* infrastructure, conservation and agricultural development).

Prior LCLUC-SYPR results (see Geoghegan et al., 2004; Klepeis & Vance, 2003) found that PROCAMPO increases regional-scale deforestation (e.g., by facilitating labor hired for forest clearing) while reducing it at the parcel-level (e.g., by facilitating purchases of chemical inputs that permit agricultural intensification and release pressure on forests). This study finds that when other structural and institutional factors are controlled for (along with biophysical factors and household characteristics), neither summer nor winter-cycle PROCAMPO inscriptions are significant in driving deforestation probability on the land parcels studied.

Aside from PROCAMPO, all other institutional household variables were statistically significant in the model. The probability of deforestation at parcels is inversely linked to a household's total PRONASOL loans requested over 1991–1999, QOL improvement subsidies tapped by the household, the household's links to NTFP cooperatives and *ejido*-level state investment. On the other hand, extension and access to local intra/inter-*ejido* producer societies and municipal programs increases deforestation probabilities. When households have access to such programs, their economic or social capital is directly or indirectly improved, but these improvements have complex and contradictory implications for parcel forest cover. Interestingly, parcels belonging to households that have registered larger areas under NGO or state-subsidized green projects such as agroforestry/reforestation or agricultural sedentarization involving green fertilizers (the RPS program) were more likely to undergo deforestation over 1987–1996. Most individuals that captured such opportunities for state/NGO assistance tended to also be longer-established *ejidatarios* that greater proportions of their parcels deforested during the time period modeled, but the tenancy variables control for such factors, throwing into question the utility of 'green' projects for forest preservation on land parcels. In fact, Calakmul's communities and forests continue to suffer from a woefully inadequate commercialization of non-timber forest products, such alternative product thus far enable to provide rural incomes sufficient to match those in traditional, extensive agriculture.

Model validation

Following Mertens and Lambin (2000), the parameter estimates from the logistic regression model were used to generate maps of predicted deforestation probability across all the parcels studied (Fig. 4). The probability maps were then reclassified into categorical predicted transitions following Geoghegan et al. (2001). Rather than adopting a 50% threshold (wherein a pixel is predicted to be 'deforested' if its deforestation probability is over 50%), the n highest probability pixels were assigned to be deforested, where $n =$ actually observed number of deforested pixels during the modeled time period. The predicted deforestation/forest persistence map was then cross-referenced with actually observed transitions to derive the spatial pattern of model performance (Fig. 5).

The model accurately predicts about 80% of forest persistence and 66% of deforested pixels in the parcels studied, compared with prior LCLUC-SYPR results of 89% and 46% respectively (Geoghegan et al., 2004). In *ejido* 1, most correct predictions of forest persistence followed a distance-based logic, located in parcel areas far from the road. This is not the case in *ejido* 2, where the correct predictions for forest persistence as well as deforestation appear to be unique to each land parcel, possibly indicating the role of household survey-derived variables here. Correctly predicted agricultural deforestation shows spatial contiguities in *ejido* 1, located close to existing agricultural plots. In both *ejidos*, incorrect predictions of deforestation (where forest actually persisted) were strongly related to actual deforestation, indicating that the model over-predicts deforestation, likely due to variables capturing distance and landscape structure. Areas in the *ejidos* where the model mistakenly predicted forest persistence display a spatially aggregate rather than dispersed pattern. Aside from this clumped aspect, it is difficult to interpret a consistent spatial pattern, e.g., only some of these areas are located near pre-existing agricultural lands. This indicates that other factors not captured by the model may be at play at site selection for agricultural deforestation, e.g., differences in micro-topography or site quality not captured in the coarse-scale soils and DEM data. Four of the independent variables used in the model focused on the landscape context in immediate pixel neighborhoods,

