

# Comparative Spatial Analyses of Forest Conservation and Change in Honduras and Guatemala

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Catherine M. Tucker, Darla K. Munroe, Harini Nagendra  
and Jane Southworth

**Abstract:** *The degradation of dry tropical forests proceeds more rapidly than that of most moist tropical forests, but despite their importance for human populations as a source of products and environmental services, dry tropical forests rarely become the focus of conservation efforts. This study explores processes of land cover change in study sites in eastern Guatemala and western Honduras, where dry tropical forests have been declining with the introduction and expansion of export market crops, especially coffee. Through analyses of remotely sensed images, landscape metrics, and spatially explicit econometric modelling, the transformations occurring across these landscapes are examined and compared for the period between 1987 and 1996. The results show that the Guatemala region presents greater forest fragmentation, well-developed transportation networks and immigration in a context of strong linkages to coffee export markets. Net forest regrowth occurs in the Honduran region, while net deforestation occurs in the Guatemalan region. Spatially explicit models indicate that market accessibility and topography alone explain about 60% of the total*

**Catherine M. Tucker**, Department of Anthropology, SB130, 701 E. Kirkwood, Indiana University, Bloomington, and Center for the Study of Institutions, Population and Environmental Change (CIPEC), Indiana University, 408 N. Indiana, Bloomington, 47405-7100 USA.

**Darla K. Munroe**, Department of Geography, and Department of Agricultural, Environmental and Development Economics, Ohio State University, 154 N. Oval Mall, Columbus, OH 43210 USA.

**Harini Nagendra**, Center for the Study of Institutions, Population and Environmental Change (CIPEC), Indiana University, 408 N. Indiana, Bloomington, IN 47408 USA.

**Jane Southworth**, Department of Geography, and Land Use and Environmental Change Institute (LUECI), University of Florida, 3141 TUR, PO Box 117315, Gainesville, FL 32611-7315 USA.

## Address for Correspondence

Catherine Tucker, Department of Anthropology, 701 E. Kirkwood, SB130, Indiana University, Bloomington, IN 47405-7100

**E-mail:** tuckerc@indiana.edu

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*variation in Honduras, but only 51% of the variation in Guatemala. Integration of social data collected through fieldwork indicates that a higher degree of community organisation to protect forests in Honduras is an important factor in the lower rate of forest transformation, as compared to Guatemala for the same period. In both cases, there is a high degree of dynamism and apparent cyclical patterns in land cover change. These results suggest that attention to human and ecological cycles, as well as market, infrastructural and topographic factors, can contribute to the development of effective approaches for the conservation of tropical dry forests.*

**Keywords:** spatially explicit models, deforestation, conservation, landscape metrics, deforestation, conservation, markets, coffee, Guatemala, Honduras

## INTRODUCTION

FOREST TRANSFORMATIONS in Guatemala and Honduras reflect complex relationships among socioeconomic, political and environmental factors. Deforestation poses a particular conundrum for these nations; the dual goals of conserving endangered natural resources and promoting economic development have proven difficult to combine, and often result in conflicting policies that fail to protect forests. Between 1990 and 2000, national level estimates indicate that Honduras lost 59,000 hectares of forest per year while Guatemala lost 54,000 hectares per year; these figures represent gross deforestation rates of 1.0% and 1.7% per year respectively (FAO 2001). The national data aggregates all forest types into one category, therefore they obscure the fact that deforestation in regions dominated by tropical dry forests has advanced faster than for regions dominated by other forest types. When compared to tropical moist forests, tropical dry forests have lower species richness; however, they boast higher levels of endemic species, greater utility for humans, higher human population densities, and also offer important environmental services such as watershed maintenance (Mooney et al. 1995; Murphy and Lugo 1995). Yet only a small fraction of the protected areas in Guatemala and Honduras encompasses dry forests. This pattern is found generally throughout Central America (Sánchez-Azofeifa et al. 2003), even though nearly 50% of the region's forests are classified as 'dry' (Murphy and Lugo 1986).

Given the importance of tropical dry forests for human populations and the environment, it is critical for research to explore the factors that contribute to their survival and transformation in the absence of formal, national protection (Gomez-Pompa and Kaus 1999). Earlier research in the region has mainly focused on the better studied and more publicised problems of deforestation in the humid tropics (e.g., Sader 1995; Hayes et al. 2002; Sánchez-Azofeifa et al. 2002). The similarly significant issues of deforestation in dry tropical forests have received much less attention (Mooney et al. 1995; Nagendra et al. 2003). Moreover, most research has overlooked the processes of forest regrowth that tend to occur simultaneously. Indeed, comparatively little research has holistically addressed spatial and temporal

variations in forest cover change, which can provide valuable perspectives on diverse economic and social processes.

In contrast to most other research in Central America (Baranyi et al. 2004), our work takes an additional step by adopting an explicitly cross-national, comparative perspective to explore the major spatial and economic factors associated with forest cover change and conservation. We focus on two study sites with tropical dry forests, one in eastern Guatemala and one in western Honduras. The sites present comparable topography, climate and vegetation, and have certain economic parallels due to the importance of coffee production. Given these comparable aspects, the study inquires as to how social, infrastructural and political differences may influence spatial patterns of forest transformations (including regrowth). We examine and quantify differences in land-cover transformations across the study sites during a 9-year period (1987-1996). We analyse how proximity to markets and accessibility for human use (as estimated by slope and elevation) influence the relative rates of transformation. We also gauge the accuracy of models used to estimate the relative significance of key variables, assess how spatial and temporal variations appear to relate to social processes, and consider some of the implications for conservation.

The approach recognises that spatial factors, such as topography, location of roads and proximity to markets, shed light on the pressures to which forests are subjected. Spatially explicit data can provide broad insights to relate land-cover transformations to underlying factors (Munroe et al. 2004). Therefore the research involves a variety of spatial techniques, including analyses of remotely sensed images, landscape metrics and spatially explicit econometric models. The integration of these techniques draws on prior research in Central America that has used remote sensing to study processes of land use and land-cover change (e.g., Sader 1995; Sánchez-Azofeifa et al. 2002).

Our method incorporates socioeconomic data, which are necessary to understand human choices that influence forest transformations, such as road construction (e.g., Pfeffer et al. 2001; Niesenbaum et al. 2004). Social data appropriate for the scale and level of analysis are critical for linking the household to the larger landscape (Ostrom et al. 2003; Nagendra et al. 2004a; Rindfuss et al. 2004). Expanding on earlier work (e.g., Munroe et al. 2002; Nagendra et al. 2003; Southworth et al. 2004a; Southworth et al. 2004b; Munroe et al. 2004), we incorporate data collection at the household, community and landscape levels to work toward this linkage. This approach builds on earlier studies that have integrated spatial data with social data to understand forest change processes (e.g., Moran et al. 1996; Wood and Skole 1998; Pfaff 1999; Mertens et al. 2000; Nyerges and Green 2000; Geoghegan et al. 2001). Through comparative study, the research gains potential to identify critical variables driving forest change and thus contribute to policies to mitigate these transformations.

We focus on the following questions:

1. How do major spatial variables, such as distance to markets and infrastructure (especially road networks), influence the dominant trends in forest change processes?

