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Land-use decision-making after large-scale forest fires: Analyzing fires as a driver of deforestation in Laguna del Tigre National Park, Guatemala

Claudia Monzón-Alvarado [a,b,*], Sergio Cortina-Villar [b], Birgit Schmook [b], Alejandro Flamenco-Sandoval [c], Zachary Christman [d], Luis Arriola [b]

[a] Department of Geography, University of Florida, USA
[b] El Colegio de la Frontera Sur, Mexico
[c] División de Ingenierías, Universidad de Guanajuato, Mexico
[d] Middlebury College, United States

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ABSTRACT

Tropical forests are increasingly subject to large-scale forest fires, which have become one of the greatest anthropogenic disturbances of these ecosystems. This study examines the relationship between forest fires and deforestation through an analysis of the impact of fires upon land-use decision-making at the household level and the impacts and patterns of these processes at the landscape level. Patterns of forest fires and deforestation in Laguna del Tigre National Park, in Guatemala's Maya Biosphere Reserve, were analyzed from 1997 to 2005, using remote sensing and logistic regression analysis. During this period, two major fires affected the region—one in 1998 and the other in 2003. Complementarily, in-depth interviews and field observations were conducted in one community to evaluate land-use decisions following a fire disturbance. Results indicate that only 9% of the burned forest was cleared for other land uses after the 1998 fire, but more than half of the burned forest was converted to agriculture following the 2003 fire. Our research reveals that a complex and variable process of land-use decisions takes place locally and is influenced not only by the presence of forest fires but more so by other variables like accessibility, topography, soils depth and presence of valuable timber and non-timber species. These findings also indicate the importance of adopting a multi-scale approach and the integration of remote sensing and social surveys to improve the understanding of landscape changes following disturbances.

Introduction

Large-scale forest fires have increasingly affected evergreen tropical broadleaf forests. Drivers are often related to a combination of multiple direct and underlying factors (Suyanto, 2007), associated with land management practices that use fire for land clearing or weed control, as well as the use of fire as arson in land conflicts (Dennis et al., 2005; Uhl & Bushbacher, 1985). Fire in evergreen tropical broadleaf forests used to be limited in extent, burning agricultural plots and fallow fields, while stopping before entering moister, closed forest (Johnson & Dearden, 2009). However, currently, large areas of this type of vegetation are burned especially after extreme events such as hurricanes (López-Portillo, Keyes, Gonzalez, Cabrera, & Sánchez, 1990) or in drier years (Roman-Cuesta, Gracia, & Retana, 2003). Escaped fires resulting from fire use in agriculture often leads to more fragmented and degraded forests (Nepstad et al., 1999). Moreover, previous burned areas are more likely to burn again due to positive feedbacks in future fire susceptibility, fuel loading, and fire intensity (Cochrane et al., 1999; Tacconi, Moore, & Kaimowitz, 2007). The changes in fire regime (frequency, intensity and severity) have implications for forest structure, floral species composition, and the economic value of forests (Cochrane & Schulze, 1999; Gould et al., 2002).

The modification of fire regimes has led scholars to examine the relationship of fire to climate variability (Flannigan, Stocks, & Wotton, 2000), ecosystem resilience (Pausas, 1999) and the impact of wildfires on land-use conversion (Cochrane, 2000). Previous efforts to examine the relationship between forest fires and deforestation in tropical forests were largely conducted in West Africa, using NOAA AVHRR satellite imagery at a spatial resolution of 1 km/pixel (Bucini & Lambin, 2002; Ehrlich, Lambin, & Malingreau, 1997; Eva & Lambin, 2000). Although these studies found an association between fires and land-use change for a few

* Corresponding author. Department of Geography, University of Florida, 3141 Turlington Hall, Gainesville, FL 32611, USA.
E-mail address: cmonzon@ufl.edu (C. Monzón-Alvarado).

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sub-regions, most concluded that the scale of analysis was inadequate for examining the diversity of purposes surrounding the use of fire and their impacts in heterogeneous landscapes (Ehrlich, Lambin, & Malingreau, 1997). Eva and Lambin (2000) further concluded that there is a need to consider the socioeconomic functions of biomass burning and the context in which such activities are undertaken.

The understanding of the relationship between forest fires and deforestation can be further bolstered by integrating a deep analysis of land management practices (Sorrensen, 2004). This matter falls within the realm of the "Human Dimensions of Environmental Change" in which human behavior is linked to environmental outcomes by linking satellite data to surveys (Wood & Skole, 1998). This approach has also been referred to as "socializing the pixel" (Geoghegan et al., 1998) or generating an "ethnography of the landscape" (Nyerges & Green, 2000). Moreover, VanWey, Mereteski and Ostrom (2005) highlighted the importance of considering a multi-scale approach to study the relationship between social and biophysical variables to better understand the human dimensions of environmental change. In this paper we examine the relationship of forest fires and deforestation between 1997 and 2005 in Laguna del Tigre National Park, Guatemala. Beyond analyzing the impact of fires upon patterns of deforestation using remote sensing, GIS and logistic regressions, we incorporate interviews at the household level to examine the preferences regarding forest clearing following major fire disturbance events.

Study area

Laguna del Tigre National Park is located within the Maya Biosphere reserve (MBR), in Petén, Guatemala (Fig. 1). The Biosphere covers 21,129.4 km^2 and is managed by the National Council for Protected Areas (CONAP). Laguna del Tigre National Park is one of the core zones of the Biosphere and, with 3350.8 km^2, is the largest protected wetland in Mesoamerica. The park provides habitat for endemic and endangered species and has approximately 66 Mayan archaeological sites (CONAP, 2006a, 135 p.). A karst landscape, dominated by thin and fragile limestone soils, characterizes the park in the southern limits of the Yucatán Platform. The terrain is mainly flat, with subtle undulations in the southeast and elevations ranging up to 300 m above sea level (CONAP, 2006a, 135 p.). Variation in soil drainage leads to two types of vegetation with high-medium forest (*selva alta-mediana*) (51%) situated in well drained soils, and seasonally flooded forest (19%) located in inundated soils, locally known as *bajos*. Other vegetation types include wetlands (16%) and seasonally flooded savannas (5%); the remaining 9% are lands used for agriculture and pasture (CONAP, 2006a, 135 p.).

