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Agriculture, Ecosystems and Environment xxx (2007) xxx–xxx
Agriculture Ecosystems & Environment
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# *Milpa* imprint on the tropical dry forest landscape in Yucatan, Mexico: Remote sensing & field measurement of edge vegetation

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Received 5 November 2006; received in revised form 16 July 2007; accepted 17 July 2007

**Abstract**

The Yucatan Peninsula hosts part of Central America's largest remaining tract of tropical dry forest and has been identified as a region of critical landscape change. This study complements the extensive research on land cover conversion in the region by investigating a subtle but important aspect of forest modification. We examine changes in the spatial characteristics of *milpa* cultivation plots in the swidden landscape of Peto municipality in Yucatan state from 1988 to 2003 using remote sensing. We also test the hypothesis that *milpa* clearings create a discernible edge effect in terms of forest structure. Results indicate that spatial patterns of *milpas* have changed over time. The amount of *milpa*/forest linear interface increased over the study period. Both satellite-based vegetation indices and field-based canopy cover measurements indicated that forest buffering *milpa* clearings had significantly lower biomass than background forest, despite that the background forest is itself a mosaic of successional forest stages. In contrast, there was no difference in stand basal area for *milpa* edge forest and background forest. Multivariate models demonstrated that the *milpa* edge indicator was the most important variable in explaining differences of vegetation indices for *milpa* edges and background forest compared with other factors that create edges in the landscape. Models were relatively effective in explaining mean values of vegetation indices; but they performed poorly in terms of explaining measures of forest vegetation heterogeneity. Comparing model results from each date suggests that the importance of *milpa* edges decreases over time, possibly as a function of the accumulated land use history as *milpas* rotate through the forest matrix. Evidence supports the notion that the effects of *milpa* land use extend beyond the clearing itself and into adjacent forest.
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*Keywords:* *Milpa*; Tropical dry forest; Land cover modification; Edges effects; Multidate remote sensing with Landsat images; Land cover and land use feedbacks; MANCOVA; Swidden agriculture; *Ejidos*; Yucatan Peninsula

## 1. Introduction

Human land use shapes ecosystem structure and function at multiple scales of time and space (Turner et al., 1995). One of the most significant global challenges in the next century relates to management of the transformation of the earth's surface occurring through changes in land use and land cover (Mustard et al., 2004). Much land change science research for tropical regions focuses on deforestation using discrete land cover classifications to study wholesale conversion, like deforestation (DeFries et al., 2000). Land cover modifications, such as forest degradation without wholesale clearing, also merit attention. Such modifications may have drastic effects on ecosystem processes and services like species composition and richness (Ferguson et al., 2003), trophic pathways (Bunn et al., 1999), carbon sequestration (Lawrence and Foster, 2004), and land-surface energy balance (Southworth, 2004).

The tropical dry forest life zone supports much of the world's agriculture, having more productive soils than those of humid tropical forests (Murphy and Lugo, 1986). The dry forest life zone covers 42% of all land area in tropical latitudes. Despite this geographic predominance, fewer

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0167-8809/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.agee.2007.07.003

studies have been conducted on this forest type relative to moist and wet tropical forests (Ramankutty et al., 2006; Perez-Salicrup et al., 2004). The Yucatan peninsula of southeastern Mexico hosts part of the largest remaining expanse of seasonally-dry tropical forest in Mesoamerica and has been identified as a ''hot spot'' for tropical deforestation, in part related to government-sponsored agrarian settlement programs (Chowdhury and Turner, 2006).

Agriculture is the major driver of land cover change in tropical regions (Lambin et al., 2001). Swidden agriculture, in particular, comprises a major land use and an important resource-management system in many parts of the tropics (Coomes et al., 2000). An extensive ethnographic literature classifies and describes these cultivation systems throughout the world (Unruh, 1990; Banerjee, 1995; Teran and Rasmussen, 1995). *Milpa* is the traditional form of recurrent swidden in Mesoamerica. It is based on rotation of maize fields and fallows, during which secondary forests are established to replenish organic matter and nutrients. *Milpa* cultivation in the Yucatan Peninsula generally occurs in conjunction with communal ''*ejido*'' tenure. This coupled land-use and land-tenure system has sustained cultivation on poor soils by regulating the number and timing of *milpa* fields; the amount of *ejidal* forest land (through deliberate set-asides); and the effects of population growth on land resources through generally non-divisible inheritance rights (Plaza, 2000).

In 1992, however, an amendment to Article 27 of the Mexican constitution provided a multi-step process through which *ejido* members may elect to privatize their long inalienable *ejidal* land. This amendment occurred as part of a national agenda to create an institutional framework favoring private investment, the development of a land market and productivity gains in agriculture (Johnson, 2001). Many *ejidal* communities have rejected these attempts to promote privatization, sometimes fearing taxation of privatized parcels. Some communities have elected to privatize parcels on which houses were located but not agricultural land, and others have delineated family parcels within the community-owned *ejidos* (Chowdhury and Turner, 2006). Other efforts aimed at ''modernizing'' Mexican agriculture include extension programs like PROCAMPO, PRONASOL, and other economic incentives that promote sedentary, intensive cultivation (Chowdhury and Turner, 2006).

Of all forested land in Mexico, 85% occurs in *ejidos*, making the country unique among both developed and developing nations (White and Martin, 2002). In Yucatan state, most *ejidos* are dominated by *milpa* land use. At broad spatial scales in the Yucatan, the precipitation gradient is the most important variable driving vegetation patterns (Lawrence et al., 2004). At local scales, like within an individual *ejido*, however, the structure and function of Yucatecan forests—from litter production to biomass and soil properties—are more strongly influenced by forest age and history of cultivation than by environmental gradients (Turner et al., 2004). The process of clearing land for swidden cultivation and the subsequent regeneration of forest during fallow periods creates a landscape mosaic of active *milpas*, forest patches in various stages of succession, and edge forest at the linear border between the two. Structural differences between mature forests and forests regenerating after *milpa* use have been well documented by many researchers. Differences in aboveground live biomass, soil fertility, species richness (Lawrence et al., 2004) and species composition of flora and fauna (Vester et al., 2007) have all been documented between mature forest and regenerating forest in the Yucatan.