2. What patterns of fragmentation exist, and how do these relate to spatial and socioeconomic variables?
3. What relationships exist between local level socioeconomic contexts, including the presence (or absence) of community organisation for forest management, and forest transformations?

First, we expect that stronger market linkages and better-developed road networks in the Guatemalan study site, related to its history of coffee production, will be associated with a higher rate of deforestation than in the Honduran site. Roads, export coffee production and market linkages are not as developed in the Honduran site, although major changes have been occurring since 1990. Second, we anticipate that forest fragmentation will be more pronounced in Guatemala given the distribution of coffee fields in the landscape. Third, we expect a lower rate of forest transformation in Honduras, not only due to less-developed infrastructure and market linkages, but also due to community-level efforts to ban logging and limit forest exploitation (Tucker 1999a). By contrast, the Guatemalan study site presents less evidence for effective community organisation to protect forests. It has experienced higher migration rates, and greater social heterogeneity exists due to economic discrepancies between large and small coffee producers (Tucker and Southworth 2005).

### *Study Sites*

Study sites in eastern Guatemala and western Honduras were selected to represent the relatively comparable forest composition and biophysical conditions found in these areas, and the range of topographic variation. The sites are located within one degree of latitude and longitude of each other. The eastern Guatemala site centred on the municipio of Camotán, while the western Honduran site focused on the municipio of La Campa. We included the area immediately adjacent to the municipios to place the analyses within a landscape context and facilitate spatial analyses (Figure 1). Following the Holdridge system of life zone classification, the dominant forests of the study sites fit within the 'tropical dry' classification. They have an average annual rainfall between 250 mm and 2000 mm, a mean annual temperature greater than 17°C, an annual ratio of potential evapotranspiration to precipitation that exceeds unity (Murphy and Lugo 1986), and a marked dry season (Mooney et al 1995). The dry season occurs between January and April. Most tropical dry forests represent a transition between savannah or semi-desert and tropical moist forests (Murphy and Lugo 1986), which is the case for the forests in our study sites. The entire region is topographically complex, and precipitation varies along an elevational gradient, therefore the study sites also include a few 'islands' of moist forest on the highest peaks. By controlling as much as possible for biophysical factors, the variation in the spatial patterns and processes of forest change could be more confidently associated with human dimensions, such as socioeconomic factors.

**Figure 1**  
*Map of Region and Study Sites with Municipal Boundaries*



### **Camotán, Guatemala**

The municipio of Camotán is located in eastern Guatemala on the border with Honduras. People of ladino heritage (mixed Hispanic and indigenous descent) dominate the population. Steep mountains interspersed with valleys characterise the region. The average annual precipitation varies with elevation and aspect from an estimated 1500 mm to nearly 2000 mm at the highest points. The pine-oak vegetation is similar to that of the Honduran study site, and they share the same dominant tree species, *Pinus oocarpa* (Tucker and Southworth 2005).

A road was built into the region around 1980, and Tesoro—the focal community for our study—obtained electricity in 1997. Due to its proximity to Honduras, many people move back and forth across the border for market-related activities, and the municipal population has grown in part because of immigration from Honduras. Most households have small coffee plantations, but grow maize and beans for household consumption. Coffee production expanded dramatically in the 1980s; it led to increasing social heterogeneity marked by the acquisition of material goods (large houses, vehicles) among the larger coffee producers. Among the poorer majority, few households own land titles, but most of the land is held under locally recognised, *de facto* private rights. Many people pursue a diversified livelihood strategy that includes seasonal work as coffee pickers on the large plantations. The study site includes private and communal forests, which have varied in forest cover changes. Fieldwork revealed that some communal forest areas experience clearing by small coffee growers, and lack coherent management due to border disputes and incursions from non-local harvesters. By contrast, a wealthy coffee grower with a private forest employed armed guards to thwart intruders. Interestingly,

shade-grown coffee fields have become a source of firewood for cooking, thus reducing some of the pressure on communal forests (Tucker and Southworth 2005).

### **La Campa, Honduras**

Similar to Camotán, the La Campa study site in Honduras presents complex topography composed of rocky slopes and narrow valleys. The study site includes all of the municipio of La Campa, the nearby departmental capital of Gracias and Celaque National Park. The park encompasses the highest mountain in Honduras, Montaña de Celaque, at 2849 m.s.l., which abuts La Campa and Gracias. Similar to Camotán, annual precipitation varies with elevation and ranges from 1300 mm to over 2000 mm on the peaks of Celaque, whose cloud forest represents an exception to the predominately tropical dry, pine-oak forests of the study site.

Within La Campa, most of the population is of Lenca Indian descent; a growing ladino population resides in Gracias. Subsistence production of maize and beans continues to be an important part of a diversified livelihood strategy for most rural households. Farmers usually have *de facto* private rights to land, complemented by access to communal forests. Many people, particularly young adults, migrate seasonally to pick coffee or find temporary jobs in a major urban centre. During the 1970s and 1980s, the La Campa region suffered forest degradation due to excessive logging by sawmills that had been granted contracts under the Honduran Forestry Development Corporation (COHDEFOR). The people of La Campa formed a grassroots organisation that achieved its goal of ending logging in the municipio in 1987. Subsequently, La Campa's people crafted institutions to protect forests from outside incursions, and limit market-related forest exploitation (Tucker 1999b). More broadly, COHDEFOR endeavoured to limit logging in the region during the early 1990s. With growing land scarcity during the past two decades, agricultural intensification has been occurring, with increased use of fertilisers and a reduction in the fallow cycle. Coffee production has become increasingly important during the 1990s, encouraged by national policies with incentives for coffee-producing regions such as funds for road construction (Tucker 1999a). As in Camotán, coffee production appears to be augmenting social heterogeneity, as those with more resources are acquiring disproportionate rights to land.

### **METHODS**

The research and analyses discussed here emphasise satellite remote sensing of land cover change, landscape metrics and spatially explicit econometric modelling. The interpretation depends upon data collected through on-site fieldwork. Data collection in both regions involved an interdisciplinary research team with members trained in ethnographic and rapid rural appraisal methods, forestry, remote sensing and GIS. The teams used ten protocols developed by the International Forestry Resources and Institutions (IFRI) Research Program to assure the collection of comparable data during the rapid rural appraisal fieldwork in each region (Ostrom and Wertime 2000). Principal data collection for this study involved a month of rapid rural appraisal in Guatemala in 1998, and nine weeks in Honduras (1997-1998). The research built upon prior fieldwork in the site (Tucker 1996).

### *Analysis of Satellite Images*

The selection of remotely sensed images aimed to minimise cloud cover and control for seasonal and rainfall-induced variation in vegetation cover. Three Landsat 5 Thematic Mapper (TM) images were acquired (1987, 1991, 1996). All of the images dated from March, which typically presents minimal cloud cover. March falls at the end of the dry season, when forest and non-forest cover can be readily distinguished. Precipitation patterns were examined to assure that image acquisition occurred for years of normal, relatively comparable rainfall. Geometric rectification was carried out using 1:50,000 scale maps and the nearest neighbour resampling algorithm, with a root mean square (RMS) error of less than 0.5 pixels ( $< 15$  m). Using a similar procedure, the rectified 1996 image served as the basis to rectify the 1987 and 1991 images via image-to-image registration. An overlay function assured that the images overlapped exactly across the three image dates. Following rectification, calibration procedures corrected for sensor drift, atmospheric conditions, and variations in the solar angle (see Jensen 2000; Green et al. 2005).