Laguna del Tigre faces major intertwined challenges, such as population growth, high rates of deforestation and an increasing number of wildfires. According to CONAP (2006b, 123 p.), in 1989, before the creation of the park, there were no human settlements within its boundaries and only two communities in its surroundings. One decade later, a total of 14 communities had been

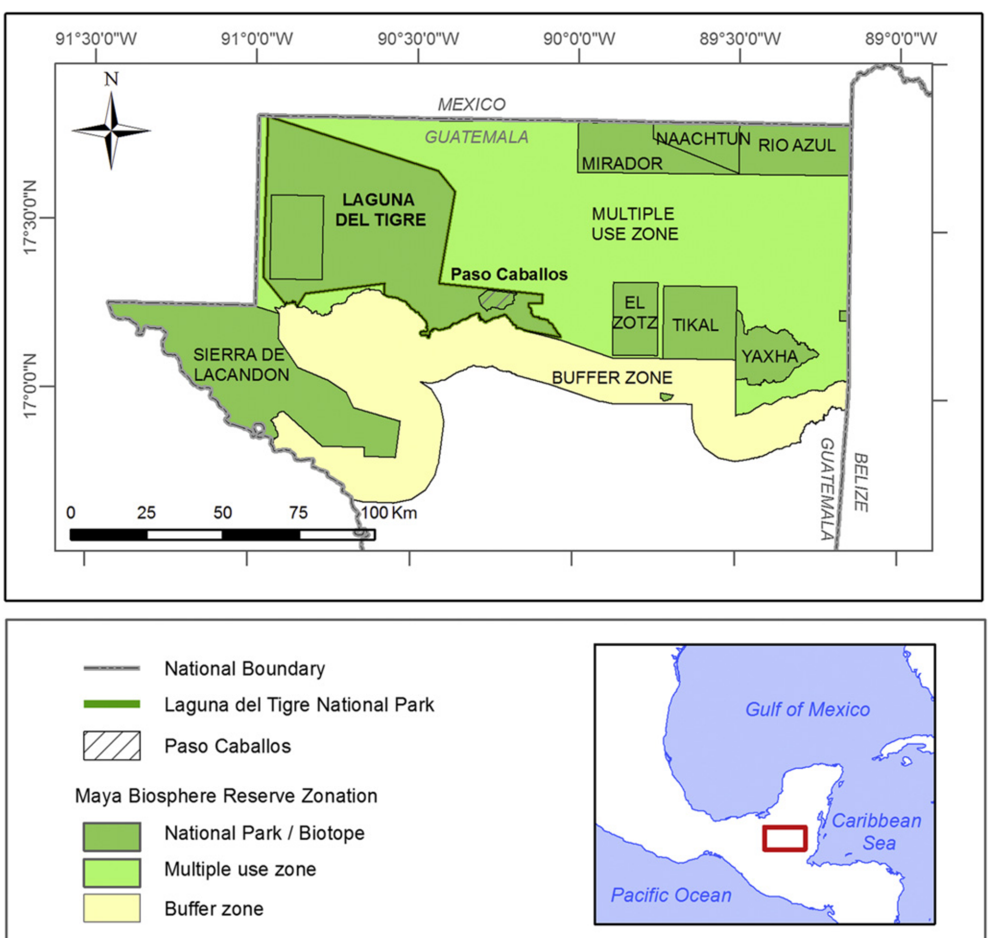

Fig. 1. Study area, including Laguna del Tigre National Park and focus community of Paso Caballos, located in the north of Petén, Guatemala.

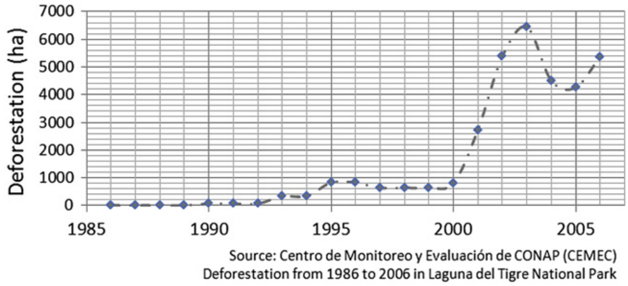

Fig. 2. Deforestation in Laguna del Tigre National Park from 1986 to 2006.

established within and near the park. From 2000 to 2003, the number of settlements almost doubled, with approximately 10,600 people living in the 22 communities inside the park and 11 close to it (CONAP, 2006b, 123 p.). From these 33 communities only 7 communities ever attained legal status in 1997 (CONAP, 2006b, 123 p.). This study focused on one of these communities, Paso Caballos, located in the southeastern flank of the park. According to local authorities, in 2006, 160 families inhabited Paso Caballos, all of them Maya-Q'eqchi' immigrants from other areas of Petén and central Guatemala. In 1997 Paso Caballos attained legal status through a collaboration agreement with the government, colloquially referred in Spanish as *acuerdos de intención*. Through these agreements between communities and CONAP, the government acknowledged the communities' rights of existence. In exchange, communities accepted a series of land-use regulations, including the prohibition to sell, transfer or lease the land, to keep demarcated boundaries, and to maintain at least 20% forest coverage within each individual plot (ProPeten, 2004, 43 p.). Despite mutually binding collaboration agreements, the relationship between government authorities and people living in the park has been characterized by a lack of trust and sometimes violent confrontations (Clark, 2000), especially for communities that face eviction from the park (CONAP, 2006a, 135 p.). To this day, living conditions in most communities within the park are poor, with no water services, no paved roads, and a lack of well-equipped health clinics and schools (CONAP, 2006b, 123 p.).

