Effectiveness of Protected Areas in Mitigating Fire within Their Boundaries: Case Study of Chiapas, Mexico

ROSA MARÍA ROMÁN-CUESTA* AND JORDI MARTÍNEZ-VILALTA†‡

*Environmental Change Institute, Oxford University Centre for the Environment, Parks Road OX13QY, Oxford, United Kingdom, email rroman@ouce.ox.ac.uk

†Institute of Atmospheric and Environmental Science, School of Geosciences, University of Edinburgh, Darwin Building, King's Buildings, Edinburgh EH9 3JU, United Kingdom

Abstract: *Since the severe 1982–1983 El Niño drought, recurrent burning has been reported inside tropical protected areas (TPAs). Despite the key role of fire in habitat degradation, little is known about the effectiveness of TPAs in mitigating fire incidence and burned areas. We used a GPS fire database (1995–2005) (*n = *3590 forest fires) obtained from the National Forest Commission to compare fire incidence (number of fires) and burned areas inside TPAs and their surrounding adjacent buffer areas in Southern Mexico (Chiapas). Burned areas inside parks ranged from 2% (Palenque) to 45% (Lagunas de Montebello) of a park's area, and the amount burned was influenced by two severe El Niño events (1998 and 2003). These two years together resulted in 67% and 46% of the total area burned in TPAs and buffers, respectively during the period under analysis. Larger burned areas in TPAs than in their buffers were exclusively related to the extent of natural habitats (flammable area excluding agrarian and pasture lands). Higher fuel loads together with access and extinction difficulties were likely behind this trend. A higher incidence of fire in TPAs than in their buffers was exclusively related to anthropogenic factors such as higher road densities and agrarian extensions. Our results suggest that TPAs are failing to mitigate fire impacts, with both fire incidence and total burned areas being significantly higher in the reserves than in adjacent buffer areas. Management plans should consider those factors that facilitate fires in TPAs: anthropogenic origin of fires, sensitivity of TPAs to El Niño-droughts, large fuel loads and fuel continuity inside parks, and limited financial resources. Consideration of these factors favors lines of action such as alternatives to the use of fire (e.g., mucuna-maize system), climatic prediction to follow the evolution of El Niño, fuel management strategies that favor extinction practices, and the strengthening of local communities and ecotourism.*

Keywords: El Niño Southern Oscillation (ENSO), fire management, forest fires, Mesoamerican Biological Corridor, parks, tropical forests

Efectividad de las Áreas Protegidas en la Mitigación de Fuego dentro de Sus Límites: un Estudio de Caso en Chipas, México

Resumen: *Desde la severa sequía de El Niño en 1982-1983, se han reportado quemas recurrentes dentro de áreas tropicales protegidas (ATPs). No obstante el papel clave del fuego en la degradación del hábitat, se conoce poco sobre la efectividad de ATPs en la mitigación de la incidencia de incendios y de áreas quemadas. Utilizamos una base de datos de GPS de incendios (1995-2005) (*n = *3590 incendios forestales) obtenida de la Comisión Forestal Nacional para comparar la incidencia de fuego (número de incendios) y áreas quemadas dentro de ATPs y sus zonas de amortiguamiento circundantes en el sur de México (Chiapas). Las áreas*

‡*Current address: CREAF/Unitat d'Ecologia, Universitat Autònoma de Barcelona, Edifici C (Facultat de Ciències) Bellaterra 08193, Barcelona, Spain*

Paper submitted April 4, 2005; revised manuscript accepted November 3, 2005.

Conservation Biology Volume 20, No. 4, 1074–1086

DOI: 10.1111/j.1523-1739.2006.00478.x

quemadas dentro de los parques varió de 2% (Palenque) a 45% (Lagunas de Montebello) de la superficie de un parque, y la superficie quemada fue influida por dos eventos severos de El Niño (1998 y 2003). Estos dos años combinados resultaron en 67% y 46% de la superficie quemada en ATPs y áreas de amortiguamiento respectivamente. Las áreas quemadas más extensas en ATPs que en sus zonas de amortiguamiento se relacionaron exclusivamente con la extensión de los hábitats naturales (área inflamable excluyendo terrenos agrícolas y ganaderos). Es probable que esta tendencia esté relacionada con mayores cargas de combustible además de dificultades de acceso y extinción. La mayor incidencia de fuego en ATPs que en sus zonas de amortiguamiento se relacionó exclusivamente con factores antropogénicos como mayor densidad de caminos y de extensiones agrarias. Nuestros resultados sugieren que las ATPs están fallando en la mitigación de impactos del fuego, ya que tanto la incidencia de fuego como la superficie quemada son significativamente mayores en las reservas que en las zonas de amortiguamiento adyacentes. Los planes de manejo deberían considerar los factores que facilitan el fuego en ATPs: origen antropogénico de los incendios, sensibilidad de ATPs a las sequías de El Niño, grandes cargas y continuidad de combustible dentro de los parques y recursos financieros limitados. La consideración de estos factores favorece líneas de acción como alternativas al uso de fuego (e.g., sistema mucuna-maíz), predicción del clima para seguir la evolución de El Niño, estrategias para la gestión de combustible que favorecen las prácticas de extinción y el fortalecimiento de las comunidades locales y el ecoturismo.