Many biophysical, structural and floristic changes occur as a result of *milpa*/forest adjacency and due to the use of fire in creating the *milpa* clearing (Eaton and Lawrence, 2006). These changes may reinforce, or be reinforced by, land use feedbacks. One such feedback is that after clearing vegetation to make a field, forest at the interface immediately experiences an increase in both photosynthetically active radiation (PAR) and wind penetration at the ground level; altered albedo; and changes in surface energy and water balances. Subsequent land use in the edge forest may include collection or harvesting of fuel wood and cultivation of fruit trees (Ochoa-Gaona, 2001). Both these biophysical and land-use effects reinforce longer-term changes in soil properties, floristic composition, and plant and animal dispersal (Fig. 1).

Remote sensing and geographic information science have become standard tools for addressing these complex human–environment interactions at the landscape-level. Remotely sensed vegetation indices have also proven useful for coarse-scale biodiversity assessment, complementing field-based surveys (Nagendra, 2001). With such great emphasis on deforestation in the land change science arena, only recently have researchers begun to address more subtle issues of re-growth/succession and other qualitative forest changes and feedbacks (Chowdhury et al., 2004; Moran, 2004; Rudel et al., 2005). Most such studies still rely on the use of discrete land-cover classifications; yet a more effective approach is to use the full suite of continuous data available from satellite imagery (Southworth et al., 2004). Normalized differenced vegetation index (NDVI) has long been used as a proxy for biomass (Jensen, 1996) and to study structural forest attributes like canopy architecture (Eamus, 2001). Similarly, thermal band data have been useful in discriminating successional stages of forest (Southworth, 2004) given that surface energy balance is linked to the character of land cover and thus past land use.

With continuous data, both land-cover conversions *and* within-class modifications are detectable. Not only can conversion from 'agriculture' to 'successional forest' be seen after field abandonment, but also within-class changes. The latter includes processes such as changes in forest density, forest degradation or the ability to identify a greater number of successional stages as a forest matures

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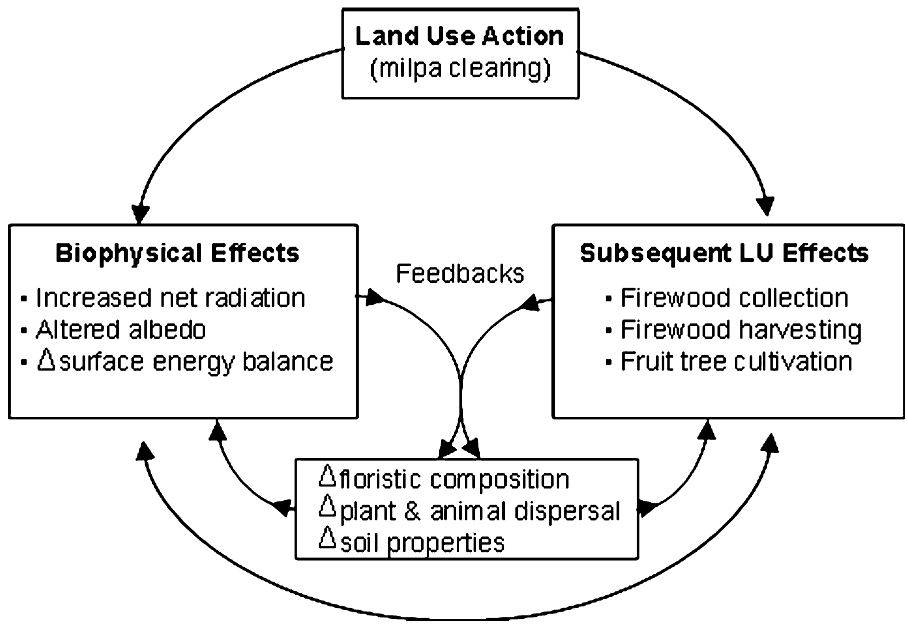


Fig. 1. Interactions and feedbacks between land use (*milpa* agriculture) and land cover properties.

(Southworth et al., 2004; Bonan et al., 2003; DeFries et al., 2000). Illumination of within-class changes greatly enhances the ability to foresee potential wholesale conversions before they occur, a key issue for biodiversity conservation and policy monitoring.

The critical link between forest cover and communal land tenure in the region underscores the importance of analyzing landscape patterns and forest attributes since the amendment of the constitution. A spatially explicit, landscape-level analysis may facilitate a better understanding of the effects of broader neo-liberal policy shifts by addressing the spatial pattern of recurrent clearings, or the landscape context that influences forest/clearing adjacency within the mosaic of successional forest stages comprising swidden-dominated land use systems. In this research we examine whether the spatial characteristics of *milpa* clearings have changed over time (1988–2003) using remote sensing. We refer to the patterns or characteristics of forest vegetation as structure. With both image and field-based data we test the hypothesis that *milpa* clearings create detectable edge effects compared to the background forest matrix (itself a mosaic of successional stages) in terms of several measurements of forest structure. With multivariate models, we also examine how this swidden-induced land cover juxtaposition compares with other factors that create linear edges and affect forest vegetation characteristics.

## 2. Methods

### 2.1. Study region

The study site lies in the interior, central portion of the Yucatan Peninsula of southeastern Mexico, within the state of Yucatan (Fig. 2). The landscape is composed of areas of mechanized, monoculture cultivation; large regions of forest within which swidden agriculture occurs (mostly in *ejidos*); and built areas of roads, communities, and other infrastructure. The region has a marked seasonality, with most precipitation occurring between May and October. A precipitation gradient exists across the peninsula, increasing toward the south. Because of the prominent karst topography of the region, the peninsula has virtually no surface hydrography. Most of the Yucatan Peninsula falls within the tropical dry forest life zone (Holdridge, 1971). This includes subdeciduous tropical forest, deciduous tropical forest and scrub areas.