Population growth resulting from high rates of migration has accompanied a pattern of land-use change. Until 1995, rates of deforestation in the park were less than 1000 ha/year (<0.25%/year), but after 1995, rates of deforestation increased considerably, peaking in 2004, with 5537 ha (1.92%/year) of forest cleared (CONAP, 2006a, 135 p.) (Fig. 2). Around 75% of households within the park cultivate *milpa*, the traditional maize–beans–squash subsistence agriculture, 20% of households have cattle farms, and the rest are laborers or other professions (CONAP, 2006b, 123 p.). Both farmers and ranchers use fire as a tool for land preparation. Additionally, people use fire in daily activities like food preparation, burning of household debris, spiritual ceremonies as well as for subsistence hunting or extraction of other non-timber forest products. Although agricultural burning and livestock are done traditionally, people occasionally lose control of the fire affecting the nearby forests, and in dry years fires can spread several kilometers. During 1998 and 2003, the most recent detrimental fire seasons, around 280,000 ha and 217,000 ha of forest were burned in the Maya Biosphere Reserve respectively (Fig. 3, Table 1). Fires devastated more than 30% of the forest cover at Laguna del Tigre and Sierra de Lacandón National Parks (the latter makes up the western portion of the reserve) while conservation units in the east of the MBR had less than 2% of their forest burned. The occurrence of forest fires has become a latent source of conflict between communities and conservation agencies, which blame "slash-and-burn agriculture" for forest fires. Authorities also argue that fires create conditions that lead to the colonization of fire-affected areas (CONAP, 2001, 82 p.).

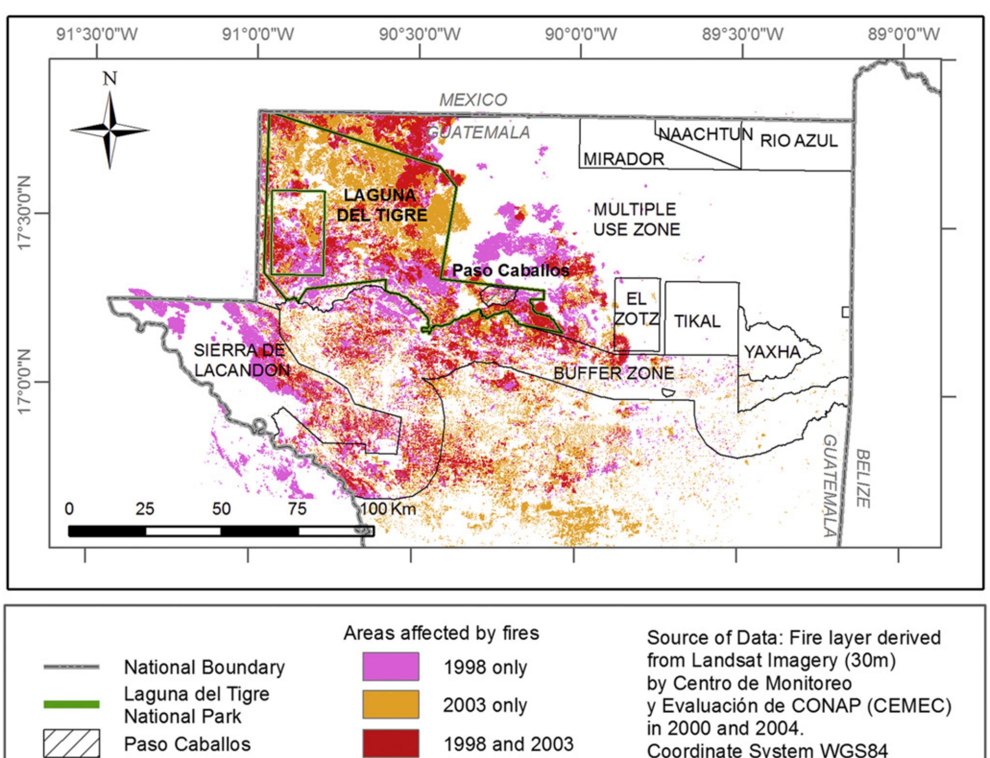

Fig. 3. Distribution of 1998 and 2003 fires in Maya Biosphere Reserve.

Table 1
Extent of 1998 and 2003 forest fires in Maya Biosphere Reserve.

	Multiple use zone	Buffer zone	Laguna del Tigre	Sierra de Lacandón	Other parks	Total
Total area	848,400	467,500	335,080	202,865	238,219	2,112,940
Fires in 1998						
Forest cover in 1997	675,247	183,364	180,125	155,766	37,783	1,216,445
Burned forest in 1998	80,239	76,039	65,908	58,179	715	280,227
Forest burned in 1998/total forest	12%	41%	37%	37%	2%	23%
Fires in 2003 (and cumulative effects)						
Forest cover in 2003	670,229	157,757	171,329	151,224	37,574	1,171,934
Burned forest in 2003	48,988	62,115	83,321	21,437	854	217,491
Burned both in 1998 and 2003	31,534	39,434	32,292	15,973	644	119,875
Burned only in 2003	17,454	22,681	51,029	5464	209	97,616
Forest burned in 2003/total forest	7%	39%	49%	14%	2%	19%

Source: From 1998 and 2003 fire layers overlaid with deforestation maps produced by Centro de Monitoreo y Evaluación de CONAP (CEMEC) 2000 and 2004.

Colonization processes, high rates of deforestation as well as forest fires have led to what Clark (2000) refers to as a “crisis of legitimacy”, in which the Government is not able to manage the boundaries of the state owned parks or enforce existing laws. In 2004 the Government issued an “Emergency Decree for the Protection of Laguna del Tigre”, an initiative that provided additional human and financial resources to reduce deforestation rates and increase governance in the area (CONAP, 2006a, 135 p.). Additionally, Park authorities proposed a land zoning plan for the park, with three management units: the “restricted area”, which includes the less disturbed areas where human settlements, land-use change and extractive activities are banned; the “recovery area” i.e., a designated restoration area; and the “special use area”, encompassing most of the human settlements within the park (CONAP, 2006a, 135 p.). Implementation of these efforts has been challenged by budget fluctuations and change of priorities within the central government. Weak institutions have exacerbated structural problems related to northern Petén’s agrarian history, rural poverty and conflictive governance (Monterroso, 2006). Moreover, and as Gould, Carter, and Shrestha (2006) point out, land policies seeking to improve property rights in the region have actually lead to a rise in land prices which has in turn incentivized colonists to speculate and sell the land rather than invest in it. These elements illustrate the convoluted dynamics around the land that takes place across the Maya Biosphere Reserve.