Image classification was then performed on each image date, with resultant classes of forest (25% or greater canopy closure) and non-forest (open pasture, early succession, soil, urban or built) to facilitate the change analysis. Bodies of water are negligible, and the non-forest class overwhelmingly entails agriculture. We field tested the individual forest and nonforest classifications for each date through an independent field validation exercise using validation data collected in the field. We obtained accuracies of greater than 85% and kappa statistics greater than 0.75 for each date. This is a fairly high degree of classification accuracy considering the mountainous nature of the landscape, which makes classification a difficult exercise. The accuracies achieved compare favourably with those of other studies of land cover change in Central America (e.g., Sader 1995). In a separate study, we evaluated the accuracy of the land cover change trajectories, utilising a separate set of validation data that was not used in the original classification procedure, or the evaluation of single time point classification accuracies, as unbiased test reference data (Jensen 1996). Based on this, our assessment of land cover change trajectories had an overall accuracy of 92.6% for the 1987-1996 land cover change map, with no individual classes less than 70% and an overall kappa statistic of 0.9006. This high degree of accuracy adds confidence that the changes we see are not due to map error but due to real changes taking place in the landscape. Further details of the procedure used for accuracy assessment, along with details of producer and user accuracies for each individual land cover class and change trajectory, are provided in Southworth et al. (2002) and Nagendra et al. (2003).

After each individual image date was independently classified, we created a change matrix and an associated image that provides information for each pixel of its trajectory of land cover across all three dates, 1987-1991-1996. Given that each individual image date consisted of two land cover classes, this gives us a total of eight change classes in the final trajectory analysis. The fragmentation analysis used the resulting three-date change image in order to explore dynamic processes. In addition, two individual paired image date trajectories were also created, each with four change classes, for 1987-1991 and 1991-1996. Such trajectory analyses,



rather than single date images evaluated individually, provide a critical tool for monitoring and hence, managing, natural resources (MacLeod and Congalton 1998; Nagendra et al. 2004b). Each image is associated with a change matrix which allows for the analysis of spatial and temporal changes across the landscape and to assess the region in terms of areas which have remained static and those areas which are much more dynamic, in terms of change.

### ***Landscape Metrics***

We calculated landscape metrics using the software Fragstats 3.3 (McGarigal et al. 2002) for the 1987-1991-1996 change image of the study sites in Guatemala and Honduras. Fragstats provides a comprehensive set of spatial statistics and descriptive metrics of pattern at the patch, class and landscape levels (Haines-Young and Chopping 1996). At the class level, our interest is in comparing descriptive metrics of land cover pattern in these two landscapes for various categories of land-cover change in order to evaluate the differences in landscape composition and configuration in these two regions. These metrics can be grouped into categories of area, shape, core, diversity and contagion/interspersion (Haines-Young and Chopping 1996). To simplify interpretation, the following metrics were used (Forman 1995; Griffith et al. 2000; Riitters et al. 2000) :

- a) Percentage land cover (% LAND): percentage of total area occupied by each class.
- b) Patch density (PD): total number of patches in this class per hundred hectares of landscape area (number per hundred hectares).
- c) Largest patch index (LPI): area of the largest patch in each class, expressed as a percentage of total landscape area.
- d) Mean patch size (MPS): average patch size for the class (hectares).
- e) Mean shape index (MSI): average complexity of patch shape for the class (the index is 1 when square, and increases without limit as the patch becomes more irregular).
- f) Mean nearest neighbour distance (MNN): average shortest edge-to-edge distance to the nearest patch of the same class (metres).
- g) Clumpiness index (CLUMPY): aggregation propensity of the class as measured by deviation from that expected under a spatially random distribution. This index is -1 when maximally disaggregated, equals 0 when the focal patch type is distributed randomly, and approaches 1 when the patch type is maximally aggregated.
- h) Interspersion-juxtaposition index (IJI): degree of interspersion of patches of this class, with all other classes (this index takes values from 0, when the class is found adjacent to only one other class type, and increases to 100 as the patch type becomes increasingly interspersed with other class types).

The indices of %LAND, LPI and MPS correspond to area metrics. Together with PD, these provide indications of the degree of fragmentation for different land



cover types and change images. MSI, MNN, CLUMPY and IJI provide metrics of shape, isolation/proximity and contagion/interspersion. This analysis does not include measures of core (we find no ecological basis for defining core distance in this landscape) or diversity (as the number of classes is constant across time, diversity indices do not vary appreciably). Complete descriptions of these metrics and equations for their calculation are provided in McGarigal et al. (2002).

### *Spatially Explicit Econometric Models*

Spatially explicit econometric models apply the insights of von Thünen (1875/1966) and Ricardo (Currie 1981) regarding two key spatial land-use incentives: land productivity and transportation costs. These continue to be important (but not the sole) components of a holistic approach. According to the theories of von Thünen and Ricardo, land users choose a use based on a variety of factors that determine the relative returns to that use. Such factors include the geophysical and agroclimatic suitability of the land, effective distance to relevant markets, the demographic characteristics of the land user (wealth, education, age), and policies that affect land-use returns (taxes, subsidies, property rights and infrastructure). These factors interact dynamically to shape processes of land-use change, often associated with land-cover transformations. Applying this framework in a spatial context allows one to identify areas where land use is likely to change as well as quantify the relative effect of each factor on observed land-cover patterns.

Many models focus on deforestation, and do not account for forest regrowth at all, even though land-cover change is often a dynamic, multidirectional process. Mertens and Lambin (2000) were the first to specify trajectories of change as a dependent variable. Land-use change is a complex process of biophysical and socioeconomic interaction and cannot be captured in one simple measure of forest cover. Building on Chomitz and Gray (1996), we posit that the observed land cover trajectories are in part a function of regional land-use incentives: market accessibility and topography (slope and elevation). Mertens and Lambin (2000) also considered forest pattern and fragmentation as another important determinant of profitability. The value of forest/non-forest at a particular parcel is dependent on that parcel's position in a patch of forest or agricultural land. In order to explain the dynamic and bi-directional changes more explicitly, we estimate a binary model of forest vs. cleared land for each individual time period, and in a panel formulation (for further details, see Munroe et al. 2002). This model lends itself to the spatial examination of model fit, a useful tool in an integrated, interdisciplinary project. We employ a regional model of land-cover change as a function of land-use incentives, and then evaluate spatially the relative fit of the model. The spatial evaluation allows the researcher to examine areas where model fit was particularly good or bad, to make further hypotheses about the underlying land-use processes.

Land-cover change trajectories are a function of the independent variables that proxy agricultural suitability and market accessibility. For topographically complex areas, important independent variables are likely to include slope, elevation and distance to markets. In Honduras, slope and elevation for the region were calculated using a Digital Elevation Model (DEM) at a scale of 1:50,000. For

Guatemala, we had a much coarser DEM, at a scale of 1:250,000. The quality of this DEM was improved slightly by using an interpolation method based on the drainage pattern to reduce the coarseness at points of maximum relief.