Within this region, we selected the municipality of Peto (3296 km$^2$), in the southern, central region of Yucatan state, as a subset for further analysis (Fig. 2). Rural areas of the municipality are characterized by *milpa* agriculture within a forest matrix. *Milpa* farmers generally reside in communities and commute to their nearby *milpas* daily.

### 2.2. Field-based vegetation structure measurements

We conducted fieldwork in March of 2004 and 2005, late in the dry season. The point-quarter method, a variable plot size technique (Bell and Dilworth, 2002), was employed at randomly-selected *milpa* edge and forest transects to calculate stand basal area and estimate canopy cover ($n = 19$). Each 60 m transect consisted of three plots ($n = 57$), where we measured the diameter at breast height (dbh) of the nearest tree ($\geq$2.0 cm) to the center of the plot for four quadrants, along with each tree's distance from the plot center. We also estimated canopy cover at each plot. We conducted semi-structured interviews with *milpa* farmers in an opportunistic fashion during field work to gain a better

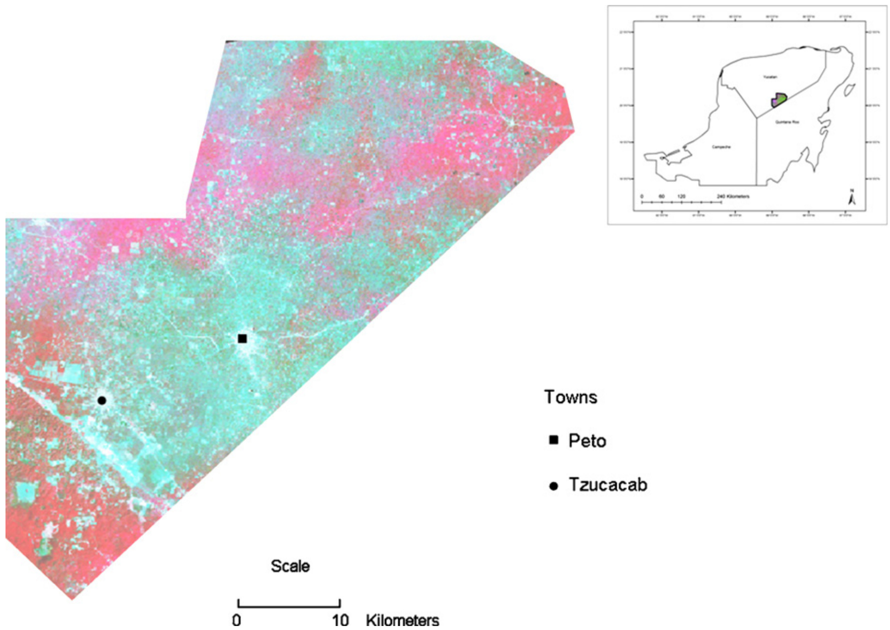


Fig. 2. Study area of the municipality of Peto within Yucatan State, illustrated with the May 7th 2007 Landsat 7 Image, Bands 4,3,2 (RGB), with larger study region in the southern, central region of Yucatan, Mexico given as inset map for location.

appreciation of the social dimensions of swidden cultivation and of land use history of key areas within the study site.

### 2.3. Image processing and GIS procedures

Three Landsat TM images covering the study area were obtained through the Working Forests in the Tropics (WFT) Program at the University of Florida (NSF-IGERT). All image processing was carried out using ERDAS Imagine 8.7. Dates selected were April 27th 1988, April 4th 1994, and May 7th 2003, with all imagery from the end of the dry season. The 1988 image represents the landscape prior to the ejido privatization amendment, whereas the 1994 and 2003 dates represent the landscape shortly after and roughly one decade after the amendment, respectively. The 2003 image was used as our base map after georeferencing it to regional topographic maps (1:50,000), obtaining a root mean squared error (RMSE) of less than half of a pixel ($<$15 m), which is considered quite accurate for such registration processes (Jensen, 1996). The remaining images were then geometrically registered to the base image through image-to-image registration (RMSE $<$ 15 m). Final positional accuracy of geocorrected images was validated in the field with the aid of a handheld GPS (positional error $<$ 5.5 m). Images were calibrated, to correct for sensor gain, atmospheric distortion, and differences due to non-anniversary image dates (Green et al., 2005). Band 6, thermal emission (low gain) was also calibrated and converted to black body temperatures (BBTemp) in Kelvin.

We subset all images to Peto municipality, masking out urban areas, industrial agriculture, and commercially developed roadside so that only forest cover and clearings remained. Unsupervised classifications were performed for all images to identify *milpa* clearings, pasture clearings (grass) and forest (Fig. 3b). Sixty-four training samples from fieldwork in March of 2004 were used for accuracy assessment (overall accuracy 88% and kappa 0.79). This is a fairly high degree of classification accuracy and compare favorable with those from other studies of land cover change in Central America (Sader, 1995). Two vegetation indices were calculated for each year for the area corresponding to the forest in the classifications. The first was the normalized difference vegetation index (NDVI),

$$\frac{\text{Band 4 (IR)} - \text{Band 3 (R)}}{\text{Band 4 (NIR)} + \text{Band 3 (R)}} \tag{1}$$

and the second was a thermal-band ratio,

$$\frac{\text{Band 6 (thermal)}}{\text{Band 5 (MIR)} + \text{Band 4 (red)}} \tag{2}$$

*Milpa* clearings that resulted from image classification did not yield sufficiently precise, linear edges for the purposes of this analysis. To surmount this challenge, texture analysis was employed as follows. Principal components analysis (PCA) was performed for each image date on all bands minus the thermal band.[1] PCA is often used to remove interband correlation in multispectral imagery as data in different wavelengths may often appear similar and convey identical information. This statistical technique will therefore capture variance in bands, and data is mapped along the two axes which explains the most variance, out to six possible principle components in this instance, with each

[1] Due to their coarser spatial resolution, thermal bands were less useful in identifying *milpas*. For Landsat 7, resolution on the thermal band is 60 m $\times$ 60 m, but on Landsat 5 it is 120 m $\times$ 120 m.