Methods

An array of methods and a multi-scale approach were used to examine the effects of forest fires in land clearing decision-making. The implementation of a mixed methods approach integrated classified remotely sensed data products based on Landsat TM imagery, Geographic Information Systems analysis, regression analysis, semi-structured interviews and field observations. The study comprised two spatial scales: the regional scale consisting of Laguna del Tigre National Park and the local scale focusing on Paso Caballos. To examine the forest fire–deforestation relationship, we defined two study periods: the first addressed the effects of the 1998 fires on deforestation that took place from 1997 to 2003, and the second considered the effects of both the 1998 and the 2003 fires on deforestation from 2003 to 2005.

Spatial data analysis: land cover change & forest fires

The land-use change maps from 1997 to 2003 and 2003 to 2005 and the fire maps for 1998 and 2003 for Laguna del Tigre were obtained from the Center for Monitoring and Evaluation of the Council for Protected Areas (CEMEC). CEMEC reported an overall accuracy of 95% for the land-use change maps and an overall accuracy of 70% for the fire maps. We created fire maps for Paso Caballos using a Normalized Difference Burn Ratio (NDBR) (Key & Benson, 2006, 51 p.; Lee, Kim, & Cho, 2004) to identify the burn scars after the fires. The 1998 fires were mapped using Landsat Thematic Mapper (TM) imagery from April 12th 1997 and January 12th 1999, whereas the 2003 fires were identified with Landsat Enhanced Thematic Mapper-Plus (ETM+) from March 17th 2003 and May 7th 2003; these images roughly correspond to the pre- and post-fire season, which usually takes place between March and May. One hundred and sixty-five validation points obtained from participatory mapping and interviews verified the overall accuracy of the data. The accuracy of the burned area maps in Paso Caballos for 1998 and 2003 fires was 87% and 89% accuracy, respectively.

Ethnographic research on land-use decision-making

Individuals who participated in the semi-structured interviews conducted in Paso Caballos met the following criteria: 1) each interviewee had one designated plot in Paso Caballos prior to the 1998 fire and 2) the interviewee was responsible for land-use decisions on the plot throughout the 8 year study period. From the 160 families living in the community in 2006, 112 families have land. We interviewed 33 heads of household, representing 29% of the population. The average age of the head of household in the sample was 38.3 years (with a range of 20–65 years), and the average number of children per household was 4.9 (with a range of 0–14 children per household).

The semi-structured interview had two goals: to evaluate land-use decisions following forest fires and to map the land-use and fire history of the plots. Each farmer was asked whether fire-affected forests had been cleared for agriculture and the reasons for doing so. Additional household’s demographic information included age, gender and education level, as well as the socioeconomic activities and forest dependence of the household. During each visit, the first author drew plot sketches, guided by the farmers’ knowledge of the land-use histories and fire occurrence since 1997. Twenty-two participants granted permission to geo-reference their plots for spatial analysis. The 1998 and 2003 fire maps for Paso Caballos integrated the resulting data.

Linking land-use decision-making and landscape analysis

Two approaches were considered to examine the relationship between forest fires and deforestation. The first relied upon analyzing the proportion of deforestation in burned and unburned forest. A GIS overlay of the deforestation and fire maps was the basis of the analysis, which considered 5 × 5 km grid cells for the regional analysis and 48-ha community plots for the local scale. For both scales, the fire–deforestation ratio (FDR) (Equation (1)) resulted in a set of values indicating the areas in which most deforestation occurred in burned forest (positive values) and areas in which most deforestation occurred in unburned forests (negative values). The analysis excluded units in which the extent of fire or deforestation was less than 1 ha.

$$\mathrm{FDR} = \frac{\text{Forest area}_{\text{cleared \& burned}}}{\text{Forest area}_{\text{burned}}} - \frac{\text{Forest area}_{\text{cleared \& unburned}}}{\text{Forest area}_{\text{unburned}}} \quad (1)$$

The second approach employed logistic regression analysis to assess the likelihood of deforestation following forest fires and considered the following variables:

Deforestation—Land-use change maps for 1997–2003 to 2003–2005 provided reference to validate the dependent variable, deforestation of burned lands.
Topography—A digital elevation model from the USGS/NASA Shuttle RADAR Topographic Mission (SRTM) (Jarvis, Reuter, Nelson, & Guevara, 2008) at a resolution of 90 m/pixel was used to generate elevation, slope and aspect maps.
Burned area—Areas affected by fires were identified using official fire maps, enhanced by field observations and interview data.
Infrastructure—distance to roads and distance to human settlements were both calculated based on layers provided by CEMEC.

For each time step, a stratified sample of 200 points were selected to generate 100 cases of deforestation and 100 cases without deforestation, according to the following two criteria: 1) a minimum distance of 200 m between each plot and 2) plots must be located within the limits of Laguna del Tigre (Regional Analysis) or Paso Caballos (Local analysis). Logistic regression models were used to predict the overall probabilities of deforestation considering the binary response of burned/unburned. A forward stepwise likelihood ratio method enabled the selection of variables considering a level of $P = 0.10$ for entry and $P = 0.15$ for removal from the equation using the statistical package, SPSS, version 19.0. Assumptions for logistic regression models were examined with the Kolmogorow–Smirnoff test to evaluate normality of residuals and the Levene test to examine homogeneity of variance. The spatial independence of the error terms was assessed using Global Moran's *I* and Local Moran's *I* with ArcGIS.

Results

Regional analysis of Laguna del Tigre National Park

Laguna del Tigre has been the most affected area of the Maya Biosphere Reserve in terms of wildfires and deforestation (Table 2). In 1998, 37% (65,908 ha) of the standing forest burned, though only 1% of these areas were deforested in the period 1997–2003, with 7% of the unburned forest cleared during the same period. Forest burned in 1998 and deforested between 1997 and 2003 (767 ha) represented a small percentage of the total deforestation (9%); most of the deforestation (91%) took place in unburned forest.

