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Deforestation in the southern Yucatán peninsular region: an integrative approach

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Abstract

The tensions between development and preservation of tropical forests heighten the need for integrated assessments of deforestation processes and for models that address the fine-tuned location of change. As Mexico's last tropical forest frontier, the southern Yucatán peninsular region witnesses these tensions, giving rise to a "hot spot" of tropical deforestation. These forests register the imprint of ancient Maya uses and selective logging in the recent past, but significant modern conversion of them for agriculture began in the 1960s. Subsequently, as much as 10% of the region's forests have been disturbed anthropogenically. The precise rates of conversion and length of successional growth in both upland and wetland forests are tied to policy and political economic conditions. Pressures on upland forests are exacerbated by the development of infrastructure for El Mundo Maya, an archaeological and ecological activity predicated on forest maintenance, and by increased subsistence and market cultivation, including lands on the edge of Mexico's largest tropical forest biosphere reserve. In this complex setting, the southern Yucatán peninsular region project seeks to unite research in the ecological, social, and remote sensing sciences to provide a firm understanding of the dynamics of deforestation and to work towards spatially explicit assessments and models that can be used to monitor and project forest change under different assumptions.

Keywords: Tropical deforestation; Land change; Modeling; Mexico; Yucatán

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Tropical deforestation is a major concern on several fronts. It is significant to global climate warming and regional climate change (Houghton et al., 2000; IGBP, 1999); global losses in biotic diversity and net primary productivity (DeFries et al., 1999; Vitosuek et al., 1997); local-to-regional land degradation (Barrow, 1991); and threats to ecosystem services and other valuable functions (Daily et al., 2000; Kremen et al., 2000). These impacts, in turn, affect the vulnerability of places and people to perturbations of all kinds (Downing, 1996; Kasperson et al., 1995). That so much of tropical deforestation takes place under the auspices of economic development compounds its complexity (Brookfield et al., 1995; Utting, 1993). For the most part, these forests are sparsely occupied and the economic value of their use is minor, once mined of precious woods and not accounting for ecosystem goods and services. Therefore, national and local governments feel compelled to pursue programs designed to enhance the economic performance of ''forest frontiers.'' These programs commonly involve forest conversion to agriculture, triggering the various environmental concerns noted.

While world attention focuses on Amazonia and Indonesia, few if any tropical frontiers are exempt from development pressures. In Mexico, most of the Gulf Coast lowlands have long been deforested, and significant land clearance is underway in the interior Lacandon forests of Chiapas (Cairns et al., 1995; Dirzo and García, 1991; Masera et al., 1997; Merino, 1996; O'Brien, 1998). The forests of southern Campeche and Quintana Roo constitute the last frontier to encounter the west to east movement of tropical lowland development in the country. The southern Yucatán peninsular region encountered significant deforestation by the late 1960s, triggered by a growth in occupancy and various development schemes. Between 1975 and 1985, for example, the estimated annual rate deforestation for a central swath through the region was 2% (Cortina Villar et al., 1999, p. 46).[1] The region's annual rate of deforestation fell to 0.2% for the next 5 years (Cortina Villar et al., 1999, p. 46). This decline, however, coincided with the economic problems of Mexico at the time, and analogies from elsewhere (e.g., Amazonia) suggest that deforestation rates may rise again as the economy recovers. Given this history and the fact that the region is home to Mexico's largest tropical biosphere reserve, Calakmul, and the center piece of the Mexican portion of El Mundo Maya (The Maya World), the largest proposed archaeo-eco-tourist zone in the world (Primack et al., 1998), the southern Yucatán peninsula region constitutes a ''hot spot'' of tropical deforestation and biodiversity as identified in various studies (e.g., Achard et al., 1998; Cincotta and Enelman, 2000).

These conditions juxtapose the pressures to increase both forest preservation and economic development. If these dual goals are to be achieved, improved means of monitoring and projecting land changes and their impacts are required (Calhoun, 1998). These improvements require understanding the human–environment relationships controlling forest and political economic conditions, detecting the kinds and trajectories of land changes underway at the regional scale, and modeling these relationships and change trajectories in spatially explicit ways. ''Where'' different kinds of land change take place is often as important in such assessments as the magnitude of change. Projects seeking such synthesis and geographical emphasis are called for by land use/cover change effort of International Geosphere–Biosphere Programme and International Human Dimensions Programme and other related efforts (Brookfield, 1995; SSC-LUCC, 1999), and involve ''integrated'' research that joins the natural, social, and remote sensing/GIS sciences Klepeis and Turner, 2001).

Understanding land change in the southern Yucatán peninsular region exemplifies these needs. The Calakmul Biosphere Reserve and El Mundo Maya, both of which require large tracts of mature forests, are pivotal to the large capital investments. Yet, agricultural communities on the borders of and within the geographical limits of these entities rely on extensive cultivation practices. Some practices expand spatially, while others intensify. Both reconfigure the character of the landscape, amount of forest, and ability of ''opened'' land to recover to forest. The southern Yucatán peninsular region project seeks to explain, model, and project the land changes underway and their implications for the forests (Fig. 1). While much of the analysis and modeling efforts remain in their

[1] Mas Caussel (1996) calculates a staggering annual rate of deforestation for the state of the Campeche of 4.5% between 1978/1980 and 1992.

infancy, its integrated program of study has yielded insights relevant to understanding the human–environment conditions and dynamics essential for developing regional models of deforestation and other land-cover changes. Here, we demonstrate how its mode of integration enhances understanding of each of its constituent research parts and points the way towards the kind of models that should permit researchers and managers to address potential land impacts.

1. The region and its forests

The southern Yucatán peninsular region occupies about 22,000 km^2 of southwestern Quintana Roo and southeastern Campeche, north of the Mexican–Guatemala border (Fig. 2).[2] The entire region is a rolling, karstic upland dominated by redzinas (mollisols) and reaching elevations of 300 m amsl along its north–south central axis (Turner, 1983, pp. 54–65). A southeast–northwest precipitation gradient runs across the region, marked by significant differences in total annual rainfall ($\sim$1400 to $\sim$900 mm) and in the duration and intensity of the winter dry season. Given high evapotranspiration, few permanent sources of surface water, and ground water sources at depths in excess of 150–200 m, acute shortfalls in surface water are common towards the end of the dry season. Vertisols even desiccate in the upper portions of *bajos* — large poljes or sinks in the karstic landscape that otherwise give rise to perched water tables and seasonal wetlands. A seasonal or wet–dry tropical forest covers the region, distinguished by upland (locally *bosque mediano*) and *bajo* subtypes (Lundell, 1934; Miranda, 1959; Standley, 1930).

[2] The study region is defined specifically for this project (Fig. 2). Its borders do not represent ecological or political boundaries, but are intended to capture the full east–west expanse of the interior uplands, between 100 and 300 m amsl, and the north–south limits of the Calakmul Biosphere Reserve. The eastern and western boundaries were extended slightly to capture former rice projects near Lago Silvituc and Laguna Om (Nicolas Bravo), respectively. This region roughly corresponds to the last forest frontier in the Mexican portion of the Maya lowlands. Almost all of the project's data collection, however, focuses on that land and people whose tenure limits reside wholly within the boundaries of the region; not those crosscutting the boundaries as defined. This "analysis" region is slightly smaller (18,703 km^2) and is illustrated in Figs. 5 and 7.