Distance to nearby markets is an important determinant of the agricultural suitability of a particular parcel. In this region, there are many different types of roads ranging from paved roads and seasonal roads to footpaths. Based on the most recent road coverage maps available, 1992 for Honduras and 1998 for Guatemala, we weighted the distance to market destinations by road type by assigning an impedance factor. Cleared land was assigned a base impedance factor 1, and forested land, 2. To account for variations in slope, these base costs were multiplied by a slope function:  $(1 + \text{slope}^2/50) * \text{land-cover cost}$  (Nelson et al. 2001).

There are roads leading to two types of destinations. In Honduras, one road out of the region leads to both Santa Rosa de Copán (regional centre of exchange) and Tegucigalpa (the capital city). In addition, much local exchange takes place in nearby towns and villages, so we include these population centres as local market destinations. Similarly in Camotán, there are roads linking to local markets, and two major regional markets, Chiquimula, Guatemala to the south, and Gualán, Honduras to the east. Roads and paths are weighted according to an impedance factor that reflects their traversability: 0.05 for two-lane roads, 0.10 for one-lane, 0.15 for seasonal and 0.20 for paths. The weights relate to the decreasing ease of movement as roads turn into footpaths. Combining the cumulative effects of land cover, slope and road, the least-cost path from every pixel to the road out of the region, and to the nearest town or distance on this base cost surface was calculated, providing a weighted measure of distance to markets. Patch size was also calculated using Arc/Info as the total area in which each sample pixel was found, in square kilometres. To reduce spatial autocorrelation endemic in spatial data sets, we sampled the data (following Besag 1974) using every 25<sup>th</sup> pixel, meaning that 750 m spacing was left between each observation. The impacts of spatial sampling on model estimation are presented in Munroe et al. (2002); care was taken so that the grids were not 'oversampled', i.e. to the point where standard errors increased significantly.

Table 1 shows mean values for the independent variables across land cover classes, which were derived from the three-date change image. The minimum mapping unit from the satellite image, the 900 m<sup>2</sup> pixel, serves as the econometric unit of analysis, which roughly conforms to the size of the smallest plots. Mertens and Lambin (2000) developed a schematic to link a three-date land-cover change grid to underlying land uses. In the case of western Honduras, there are three main processes of land-use change. First, since 1987 there has been an abandonment of marginal areas, on steeper slopes and closer to roads and towns, which were formerly used in swidden maize and bean cultivation. Secondly, from 1991 recent clearings appeared at higher elevations, farther from roads and towns; these are small and typically represent coffee clearings (Southworth et al. 2002; Nagendra et al. 2003). Lastly, there is a fallow cycle, shortened though it may be, for staple crop production. In Guatemala, the major processes of land cover/land-use change appear to be clearing for coffee, expansion of agricultural fields, and fallow cycles associated with coffee and staple crops.

**Table 1**  
*Mean values of independent variables across land cover classes, Camotán and La Campa study sites, 1987-1991-1996*

	Stable Forest (F-F-F)	Deforestation (F-N-N, & F-F-N)	Fall of (F-N-F & N-F-N)	Forest Regrowth (N-F-F & N-N-F)	Stable Agriculture (N-N-N)	All Classes	Units
Honduras							
Area	401.40	97.13	93.95	102.72	319.91	1,015.12	square kilometres
Elevation	15.89	12.46	12.83	12.53	11.67	13.59	100 metres
Slope	18.43	15.30	14.51	16.95	14.54	16.39	degrees
Distance to Nearest Town	11.71	7.59	6.57	6.21	5.21	8.20	Scaled, weighted cost of access
Distance out of Region	19.99	16.81	16.97	16.28	16.60	17.94	Scaled, weighted cost of access
Patch Size	1.79	1.33	1.33	1.01	2.83	2.17	square kilometres
Guatemala							
Area	305.15	117.92	99.69	87.34	442.66	1,052.77	square kilometres
Elevation	10.76	9.45	9.78	9.81	8.63	9.54	100 metres
Slope	12.21	9.42	10.25	10.23	8.14	9.82	degrees
Distance to Nearest Town	14.32	11.56	12.37	11.10	7.55	10.67	Scaled, weighted cost of access
Distance out of Region	11.38	9.41	9.66	10.80	8.82	9.87	Scaled, of weighted cost of access
Patch Size	3.36	3.16	3.46	3.42	3.38	3.36	square kilometres

**Notes:** Each land cover class is represented by the combination of forest (F) or nonforest (N) conditions associated with each of the associated images: 1987, 1991, 1996, e.g., F-F-F indicates forest for 1987, 1991 and 1996, which is stable forest. The data on the transportation networks used to calculate weighted cost of access were derived from topographic maps from 1998 and 1992 for Guatemala and Honduras, respectively.

## RESULTS

### *Landscape Metrics*

Table 2 compares the spatial pattern of distribution of the eight land cover change categories in the two landscapes in Guatemala and in Honduras. Both landscapes are predominantly composed of stable forest and stable agriculture. The Honduras landscape is dominated by the stable forest category (39.08%) and the next most dominant class in terms of land cover is stable agriculture (28.66%). The remaining 32.26% of the study area experiences some alteration in land cover between 1987

and 1996. In contrast, the Guatemalan landscape is dominated by the stable agriculture category (41.86%) and the next dominant class is stable forest (28.86%), with 29.28% of the study area undergoing a transformation in land cover during the period of study.

**Table 2**  
*A comparison of class level landscape metrics for eight land cover change classes, 1987-1991-1996, for the landscape in Honduras and Guatemala*

Change category	Study area location	% LAND	PD	LPI	MPS	MSI	MNN	CLUMPY	IJI
F-F-F	Honduras	39.08	6.55	22.35	5.96	1.31	88.71	0.77	82.00
	Guatemala	28.86	8.06	18.41	3.57	1.30	88.68	0.73	84.71
F-F-NF	Honduras	8.49	20.01	0.30	0.42	1.22	82.93	0.36	75.46
	Guatemala	7.76	20.72	0.06	0.37	1.18	85.00	0.36	78.52
NF-F-NF	Honduras	3.85	15.91	0.04	0.24	1.12	98.46	0.38	81.89
	Guatemala	7.84	21.74	0.10	0.36	1.18	84.17	0.34	80.15
F-NF-F	Honduras	11.73	19.47	0.31	0.60	1.29	77.50	0.39	74.00
	Guatemala	1.73	9.77	0.01	0.17	1.07	126.75	0.20	88.65
NF-F-F	Honduras	2.71	12.40	0.01	0.22	1.11	109.89	0.25	85.78
	Guatemala	5.52	19.31	0.03	0.28	1.15	89.16	0.29	80.74
NF-NF-NF	Honduras	28.66	7.18	11.15	3.99	1.28	88.02	0.72	73.76
	Guatemala	41.86	6.18	35.19	0.76	1.25	89.32	0.76	89.18
NF-NF-F	Honduras	2.37	12.73	0.03	0.19	1.08	111.41	0.22	87.32
	Guatemala	2.88	13.99	0.04	0.20	1.09	105.91	0.24	79.85
F-NF-NF	Honduras	3.11	12.59	0.16	0.25	1.11	109.99	0.32	83.07
	Guatemala	3.55	15.51	0.02	0.22	1.12	101.60	0.25	79.53

**Notes:** Percentage land cover (%LAND); patch density (PD), largest patch index (LPI), mean patch size (MPS), mean shape index (MSI), mean nearest neighbour distance (MNN), clumpiness (CLUMPY) and interspersions-juxtaposition (IJI).