These proportions changed drastically following the 2003 fires, during which 49% (83,321 ha) of the standing forests burned. Approximately 4% of the burned forest (4201 ha) was cleared during 2003–2005, representing 60% more deforestation than in unburned forest. Overall, 63% of deforestation took place in forest previously affected by fires, including 1) forest burned in 1998 (24%), 2) forest burned in 2003 (58%), or 3) forest burned in both 1998 and 2003 fires (18%). By 2003, only 32% (55,658 ha) of the standing forest had not been affected by fires in 1998 or 2003. Over this period, the location of deforestation changed as well; from 1997 to 2003, most clearing took place in the Special Use Zone (SUZ) and Recovery Zones (RZ), where nearly all human settlements are located (Fig. 4). The FDR indicates that most of that deforestation took place in unburned forests (green). From 2003 to 2005, deforestation expanded into the most preserved zone, the Restricted Area (RA) and included both, burned (red) and unburned forests (green). Additionally, the annual area deforested increased markedly from one period to the other—in 1997–2003, rates of deforestation were 1466 ha/year while 3335 ha/year in 2003–2005, representing an increase of 120% over this period.

Fire maps for the two dates indicate considerable overlap between the forest affected in 1998 and 2003; almost half of the forest affected in 1998 was burned again in 2003 (Fig. 3, Table 2), and 11% of the deforestation in 2003–2005 took place in forest affected during both the 1998 and 2003 fire seasons. However, results from logistic regression analysis fail to show the significant contribution of fires as an explanatory variable for deforestation during that period.

Logistic regression models also indicated a change in the relationship between forest fires and deforestation from one period to another. For the first period, the odds ratio indicated an inverse relationship between fires and deforestation, but during the second period, the coefficient for the fire indicated a positive relationship between these variables (Table 3). In Paso Caballos, the odds ratio for fire in 2003 was 22.64, indicating a positive relationship, however, the goodness of fit was very low (Pseudo $R^2 = 0.101$). With the standard of a "good fit" of a Pseudo $R^2 > 0.20$ (Clark & Hosking, 1986), the only model with good fit was the one for the local analysis in the 1997–2003 period. This model met the logistic regression assumptions of normal distribution in its residuals ($P = 0.000$) and homogeneity of variance in the error structure. The other three models have very low values of goodness of fit and hence should be interpreted with caution.

Local analysis

The 2006 land-use map reveals that most parcels had more than 50% forest cover, except for the parcels located next to the village, where the initial colonization and deforestation took place from 1994 to 1997 (Fig. 5). This, in part, reflects the agreement between the community and CONAP to preserve at least 20% of the original forest cover in each parcel (ProPeten, 2004, 43 p.). Land-use change analysis of this community indicates that, on average, 1.6 ha of forest was cleared per household each year and that farmers cultivated 4.2 ha/year. Based on this evidence, we infer that approximately one third of the land used for agriculture comes from forest clearings, with the remaining portion coming from secondary vegetation resulting from fallow areas.

Interviews on land-use decisions following forest fires enabled the identification of criteria that farmers consider to identify zones in which to establish their agricultural plots: 1) soil richness, in

Table 2
Deforestation and forest fires in Laguna del Tigre National Park.

		1997–2003	2003–2005
% total forest	Deforested	5%	4%
	Burned	37%	49%
% of deforested	All burned areas	9%	63%
	Burned in 1998	9%	15%
	Burned in 2003	n/a	36%
	Burned in both years	n/a	11%
	Unburned areas	91%	37%

Source: From 1998 and 2003 fire layers overlaid with deforestation maps produced by Centro de Monitoreo y Evaluación de CONAP (CEMEC) 2000 and 2004.

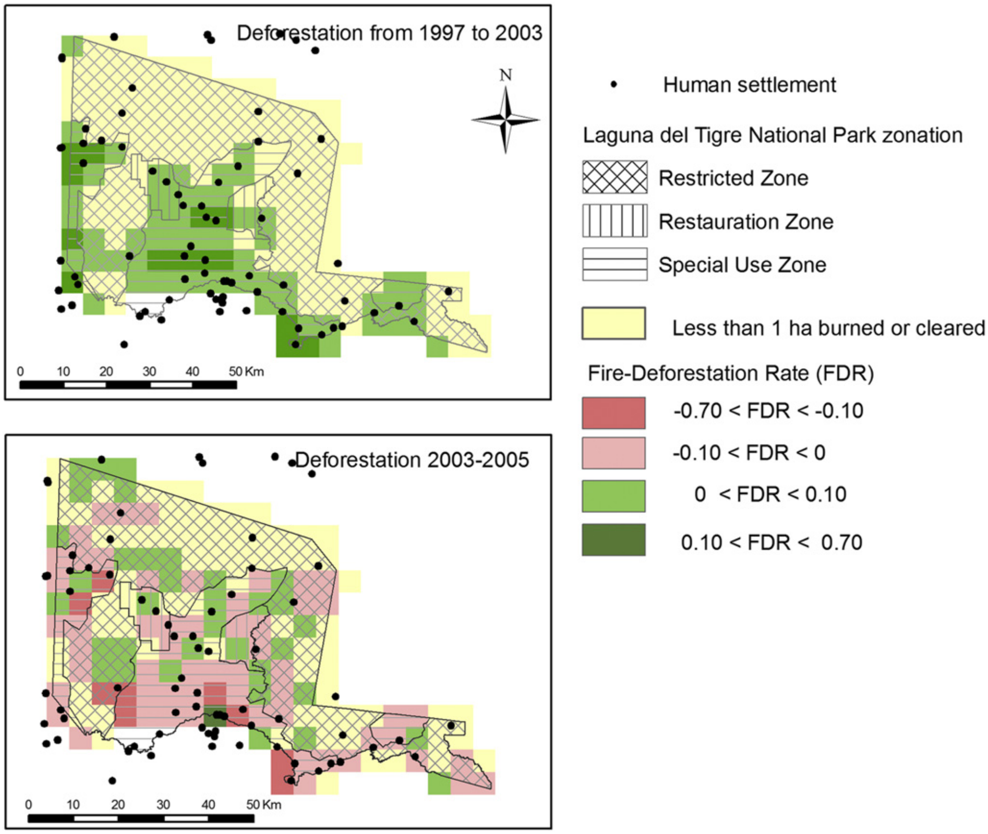

Fig. 4. Deforestation in burned forest from 1997 to 2005 in Laguna del Tigre National Park. Positive values of FDR (green) indicate that most of deforestation in that unit took place in non-burned forest; negative values (pink) show the areas where most of deforestation took place in burned forests. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

terms of organic matter and nutrients, 2) topography, avoiding areas prone to flooding and hills with shallow soils, and 3) proximity to roads, for better access. The spatial analysis of deforestation confirmed this association between deforestation and slope in both periods, in which most of the clearings occurred in areas with slopes ranging from 3 to 6%.