This forest frontier encompasses the northern part of the central (Turner, 1983) or southern (Rice and Rice, 1990) Maya lowlands, depending on definitions. As such, the region has witnessed one long wave in the rise and decline of occupation and use associated with the entry of the ancient Maya previous to about 1000 B.C. and the subsequent collapse of the Classic Period civilization and depopulation of the region between A.D. 800 and 1000 (Whitmore et al., 1990). At the zenith of Maya dominion, the region held a large number of settlements and maintained population densities approaching and/or exceeding 100 people/km^2 (Turner, 1990), contributing to significant denudation of the upland forests as well as some *bajo* forests. From the Maya collapse until the middle of the 20th century, forests re-established themselves in the "vacated" region, and this forest frontier served as a refuge for those Maya fleeing Spanish and Mexican domination through the 19th century.

This history affected the character of the forests encountered by researchers in the early part of the 20th century (e.g., Lundell, 1934). Most of the upland forests were virtually undisturbed by humans during the previous millennium, but their species abundance and distribution apparently mirror past Maya activity in at least two ways: (i) abundant economic species presumably reflecting Maya orchard-gardens and forestry practices (Gómez-Pompa et al., 1987; Whitmore and Turner, 1992), and (ii) common stands of species, such as ramón (*Brosimum alicastrum* L.), edaphic to Maya disturbed soils (Lambert and Arnason, 1981).

Chicle extraction (resin from *Manilkara zapota* L. Van Royen) in the first half of the 20th century brought the first "wave" of settlers into the region. The scale of deforestation following from this occupation was apparently modest, given the small populations involved. Modern forest use with significant land-cover impacts began in the mid-20th century, precipitated by a federal decision to open the region for timber extraction, specifically for mahogany (*Swietenia macrophyla* King) and Spanish cedar (*Cedrela odorata* L.). Between 1930 and 1960, an estimated 93,633 mahogany trees (250,000 m^3 of timber) were removed from the region (Klepeis, 2000), and by the 1980s, if not before, these species were virtually eradicated in the upland forests (see Snook, 1998, pp. 62–66). Replanting efforts are underway (Snook, 1998), but the practice undertaken raises questions

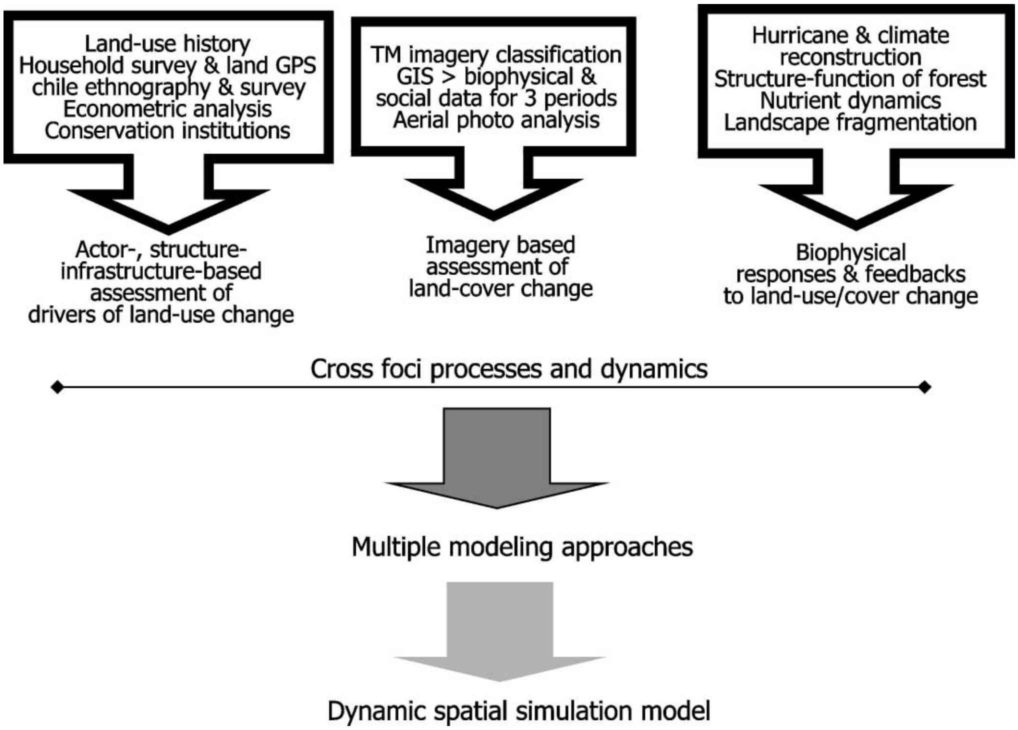


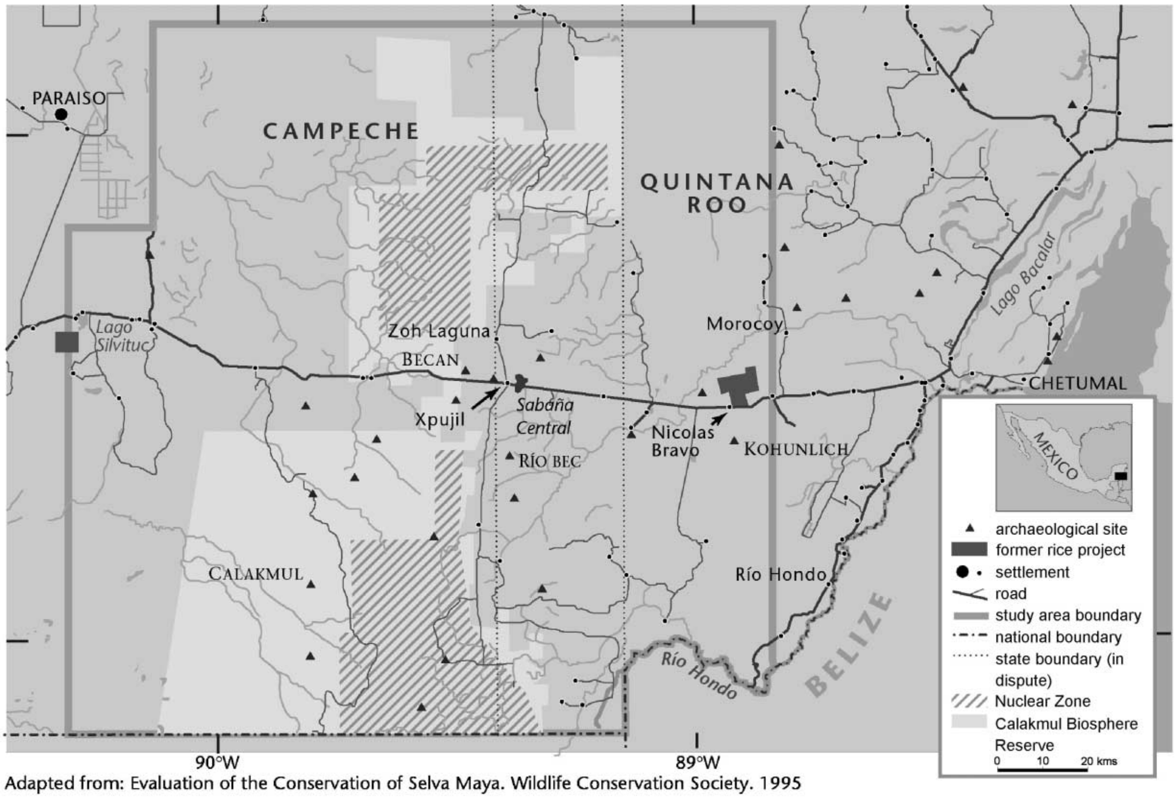
Fig. 1. Model of the southern Yucatán peninsular region project.