Of the two areas, the Honduran landscape appears to be composed of larger patches (greater MPS), with correspondingly lower patch density (ED), and more complex shapes (higher LSI and MSI) across all change categories. It is therefore less fragmented when compared to the Guatemalan landscape. While no consistent difference can be discerned between landscapes based on the mean nearest neighbour (MNN) distance and interspersions/juxtaposition (IJI) values, the clumpiness index (CLUMPY) tends to be higher for Honduras than Guatemala, irrespective of change category. This result also indicates greater fragmentation in the Guatemalan landscape. These findings are consistent with the data showing that the Guatemala site has more agricultural land and greater deforestation than the landscape in Honduras; hence it is more likely to be fragmented by human activities on the landscape.

*Spatially Explicit Econometric Model*

In accordance with the results of the landscape metrics, the results of the spatially explicit econometric model show some significant differences in the overall land-cover composition and land-cover changes between the study sites. Descriptive statistics for the land-cover change trajectories are given in Table 1. In both countries there was significant, multidirectional change during the study period 1987-1996. Net forest regrowth occurred in Honduras, whereas in Guatemala, the overall trend was that of deforestation.

The estimated marginal effects for the probability of non-forest are presented in Table 3, grouped by the following classes: stable forest, deforestation in the first time period, deforestation in the second time period, stable agriculture, and across all observations. These marginal effects can be interpreted in the following manner: for deforestation in Honduras between 1987 and 1991, a unit increase in elevation implies a decrease of 0.042 in the probability that that area would be non-forest. All effects were significant at the 95% level, except for the impact of slope in Honduras, and the impact of patch size in Guatemala, both of which were insignificant.

**Table 3**  
*Marginal effects on probability of non forest evaluated at the mean  
for each independent variable*

	Stable Forest (F-F-F)	Deforestation 1987-1991 (F-N-N & F-F-N)	Deforestation 1991-1996 (F-N-N & F-F-N)	Fallow Cycle (F-N-F & N-F-N)	Stable Agriculture (N-N-N)	All Obs.
<b>Honduras</b>						
Variable						
Constant	0.19730	0.22990	0.22580	0.22800	0.20880	0.2285
Elevation	-0.03670	-0.04270	-0.04200	-0.04240	-0.03880	-0.0425
Slope	-0.00120	-0.00140	-0.00140	-0.00140	-0.00130	-0.0014
Distance to Nearest Town	-0.01320	-0.01540	-0.01510	-0.01530	-0.01400	-0.0153
Distance out of Region	0.00550	0.00640	0.00620	0.00630	0.00580	0.0063
Patch Size	0.00010	0.00010	0.00010	0.00010	0.00010	0.0001
<b>Guatemala</b>						
Variable						
Constant	-0.45563	-0.4281	-0.45137	-0.45368	-0.42855	-0.44618
Elevation	1.44845	1.36091	1.43491	1.44225	1.36235	1.41841
Slope	-0.1073	-0.10081	-0.10629	-0.10684	-0.10092	-0.10507
Distance to Nearest Town	-0.16424	-0.15431	-0.1627	-0.16353	-0.15447	-0.16083
Distance out of Region	0.36915	0.34684	0.3657	0.36757	0.34721	0.3615
Patch Size	0.00144	0.00136	0.00143	0.00144	0.00136	0.00141

The impact of elevation was much stronger in Guatemala than in Honduras. For deforestation in the first period (1987–1991), a unit increase in elevation increased the probability of a change to non-forest less than at the mean for all observations, but for the period 1991–1996, a unit increase in elevation increased the probability of a change to non-forest greater than at the mean for all observations. This finding indicates that overall, the probability of deforestation increased with elevation, and much more strongly in the second period. In other words, the processes of deforestation were increasingly occurring at higher elevations most likely due to the fact that most remaining forests were found there.

The impact of regional accessibility is also stronger in Guatemala than in Honduras. The variable (weighted distance to regional markets) is inversely related to accessibility: accessibility increases as weighted distance decreases. In Honduras, deforestation in both time periods (1987–1991 and 1991–1996) occurs for increasingly inaccessible areas. In Guatemala, deforestation in the first period occurs at more accessible areas relative to the average accessibility of stable forest, but in less accessible areas in the second period. These processes appear to be related to the spread of coffee throughout the study site, and associated clearing for subsistence agriculture among those with fewer resources. Clearings represent a larger part of the Guatemalan landscape, therefore as available land decreases in accessible regions, pressure is increasing on less-accessible areas.

Overall, the random-effects probit model showed that topography and market accessibility explained roughly 60% of total variation in Honduras and 51% of total variation in Guatemala in land-cover change from 1987 to 1996, according to the pseudo- $R^2$  measures calculated by LIMDEP. An additional means for evaluating model accuracy is to generate fitted values of land cover for each observation. A fitted value was assigned to each observation (with probability > 0.50) for each time period. Overall model accuracy was 0.58, but the Kappa statistic was only 0.42 in Honduras (Table 4). We were able to separate out stable forest and stable non-forest at greater than 60% accuracy. In Honduras, user's accuracy (of correctly fitted values) for reforestation ranged from 8.62% to 61.11%, whereas accuracy of deforestation ranged from 31.17% to 47.83%. Following Pontius (2002), the amount of error attributable to disagreement between actual and fitted land cover classes, deemed 'quantity' error, was 31% in Honduras, whereas errors due to location (i.e., accounting for the proportion of correctly fitted values overall in the data, but these fitted values not occurring in the proper location) was 11%.

In Guatemala, overall accuracy was 38% whereas the Kappa statistic was only 0.28. Stable forest and stable agriculture were estimated with about 65% and 62% accuracy respectively. Surprisingly, recent deforestation events were estimated with 15% accuracy (higher than the 12% accuracy estimated in Honduras), but there were no correctly fitted values for either older deforestation events (F-N-N) or the fallow cycle (F-N-F). In Guatemala, the error due to quantity was 45%, and location error 18%. The model for Honduras appears to do a better job capturing the overall proportion of forest and non-forest in the data, as well as matching these values to their actual location.