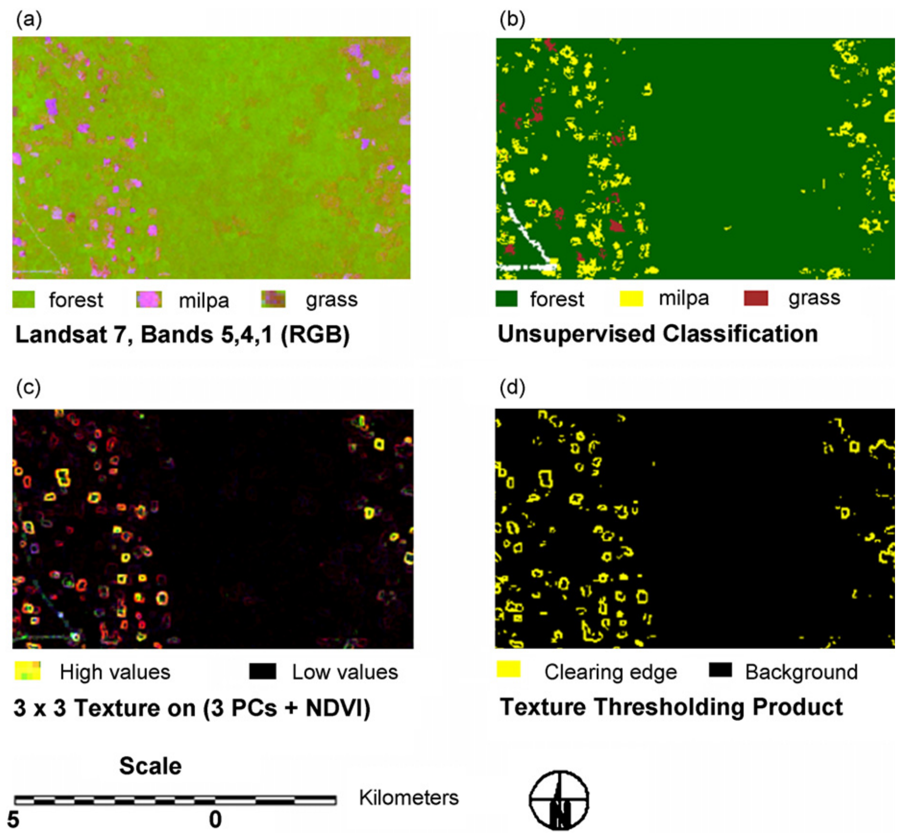


Fig. 3. Examples of the main intermediate remote sensing products from a small random subset area, used to isolate clearing edges from forest for the May 7th 2003 Landsat image. (a) The Landsat image in a color composite of RGB = 5,4,1 which best highlights the land covers of interest within the subset, with green = forest, yellow/lime = regenerating forest (classed as forest for the purpose of this study), magenta = *milpa*, purple = pasture/grass. (b) The results of the unsupervised classification clustered into the final three classes of interest: forest, *milpa* and pasture/grass. (c) The results of the 3 × 3 texture filter run on a layerstack of the first three PC's and an NDVI image to highlight areas of high and low texture in the image. (d) The results of (c) once thresholded to highlight only areas of high texture, i.e. edges as distinct from the background forest mosaic. Note that the areas of pasture/grass from (b) are then subtracted from (d) to produce the final edge areas for analysis, i.e., only *milpa*'s. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

explaining less and less of the variance in the data. Texture analysis was then performed on the first three resulting PCs (which explained greater than 85% of the image variance) for each image date using a 3 × 3 pixel window. Texture was calculated as

$$\frac{\sum \left[ \sum (x_{c\lambda} - x_{ij\lambda})^2 \right]^{1/2}}{(n-1)} \tag{3}$$

where $x_{ij\lambda}$ is the PC score for pixel $(i, j)$, $x_{c\lambda}$ is the PC score for center pixel of window (kernel), and $n$ is number of pixels in a window.

The texture images clearly and precisely delineated the edges of clearings in the forest (Fig. 3c). Thresholding of high texture values, compared with the relatively low texture values of the background forest, was used to create an image of raster cells corresponding only to the edges of clearings (Fig. 3d). These raster "edges" were vectorized to make polygons out of all clearings in the forest. These forest clearing polygons for each year were overlaid on their respective unsupervised classifications and subsets of the polygons were created responding only to *milpa* clearings (i.e. the final product excluded grass [which are pasture clearings] still evident in Fig. 3d).

From the *milpa* polygon vector files for each date, we filtered patches finer than the level of interest for this research (≤0.09 ha) and calculated *milpa* area, perimeter and average density for each image date. A spatially distributed random subset of 50% of the *milpa* polygons was selected for each year ($n_{milpa} = 527$, $n_{milpa} = 796$, and $n_{milpa} = 819$ for 1988, 1994 and 2003, respectively). This ensured sufficient sample size for multivariate analysis while reducing the problems associated with spatial autocorrelation. The latter inflates the risk of type I error in statistical analyses (Hoeting et al., 2006). Each *milpa* polygon was buffered, creating a zone corresponding to two pixels, equal to the length of the 60 m field transects. Overlapping buffer areas for closely-spaced *milpa*s were subtracted so that overlap was eliminated from the analysis. The mean and variance were calculated for the NDVI and thermal band ratio within the area corresponding to the