about impacts on upland forests whose integrity is essential to aims of El Mundo Maya and the Calakmul Biosphere Reserve.[3]

Despite a long history of botanical research in the Yucatán peninsula (Standley, 1930; Lundell, 1934; Miranda, 1959), little published work exists on the composition, structure and function of the forests in the study region. Baseline research conducted by the project confirms the identification of two major natural forest types: *bajo* forests in seasonal wetlands possessing deep clay soils (see above), and upland forests on well drained terrain (Pérez-Salicrup and Foster, 2000). Both forest types share 80% of their tree species, but can be distinguished in the relative abundance of each tree species, and in their structural appearance. In addition, upland forests rapidly recover a tree species community indistinguishable from extant mature forest relatively fast (25–30 years; Fig. 3), apparently owing to three factors: (i) the selection by the ancient Maya of the extant tree species; (ii) the recency of the current agricultural episode subsequent to the ancient Maya collapse about 1000 years ago; and (iii) the relatively small area under cultivation compared to the large matrix of forest.

As noted above, *Swietenia macrophylla* (mahogany), and *Cedrella odorata* (Spanish cedar) were subject to intensive logging in the mid-1900s. Both species, but especially *S. macrophylla* were noted by botanical researchers previous to the apex of the timber operations to have been "locally abundant" in the upland forests (e.g., Miranda, 1959; Pennington and Sarukhan, 1968). Today, the populations of these two species have been drastically reduced (mahogany regeneration apparently poor in selectively logged

[3] The International Center for Research in Agroforestry (ICRAF) sponsored a number of research and agroforestry projects in the zone east of the Calakmul Biosphere Reserve. Between 1994 and 1999, approximately 700 ha of agroforestry land were established in 42 different *ejidos* in the buffer zone of the reserve (Snook and Zapata, 1998). The plots consisted of alternating rows of timber trees, mahogany, cedar, and orange trees, as well as maize and other crops associated with *milpa*. This effort focuses on agroforestry, not on re-establishing the role of mahogany and cedar in the upland forests.



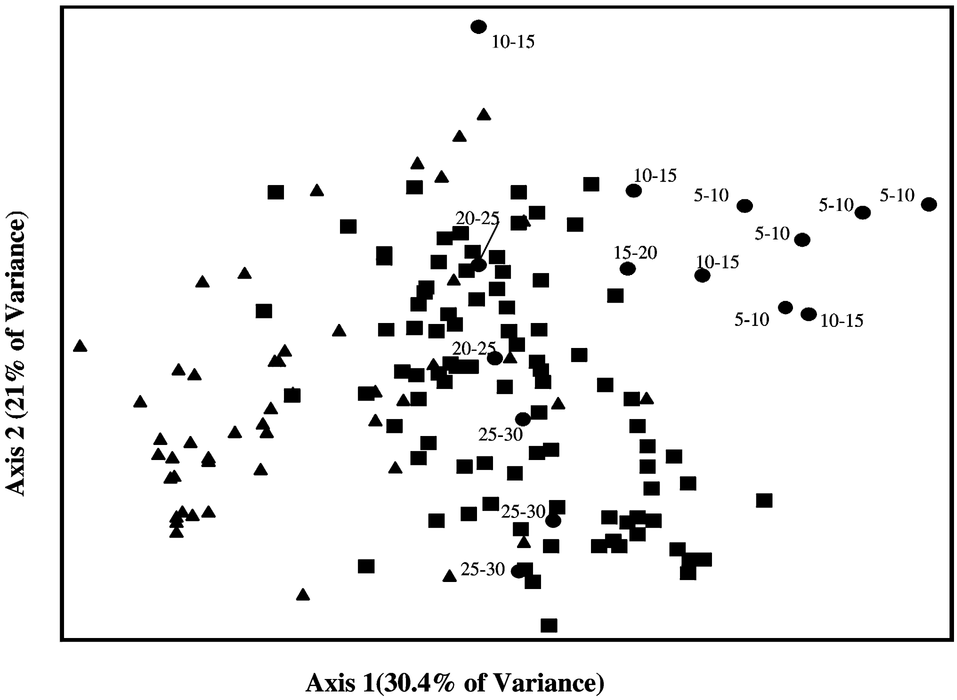
Adapted from: Evaluation of the Conservation of Selva Maya. Wildlife Conservation Society. 1995

Note: The thick gray line represents the boundaries of the general region of study, comprising about 22,005.6 km².

Fig. 2. The southern Yucatán peninsular region.

forests (Snook, 1998)). *S. macrophylla* and *C. odorata* rank 56 and 92, respectively, in terms of numeric importance out of 119 tree species that grow in mature upland forests. Transect counts revealed that no individual of either species had a diameter at breast height larger than 40 cm. In fact, both species had larger and more individuals in *bajo* forests, perhaps reflecting less intensive logging in this difficult environment from which to extract large trees. Furthermore, these species tend to have shorter and less straight trunks in *bajos* than in the upland forests.

Agriculture dominates current deforestation of these forests. Preliminary analysis of total above ground biomass (TAGB), as indicated by basal area, suggests that biomass accumulates rapidly during forest regeneration following agriculture. In the first 25 years, basal area increases to 80% of present mature forest levels. Assuming a 50% slow down in subsequent growth as canopy structure matures, we estimate TAGB recovery to a pre-agricultural state in 40–45 years. If growth rates were to slow by 75%, recovery could take 60–65 years. As noted above, the mature forests of study were heavily logged, removing the largest stems consisting of mahogany and Spanish cedar. If these or other large species come to dominate the forest canopy once again, recovery to an un-logged state might take an additional 10–25 years, assuming an ultimate density of 6 trees/ha with diameters about 100 cm (see Rodriguez Caballero, 1944; Snook, 1998). Thus, we estimate that forests similar in TAGB to those apparently observed in the 19th century might be reached 50–90 years after agricultural abandonment. In comparison, regenerating wet tropical forests in Los Tuxtlas region of Gulf Coast Mexico my take over 70 years to reach TAGB equivalent to mature or primary forests (Hughes et al., 1999). Hughes et al.



Note: The ordination was based on abundance of tree species. A similar result was obtained using tree species presence, and tree species basal area. Triangles = bajo forest; squares = upland forest; circles = plots of successional ages indicated by numbers. All successional forest plots were originally upland forest. Plots on bajo and upland forest are clearly distinguishible along these two axis, as supported by a MRPP test ($p<0.001$). As abandoned agricultural fields reach 20-30 years of succession, they aquire a tree species composition undistinguishible from that of mature upland forests (Pérez-Salicrup and Foster nd).