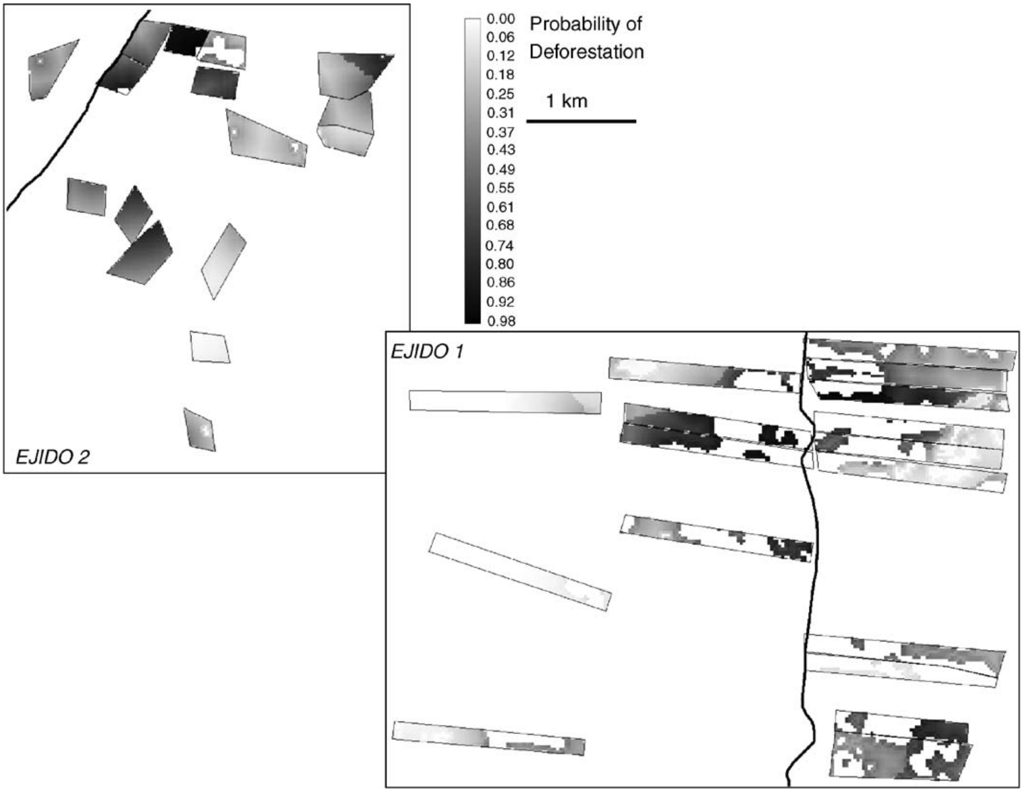

Fig. 4. Predicted deforestation probabilities in *ejidatario* parcels.

yet, the omission of other unobserved but spatially important variables may lower model goodness-of-fit and produce spatially autocorrelated model residuals. When datasets are spatially autocorrelated or when unknown spatial processes cannot be otherwise quantified, it may be possible to improve model goodness-of-fit by incorporating an additional spatial autoregressive parameter or using spatially lagged sampling schemes (Anselin, 2002; Anselin & Griffith, 1988; Munroe, Southworth & Tucker, 2002; Overmars, De Koning, & Veldkamp, 2003). Such spatial dependencies in the modeled region will be explored in greater detail in future analyses.

Summary and conclusions

Lambin, Geist, and Lepers (2003) note that land change research has been moving consistently away from simplistic, mono-causal explanations of land use change to analyses eliciting the multiple, interacting factors in land transformations. They also exhort systematic analysis of coupled human–environment systems through local, place-based land use change studies. While many spatially explicit models focus on aggregate biophysical and/or census-derived socioeconomic variables in order to explain land use changes, this analysis joins an emerging cohort of studies linking land change observations to social surveys of the primary local agents of land change (Fox, Rindfuss, Walsh, &