**Table 4**  
*Cross-tabulation of Land-Cover Change Trajectories, Actual versus predicted*  
*(f = forest; n = non-forest)*

Land Cover 87 - 96	f-f-f	f-f-n	n-f-f	n-f-n	f-n-f	f-n-n	n-n-f	n-n-n	Total	Percent Correct
Honduras										
f - f - f	453	1	115	29	0	0	4	55	657	68.95%
f - f - n	30	11	23	11	0	0	5	9	89	12.36%
n - f - f	43	3	20	4	0	4	2	4	80	25.00%
n - f - n	22	1	10	24	1	0	1	5	64	37.50%
f - n - f	28	0	16	2	22	1	10	16	95	23.16%
f - n - n	14	0	14	0	2	10	5	14	59	16.95%
n - n - f	31	4	5	3	8	1	31	21	104	29.81%
n - n - n	59	3	29	4	3	13	17	404	532	75.94%
Total	680	23	232	77	36	29	75	528	1680	
Overall Accuracy	0.58			Location Error			31%			
Kappa	0.42			Quantity Error			11%			
Guatemala										
f - f - f	139	92	34	40	0	2	18	214	539	64.95%
f - f - n	27	22	10	12	1	0	8	65	145	15.17%
n - f - f	13	13	9	6	0	0	3	52	96	9.38%
n - f - n	28	20	4	12	1	0	4	54	123	9.76%
f - n - f	5	2	1	0	0	0	1	16	25	0.00%
f - n - n	2	4	2	8	0	0	9	46	71	0.00%
n - n - f	7	3	1	5	0	0	4	33	53	7.55%
n - n - n	76	49	50	82	0	0	46	486	789	61.60%
Total	297	205	111	165	2	2	93	966	1841	
Overall Accuracy	0.37			Location Error			45%			
Kappa	0.28			Quantity Error			18%			

**Note:** See Pontius (2002) for a method to decompose the error in terms of incorrect quantity (wrong class), vs. incorrect location.

One important baseline for the explanatory power of a spatial model is whether the amount of estimated persistence matches the true persistence in the landscape (Pontius et al. 2004). Accordingly, 67% and 71% of the landscape in Honduras and Guatemala, respectively, did not actually change. Estimated persistence in the Honduran model was 58%, whereas it was only 37% in Guatemala. Therefore, this simple model performs much better in Honduras than in Guatemala. In Guatemala there is evidently more driving the observed changes in the landscape than can be modelled by market accessibility and topography alone. Actual and modelled land cover change for Guatemala and Honduras are presented in Figures 2a, 2b, 3a and 3b.



Figure 2  
(a) Actual Land Cover, and (b) Modelled Land Cover, Guatemala

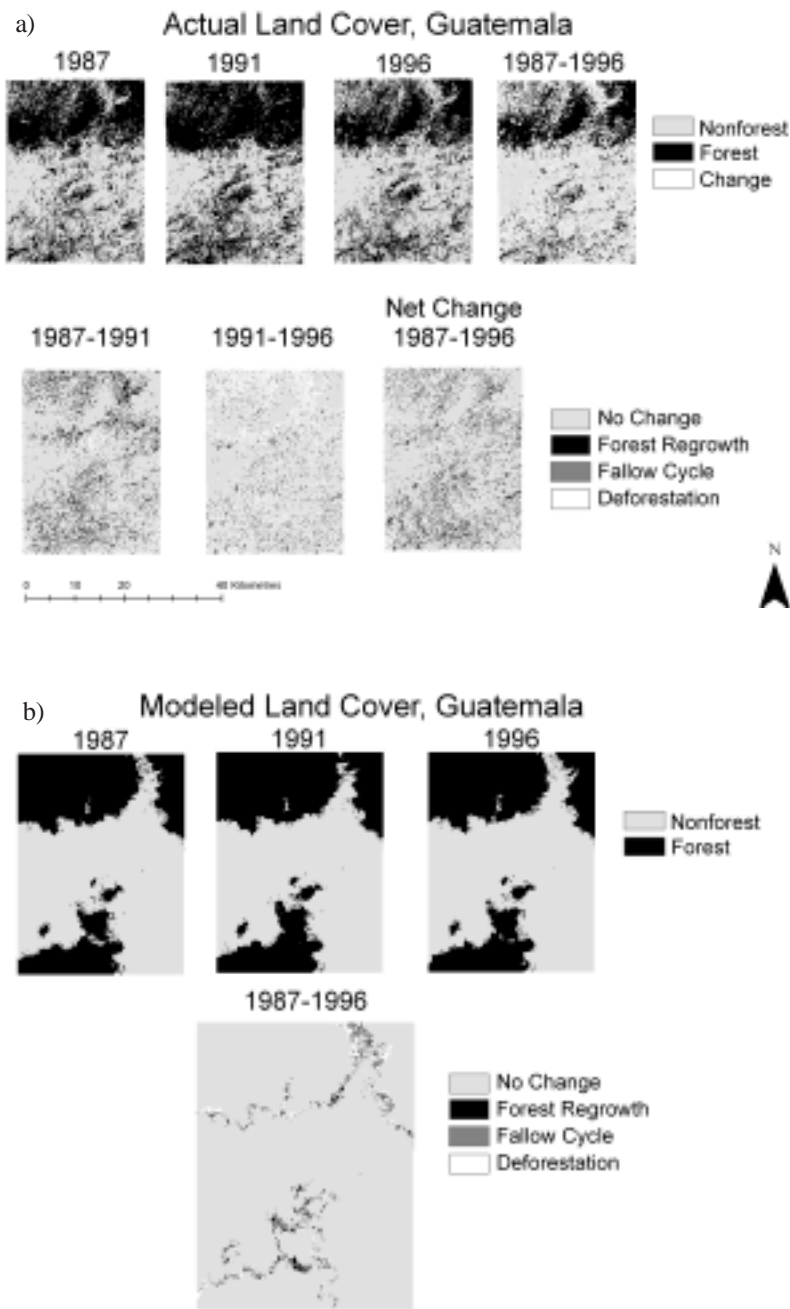
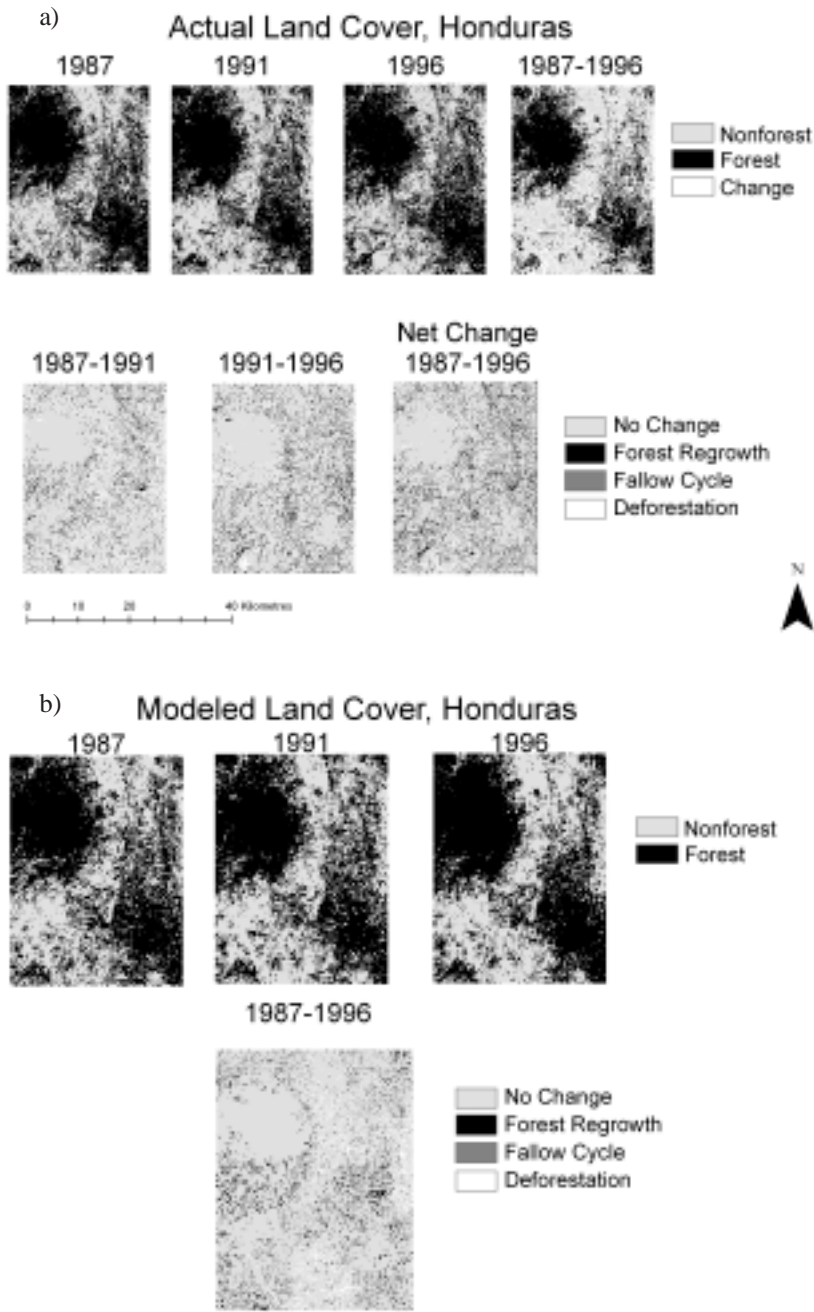
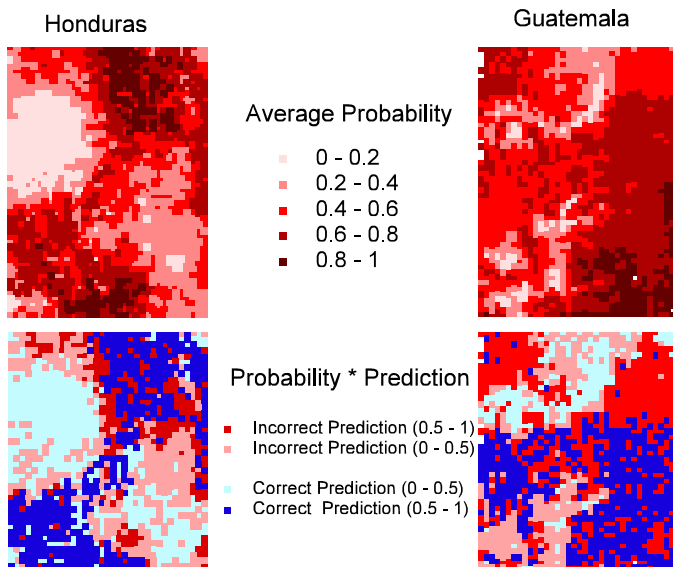