Palabras Clave: bosques tropicales, Corredor Biológico Mesoamericano, gestión del fuego, incendios forestales, oscilación sureña de El Niño-OSEN

Introduction

Increased deforestation and fragmentation of tropical forests have focused attention on the best approaches for conservation and management of tropical protected areas (TPAs) (Soulé & Sanjayan 1998; Foster et al. 1999; Du Toit et al. 2004). Forest fires pose one of the biggest threats to conservation of these areas and have received increased public attention, especially following severe El Niño events (Malingreau et al. 1985; Crutzen & Andreae 1990; Nepstad et al. 1999; Cochrane 2001). Fire is an old disturbance agent in many tropical forests (Sanford et al. 1985), and in fire-dependent and influenced forests (e.g., pine forests or savannas) its presence is required for ecosystem stability (Fulé & Covington 1999). However, growing human populations, careless use of fire, land-use changes, climatic pressures, and particular political and socioeconomic scenarios have resulted in altered tropical fire regimes in which both too much or too little fire represent a threat to biodiversity.

Although there are tropical areas where too little fire is a problem, the increasing size and frequency of fires in tropical forests appear to be more of a concern (Kinnaird & O'Brien 1998; Cochrane 2003; Du Toit et al. 2004). These fires are threatening fire-sensitive and poorly fire-adapted ecosystems (e.g., moist broadleaf forests) (Holdsworth & Uhl 1997; Goldammer 1999; Cochrane & Laurence 2002) and promoting the spread of fire-dependent stands (e.g., pines) outside their natural areas of occurrence (Goldammer & Seibert 1990; Rodríguez-Trejo & Fulé 2003).

The virtues of fire as a traditional farming tool are being denigrated because of its destructive power. Moreover, since the severe global 1998 El Niño Southern Oscillation (ENSO) drought, large burned areas have been reported inside TPAs in Brazil (Elvidge et al. 2001; Brito et al. 2004), Indonesia (Kinnaird & O'Brien 1998), Malaysia (Cleary & Genner 2004), Thailand (Giri & Shrestha 2000), Guatemala (Albacete 2003; Ramírez 2003), and Mexico (Román-Cuesta et al. 2004; Eastmond & Faust 2006). But how effective are protected areas at mitigating fire incidence and burned areas within their boundaries compared with their adjacent surroundings? In 2001 a global review concluded that on average, burned areas were smaller inside TPAs than in adjacent unprotected areas (Bruner et al. 2001). However, the pressure due to fire was substantial in many reserves: 19% of the parks sampled (12 out of 63) suffered more fire than surrounding unprotected areas, and in approximately 18% of the sample, the burned area inside parks over just 5 years accounted for more than 30% of their total land area (Fig. 2 of Bruner et al. 2001).

Although higher levels of fire within tropical-park boundaries in comparison with their buffers (defined as concentric areas surrounding TPA boundaries, whose final areas equaled the total burnable land of each TPA) represent an undesirable situation in terms of park efficiency, it is not necessarily undesirable in terms of fire ecology. The ecologically appropriate levels of fire and park fire management strategies depend on contrasted and frequently unavailable factors such as the knowledge of the "natural" (e.g., preindustrial?) versus "acceptable" fire regimes (based on socioeconomic needs). Emulating "natural" fire regimes may or may not be well suited for contemporary management because a full range of social and economic factors needs to be considered (Goldammer 1993; Fule & Covington 1999). We do not debate "natural" or "acceptable" fire regimes in this study; rather, we focus on how effective protected areas are in mitigating fire within their boundaries.

The National Forest Commission (CONAFOR) maintains a global positioning system (GPS) fire database for Chiapas (southern Mexico) that allows examination of the effectiveness of regional parks to mitigate fire. We chose to examine this tropical state because the factors influencing the presence of fire are similar to those in other tropical areas (e.g., anthropogenic origin of fires, sensitivity to ENSO droughts) (Román-Cuesta et al. 2004). Moreover, Chiapas and Oaxaca are the most biodiverse Mexican states (Deininger & Minten 2002) and have the largest number of fire incidence and burned areas in Mexico (SEMARNAT 2002). Twelve percent of Chiapas is under different levels of legal protection (CONANP 2005), although this protection responds more to recreational and aesthetic concerns than to biodiversity conservation goals (Cantú et al. 2004).

We sought to (1) evaluate whether TPAs in Chiapas have higher fire incidence and larger burned areas than their unprotected surroundings, (2) establish whether any differential fire mitigation effectiveness between TPAs and their surroundings is altered by the El-Niño-driven droughts, and (3) determine which variables (e.g., vegetation, infrastructure, population density) are related to more severe fire impacts in TPAs.

Methods

Study Area

Chiapas, a southeastern state of the Mexican Republic (14° 32′ to 17° 59′ N; 90° 22′ to 94° 14′ W; elevation range 0 m to 4093 m asl) (Fig. 1), has an area of 75,635 km^2 (3.8% of the Mexican territory). It is composed of 118 municipalities grouped into nine administrative regions. Due to its location in the tropical region, Chiapas is dominated by climates corresponding to the warm and semiwarm groups with varying degrees of humidity (climate A following the Köppen climatic classification), but temperate and semicold climates are also present in areas above 2000 m a.s.l (type B and C). Mean annual precipitation in Chiapas is 1982 mm (range: 1000–4500 mm; series: 1941–1996; SMN 2000), with a wet season from May to October and a dry season from November to April.