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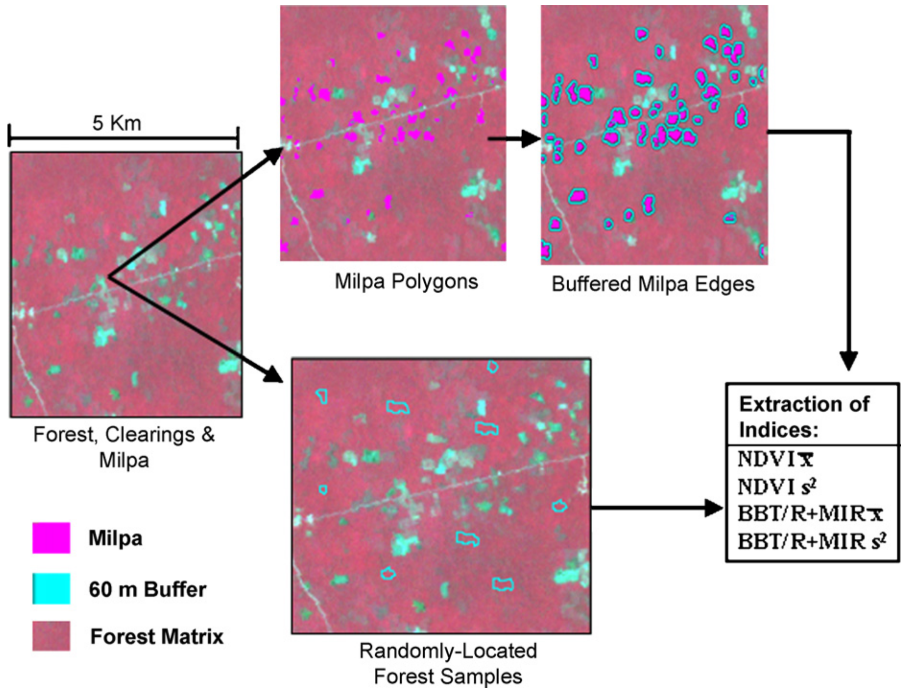


Fig. 4. Flowchart illustrating the protocol for extracting vegetation indices for forest region buffering *milpas* (top) and background forest (bottom) for a small random subset of the Peto study region (RGB = 4,3,2).

*milpa* buffer polygons. Only forest pixels were included in the vegetation index computations so that if a given *milpa* was located along a road or other land cover type, only the adjacent forest pixels for that *milpa* were included. Further, any effect from shadow that may affect the dependent variables was averaged out by using ratios in the vegetation indices (Jensen, 1996), along with the small forest stature would also minimize any shadowing. These vegetation index summary statistics for *milpa* buffers were extracted from the GIS and exported to a database (GIS overlay and extraction illustrated in Fig. 4).

To sample the remotely-sensed vegetation indices for the background forest matrix while controlling for the size and shape of the sample units (i.e. *n* uniquely-shaped *milpa* buffers), random points were generated within the background forest and the coordinates of those random points were assigned to *milpa* buffer polygons. This randomly repositioned the *milpa* buffer sample units over the background forest matrix (illustrated in Fig. 4). Buffer overlap was again subtracted to exclude any such overlap and indices were extracted as done for the *milpa* buffer regions ($n_{forest} = 519$, $n_{forest} = 776$, and $n_{forest} = 796$ for 1988, 1994, and 2003, respectively). Finally, distance from the sample centroid to the nearest road and the nearest forest clearing (be it *milpa* or pasture) was calculated for all samples.

### 2.4. Statistical analyses

To determine whether spatial landscape characteristics of the *milpa*/forest mosaic have changed over time, we compared combined *milpa* patch metrics (*milpa* area, *milpa* perimeter and the perimeter-to-area ratio) across three dates using MANOVA with follow-up ANOVAs for comparisons of individual metrics across the three dates. We tested for differences in means of stand basal area and canopy cover between *milpa*-edge sites and forest sites using Mann Whitney tests with Bonferoni corrections for multiple comparisons.

The means and variances of both vegetation indices were compared for *milpa* edges and the background/control forest for each image date using MANCOVAs. *Milpa*-edge indicator (*milpa* buffer zone or forest site) was the binary, independent variable of interest. Covariates in the model were distance to nearest road and distance to nearest forest clearing. The effect size for independent variables was assessed via partial eta-squared ($\eta_p^2$) values which indicate the percent of remaining variance explained by a given independent variable after accounting for the effects of other independent variables in the model (i.e., $SS_{effect}/[SS_{effect} + SS_{error}]$) (Norusis, 1990). Finally, ANCOVAs were used to test for a difference of means for individual vegetation indices (*milpa*-edge versus control forest sites) for each time step. ANOVAs were used when covariates were not significant for a particular index.

Appropriate descriptive statistics were calculated for all variables prior to each analysis, including checking for correlations among dependent variables, between dependents and factor levels (where applicable), and between covariates. Assumptions for each statistical test or model were tested appropriately. All analyses were performed on standardized variables using SPSS 11.5.

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Table 1
Mean *milpa* patch metrics across the three years of analysis: 1988, 1994 and 2003 to show changes in patch number ($N$), area, perimeter, and perimeter to area ratio ($P/A$) across the study period

| Patch metric | 1988 | 1994 | 2003 | Significance |
|---|---|---|---|---|
| Number ($N$) (total count) | 1054 | 1593 | 1639 | n/a |
| Area (ha) | 1.38 (±1.21) | 1.41 (±1.02) | 1.41 (±1.27) | All $p \geq 0.45$ |
| Perimeter (m) | 583.95 (±323.20) | 729.11 (±400.17) | 641.48 (±398.77) | All $p < 0.00$ |
| $P/A$ (m/m$^2$) | 0.057[a] (±0.02) | 0.058[a] (±0.01) | 0.061[b] (±0.02) | For [a]$p = 0.63$, for [b]$p < 0.00$ |

Where values in parenthesis shows the associated standard deviation.

## 3. Results

### 3.1. Milpa spatial characteristics

MANOVA revealed that significant differences of means for the combined *milpa* patch metrics exist across the three dates of the analysis (Wilks' λ: 0.836; $F_{(6,\ 8562)} = 133.51$; $p = 0.000$). The number of *milpa*s increased over time from 1054 in 1988 to 1639 in 2003 (Table 1). Comparing individual metrics in pair-wise fashion for the three dates showed no significant difference in mean *milpa* size ($p > 0.45$ for all cases), with the average *milpa* being slightly less than 1.5 ha in area. In contrast, *milpa* perimeter was different for each date ($p < 0.00$ for all cases), increasing from 583.95 m to 729.11 m from 1988 to 1994 but decreasing to 641.48 m by 2003. Mean perimeter to area ratio was the same for 1988 and 1994 at just less than 0.06 m/m$^2$ ($p = 0.633$), while the ratio was 0.061 m/m$^2$ in 2003 ($p < 0.000$). Though statistically significant, this difference is miniscule on the ground.