Fig. 3. First two axes of a non-metric multidimensional scaling of 500 m^2 forest plots in SYPR.

(1999) also find that aboveground biomass accumulation in the secondary forests of Los Tuxtlas region to be inversely related to the duration of prior land use. This finding is consistent with our results on litter production.

Preliminary findings indicate that peak litter fall (one measure of forest productivity) within a given site can be equivalent or higher in older secondary forests, about 12–25 years in age, than in mature forests (Fig. 4). Current slash-and-burn rotations do not normally involve fallowing plots for 12 years or more, raising questions about the capacity of litter production in early to mid-successional growth to restore adequate fertility to surface soils exploited by crop plants. Litter production is also lower on sites that have been through several crop-fallow cycles or where the cultivation period was long (ca. 5 years). Thus the use of short fallow periods without other inputs may lead to long-term soil degradation and, perhaps, precipitate the invasion of bracken fern (*Pteridium aquilinum* L.; locally, *helecho*) on plots long taken to cultivation, a subject the project will investigate in the future (for Amazonia, see Uhl et al., 1982). Other invasive species of importance are *tajon* (*Viguiera dentata* [Cav.] Spreng) and *Cecropia peltata* L.

2. Modern land-use history

Significant, permanent occupation of the region began in the late 1960s, at the end of an episode of intensive, selective logging and with the completion of highway 186 (Fig. 2), which bisects the region and connects it to the capitals of Quintana Roo (Chetumal) and Campeche (Campeche) as well as the remainder of Mexico. With this road and government support, requests for *ejido* land rose rapidly, and the number of *ejidos* in the region jumped from 14 prior to 1970 to 45

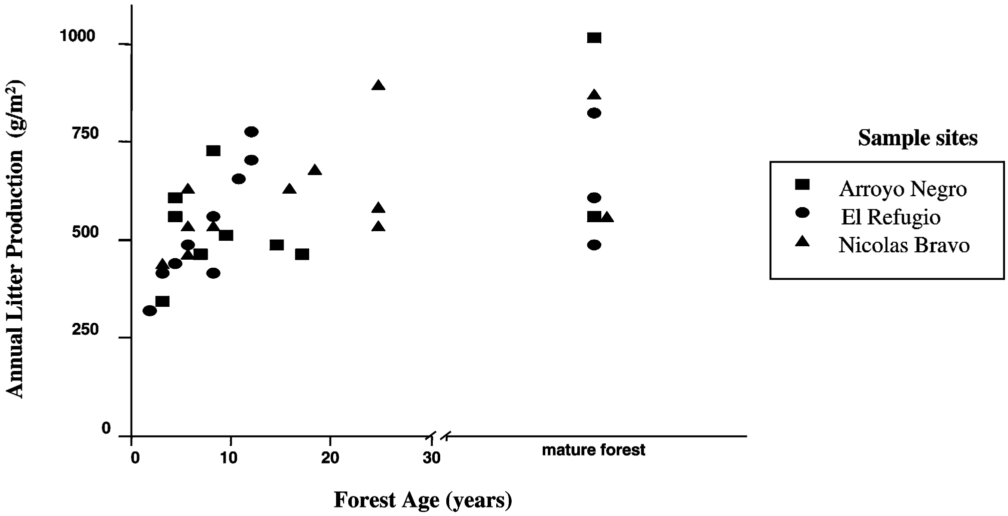


Fig. 4. Variation in litter production with forest age.

after 1980, not including those designated as *ejido* forest extensions (Fig. 5).[4] During the petro-boom of the late-1970s–early-1980s, Mexico invested in large development projects in the region, bent on reshaping this forest frontier into a rice and cattle producing area. As much as 10,000 ha were clear-cut in *bajos* on the eastern and western flanks of the region for mechanized rice and cattle projects, 3000 ha alone in the Bajo de Morocoy in the east (Fig. 2; Klepeis, 2000). The rice projects ultimately failed due to interlinked environmental and management reasons, and most were converted into cattle operations.

With this collapse, the episode of large-scale projects ended. The overall population of the region had grown from about 2500 in 1960 to over 28,000 in 1990. While significant, this growth may be deceiving given the size of the region. The regional population density in 1990, including government-controlled land and lands designated as *ampliaciones* (land extensions), which were awarded to *ejidos* located outside the region for forestry use only (Fig. 5), was just below 2 people/km^2; density within agriculture *ejidos* only was 3.5 persons/km^2 (ranging from ~1 to ~10 persons/km^2). Many *ejidatarios* (members of *ejidos*) are land rich, indicated by the average of 4–7 ha planted annually and the much larger area in fallow. In a semi-subsistence/semi-market economy, however, such riches do not necessarily lead to improved livelihoods (Table 1).[5] With the petro-bust and devaluation of the peso in 1982, local *ejidatarios* were left with few options other than to maintain subsistence cultivation, taking the form of slash-and-burn or swidden, locally known as *milpa*, and invariably including maize (*Zea mays* L.), beans (*Phaseolus* spp.), and squash (*Cucurbita* spp.). Most crops designated for the market, such as chili, are grown in some rotation with *milpa* crops.

In addition, various government and NGO-sponsored experiments in agroforestry, beekeeping, and gardening began after the episode of big projects, although a few efforts predate this period. The impacts

[4] *Ejidos* are communally managed lands awarded by the Mexican government to *campesinos* (usually poor smallholders and tenant farmers) upon requests made by groups of 20 or more farmers. Originating in agrarian reform acts, the *ejido* was intended to insure that *campesinos* would have access to land that could not be sold. In the study region, almost all *ejido* land is farmed under usufruct conditions — permanent access to certain parcels by individual households — although the rules of access and other conditions are set by the community at large.

[5] The larger and older *ejidos* in the eastern and western portions were originally designed as forestry communities based on chicle extraction; each original member was granted 420 ha, assumed to be sufficient to maintain a chicle-livelihood for a household. These *ejidos* have long shifted to agriculture as the principal economic activity. In contrast, the *ampliaciones* or forest extensions, also large in size, belong to *ejidos* outside the region and can be used only for forest activities. The small-size *ejidos* are invariably recent in origin.

Fig. 5. Land held by *Ejidos*, Mexican government, and private holders in the region.

of one such program — Plan Piloto Forestal (Pilot Forest Plan, funded by Gesellschaft für Technische Zusammenarbeit (German Association of Technical Cooperation or GTZ)) with goals to increase the livelihood that could be gained from sustainable forest extraction and use — lay partly in the eastern portion of the study region. The best known sustainable development program within the region, Bosque Modelo de Calakmul (Model Forest of Calakmul), began in 1993 and has operated in an area of 380,000 ha immediately east of the Calakmul Biosphere Reserve. Bosque Modelo promotes agroforestry, reforestation, apiculture, and eco-tourism projects, while facilitating *ejido*-directed resource management strategies as well as basic research. International acclaim in conservation circles notwithstanding, the impacts of these programs within the study region appear to be more social (e.g., institution building within and between *ejidos*) than biophysical. It is not clear how much these programs have slowed the rates of or reduced the

Table 1
Amount of land uses by smallholders (ha): survey generated ($n = 188$)[a]

Land use or crop	Percentage of sample	Mean amount land	S.D. amount land	Median amount land
Maize (*milpa*)	100	4.64	4.34	4
Chili	58	1.34	1.36	1
Pasture used	28	25.9	28.9	15
Pasture unused	23	12.9	20.8	5.75

[a] Amount of land for maize and chili refers to the total hectares planted annually by a household, usually in one plot. That for maize also includes the mix of all other crops in the *milpa* or swidden. That for chili is monocropped for the year in question, see the text on ‘‘unused’’ pasture.

amount of deforestation, restored the growth of hardwoods outside managed lots and within the structure of the upland forest, and/or led to sustainable agroforestry from an economic perspective (e.g., Acopa and Boege, 1998; Steadman-Edwards, 1997).