Fifty-five percent of the state is forested, mainly temperate (19%) and rain forests (36%) (NFI 2000). With 44% of its area already covered by cattle pastures, Chiapas is suffering from severe deforestation rates: 1.84% and 2.48% for temperate and rain forests, respectively (1975–1993), and 0.9% and 1.1% for temperate and rain forests (1993–2000) (Castillo-Santiago 2002), respectively. Moreover, human pressures have increased forest fragmentation, with a progressive substitution of species-rich forests with species-poor and more flammable types (similarly described in other tropical areas by Laurance et al. [1998] and Cochrane et al. [1999]).

The population in Chiapas in 2000 was almost 4 million, and it had one of the highest mean annual population growth rates in Mexico (INEGI 2000). More than 60% of the population lives in rural areas and most of them rely on subsistence agriculture (INEGI 2000). Population densities vary from 115 persons/km^2 in the central region of Los Altos to 25 persons/km^2 in the southwestern Frailesca region.

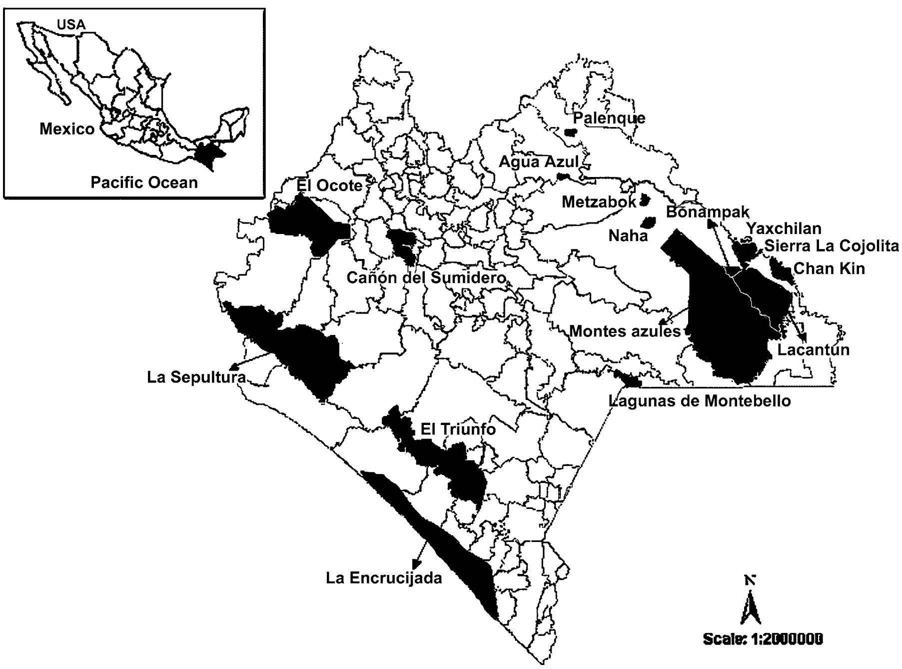

Figure 1. Geographic location of Chiapas and the 15 + 1 tropical protected areas (TPAs) included in this study (+1 refers to the nonfederal reserve of Sierra Cojolita). Montes Azules, Bonampak, Yaxhilan, Lacantun, and Sierra Cojolita were all merged to form the Lacandona TPA.

Table 1. Main attributes of the tropical protected areas (TPAs) in Chiapas.

TPA	Category[a] Mexican	Category[a] IUCN	Created	Plan[b]	Total area (ha)	Core or restricted area[c] (%)
Montes Azules	RoB	VI	1978	yes	323,266	6.9
La Sepultura	RoB	VI-Ia	1995	yes	192,526	7.1
El Triunfo	RoB	VI-Ia	1990	yes	121,380	21.2
El Ocote	RoB	VI-Ia	1982	yes	101,273	39.9
La Encrucijada	RoB	VI-Ia	1995	yes	118,410	30.6
Lacantun	RoB	VI	1992	no	63,803	*
Palenque	NP	III	1981	no	1,819	21.7
Cañón del Sumidero	NP	II	1980	no	21,532	NA
Lagunas de Montebello	NP	II	1959	no	6,603	NA
Chan-Kin	FFP	VI	1992	no	12,019	*
Naha	FFP	VI	1998	no	3,839	*
Metzabok	FFP	VI	1998	no	3,339	*
Cascadas Agua Azul	FFP	VI	1980	no	2,223	*
Yaxchilan	NM	III	1992	no	2,625	*
Bonampak	NM	III	1992	no	4,031	*
Sierra Cojolita	CR	VI	n/a	no	12,979	

[a] *Category codes: RoB, reserve of biosphere; NP, national park; FFP, area of fauna and flora protection; NM, natural monument; CR, communal reserve (state reserve, not a federal reserve). Source: CONANP 2005. Further information on IUCN categories is available from www.iucn.org.*
[b] *Plan refers to the existence of a published park management plan.*
[c] *Codes: NA, not available; asterisk (∗), parks where the total area is under communal land tenure.*

Data Sets

TPAs

We obtained a 1:250,000 digital layer with Chiapas' protected areas from LAIGE (Laboratorio de Análisis Geográfico, ECOSUR). We focused on TPAs larger than 1000 ha, managed and funded by the Mexican Federal Government (federal reserves such as biosphere reserves, national parks, areas of flora and fauna protection, and natural monuments, CONANP 2005). Due to their higher degree of legal and financial protection, we believe federal reserves are more likely to develop and reinforce conservation strategies. Fifteen of the 23 reserves in Chiapas fulfilled these conditions (Fig. 1; Table 1). Due to the physical continuity of the protected areas in the southeastern part of the state (Fig. 1), we consider the reserves of Montes Azules, Bonampak, Lacantun, Yaxchilan, and the state reserve of Sierra Cojolita a single TPA (hereafter referred to as Lacandona Reserve). Thus, we examined a total of 12 reserves. Of these all but two had fires either inside or in their buffers during the study period (Table 2).