The deforestation analysis from 1997 to 2003 revealed that around one third of the cleared forests were affected during the 1998 fire season. However, most deforestation occurred in areas untouched by fires, especially in areas located near the village or next to roads (Fig. 5a), as shown with logistic regression analysis. In the second period, from 2003 to 2005, the proportion of deforestation in burned forest increased by almost half, demonstrating that 45% of the deforestation took place in forests affected by the 2003 fires.

Farmers explained that if a patch of forest were ever burned, such event would not necessarily lead them to clear the vegetation—20% of interviewed farmers mentioned that they had no intentions of clearing a burned forest. Field observations and interviews revealed that most of the forest fires in the community

Table 3
Logistic regression models for deforestation after 1998 and 2003 fires in Laguna del Tigre National Park (LTNP).

1997–2003			2003–2005		
Local analysis – Paso Caballos					
Independent Variables	Exp(B)	Wald	Independent Variables	Exp(B)	Wald
Fire 1998	0.093	33.121	Fire 2003	22.646	6.686
Elevation	0.982	6.294	Distance to roads	1	4.592
Distance to town	1	3.742	Elevation * fire 2003	0.976	4.838
			Fire 1998 * slope	1.14	5.265
Goodness of fit: 0.294[a]			Goodness of fit: 0.101		
Overall prediction capacity: 71%			Overall prediction capacity: 61%		
Regional analysis – Laguna del Tigre					
Independent Variables	Exp(B)	Wald	Independent Variables	Exp(B)	Wald
Fire 1998	0.189	31.753	Elevation	1.016	3.308
Distance to roads	1	30.743	Fire 1998	1.823	3.154
Slope	6.967	5.963			
Goodness of fit: 0.158			Goodness of fit: 0.048		
Overall prediction capacity: 62.5%			Overall prediction capacity: 56%		

[a] According with Clark and Hosking (1986), this is the only model with satisfactory goodness of fit (Pseudo $R^2 > 0.20$). This model shows an inverse relationship between fire 1998 and deforestation indicated by an odds ratio (Exp(B)) close to zero.

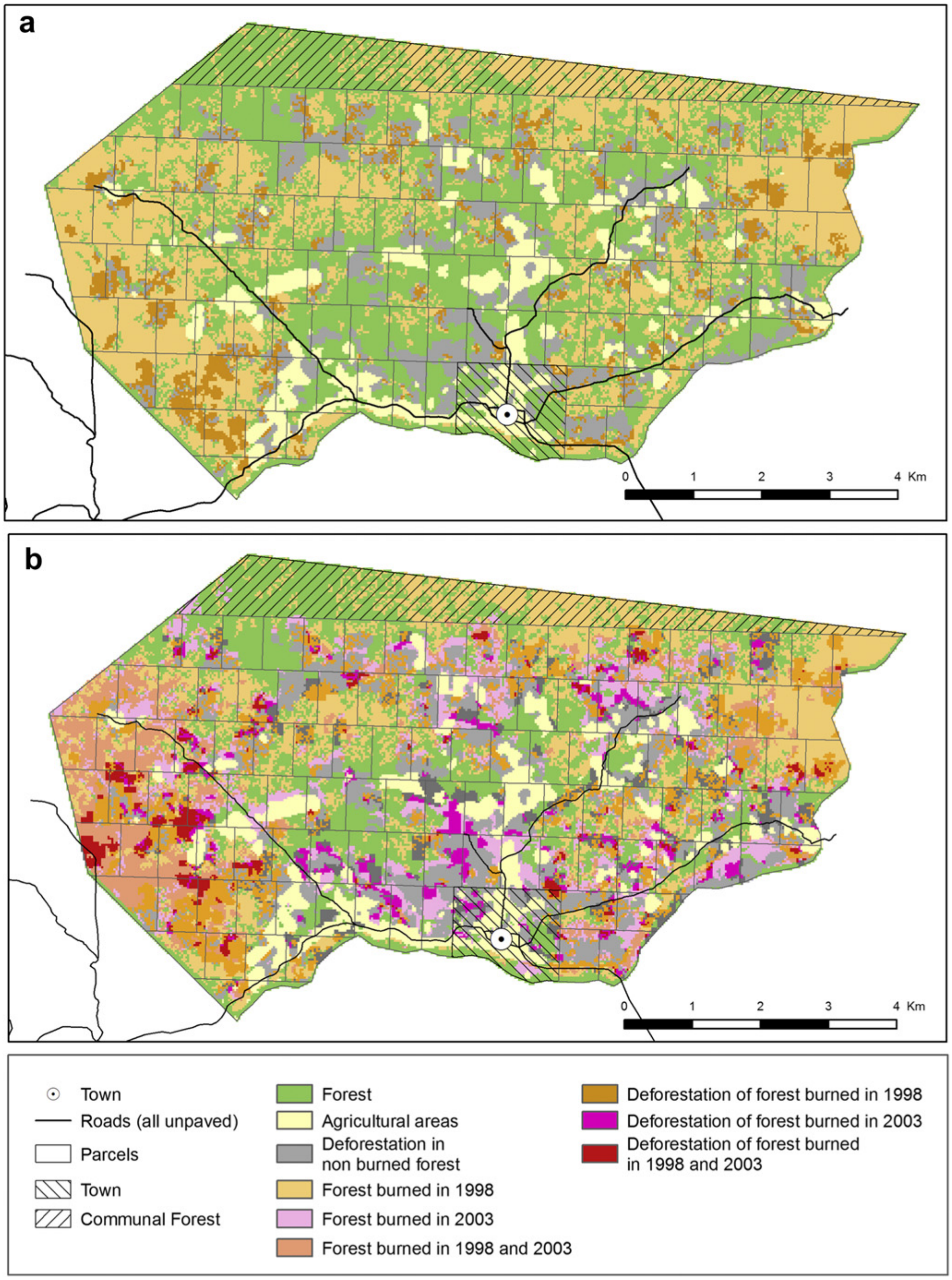

Fig. 5. Forest fires and deforestation in Paso Caballos a) from 1997 to 2003 after 1998 fires, b) from 2003 to 2005 after 2003 fires.

were low-intensity understory fires. This type of fire results in scorched vegetation that requires intensive labor to remove stalks, trunks, and other woody matter. By contrast, agricultural burning consumes most of the biomass, previously cut and dried as part of the traditional *milpa* cultivation. These two types of fire have different effects upon the vegetation, and farmers argued that there is no labor advantage of clearing a burned forest since they would need to invest at least the same amount of labor in a burned forest as in an unburned forest.