As adaptive agents, many farmers in the region looked for alternative production strategies to those sponsored by NGOs. In excess of 60% of the *ejidatarios* in the region migrated from the Gulf Coast lowlands of Mexico where chili production for the national market in Mexico, D.F., is common practice. The initiative of a few individuals to attract chili buyers to their new *ejidos* spawned the second largest current land-use option undertaken in the region — the production of *jalapenos* (*Capsicum annuum* L.). A survey drawing on stratified random sample of 11 ejidos and 188 households throughout the region reveals that 52% of the *ejidatarios* engage in chili cultivation, which typically involves the use of herbicides and, in some cases mechanized plowing (Table 1), and 28% sell maize. Increasingly, therefore, farmers in the region are becoming semi-market producers, mixing household consumption behavior (risk averse and linked to consumer–producer ratio) with market behavior (satisfying principle as constrained by assets), including buying and selling labor (Table 2). Yet, analysis of survey results demonstrates that households in the region exhibit production decisions slightly more consistent with those of subsistence farmers than market farmers, reflecting the self-sufficiency of most households in regard to basic food production and labor, regardless of their role in chili cultivation (Vance, 2000). Such production distinctions are important because assessments of household needs and expectations change with shifts in the relative degree to which households engage subsistence and market objectives. In turn, these changes affect the rates and amount of cultivation and, of course, the way in which models of land change are constructed (see below).

In addition, subsidies from PROCAMPO (Programa de Apoyo Directo al Campo (Direct Rural Support Program) received by 88.3% of the *ejidatarios* sampled) stimulated some farmers to cut forest and successional growth for pasture, of which approximately 50% sits empty of livestock (unused; Table 1). This strategy may have been followed, akin to conditions in Amazonia, to gain access to additional subsidies as well as to claim land in the face of Mexico's move to privatize the *ejido* sector (Klepeis and Vance, 2000). The overall neoliberal economic reforms in Mexico, however, have not led to privatization of this sector yet. Although most *ejidos* have had their boundaries officially demarcated by PROCEDE (Programa de Certificación de Derechos Ejidales y Titulación de Solares Urbanos (Program for Certification of *Ejido* Rights and Titling of Urban Commons)), virtually no *ejidatarios* have had their individual parcels surveyed.

The pasture story notwithstanding, the current occupation and use of the region is not likely to be reduced, and increased land pressures will undoubtedly follow from population growth rates that approach 4% per annum in portions of the region (Ericson et al., 1999), reforms in the Mexican economy, and the new, grand development scheme — El Mundo Maya. Building off of the tourist industry on Yucatán's east coast and on the aims of preserving much of the forests of the Maya lowlands, this scheme envisions archaeo-eco-tourism focused on the many Maya ruins in the region (Fig. 2) and the Calakmul Biosphere Reserve, linked to a pan-Maya route of the same in Belize, Guatemala, Honduras, and El Salvador. El Mundo Maya requires improved infrastructure, foremost road networks which have begun. Roads, of course, open the land to people and, in principle, foster

Table 2
Smallholder economic characteristics: survey generated (% households in sample; $n = 188$)

Characteristic	Sell chili	Do not sell chili	Sell labor	Do not sell labor
Sell maize	28	14	–	–
Self-sufficient maize	16	15	–	–
Purchase maize	10	17	–	–
Hire labor	–	–	57	24
Do not hire labor	–	–	14	5

improved market participation. The current episode of economic diversification is likely to maintain the region on various lists of "hot spots" of deforestation, precisely because of the role envisioned for El Mundo Maya.

3. Land-cover changes

This abbreviated land history indicates the kind and general location of forest changes within the southern Yucatán peninsular region. The upland forests have been depleted of mahogany and cedar. Lands designated as either "regular" *ejidos* or private holdings, even those located within or on the edges of the Calakmul Biosphere Reserve, witness significant upland deforestation and increasing cultivated lands and successional growth. If left to regrow for about 25 years, these forests may recover a tree species community similar to extant mature forests, although the abundance of mahogany and cedar absent replanting efforts is not clear. This pathway seems unlikely, however, given the search for land-based household maintenance and development, unless the region loses significant population. In addition, significant areas of *bajo* forests and other wetland vegetation on the eastern and western flanks of the region were cleared for cultivation and subsequently converted to pasture. While it is unlikely that these cleared lands will be allowed to regrow, wetlands elsewhere in the region remain intact and are not likely to be altered in any significant way under current techno-managerial and economic conditions favoring agricultural experiments in the wetlands.

Such assessments are insufficient for monitoring and projecting land change, however, owing to their coarse resolution. The emerging economy planned around El Mundo Maya and the biosphere reserve stress the need for the maintenance the forests of large portions over the region and low demands on remaining forests on *ejido* lands. The specifications of where land-change takes place, therefore, are a critical component of land and forest management. To provide such assessments, the project turned to the spatially fine-tuned data arrays that can be produced from TM Landsat imagery. Cloud free imagery was located for the two scenes that cover most of the region. Yearly "matches" of the two consisting of 1984 and 1987, 1992 and 1994, and 1996 and 1997 permitted composite period assessments but missed the earlier period of modern deforestation, including the large-scale wetland deforestation of the 1970s. Aerial photographs taken in 1969 provided supplemental information for about 63% of the region.

Following the lead of Moran and Brondizio (1998), Sohn et al. (1999), and others, an intensive field training and verification methodology was employed and continues to be refined (Fig. 6; Geoghegan et al., 2001). The normal image preparatory steps were followed: geometric correction, haze removal, and noise removal through principal component analysis (PCA). Information on texture analysis (using 3 PCA bands) and NDVI (normalized difference vegetation index) was added to the 3 PCA bands to create a seven-band image (Fig. 6). Training-site development involved "ground-truthed" data derived from GPS-assisted field visits, and topographic, vegetation and land-use maps. To this array of information was added detailed, sketch maps on recent land-use history linked to household surveys. These maps are registered by GPS and used to focus on extant and past signals in the imagery Klepeis and Turner, 2001). The land-cover signatures were further refined by accepted measures of separability (e.g., Euclidean distance), divergence, transformed divergence, and Jefferies–Matusita distance. Maximum likelihood supervised classification methods produced the land covers used to date. Separate ground truthing was undertaken on areas where the pixels' value did not fit any identified class well, leading to the creation of new training sites for new classes. All classes were subjected to accuracy assessments.