Most of the parks included population centers at the time of their legal creation and now have varying percentages of their total area under communal land tenures. They are, consequently, human-influenced reserves. Restrictions of use mostly apply to national land tenures (nuclei area), whereas lower levels of restriction affect the rest of the reserve (Table 1). The prohibition of establishing new population centers and the resettlement enforcements that have been derived from it have been among the most conflictive social measures.

For statistical purposes, we considered all TPAs equally important and did not prioritize them by any external factor (e.g., legal degree of protection, total national land, ecosystem type).

Fire Data

The fire database we used belongs to CONAFOR and includes detailed information on forest fires that occurred over 11 years (between 1995 and 2005). This data set is based on field fire reports and is described in detail in Román-Cuesta et al. (2004). The variables relevant for this study are the municipality and the location where the fire was detected, the dates when fire started and finished, fire causality, type of fire, and the total area affected. The CONAFOR database includes 3590 fire incidences, of which 259 were excluded because they were either not geopositioned, incorrectly positioned (e.g., fire in water), or corresponded to fires smaller than 1 ha.

The original database does not include all fires that occurred in the state. Fires set intentionally to eliminate crop residues and to favor pasture regrowth are not included in CONAFOR's database. Moreover, fires in remote areas may not have been detected, and when the fire season is severe, fire-fighting capabilities can be exceeded, which reduces the number of reported fires.

A single GPS point, corresponding to an easily accessible location, characterizes each fire. This leads to limitations: (1) Information regarding the shapes of the fires is unavailable. (2) The GPS positioning errors result in a certain degree of fire mispositioning in the database. Position errors are randomly distributed and affect fires in TPAs and buffers similarly (e.g., fire in TPAs are not better located) (F. Gamboa, personal communication). (3) Vegetation analyses are restricted to one point.

Table 2. Land-cover composition of Chiapas' reserves and correspondent buffers, and area burned in each tropical protected area (TPA) and buffer for the different vegetation types.[a]

	Land-cover composition (%)													
	pastures		*agriculture*		*pine-oak*		*evergreen rainforest*		*deciduous rainforest*		*cloud montane forest*		*other*	
TPA	*TPA*	*buffer*	*TPA*	*buffer*	*TPA*	*buffer*	*TPA*	*buffer*	*TPA*	*buffer*	*TPA*	*buffer*	*TPA*	*buffer*
Lacandona[b]	4.3	29.1	1.5	4.7	0.3	0.7	86.0	54.4			5.5	8.1	2.5	3.1
El Ocote	16.1	33.9	0.6	3.6	0.1	2.8	77.0	36.6	5.6	12.5			0.6	10.7
Cañón del Sumidero	5.1	5.5	8.9	24.8	16.6	25.9	21.9	13.5	41.0	26.0			6.5	4.3
Lagunas de Montebello	5.6	15.0	6.8	27.3	17.3	26.6					53.6	30.7	16.7	0.4
La Sepultura	9.8	18.3	9.4	32.9	41.4	27.7	4.3	2.7	20.6	14.0	14.3	3.8	0.2	0.7
El Triunfo	4.2	16.1	10.6	9.9	6.9	23.1	17.8	28.4			59.6	21.5	0.9	1.0
La Encrucijada	39.6	69.7	3.1	26.5			0.0	0.2					57.4	3.2
Palenque	55.0	48.9					45.0	51.1						
Naha	7.2	25.7					51.0	48.8			39.8	25.0	2.0	0.5
Chan K'in	2.4	4.8					97.6	95.2						
Agua Azul	6.4	5.8	49.2	41.0			44.4	53.2						
Metzabok	11.3	40.2					88.8	59.8						
Exterior[c]	27.2		19.5		17.9		17.1		7.0		7.9		3.4	
	Area burned (%)													
Lacandona	9.0	24.3		13.5			82.0	40.5			9.0			21.6
El Ocote	15.0	33.0				20.0	80.0	6.7	5.0	20.0				
Cañón del Sumidero	17.0	31.3	6.0	37.5	12.0	6.3	6.0		59.0	25.0				
Lagunas de Montebello	14.0	23.0	14.0	23.0	14.0	53.9					57.0			
La Sepultura	6.7	18.5	10.0	24.2	56.0	39.5	5.0	0.8	13.0	14.5	8.0	1.6		
El Triunfo	3.0	13.9	27.0	9.2		41.5	8.0	10.8			62.0	24.6		
La Encrucijada	17.0	100.0											83	
Palenque							100.0							
Naha							100.0							
Chan K'in							100.0							
Agua Azul	no fires													
Metzabok	no fires													
Exterior	15		22.6		45		3		6.2		4.1		4.1	