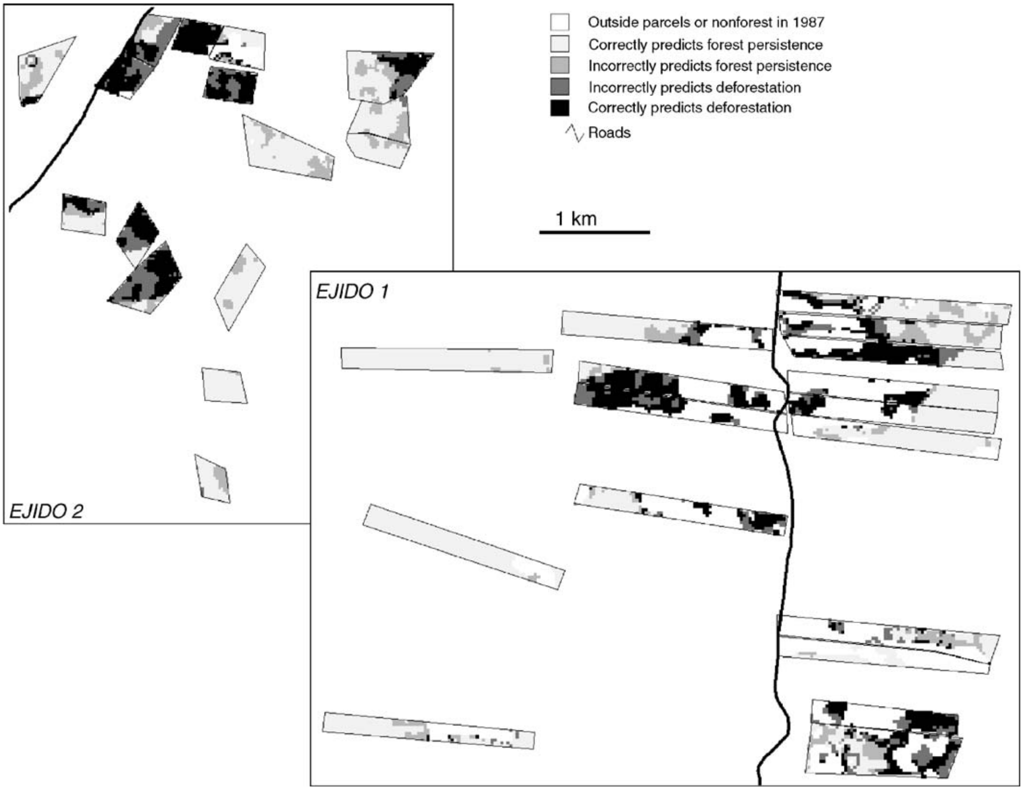

Fig. 5. Model validation.

Mishra, 2003; Liverman, Moran, Rindfuss, & Stern, 1998). In the most dynamic regions of the CBR, *ejidatario* households and their parcels comprise the fundamental agents and units of land management. This analysis documents observed trajectories of land use/cover change in the reserve and by property regime, and, following Lambin et al. (2003), highlights the complexity of factors modulating deforestation on local *ejido* parcels.

By revealing how local environmental and wider structural forces can influence the actions of land managers, the results contribute insights relevant to environmental and land use policy. While biophysical and infrastructure-related factors, most notably soils and distance to markets and nearest open agricultural lands, are strong predictors of deforestation probability; the study reveals that local household characteristics and institutional factors are also important in driving landscape change (also see Paudel & Thapa, 2004). Local land clearing decisions are strongly linked to household labor and non-farm wage strategies, and household size appears to hold a counter-intuitive relationship to land change. This study finds that some of the main sustainable development initiatives promoted locally are linked to higher probabilities of deforestation on smallholder land parcels,[9] partially corroborating wider critiques of integrated

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[9] These initiatives have been explored elsewhere in a sectorally sensitive analysis for their implications for household land allocations to different land uses (Roy Chowdhury & Turner, nd).

conservation-development programs in protected areas. Yet, other aspects of such programs, particularly those focused on improving living standards, rural credit and strengthening local NTFP cooperatives, show more promise to stem deforestation rates at the local level. It is noteworthy that beyond the necessary agricultural deforestation necessary to secure their livelihoods, smallholders in Calakmul and throughout Middle and South America typically maintain significant areas in mature forests and secondary forest succession (see Abizaid & Coomes, 2004; De Jong et al., 2001; Kass & Somarriba, 1999; Perz & Walker, 2002). Furthermore, rates of successional regrowth on land parcels throughout the region have increased in the past decade. Future studies will highlight the scalar dynamics of and differences between regional and parcel-level analyses of driving forces of land change, and investigate the dynamics of forest succession.

Mexico, like many developing nations, is faced with reconciling an aggressive national development agenda with the need for better environmental protection. Approximately 60% of the nation's lands and 80% of its forests are owned by *ejidos* (INEGI, 1990; Klooster, 1997; World Bank, 1995, p. 22). Having become a signatory to Rio-UNCED 1992 and established a national network of Biosphere Reserves that largely encompass forested ecosystems, the country needs to address issues of conservation and sustainable development in its rural *ejidal* sector. *Ejido* lands and livelihoods are under increasing pressures due to their incorporation into global regimes championing economic development (e.g., NAFTA) and/or conservation (e.g., UNESCO MAB program and the Mesoamerican Biological Corridor). Under such circumstances, protected areas in Mexico and similar regions of Latin America and the developing tropics have had mixed results in meeting their ecological and social development mandates. In calling attention to some fundamental deficiencies within South American conservation projects, Southgate and Clark (1993) highlighted, among other problems, an inadequate understanding of the complementaries between conservation and development, and of the link between local economic activities and environmental change. In evaluating the performance of protected areas, it is essential not only to assess rates and patterns of forest loss, but also to (1) identify the driving forces of forest change in forest/frontier economies and (2) rather than apportion blame to the proximate agents of change, understand how larger policy structures, including conservation-development programs, may influence the actions of local land managers by providing incentives to either maintain or fell forests. Land change research that aims to aid local conservation and rural development policy must identify synergies amongst multiple factors that affect deforestation pressures, evaluate existing institutional programs, including sustainable development initiatives, and address any unintended consequences of such institutions for local livelihoods and forest cover.

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