As part of the household survey, the plots of all *ejidatarios* sampled were "sketch-mapped" and tied to TM Landsat imagery with global positioning systems. Matching sketch map and imagery information permits the range of the signals for each of 10 classes to be detected by site: mature upland forests, *bajo* forests, savanna (seasonally wet), *tular* (herbaceous wetland), three stages of upland successional growth (herbaceous, shrub-dominated, arboreal), cropland, pasture and one significant invasive (bracken fern). The annual variability in precipitation throughout the region and the temporal variation in the imagery used to create the regional mosaics for the three periods of assessment, however, impeded such detail for the

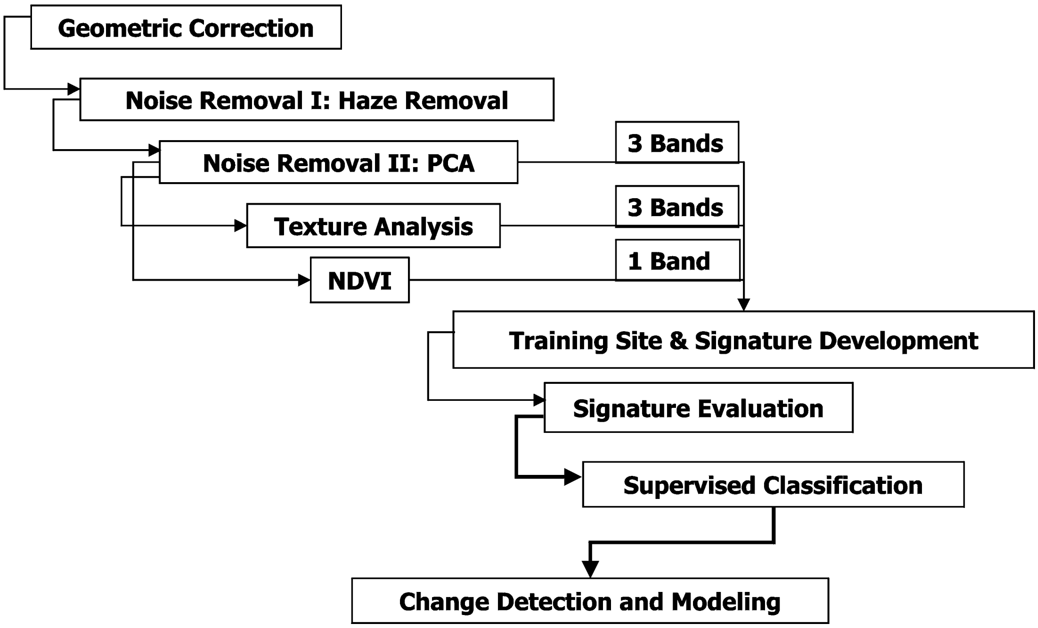


Fig. 6. Landsat TM classification method.

region at large. Ten land-vegetation classes are reduced to six for the regional analysis: upland forest, bajo forest, early and late successional growth (4–15 years), *tular*-savanna ("natural" inundated and seasonally inundated grasslands, respectively) cropland-pasture, and bracken fern.

By combining the air photo and TM imagery analysis, a spatially explicit picture of land-cover change emerges (Fig. 7a and b; Tables 3–5). In 1969, just after the completion of highway 186, about 11,042 km^2 of the photographed area's (central SYPR) forests were intact (Table 3). 6.2% (686 km^2) of this forest was lost

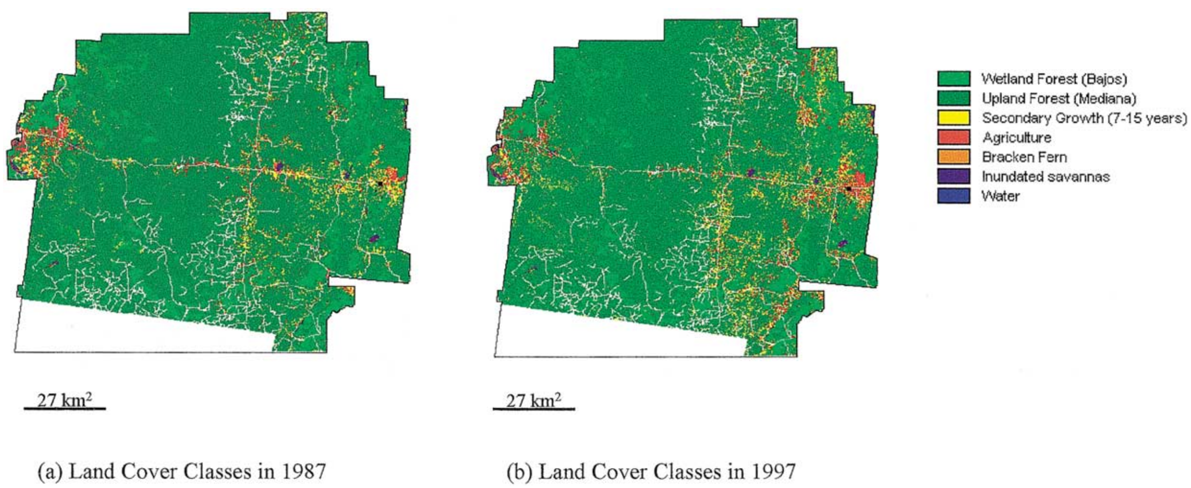


Fig. 7. (a) and (b) Regional land cover change, 1987–1997 (Landsat TM imagery).

Table 3
Land-cover change (km^2) in SYPR, 1969–1997

Land cover classes	1969[a]	1987[b]	1997[b]
Forest (upland + bajo)	11042	10356	10068
Secondary growth	111	634	845
Agriculture	228	391	468

[a] Based on aerial photographs covering 63% of the study region or 11,318 km^2.
[b] Based on TM Landsat imagery for same area as photographs.

by 1987, mostly within the older *ejidos* on the western and eastern edges of the study region. Over the next decade (1987–1997), another 2.8% (288 km^2) of this central area was deforested. For the same period, however, 3.9% (617 km^2) of the forest of the entire study region fell, reflecting the increased agricultural activity in the southeastern section not captured in the area covered by the 1969 aerial photographs (Tables 3 and 4). Given the spatial incongruity between aerial and TM images, precise figures for deforestation in the region since the advent of the highway cannot be generated. It would appear, however, that the anthropogenic disturbance of the regional forests between 1969 and 1997 was greater than 8.8% and as high as 10%, leading to crude annual deforestation rates of 0.32 and 0.39%, respectively. These figures are consistent with the 0.4% annual rates of deforestation found by Sader et al. (1994) for the northern Petén, Guatemala, immediately south of our study area.

While the role of large projects in *bajo* forests was important for deforestation before the mid-1980s, subsequent human disturbance has focused almost solely on upland forests, as indicated by the ''pixels'' transitioning to and from the non-wetland land-cover categories (Table 5). Over the last decade examined, the amount of cultivated lands taken from mature upland forests seems to have decreased, and the focus of cultivation shifted to successional growth. This shift is illustrated by the amount of land cleared in the 1987 imagery and the amount fallowed (regrowth) in the 1997 imagery, especially along the southern roadway (Fig. 7a and b). This shift may suggest a reduction in the *milpa* fallow cycle (less land taken from mature forest; more taken from early successional growth), a direction apparently indicated by the fourfold increase in area invaded by bracken fern (18–92 km^2) (Table 5). This fern, the subject of future study, appears more common to those areas entering second or third ''generation'' crop-fallow cycles and/or plots excessively depleted of their nutrients before fallowing.