[a] *Vegetation data were extracted from Chiapas' digital vegetation layer.*
[b] *The Lacandona TPA includes the following reserves: Montes Azules, Lacantun, Sierra Cojolita, Bonampak, and Yaxchilan. All but Yaxchilan had fires during 1995–2005.*
[c] *Exterior refers to the rest of Chiapas that is not included in the reserves or their buffers.*

VEGETATION

We obtained a 1:250,000 digital layer of Chiapas' vegetation (in the year 2000) from LAIGE. This map corresponds to the National Forestry Inventory and is based on unsupervised classification of Landsat images from the early 2000s and expert knowledge. It contains 39 categories, with information regarding the degree of disturbance of the vegetation. We merged vegetation communities into eight main land covers: agriculture; pastures; pine-oaks (monospecific and mixed stands); cloud montane rainforests; evergreen and semideciduous rainforests; deciduous rainforest; mangroves; and unburnable areas (e.g., water bodies, denuded soils, urban areas).

ROAD AND POPULATION DENSITIES

We obtained a digital layer of Chiapas' roads from LAIGE. This layer was based on data from the Mexican Transportation Institute and Landsat images from year 2000. It contains different types of roads (e.g., paved permanent, unpaved temporary, rural paths) and their lengths. Most of the roads in the state are local, unpaved paths (rural paths), which are the basic communication networks among rural areas.

We obtained a digital layer with 16,404 Chiapas' population centers from LAIGE (1:250,000 scale). This layer contains Chiapas census data compiled by INEGI in 1995 (e.g., name of locality and municipality, number of inhabitants in 1995, geographical coordinates).

Digital Analyses

We used the GIS package MIRAMON 5 (Pons 2000) for all the digital analyses.

BUFFERS

We created buffers to compare fire impacts inside TPAs with their exteriors. The final areas of buffers equaled the total burnable land of each TPA (e.g., every land cover able to sustain a fire, excluding unburnable land) and ranged from 810–15,000 m (Palenque and Lacandona, respectively). For the southeastern reserves, the inclusion of all reserves as independent units resulted in the overlapping of buffers with adjacent protected areas and/or adjacent buffers. We unified most of the reserves and calculated a single unified buffer. When buffers reached the limits of the state (e.g., Lagunas de Montebello) or the ocean (e.g., La Encrucijada), we used wider buffers and cut off the external areas of the buffer.

FIRE

The original geographic coordinates were transformed into UTM Zone 15 (NAD27-Mexico). Information about the municipality and the local area where the fire had occurred helped in the replacement of inaccurately mapped fires. For fires that were improperly located, we searched for repeated fires in the same location with correct coordinates and reassigned these new coordinates. Whenever possible, misplaced fires without repeated cases but whose locality was easily identifiable in a map were relocated. Fires that could not be corrected were excluded. Finally, we tested the positional accuracy of our fire database by selecting 15% of the total fires in both TPAs and buffers and contrasting the name and location (from CONAFOR's database) of these fires with the INEGI population-vector layer (which contains the names of all localities in the state). There was 80% agreement between the spatial distribution of CONAFOR's fire database and the distribution of the localities in INEGI.

To detect biases in burned area during the 11-year period, we contrasted fire values reported inside TPAs in CONAFOR's fire database with those offered by other sources, mainly management programs of TPAs (CONANP 2005). CONAFOR's fire database displayed conservative total burned areas. For example, the TPA Montes Azules had 10,000 ha burned in the 1998 El Niño season alone versus 9,487 ha reported burned in the database for the Lacandona TPA (which is an aggregation of five reserves, four of which had fires) (CONANP 2003). For Selva El Ocote, managers reported 19,000 ha of burned area in the 1998 El Niño fire season (22,000 in IHN 2004). For that year the fire database showed 18,100 ha burned and a total of 23,261 ha in that reserve over the 11-year period. In El Triunfo annual mean burned area was reported as 600 ha. Based on this average 6,600 ha would be considered burned over the 11-year period; however, fires in the database covered 2,759 ha. No fire data were available from the Sepultura and Encrucijada management programs (CONANP 2005) (Table 1).

We measured fire impacts based on (1) fire incidence (total number of fires per total burnable area, for TPAs and their buffers, for the total time period [1995–2005] and (2) burned area (total area burned per total burnable area, for the total time period, in TPAs and their buffers). To favor the visualization of these values (Fig. 2), we