Figure 3  
(a) Actual Land Cover, and (b) Modelled Land Cover, Honduras



The assignment of forest or non-forest based on probability values only provides some information on explanatory power. As expected, the estimated probability of non-forest is the lowest at high elevations, far from roads, and highest at low elevations, close to roads, but there is a lot of variation along the edges (Figures 4). In particular, the estimated probabilities of non-forest are closest to 0.5 (implying roughly equal probability of forest or non-forest) at edge areas. Incorrectly fitted values were more likely to occur in smaller patches around the edges of more stable forest or non-forest.

**Figure 4**  
*Estimated Probability of Deforestation and Accuracy of  
Predicted Land Cover, 1987-1996*



These estimated probabilities can serve as a tool for further analysis. For instance, one could use fieldwork to investigate areas where estimated probabilities were lower to determine what other significant variables might be missing from the analysis, and could be incorporated in the future. In Guatemala in particular, there were almost no estimated values of forest in the south-eastern corner of the image, indicating that there is a missing incentive for forest cover in that area not captured by the variation in the independent variables in the models. There was a similar area in Honduras (in the north-eastern corner), where, though not as starkly as in Guatemala, there is much greater spatial error because of overall similar values for both topography and accessibility in these areas.

## DISCUSSION

The experiences of Honduras and Guatemala with forest transformations have relevance throughout Central America and Mexico. While tropical dry forests in particular receive little formal protection as protected areas, they often represent key resources for local populations and shelter rare endemic species. By studying two sites with similar forests and environmental conditions with contrasting national contexts, we were able to explore whether processes of forest cover change differed by nation. Our analyses pointed consistently to greater land cover transformation and fragmentation in Guatemala as opposed to Honduras, although both locations revealed dynamic patterns of change in land cover.

We incorporated multiple data sources and analytical methods to achieve a holistic approach. The fieldwork data provided fundamental information, including training samples to classify the images and distance factors to set up the spatially explicit model, as well as much valuable insight on the land-use processes that drive landscape change in these study areas. Ethnographic data imparted invaluable contextual perspective with which to interpret the forest conditions and factors that shape forest users' activities. Researchers' familiarity with the study sites' economies, travel conditions, local patterns of forest use and market relationships permitted more confident application and interpretation of the spatial analyses.

The modelling exercise gained insight into the relationship between underlying land-use incentives and observed land-cover changes at the regional level for Guatemala and Honduras. The trend across time was different in the two countries, and this overall difference was reflected in the parameter estimates for the two models. In Honduras, the overall trend was to forest regrowth and regeneration, whereas in Guatemala, net deforestation occurred. There was no difference across the study sites in the sign (positive or negative) of the effects of the independent variables on the estimated probability of non-forest, with the exception of elevation. The signs for elevation were opposite, such that across all observations, the probability of a change to non-forest increased (positive sign) with elevation in Guatemala, and decreased (negative sign) with elevation in Honduras. Elevation, which is constant across time, thus absorbs some of the time-dependent effect: the overall trend for deforestation in Guatemala and forest regrowth in Honduras.

The model revealed that there is more dynamism apparent in the pattern of deforestation in Guatemala than Honduras between the two time periods (1987-1991 and 1991-1996). It is exceedingly clear that deforestation in the latter period is occurring at significantly higher, more remote locations than in the first period. Overall, the results for the Honduras model were more accurate, but the model for Guatemala did a better job of explaining deforestation with spatial accuracy (i.e., forest going to non-forest in the last period).

Both the landscape metrics and the model point to the advanced stage of forest transformation in the Camotán region. The analyses also considered which social, economic and spatial variables were most strongly associated with forest persistence or transformation. As indicated by the high proportion of stable

agriculture and advancing deforestation, the conditions in Camotán appear to relate to more fully developed market linkages as compared to the Honduran study site. Camotán is readily accessible to several important regional markets in eastern Guatemala as well as western Honduras. While La Campa and Gracias are now located only a few hours from the largest regional market in western Honduras (Santa Rosa de Copán), this trip took 6-12 hours until 1994, when a road improvement and bridge-building project was completed. The La Campa study site may well experience a reversal of the forest regrowth noted for the 1987-1991-1996 period, as continuing road improvements, improving access to large market centres, and availability of credit through national programmes, encourage farmers to expand market production.