4. Modeling change

Land-change models enhance understanding of the dynamics at play and provide a means of projecting near-term, future changes. To date, deforestation models in general focus largely on explaining the causes of this change and linking them to the prevailing behavioral and structural processes (Angelsen and Kaimowitz, 1999).[6] Those attempting to project or forecast deforestation are more successful in addressing the magnitude than the location of deforestation, especially at the regional or aggregate scale (but, see Mertens and Lambin, 2000), save in broader terms, such as proximity to roads (e.g., Chomitz and Gray, 1996; Pfaff, 1999).

The SYPR project pursues both aggregate and disaggregate approaches with the aim of improving the robustness and spatial explicitness of the results. For example, the details of cropping strategies are gained by locating household plots on TM imagery through the use of global positioning systems and adding detailed historical information to the sets of plots gained through survey and field mapping. With this and other survey information, Vance (2000) demonstrates through disaggregated household models the prevalent decision-making behavior of *ejidatarios* in the region: those not engaged in significant chili and maize marketing display production decisions consistent with subsistence strategies; and those engaged in this marketing display production decisions consistent with market strategies. Given that these strategies lead to different crop-fallow cycles and choice of cropping inputs, fine-tuned differences

[6] Interestingly, the modeling literature is ambiguous in regard to empirical findings supporting macroeconomic factors (e.g., population growth or economic development) in deforestation, but relatively strong in support of those factors immediately linked to household decision-making, including roads, prices, wages, and labor availability (e.g., Angelsen and Kaimowitz, 1999). Some of the research also indicates that while policy and other structural initiatives may be needed to start the deforestation process, once underway market forces may become more important explanatory variables (e.g., Andersen, 1996).

Table 4
Land cover in the southern Yucatán peninsular region based on Landsat TM imagery, 1987–1997 (km^2)[a]

	Bajo forest	Upland forest	Secondary growth (4–15 years)	Agriculture	Bracken fern
1987	3228	12,588	847	473	18
1997	3175	12,024	1271	592	92

[a] Figures apply to the entire study region.

in forest and successional growth impacts are gained. These findings inform assessments of the amount of deforestation by individual *ejidatario* and explain this change as a function of individual socio-demographic, market, environmental, and geographic variables (Geoghegan et al., 2001). An initial cross-sectional regression (OLS) model produces a positive and significant result on deforestation by combining subsistence and market indicators of individual farmers, while the education of head of household and off-farm income are negative and significant in terms of forest cut. In addition, *ejidatarios* prefer to cut the lower slopes of their lands, and the amount of forest cut increases in relation to the total land controlled by the household. Estimating the amount of forest cut by household improves by adding layers of information about the socioeconomic conditions of the households and the stock of production factors each possesses.

Ultimately, this kind of information will be built into aggregate models of the region following a framework illustrated through a recent trial model (Geoghegan et al., 2001). This trial employs TM imagery and environmental and aggregate socioeconomic data in GIS format in a discrete-choice (logit) model to estimate the probability that specific pixels in the landscape of a portion of the western scene (16 *ejidos* and 1600 km^2) will be deforested as a function of explanatory variables. The imagery classifications are combined and reduced into three categories of land cover — forest (all types and successional stages), crop and pasture land, and all other covers — to examine the binary choice of remaining forest (successional growth deemed to be early stages of forestation) or deforestation (cutting forest or successional growth).

A binomial logit model of these two choices is estimated, where the unit of observation is the TM pixel $(28\,m \times 28\,m)$. GIS layers of environmental (e.g., elevation, slope, soil), distance (e.g., to roads, markets), and socioeconomic census data (e.g., subsistence demand), selected on the basis of prevalent theories of smallholder behavior, are employed; in addition, spatial indices of the land uses surrounding a pixel are used to capture the effect of landscape diversity or fragmentation on land cover in an area.

Table 5
Land-cover transitions 1987–1997 (% pixels based on Landsat TM imagery)[a]

		Land Cover 1987				
		Wetland forest (Bajos)	Upland forest	Secondary growth (4–15 years)	Agriculture	Bracken fern
Land Cover 1997	Wetland forest (Bajos)	98.3	0.0	0.0	0.0	0.0
	Upland forest	0.0	91.1	44.9	38.2	0.0
	Secondary growth (4–15 years)	1.2	6.7	32.8	24.7	0.0
	Agriculture	0.4	2.0	17.6	35.1	30.1
	Bracken fern	0.0	0.2	4.7	2.0	69.9

[a] The use of the compilation of scenes (see text) to create full regional coverage creates problems for separating agriculture (all lands cropped within past 4 years) and secondary growth (all lands between 4–15 in fallow/succession). For this reason, some pixels on plots situated on the 4–5 year boundary are difficult to separate into their appropriate classes. This explains the 38.2% transition from agriculture to upland forest, which, in this scheme, constitutes all upland woody vegetation older than 15 years. These pixels were transitioning into secondary growth (4–5 years fallow) in 1987 but were classified to be within the 4-year window designated as agricultural land here. Rather than mask these issues, the project treats them openly.