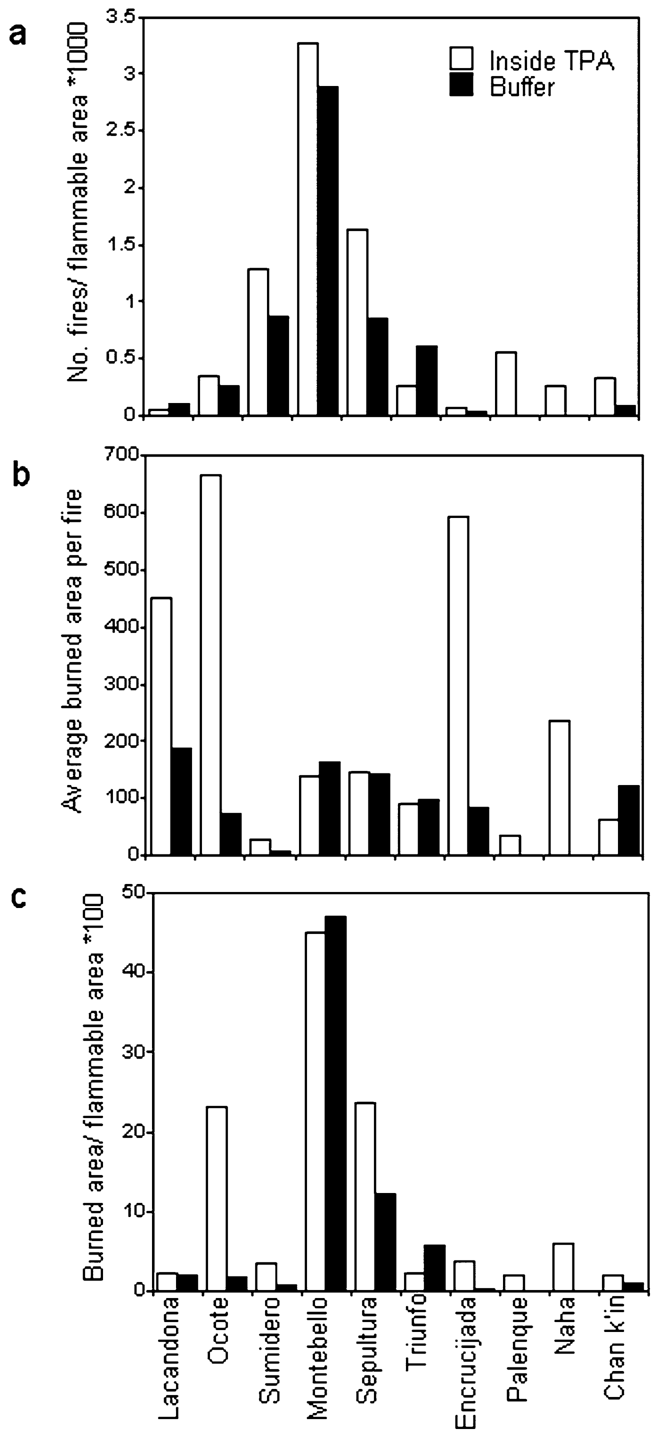

Figure 2. (a) Fire incidence in tropical protected areas (TPAs) and their buffers (number of fires/flammable area × 1000) in Chiapas from 1995 through 2005. (b) Average burned area (in hectares) for fires in TPAs and their buffers in Chiapas (1995–2005). (c) Total area affected by fires (area burned/flammable area × 100) in TPAs and their buffers in Chiapas from 1995 through 2005.

multiplied fire incidence by a constant factor of 1000 and burned area by 100 (e.g., fire incidence in Montebello TPA equals 0.00327×1000; whereas the burned area equals 0.45×100). Most fires in Chiapas are surface fires (Román-Cuesta et al. 2004); the total burned area does not correspond, therefore, to complete overstory mortality but to fire-disturbed forests with occasional crown fires (torching). Low-intensity fires in the tropics, however, can result in fires of high severity (Cochrane et al. 1999; Goldammer 1999).

We searched for causality differences between TPAs and buffers (e.g., deliberate burning) in the CONAFOR database as a way to explain enhanced fire incidence in any of these areas. For this purpose we calculated the percentages of fire negligence, deliberate burning, and unknown causes of fire for TPAs and buffers for the 11-year period.

VEGETATION

To learn which land covers suffered from higher fire ignitions, we overlayed the fire GPS layer on the vegetation layer, both for TPAs and buffers, to determine the percentage of fires in each land cover (Table 2). To test whether the vegetation flammability properties had an influence on the number of fire ignitions (fire incidence), we calculated fire incidence per vegetation type by dividing the number of fires in each considered vegetation type by the area of each vegetation type. The presence of larger areas of more flammable material (e.g., pastures, agricultural lands, pine-oak habitats) inside TPAs than in their buffers could be responsible for differential distributions of fire ignitions between TPAs and buffers.

To determine the level of occupancy of different land covers inside TPAs and buffers, we overlaid the vegetation layer with the TPA and buffer-polygon layers. Land cover results were given in percentages to minimize the area differences among TPAs. Not all land cover types were represented both inside the parks and in their buffers (e.g., cloud montane rainforests inside the park but not in the buffer) (Table 2). When this happened, these land covers were excluded from the statistical tests, reducing the number of paired samples for some variables (Table 3). To minimize this low sample number, we included an extra category: natural habitats for both TPAs and buffers. This land class referred to the percentage of area covered by all vegetation types with the exception of anthropogenic habitats such as pastures and agricultural areas.

ROAD AND POPULATION DENSITY

To obtain the density of roads (meters per hectare), we isolated those sections of roads inside TPAs and then isolated those inside the buffers. We divided these values by their respective total areas in each TPA and buffer. We estimated population density (inhabitants per hectare) by dividing the total number of inhabitants inside a reserve or a buffer by the total area of each reserve or buffer.