Table 2
Forest structure measurements for *milpa*-edge and control sites

| Vegetation attribute | Mean | Standard deviation (±) | Significance $p$ |
|---|---|---|---|
| Stand basal area | | | |
| *Milpa* edge | 25.66 | 28.25 | |
| Control | 30.67 | 16.09 | 0.137 |
| Canopy cover | | | |
| *Milpa* edge | 7.1 | 4.49 | |
| Control | 37.0 | 16.05 | 0.00 |

### 3.2. Milpa edge effects

Mann Whitney results (Table 2) comparing field measurements of vegetation structure for *milpa*-edge and control sites indicate only limited difference in stand basal area for the *milpa*-edge (25.66 m$^2$/ha) than the control (30.67 m$^2$/ha) ($p = 0.137$). Canopy cover is significantly greater on average for the control (37.0%) compared with the *milpa*-edge sites (7.1%) ($p < 0.00$).

The three separate MANCOVAs (Table 3) reveal significant effects of all covariates and the *milpa* indicator for each date (for all independent variables, $p = 0.000$) and that significant differences exist among combined vegetation for *milpa* and control sites for each date (for all models, Wilks' $\lambda < 0.67$; $p = 0.000$). The partial eta-squared ($\eta_p^2$) values indicate that, after accounting for the effects of the two covariates (distance to nearest road and distance to nearest clearing), the *milpa* indicator explains nearly half of the remaining variance in the combined vegetation indices in 1988 ($\eta_p^2 = 0.470$). For 1994 and 2003, the *milpa* indicator respectively explained roughly one-third ($\eta_p^2 = 0.300$) and one-fifth ($\eta_p^2 = 0.193$) of the variance remaining after accounting for the effects of proximity to the nearest road and nearest forest clearing.

Not all covariates were found to be significant for all vegetation indices across the three years of the study. ANCOVAs (or ANOVA where applicable), performed separately for each time step, revealed significant effects for the *milpa* indicator for all four vegetation indices, for all years ($p < 0.001$ for all cases) (Table 4). For 1988, 1994 and 2003, means for both NDVI and thermal band ratio indices

Table 3
MANCOVA results for all three dates indicating the effects of all covariates and the *milpa* indicator on the combined vegetation indices

| Year | Variable | Wilks' λ | $\eta_p^2$ | (d.f.$_1$, d.f.$_2$) | $F$ | $p$ |
|---|---|---|---|---|---|---|
| 1988 | Distance to nearest road | 0.924 | 0.077 | (4, 1039) | 21.4 | 0.000 |
| | Distance to nearest clearing | 0.916 | 0.084 | (4, 1039) | 23.7 | 0.000 |
| | *milpa* indicator | 0.297 | 0.470 | (4, 1039) | 615.3 | 0.000 |
| 1994 | Distance to nearest road | 0.949 | 0.069 | (4, 1565) | 20.90 | 0.000 |
| | Distance to nearest clearing | 0.964 | 0.077 | (4, 1565) | 14.55 | 0.000 |
| | *milpa* indicator | 0.663 | 0.300 | (4, 1565) | 199.06 | 0.000 |
| 2003 | Distance to nearest road | 0.927 | 0.042 | (4, 1608) | 31.87 | 0.000 |
| | Distance to nearest clearing | 0.914 | 0.030 | (4, 1608) | 37.84 | 0.000 |
| | *milpa* indicator | 0.513 | 0.193 | (4, 1608) | 380.95 | 0.000 |

The partial eta-squared values ($\eta_p^2$) of each covariate and the *milpa* indicator, along with their significance are given. $\eta_p^2 = SS_{effect}/[SS_{effect} + SS_{error}]$ (Norusis, 1990). d.f. = degrees of freedom. $F$ and $p$ relate to the statistical significance.

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Table 4
ANCOVA/ANOVA results for each time-step with Bonferroni-adjusted significance for each individual vegetation index

| Year | Vegetation index | *Milpa* edge | Control | d.f. | $F$ | $p$* | Adjusted $R^2$ |
|---|---|---|---|---|---|---|---|
| 1988 | NDVI x | 0.535 (±0.591) | 2.124 (±0.446) | 1 | 1569.91 | 0.000 | 0.711 |
| | BBT/R + MIR x | 0.983 (±0.329) | 2.109 (±0.485) | 1 | 1183.32 | 0.000 | 0.697 |
| | NDVI $s^2$ | 0.424 (±0.882) | −0.512 (±0.351) | 1 | 337.36 | 0.000 | 0.343 |
| | BBT/R + MIR $s^2$ | 1.204 (±1.386) | 0.052 (±1.211) | 1 | 156.10 | 0.000 | 0.167 |
| 1994 | NDVI x | −0.250 (±0.394) | 0.409 (±0.338) | 1 | 769.28 | 0.000 | 0.482 |
| | BBT/R + MIR x | −1.099 (±0.069) | −0.920 (±0.284) | 1 | 111.47 | 0.000 | 0.217 |
| | NDVI $s^2$ | −0.270 (±0.451) | −0.534 (±0.188) | 1 | 149.33 | 0.000 | 0.130 |
| | BBT/R + MIR $s^2$ | −0.391 (±0.849) | 0.318 (±1.130) | 1 | 86.22 | 0.000 | 0.139 |
| 2003 | NDVI x | −0.913 (±0.751) | 0.312 (±0.480) | 1 | 853.05 | 0.000 | 0.530 |
| | BBT/R + MIR x | 0.053 (0.192) | 0.469 (0.180) | 1 | 1127.58 | 0.000 | 0.632 |
| | NDVI $s^2$ | 0.635 (1.425) | −0.408 (0.563) | 1 | 207.81 | 0.000 | 0.200 |
| | BBT/R + MIR $s^2$ | −0.123 (0.346) | −0.502 (0.269) | 1 | 340.27 | 0.000 | 0.289 |