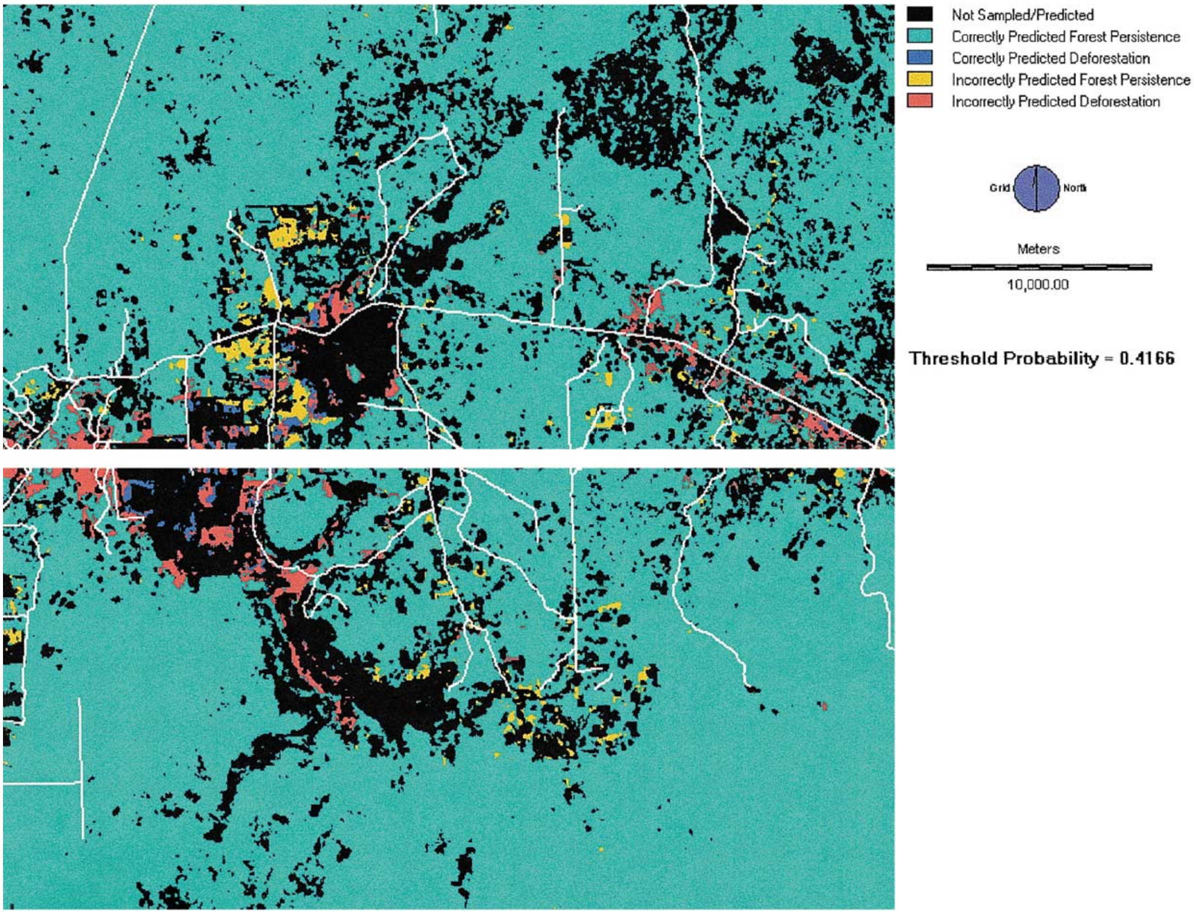


Fig. 8. Comparing estimated and actual deforestation in SYPR.

The model fits well and the results are encouraging, especially given the incipient stages of the model's development (Fig. 8; Geoghegan et al., 2001) — minor imagery classification and socioeconomic data problems remained to be resolved at the time of the model run. Most of the signs on the coefficients meet expectations: deforestation is less likely as elevation and distance from road increase; and it is more likely as a pixel's proximity to a market, village, or other crop land increases, as population density increases, and conditions of earlier stages of regrowth appear. Most of these results are consistent with those from other modeling approaches, save for the last, which indicates that land expansion and, hence, increased deforestation of mature forest, is a less likely option than repeated cropping of land fallowed for short periods (<10 years). This finding appears to be consistent with the changes in the most recent TM imagery for the region at large (Fig. 7).

A probability value must be assigned to render the absence or presence of change in the pixel in order to compare the predicted changes in the estimated model to the actual changes. This assignment is not predetermined as in other models (usually at 50%); rather, the total amount of pixels that were actually deforested was determined, and the highest probability pixels that would "match" that amount were employed. Thus, the model takes the amount of deforestation as given, and predicts the spatial distribution of that deforestation over the landscape. For the episode in question, the "cut-off" probability that a forested pixel would deforest was 42% (Fig. 8). In and out of sample maps were then produced and compared to gain insights on potential problems and limitations of the model.

A cursory view of the "missed" pixels (Fig. 8) suggests a consistent error of over-predicting deforestation on land adjacent to roads and under-predicting forest persistence on lands more distant from cultivated plots. Part of this error undoubtedly follows from the imagery and data problems noted above, especially the incorrectly predicted deforestation within the large cattle projects in the western and eastern portions of the scene. But part of the misses follows from considerations that were not covered in the trial data set and to which future models will consider. Foremost among these, we suspect, are: households entering the PROCAMPO pasture program; households engaging in market production and off-farm employment; time in resident by household and age of *ejidos*; and choice restrictions based on land availability by household. These problems notwithstanding, the trial model indicates one of the directions in which land-change modeling must move, toward a suite of models that combine magnitude and location change (Chomitz and Gray, 1996; Hall, 2000; Geoghegan et al., 1997; Lambin, 1994; Mertens and Lambin, 2000; Pfaff, 1999).

5. Integrated land-change studies and forest management

Land-change science forms a central cog in the interdisciplinary subfields of global environmental change, and environment and development. The dynamics of deforestation and land change in general are complex, strongly influenced by contingency, and require integrated approaches and assessments. Determining the fine-tuned location of change has proved as difficult to achieve as it is essential to determine (e.g., Liverman et al., 1998). Yet, in the southern Yucatán peninsular region the importance of the location of deforestation and land-change more broadly is heightened by the dual goals of farming and forest preservation for the Calakmul Biosphere Reserve and El Mundo Maya. Such juxtapositions and the significance of location are, of course, common in other tropical forests.

The SYPR project is in the midst of an analytical phase attempting to improve upon spatially explicit understanding and projections of deforestation. We believe that the project has illuminated the potential value of its "integrated" approach to the problem and points toward the kind of understanding and models that can serve the needs of land-change science. The various parts of this project inform one another the following:

- Species abundance in "mature" upland forests registers the mark of conversions and uses in antiquity and selective logging in the middle of the 20th century that depleted most mahogany and cedar. The impacts of efforts to replant these species are not well understood.
- With the exception of several large but failed experimental agricultural projects in the 1980s, *bajo* forests have been only slightly disturbed in modern times. Given current socioeconomic conditions, there is little likelihood this kind of forest is endangered.
- Upland forests constitute the overwhelming focus of deforestation in the recent past; increasing land pressures under current socioeconomic conditions strongly suggest that this disturbance will continue into the near future.
- Land pressures emanate primarily from increased occupancy and its requisite *milpa* (subsistence), current investment in chili (market) cultivation, and, in the recent past, programs promoting pasture creation.
- Economic problems in livestock rearing suggest that pasture creation should slow dramatically, unless livestock or pasture subsidies are resurrected.
- Occupancy and forest conversion are not evenly distributed across the region but focused along the east–west and north–south roadways that crosscut the region, in the western area near Lago Silvituc, and in the entire Quintana Roo portion of the region.
- These areas witnessed an explosion of forest clearance from the 1960 to 1980s, a lull in activity in the 1990s with significant growth in successional vegetation, and more recently, an increase in cutting this regrowth as it reached peak litter fall (10–15 years). Fallowed land is not permitted to regenerate sufficiently (25–30 years) to reach a mature structure and composition.
- *Milpa* cultivation in those areas most densely occupied for the longest period (along highway 186 in

the east) may degrade the land as indicated by significant invasion of *P. aquilinum* L. This invasive may follow elsewhere under sustained cultivation with insufficient fallow, practices that appear to be increasing along the edges of the Calakmul Biosphere Reserve.
- Satellite imagery can be used to track the details of forest and other land-cover changes, including successional growth and *P. aquilinum* L.
- Trial models indicate that it may be possible to understand the basic dynamics leading to fine-tuned, spatially explicit assessments of land-cover change in the region. Such models, however, are highly sensitive to major changes in the regional political economy, which is, in turn, sensitive to major changes in policy and development directions. The models have yet to incorporate the impacts of biophysical feedbacks on land-use decisions and, hence, land-cover consequences.
- These modeling efforts provide the fundamentals for integrated assessments, including scenario models, of forest conversion and land-cover change as they affect the regeneration and maintenance of forests within the biosphere reserve and without, as well as the potential for agricultural intensification and/or expansion in the region.

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