STATISTICAL ANALYSES

Because most variables were not normally distributed even after applying transformations, we used nonparametric tests. We selected paired-sample Wilcoxon signed-rank test to compare fire incidence and burned areas between TPAs and their buffers. We used a contingency table and a chi-square test to search for differential behaviors between fire incidence and burned areas during El-Niño-driven droughts. We selected a paired-sample Wilcoxon signed test to evaluate whether fire incidence was associated with certain land covers (e.g., enhanced ignitions due to the presence of flammable land). Spearman's correlations tested the association between several independent variables (land covers, population, road densities) and fire impacts. Two approaches were used in these correlation analyses: (1) relative fire impacts between TPAs and their buffers (offers clues about variables

Table 3. Rho coefficients of the Spearman correlations for fire factors (incidence and burned area) and the considered explanatory variables for the tropical protected areas (TPA) and their buffers in Chiapas.[a]

	Fire incidence			*Burned area*			
Variable	*TPA*	*buffer*	*relative[b]*	*TPA*	*buffer*	*relative[b]*	n
Burned area	0.68**	0.88**	0.52*	—	—	—	11
Pine-oak	0.77*	0.83**	ns	ns	ns	ns	6
Evergreen-semideciduous rainforests	ns	−0.74**	ns	ns	ns	ns	9
Natural land cover	ns	ns	ns	ns	ns	0.62**	11
Pastures	ns	ns	ns	ns	ns	ns	11
Agriculture	ns	ns	−0.77**	ns	ns	ns	8
Population density	ns	ns	ns	ns	ns	ns	11
Road density	ns	ns	0.57*	ns	ns	ns	10
Land cover changes	ns	ns	ns	ns	ns	ns	11

[a] *Significance: *$p < 0.1$, **$p < 0.05$. The probability value of each cell refers to the row-column correlations for TPAs or buffers (e.g., burned area in TPA vs. fire incidence in TPA [e.g., 0.68**] or burned area in buffer vs. fire incidence in buffer, 0.88**). Crossed correlations (e.g., burned area in TPA vs. fire incidence in buffer) are not shown here because they were considered difficult to interpret.*
[b] *Standardized difference between TPA and its buffer.*

that might condition fire differences between the reserves and their buffers) and (2) absolute fire impacts for both buffer and TPA (concentrates on variables that might influence the amount of fire impacts [fire incidence and burned area] in each site).

We believed both approaches were equally interesting and therefore considered them both. For the relative analyses, all the explicative variables were also calculated in relative terms (e.g., pasture in TPA minus pasture in buffer). Due to the diversity of scales and units, the resulting variables were *z*-score standardized:

$$y_s = (y_{i,j} - \tilde{y}_j)/s_j, \tag{1}$$

where y_s is the standardized difference value for each reserve, y_i is the subtracted value between TPA and its buffer for the *i*th reserve for the *j*th variable, $\tilde{y}$ is the mean of the differences between TPA and buffer values for the *j*th variable, and *s* is the standard deviation of $(y_{i,j} - \tilde{y}_j)$, for the *j*th variable. We also standardized the absolute fire impacts, following Eq. 1.

We considered 10% an appropriate level of statistical significance because of our small sample size ($n = 12$) and the large variability expected across reserves. We used SPSS (version 11.5, SPSS, Chicago, Illinois) for the statistical analyses.

Results

Fire Incidence

From 1995 through 2005, TPAs in Chiapas displayed higher fire incidence than their buffers (TPA buffer) ($Z = 1.99$, $W = 8$, $p \leq 0.05$, $n = 12$; Fig. 2a). The variability among reserves was high however, and not all of them contributed to these trends (Fig. 2). Most reserves (10/12) had at least one fire during the 11-year time span, and 8 out of those 10 reserves displayed enhanced fire incidence inside the parks than in their buffers (Fig. 2a, Table 2). Although acceptable fire levels are yet to be defined in Chiapas' parks, most reserves in Chiapas contain large areas of fire-sensitive ecosystems, which were the ones with higher fire incidences (Table 2).

Comparative analyses of fire incidence inside and outside reserves for each land cover—as a way to consider flammability properties—yielded no significant differences for any vegetation type (Wilcoxon signed-rank test). Higher fire incidences in TPAs were, therefore, not related to a particular vegetation type burning consistently more frequently inside than outside reserves. Fire causality—as a potential explanation for the enhanced fire incidence inside TPAs—was similar inside TPAs to their buffers, with agrarian negligence being responsible for the majority of fires (58 and 56% of the total known causes, respectively). Deliberate burning accounted for 25 and 23% of fires in TPAs and buffers. Unknown causes corresponded to 13 and 18% of fires in TPAs and buffers, respectively.

Among the factors that influenced the relative fire incidence (TPAs buffers), only anthropogenic factors displayed significant trends. Enhanced fire incidence in TPAs was related to larger extensions of agrarian fields in the buffers than in the TPAs ($\rho \geq -0.77$, $n = 9$, $p \leq 0.01$) and to higher road densities inside TPAs than in the buffers ($\rho \geq 0.57$, $n = 11$, $p \leq 0.06$) (Table 3).

In absolute terms, pine-oak habitat was related to increased fire incidence both in TPAs and buffers, whereas evergreen rainforests were related to decreased fire incidence only in buffers (Table 3). None of the habitats we examined were significant in the relative analyses, meaning their presence influenced the amount of fire but did not explain the relative fire differences between TPA and their surrounding boundaries.

Burned Areas

On average, TPAs displayed larger burned areas than their buffers ($Z = 1.68$, $W = 11$, $p \leq 0.09$, $n = 12$; Fig. 2c). This pattern resulted from higher fire incidence and higher mean fire sizes inside TPAs than in their buffers ($Z = 1.68$, $W = 8$, $p \leq 0.09$, $n = 12$; Fig. 2). The total area burned was 87,645 ha (8.9% of the state protected area) and 43,520 (4.4% of the total buffer area) inside TPAs and in their buffers, respectively. Burned areas inside protected land ranged between 2% (Palenque) and 45% (Lagunas de Montebello) of the total protected area.