Among the farmers who had cleared a burned forest (80% of the sample), one quarter cited severe fire impacts on the vegetation as the main reason for clearing. Interviews and fire maps indicate that in 2003, a large forest fire affected the western section of the community, which had also been burned in 1998, and experienced some deforestation. Around one quarter of the forest burned in both years underwent deforestation during the period 2003–2005. Six farmers (20%) mentioned fire severity as a contributing factor in the decision to clear a burned forest. Farmers pointed out that forests, burned more than once, have fewer valuable timber species, vines, fuel wood, fruits, palms and resins—once these species disappeared from a plot, farmers were more likely to clear it. In addition to losing valuable forest products, some farmers mentioned the effects of fires on human health. During the fire season, farmers cited a rise of respiratory and ocular ailments as a result of the smoke and particulate matter. Fire risk also influenced decisions regarding the establishment of agroforestry systems. In 2003, many agroforestry plots and nurseries suffered because of accidental burning of several fruit trees and nurseries of *xate* palm (*Chamaedorea sp.*). Furthermore, the risk of fire recurrence has discouraged some farmers from maintaining agroforestry plots and nurseries, given the need to re-establish parcels following a fire event.

Besides the household land-use decisions, there are other land management practices and regulations, determined at the community level, that relate to the incidence of fire. Such is the case of the communal forest area protected by the community, in which land-use changes are prohibited. This protected forest could not be cleared, even if it were burned. Other collective decisions relate to preventing and controlling fire: during the burning season, farmers organize themselves into groups to practice collective agricultural burnings as a fire management strategy. If a fire becomes excessively intense or exceeds its borders, there is an organized group ready to respond. Further, the community assembly collectively assesses penalties to be imposed to the responsible party for the damage.

Discussion

The examination of the relationship between forest fires and deforestation in Laguna del Tigre through an 8 year period allowed identifying that during the 1997–2003 period, the proportion of cleared burned forests represented 9% of the total deforestation, in contrast to 63% of deforested burned areas in the period 2003–2005. More so, during that time span deforestation rates showed an increase, especially in the restricted, "less disturbed" area. Although this might suggest that the northward expansion of slash-and-burn agriculture favored the spread of forest fires, it is important to note that after the 2003 fires, only one third of the National Park forest remained unburned and yet, deforestation in this area took place in both burned and not burned forest (Fig. 4). Moreover, the logistic regressions established no significant relationship between these two variables, a finding that weakens the argument in favor of attributing deforestation to forest fires.

Local context of the fire–deforestation relationship

Based upon results of the local analysis, we argue that the decision about whether to let a burned forest recover naturally or transform it into an agricultural plot depends on many factors. These factors are related to the farmers' experience and cultural background. Ewell and Merrill-Sands (1987), Hernández (1959) and Steggerda (1941), among others, have reported that Yucatec Maya farmers apply several criteria for selecting the sites to be cultivated: the foremost are the age and floristic composition of secondary vegetation, the soil type, the location of water supplies and the convenience of access to the village. The traditional knowledge of these factors, particularly of the relationship between vegetation and soil, gives the farmers the opportunity to anticipate the future yield of the site (Arias, 1980). Data from Paso Caballos on site selection suggest that Maya Q'ekchi' share cultural roots with Yucatec Maya farmers. When Q'ekchi' farmers establish their agricultural plots, they give higher priority to plot accessibility, soil characteristics and land morphology rather than access to previously burned forest. This can be appreciated through deforestation and fire mapping in the community, which shows that forests closer to the village and located in flat terrains are more likely to be deforested regardless of their fire history. Evidence supports that having high rates of deforestation in burned forest does not indicate that forest fires lead to deforestation, but rather relates to the fact that most of the forest has been previously burned.

A key aspect for the decision on whether to clear a forest affected by fires is related to severity, the effect of fire upon vegetation and soils. There is a series of species used locally for house construction (vines, saplings and palms) as well as resins like *chicle* and incense for ceremonies. Farmers mentioned that they would be likely to clear a burned forest that had lost most of the valuable forest species due to fires. Evidence in Amazonian forests suggests that even light forest fires can remove more than 70% of the sapling and vine populations (Cochrane & Schulze, 1999), which are especially susceptible to damage because they are not protected by a thick bark (Secretariat of the Convention on Biological Diversity, 2001, 42 p.). The reduction of those forest products influenced the land-use decision-making, especially if the forest were located in areas considered adequate for the establishment of agricultural plots.

A second element related to fire severity is illustrated through farmer's avoidance to cultivate in forest recently affected by forest fires. This aspect has been reported in the Mexican forests of Quintana Roo (Barrera, Gómez–Pompa, & Vásquez-Yanes, 1977). Studies regarding the effects of fire on soil (González-Pérez, González-Vila, Almendros, & Knicken, 2004; Michelsen, Andersson, Jensen, Koller, & Gashew, 2004) and vegetation (Cochrane & Schulze, 1999; Gould et al., 2002; Uhl & Kauffman, 1990) indicate that the effects of fire are highly variable and depend on intensity, severity and frequency of fire. This leads to the hypothesis that not all forest fires reproduce the same conditions of intensity and severity required for a successful agricultural burn. Most of the forest fires in Laguna del Tigre are understory fires that consume soil litter and dead branches and kill young trees. In such case, we argue that there must be sufficient time after the fire so that enough fuel is accumulated to allow an adequate agricultural burn, controlled in its intensity and severity.