NDVI x = mean normalized difference vegetation index, on Landsat NDVI = (Band 4 − Band 3)/(Band 4 + Band 3). BBT/R + MIR x = mean thermal band ratio vegetation index, on Landsat = Band 6/(Band 5 + Band 4). NDVI $s^2$ = standard error of the NDVI. BBT/R + MIR $s^2$ = standard error of the thermal band ratio. d.f. = degrees of freedom. $F$ = $F$ statistic. $p$* Bonferroni adjustments for multiple comparisons made to significance interpretations ($p$ must be <0.006 for significance).

were greater for control sites relative to forest at *milpa* edges ($p = 0.000$). The magnitude of the difference between *milpa* edge and control sites decreases over time, however (Table 4). In terms of the indices' variance for all years, *milpa* edge sites proved to be more heterogeneous than control sites ($p = 0.000$) with one exception. The exception is the thermal band ratio index variance for 1994 where the control site was significantly more heterogeneous than the *milpa* edge site ($p = 0.000$).

Across all years of the study, mean values of both NDVI and thermal band ratio indices are better predicted than the variance of the indices as evidenced by consistently higher $R^2$ values (Table 4). Except for the thermal band ratio index mean for 1994, the simple models with only three predictor variables explained nearly or over half of the variance in mean vegetation index values. In contrast, vegetation heterogeneity for both indices across all years was poorly explained with the highest adjusted $R^2$ value at 0.343 for 1988 (NDVI).

## 4. Discussion

Swidden agriculture, or regions characterized by this land use, have primarily been examined in terms of the way that cultivation decreases the *amount* of forest cover (Myers, 1993; Lawrence et al., 1998; Vance and Geoghegan, 2004). Of the research that has focused on the full, episodic swidden-fallow cycle (e.g., Walker, 1999), none has examined edge effects of the agricultural clearings. Rather, focus has been on the space corresponding to the confines of cleared patches themselves. Ecological edge research has rested predominantly in the domain of conservation literature, generally examined as a result of longer-term, relatively "permanent" fragmentation processes (Bierregaard et al., 1992), not as part of an episodic land use pattern (but see Ochoa-Gaona, 2001). Forest age, cultivation history and management (land use, owner preferences) are the major drivers of the rates and dynamics of ecosystem functioning (Eaton and Lawrence, 2006). Here, we have complemented the growing literature on land cover modification with a subtle but important aspect of swidden land use effects and feedbacks. Results supported the hypothesis that *milpa* clearings create discernible ecological edge effects.

### 4.1. Milpa edge effects

The *milpa* indicator variable is consistently the most important variable in explaining variance of the combined vegetation indices across all dates (Table 3). Coupled with the finding that forest in the *milpa* buffers was both consistently lower in biomass and more heterogeneous (as indicated by NDVI and thermal ratio indices), this confirms that at this scale of observation, *milpa* land use creates a discernible edge effect in the forest. Forest areas buffering *milpas* should favor edge species, managed species and habitat generalists at the expense of mature forest species and understory plant communities. Relative to other factors that create linear land cover juxtapositions (i.e. roads and the next-nearest clearing), local *milpa* edges clearly have the dominant impact on local vegetation structure, according to the relative partial eta-squared values (Table 3). That is, if the more distant edges created by the covariates (other clearings in the forest or roads) affected broader spatial patterns of forest structure, the effect sizes for these variables would have been greater. This result conforms with other findings of scale-dependency in edge effects related to the ecological process in question (Baldi and Kisbenedek, 1999; Huhta et al., 1998). Nonetheless, when these local effects of *milpa* edges on forest structure are multiplied across the Yucatan landscape for thousands of *milpas*, this local land use/cover juxtaposition is clearly important in structuring broader regional vegetation characteristics. The spatiallyradiating effects of *milpa* clearings should be considered in examining forest regeneration in swidden cycles, as opposed to focusing only on clearings themselves.

### 4.2. Forest regeneration

Examining the vegetation indices separately across *milpa* and forest sites, however, there is an appreciable discrepancy in the efficacy of the *milpa* indicator and covariates to predict mean vegetation heterogeneity relative to mean biomass, as indicated by the adjusted $R^2$ values (Table 4). Clearly, there are substantial drivers of spatial patterns of vegetation heterogeneity that were not considered here given the relatively low $R^2$ values (other than biophysical gradients which average out by virtue of the sampling scheme). Since all organisms and ecosystem processes respond to environmental variability, and *not* to the arbitrary concept of mean values, exploring which factors do effectively explain vegetation heterogeneity represents an important area for future research.

Lawrence and Foster (2004) found that after 25 years of forest regeneration in this region, woody basal area had recovered to 63% of total mature forest levels and that recovery of total live biomass took even longer. Comparing our stand basal area results with those of Read and Lawrence (2003) suggests that, on average, the successional forest matrix of *ejidal* land in Peto is at least 10 years of age. Other research has shown that *milpa* sites which have been cultivated multiple times, rather than just once, regenerate live biomass even more slowly (Lawrence et al., 2004). Given the fact that Peto is drier and has a longer cultivation history than the southern region of the Yucatan Peninsula, where the Read and Lawrence (2003) and Lawrence et al. (2004) studies were conducted, the forest may be on average even greater than 10 years in age. Since we found no significant difference between stand basal area for *milpa* edge forest and control forest, this suggests either that none of the *ejidal* background (''control'') forest was sufficiently mature to differ from *milpa* edge forest; or that in terms of this particular measure of vegetation structure, edges have no consequence on woody biomass in a matrix of secondary, successional forest. In contrast, vegetation biomass was greater for background forest than for forest at *milpa* edges as indicated by both canopy cover and the two remotely-sensed indices. The latter are particularly suited to indicate the photosynthetic capacity of vegetation. Thus, taking all three forms of forest structure measurement together, results may indicate that edge effects have greater impact in terms of green, leafy biomass than woody biomass. Leaf litter contributes to the accumulation of organic matter in the soil, as well as nitrogen concentrations (Lawrence and Foster, 2002). Thus, perhaps after some lag in time, even within a matrix of successional forest as in this landscape, edges may feedback to influence woody basal area through changes in nutrient cycling.