The factors that this study reveals as important have been implicated in driving land cover change in other regions of Central America as well. In a study of the Mayan Biosphere Reserve in Guatemala, Hayes et al. (2002) found that the highest rates of forest clearing occurred in closer proximity to roads and rivers. Schelhas (1991) found extensive deforestation and conversion to pasture in the lands adjacent to Braulio Carrillo National Park, Costa Rica. This was attributed to waves and cycles of colonisation that drive people to settle forested lands. While we find similar pressure on the land adjacent to Celaque National Park (Nagendra et al. 2004b; Southworth et al. 2004c), colonisation due to external migration is not significant in this region. In studies of land-cover change in and around protected areas in Costa Rica, Sánchez-Azofeifa et al. (2003) however conclude that although rates of deforestation in Costa Rica continue to be alarmingly high, the establishment of protected areas has dramatically curtailed the rate of deforestation and forest fragmentation inside reserves. Nevertheless, they also find that pressure on these parks appears to be increasing with rapid deforestation in the surrounding areas.

The comparative approach adopted in this study provides insights as to some of the ways in which contrasts in local and national contexts can result in differences in patterns of forest change. For example, community organisation and local institutions for forest protection are specific to each location, and differ between these two study areas. We are able to identify the separate impacts of these processes on land-cover change and fragmentation as a result of a) the integrated methods we use and b) our comparative approach across two study areas. The presence of community organisation in La Campa appears to have provided a context in which forest transformation was slowed or delayed, yet this process also reflected individual economic decisions to abandon marginal agricultural parcels, apparently in order to pursue agricultural intensification and coffee expansion (Southworth and Tucker 2001). Thus community organisation interacted with other economic and political factors to result in the observed patterns. Thus these sites vary in the patterns of resource use even when the people share similar resources and economic options. The recent collapse in coffee prices that began in the late 1990s is also likely to impact land cover and forests as poorer farmers choose among limited options. They may wait for prices to improve, abandon coffee fields, replace coffee with alternative crops, and (or) expand subsistence production into forest areas.

The techniques that we employ offer an approach to synthesising diverse sources of information to examine change processes, and consider the significance of major variables. Such regional analyses also serve as useful representations of the nexus between global and local processes. In these regional-level analyses, we were able to discern the effects of higher-ordered processes (such as coffee price changes) though they are not explicitly modelled, while at the same time capturing how these higher effects are distributed across space and mediated by the locally heterogeneous environment. Based on our study and others, the historical development and expansion of coffee markets appear to involve similar processes across the region. As in Costa Rica (Schelhas 1996; Thacher et al. 1997), we find the pressure for conversion to coffee to be a significant factor driving deforestation in our study sites. Corroborating other findings from Central American coffee regions (Daily et al. 2001), we find that coffee is grown initially as small clearings at higher elevations and on steeper slopes, which expand in area during subsequent years. While our study sites present different patterns of forest change, they also present different time depths of involvement in export coffee markets. This implies that the forest change patterns currently observed in Camotán may eventually emerge in La Campa, unless something occurs to alter the patterns. La Campa's more recent expansion of export coffee production (compared to Camotán) relates to historical differences in national policies promoting coffee and associated infrastructural development. Guatemala established incentives and continuing investments in infrastructure for coffee production starting in the late 1800s. Honduras did not create effective policies and incentives for export coffee production until the 1950s (Williams 1994).

The conditions and patterns of change noted for these landscapes indicate a range of variation in forest change and conservation. The variables that drive the metrics and the models reflect underlying biophysical conditions as well as human drivers. The models demonstrate that slope, elevation and distance from markets represent key variables for understanding the probability for forest transformation. The degree to which the models fail to accurately explain forest clearing implies that the roles of institutions and other social variables are important, and merit further research.

An important implication of this research is the extent to which land cover changes in each area are dominated by processes of agricultural intensification leading to marginal land abandonment (and thus forest regeneration), vs. greater export crop expansion (resulting in deforestation, particularly at higher altitudes). Our fine-scale spatial analyses indicate that both processes are occurring in Honduras and in Guatemala, but in Honduras the former appears to dominate, whereas in Guatemala, it is the latter. This analysis also illustrates the dilemma that policy makers face when attempting both to alleviate rural poverty and reduce pressure on natural resources such as forests. Technological change can reduce pressure on forests when associated with intensification, but depending on the contexts, it may also result in extensification of production (Angelsen and Kaimowitz 1999). Moreover, if technical change leads to the expansion of production for export, the

relatively wealthy are better positioned to expand landholdings and production than the rural poor. Such processes could also increase rural poverty. In Guatemala, it does appear that earlier expansion of export coffee production has resulted in continual deforestation processes and land concentration.

Our results indicate that spatial locations of greatest forest fragmentation are changing over time, indicating a change in underlying socioeconomic processes associated with land clearing. For instance, we find that much of the deforestation in the past has occurred along edges or fringes of the forest classes, predominantly near areas of stable forest. In recent years this pattern has changed, with clearings for mountain coffee now occurring within large, relatively isolated patches of stable forest. This change in the pattern of clearings indicates that it is essential to curtail the expansion of mountain coffee production into forest areas if we are to limit the impact of forest fragmentation on rare endemic mountain forest species. In cases where high biodiversity forests occur in highly accessible places that are susceptible to increased fragmentation, protection may be merited despite the costs. It is important nonetheless to recognise that it is not feasible for nations to protect all forests, especially given the generally high costs of enforcement.

This study implies that it may be nearly futile to establish protected areas where key spatial variables show great likelihood of rapid transformation. Many of Central America's forests are increasingly accessible for roads and markets, and thus face pressures that complicate effective conservation and imply high costs for protection. Throughout the region, deforestation continues at high rates (FAO 2001). The outcomes of conservation efforts have been mixed despite the creation of protected areas and implementation of forest policies intended to reduce deforestation. Thus far no policy approach has emerged as broadly effective to promote conservation across Central America's diverse ecological and social conditions.

If the goal for conservation is to find a pragmatic approach that actually protects resources, then attention to spatial patterns and change through time at the landscape level must be a component in the process. The dynamism found in our analyses suggests that conservation and forest management that aim for static conditions in forest cover may be unrealistic. Forest ecosystems and vegetation experience natural cycles, and our results suggest that human activities on the landscape also experience fluxes, which are likely related to socioeconomic processes (such as volatility in coffee prices). The opportunities for improved forest conservation may lie in understanding and taking advantage of these ecological and social cycles.

In addition, this research complements earlier findings that local institutions constitute an important influence on patterns of forest change (Tucker and Southworth 2005), and effective institutions are increasingly recognised as critical for forest management (Dietz et al. 2003; Gibson et al. 2005). Therefore, it may be ever more relevant to facilitate and support local institutions for forest protection. Provision of local incentives and recognition of the potential of individuals and



groups to protect forests represents an alternative to the creation and enforcement of protected areas at the national level. To some degree, the recent pattern of decentralisation of governance and natural resource management in Latin America is premised upon the assumption that local entities can successfully take on forest management and protection responsibilities (Larson 2003). Thus while protected areas can play a critical role in resource protection, they are inadequate as a sole option to effectively slow deforestation. It is particularly the case for tropical dry forests that innovative approaches to conservation are needed, for these areas are rarely protected, and are disappearing more rapidly than moist forests. Our research suggests that approaches to conserving biodiversity require recognition for local or regional contexts that shape outcomes, and efforts that fit these contexts.

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