Laguna del Tigre: broader context of the fire–deforestation interface

Findings from the regional analysis support what Bray et al. (2008) have indicated regarding the spatial variability of deforestation rates throughout the Maya Forest. They suggest that deforestation rates of inhabited parks such as Laguna del Tigre are significantly higher than those in other uninhabited parks like Tikal, or in long-inhabited community forests concessions east of the Maya Biosphere Reserve. Regardless of differences among deforestation trends within the Maya Biosphere Reserve, we include the temporal analysis that suggests that deforestation within the park has accelerated since the early 2000's. From 1998 to 2002 the rate of forest loss in the park remained at approximately 2000 ha/year (CEMEC, 2007). However, there was a sudden increase in the annual deforested area, which reached 6000 ha/year in 2004 (CEMEC, 2007).

In addressing whether forest fires lead to deforestation, one must recognize that deforestation is a multi-causal phenomenon in which a combination of direct and underlying factors triggers land clearing. Drivers of deforestation in the tropics have been well documented (Geist & Lambin, 2001, 116 p.); at the household level, there is a relationship between forest clearing and household composition, institutions, socioeconomic and ecological drivers (Carr, 2005; Perz & Walker, 2002; Tucker, Munroe, Nagendra, & Southworth, 2005; Turner et al., 2001). At a regional level underlying drivers are policy, migration, and commodity markets (Angelsen & Kaimowitz, 1999; Geist & Lambin, 2001, 116 p.; Lambin et al., 2001; Tucker et al., 2005; Turner et al., 2001). In the case of Laguna del Tigre, special attention should be paid to the governance of natural resources in the region.

The Guatemalan Government has defined rules and management plans that limit access to the park resources and define rights and duties among stakeholders. However, these policies are often contradictory, ineffective and lead to negative and unforeseen consequences. Such is the case of land administration efforts, promoted by the World Bank, seeking to improve property rights in Petén and limit the ongoing colonization process. As mentioned earlier, instead of acting like a long-term incentive to invest in the land, land regularization heightened land speculation and rather enhanced the existing extra-legal land market (Gould et al., 2006). With less than a fifth of the communities within the park currently holding legal status (CONAP, 2006b, 123 p.), Laguna del Tigre might fall as an example of an open-access resource, characterized by weak institutions associated with an unstable land tenure system, legal and extra-legal land markets and ineffective natural resource management. The structural issues regarding land tenure insecurity, ongoing migration to Petén and lack of governance have led to a cycle of degradation of natural resources.

Management implications

In many tropical countries, in which farmers rely on fire for land management practices, the government has criminalized this activity, blaming farmers of forest destruction (Kull, 2004, 324 pp.; Tacconi, Moore, & Kaimowitz, 2007). Ascribing human behavior as the cause of disasters often increases conflict between stakeholders (McCaffrey & Kumagai, 2007). This is also the case in the Maya Biosphere Reserve, where the Council for Protected Areas (CONAP) asserts that out-of-control agricultural burnings lead to forest fires. CONAP (2001, 82 p.) further argues that forest fires “not only negatively affect the ecosystem and cultural patrimony, but additionally create conditions for the colonization of affected areas.” Our research has provided evidence suggesting that the conditions to establish agricultural plots in previously burned forest are not generally met following burns. Therefore, attributing deforestation to forest fires is a limited and skewed view of the diverse triggers of land-use change and also a simplification of the complex role of fire as a land management tool.

Farmers practicing slash-and-burn agriculture benefit from fire as a land management tool but are also affected by out-of-control fires that burn their forests. Beyond the impacts of forest fires as triggers of ecosystem disturbances, fire also increases uncertainty in land-use decisions. After the 2003 fires affected the 3-year-old agroforestry plots in Paso Caballos, the attitudes of many farmers shifted. While some preferred to abandon agroforestry practices, others promoted local organization for improving fire management and preventing “escaped fires” from agriculture. For example, people in this community defined a burn calendar system as well as teams for burning, organized by a local fire committee. Conservation practitioners in the area must have a wider recognition that formally established communities do not benefit from forest fires and that they organize to prevent them and ensure a responsible use of fire. Following the literature on management of common-property resources, conservation strategies should aim to incentivize and promote local organization for fire management. Moreover, designing a strategy for reducing forest fire in the park has implications for both conservation and development policies.

Conclusions

This study evaluated the relationship between forest fires and deforestation using medium-resolution Landsat imagery (30 m/pixel) to identify burned and deforested areas. This approach enabled the assessment of both long-term and cumulative effects of wildfires in land-use change. In spite of demonstrating that a high proportion of deforestation took place in burned areas during the 2003–2005 period, it is difficult to establish a causal relationship because, after 2003, only one third of the forest in Laguna del Tigre remained unburned. The sudden increase in deforestation rates that the park suffered after the year 2000 was more likely due to a combination of immigration to the area and a lack of governance that the region has been experiencing ever since.

High rates of deforestation in burned forest do not imply that forest fires trigger forest clearing. Information from farmers taking land-use decisions allows us to understand the decision on whether or not to clear a burnt forest. Farmers would consider clearing a burned forest only if a combination of criteria is met: when burned forest are located near a road or town, good soils that are not susceptible to flooding, and when valuable timber and non-timber forest products are significantly diminished. Previous fire severity on vegetation constitutes the sole motivation expressed during interviews that would lead farmers to clear a burned forest. However, regression analysis showed only one significant negative relationship between forest fires and deforestation. Future studies examining the relationship between forest fires and deforestation must address not only burned area but also fire severity. Moreover, it is important to consider even longer study periods, particularly since forest fires have a positive feedback on the frequency, intensity and severity of future events and a land-holder might decide to clear a repeatedly burned forest, impoverished after several years of disturbance.

Interviews and field observations in Paso Caballos enabled better understanding and the explaining of the patterns detected in the regional analysis. This study demonstrated a link between the land manager and the parcel being analyzed, which is one of the many challenges to better understand the patterns and processes in land-change science (Rindfuss, Walsh, Turner, Fox, & Mishra, 2004). However, our capacity to generalize the understanding about the effects of fires in land-use decision-making is limited due to the limited scope of only one specific community. A deeper and better understanding of the fire–deforestation relationship will be gained through the study of diverse types of human settlements, particularly those with cattle-ranching. Burning pastures represent a riskier fire management activity because of fuel flammability and continuity. Furthermore, future studies should include communities that experience conflicting relationships within the community or with governmental authorities. The study of communities with different local organization and settlement history would result in the identification of more or different criteria used in land-use decision-making after forest fires.

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