### 4.3. Milpas and land use change

The total number of *milpas* has increased within Peto municipality over the three dates supporting the notion that efforts to ''modernize'' the swidden landscape may potentially weaken the communal land tenure institution (Klepeis and Vance, 2003), which has traditionally limited the number of fields cultivated through non-divisible inheritance rights to *ejidal* land. While none of the farmers interviewed had privatized their land, several alluded to an existing informal land market and expressed interest in eventually pursuing the multi-step privatization process if their *ejido* elects; further south on the peninsula, Abizaid and Coomes (2004) found evidence of changes in land use made in anticipation of privatization. Increasing numbers of land users and/or decreased fallow times appear to ''unintentionally'' accompany efforts to liberalize the region's agriculture (Klepeis and Vance, 2003). Government and NGO programs such as PROCAMPO and others, have been shown to encourage the adoption of other land-use practices, beyond the traditional maize *milpas* (Chowdhury and Turner, 2006). This trend suggests a loss of agronomic services that may constrain future agricultural productivity without substantial chemical inputs, given that key aspects of forest productivity decrease significantly after multiple clearing cycles (Lawrence and Foster, 2004).

Compared with reported values in the literature for mean *milpa* area (Klepeis, 2004; Vogeler, 1976; Vogeler, 1970), field size in Peto is smaller than average (roughly 1.5 ha in Peto compared with 4 ha), for example, compared with those further south on the peninsula where, agro-forestry *ejidos* created in the 1960s were quite large by comparison. This smaller size and the static mean *milpa* area across dates for our Peto study region also may reflect both biophysical and social constraints to the expansion of average field size. Firstly, the ''cockpit karst'' topography, particularly in the southwest region of the study area (Puuc, Hills), affects site selection for agriculture, as it has in this landscape for millennia (Killion et al., 1989). Field size is necessarily limited by the area of ''*planos*'' or flat land suitable for cultivation. Secondly, farmers indicated that they generally work their fields alone, such that labor may constrain the possible extent of *milpas*, a condition confounded by out-migration of youth toward the peninsula's urban areas and coastal fringes (Lutz et al., 2000).

Results from the analysis of *milpa* patch metrics suggest subtle but important changes in the spatial characteristics of the *milpa*/forest landscape mosaic over the course of the study. The static mean of the ratio of perimeter to area (i.e. $[\Sigma_P^{milpa}/\Sigma_A^{milpa}]/n$, a simple, patch-based measure of shape complexity) across the three dates contrasts with the landscape-level trend where the average amount of edge forest created per average field size (i.e., $[\Sigma_P^{milpa}]/n : [\Sigma_A^{milpa}]/n)$ has increased. Since mean field size is constant across dates, this indicates an increased variability of *milpa* perimeter. This underscores the importance of considering both patch-level and landscape-level means when analyzing spatial land-use patterns. Lawrence et al. (2004) observed a similar result in a study of land use change in the Southern Yucatan, in which ''forest edge density,'' a proportion of all pixels in the study area determined to be at the edge of forests and other land uses, increased from 1.5% in 1987 to 3.14% in 2000. These authors interpreted the result as an indication of land use intensification. Further research is needed to determine if this trend mirrors natural variability driven by biophysical contours (e.g. topography) in the landscape or whether it represents an increase in forest-edge juxtaposition driven by policy-related land-use choices and land-use path dependency, or another trend such as increased *milpa* activity along linear features like roads.

Lawrence and Foster (2004) found past land use to be the most important factor determining forest processes and characteristics, which may provide a reason why the importance of *milpa* edges in explaining vegetation structure has decreased over time (Table 3; decrease in $\eta_p^2$ across dates). That is, edge effects from *milpa* clearings may be more significant when land use intensity is relatively low at the landscape level when edges are created in a matrix of mature forest such that the contrast between edges and the forest matrix is great. Over time, as *milpas* rotate through the landscape and the matrix is transformed to a mosaic of successional forest stages, ecological edges may not be as important in driving patterns of vegetation structure relative to past *milpa*-fallow cycles that occurred in a particular location (Eaton and Lawrence, 2006). Future research which maps *milpa* land use cycles as they occur (in contrast to this retrospective remote-sensing approach) may help discern the dynamic relative influence of *milpa* edges in determining forest vegetation characteristics.

## 5. Conclusions

In this region, past land use is a critical determinant of the rate and nature of forest regeneration, yet to date, most research has examined only forest clearings themselves. With this study, we have complemented existing research with a subtle but important aspect of *milpa* land use effects and feedbacks by examining the impact of *milpa* clearings on the structure of surrounding forest. Results supported our hypothesis that the ''footprint'' of *milpa* land use is broader in geographic extent than the patch of cleared land itself with associated constraints in agricultural productivity potentially transferring to the forest region bordering each *milpa* site. The *milpa* edge indicator variable was the most important factor in explaining variance in the examined measures of forest structure, though its influence decreased over time and appears to also be spatially scale-dependent. While mean values of various measures of forest structure were well explained by the models, factors important for explaining vegetation heterogeneity were clearly omitted and likely include past land use. We found that the amount of edges between the forest matrix and *milpas* has increased over time. Thus, understanding the role of ecological edges within a swidden landscape will contribute to sensible policy formulation and management within the matrix of remaining successional forest.

## Acknowledgements

This research was funded through the Working Forest in the Tropics program at the University of Florida (National Science Foundation-DGE-0221599). We thank our colleagues Roger Medina-Gonzalez and Ivan Dominguez-Tec from the Autonomous University of Yucatan (UADY) for their assistance in the field. We are grateful to the Peto residents who shared their knowledge with us about milpa agriculture and land use history.

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Please cite this article in press as: Daniels, A.E., et al., *Milpa* imprint on the tropical dry forest landscape in Yucatan, Mexico: Remote sensing & field measurement of edge vegetation, Agric. Ecosyst. Environ. (2007), doi:10.1016/j.agee.2007.07.003

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