Relative differences of burned area between TPAs and their buffers were related to land cover factors; anthropogenic variables were not significant (Table 3). Thus, the most extensively burned TPAs corresponded to those with larger extensions of natural habitats in relation to their buffers ($\rho \geq 0.62$, $n = 12$, $p \leq 0.05$) (Table 3). Because of the way relative factors are calculated (natural habitats in TPA minus natural habitats in buffers), this relation also meant that parks with more degraded buffers tended to have larger burned areas inside TPAs.

None of our selected variables were related to the amount of burned area in TPAs or buffers in the absolute correlations (Table 3), with the exception of evergreen rainforests in the buffer areas. There was not, therefore, a consistent pattern among land covers that allowed us to predict fire hazard (e.g., danger associated with the fuels).

El Niño Effects

El Niño events (1998 and 2003) had a strong effect on the total burned areas inside TPAs compared with their buffers ($\chi^2 = 5376.5$, df $= 1$, $p < 0.0001$), whereas fire incidence was not significantly affected (Fig. 3a,b). The accumulated burned area during years 1998 and 2003 corresponded to 67% and 46% of the total burned area in TPAs, and buffers for the period under analysis (Fig. 3).

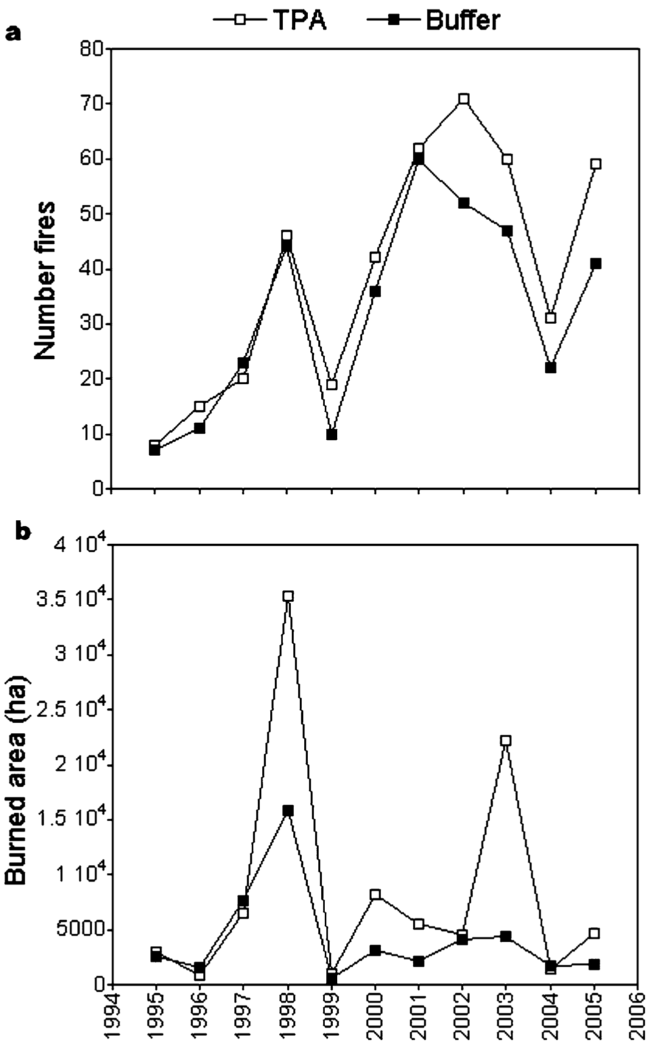

Figure 3. (a) Number of fires and (b) total burned area from 1995 through 2005 for tropical protected areas (TPA) and their corresponding buffers in Chiapas. The years 1998 and 2003 were El Niño years.

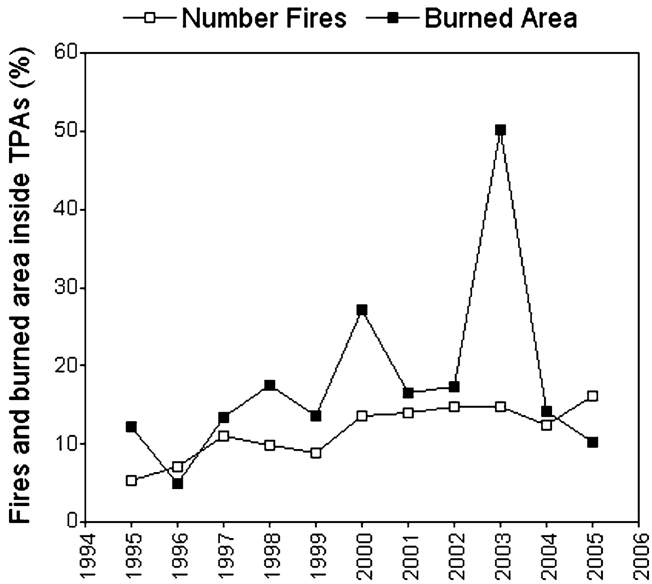

Figure 4. Percentage of total fires in Chiapas that occurred inside tropical protected areas (TPAs) and percentage of total area burned in Chiapas that occurred inside TPAs from 1995 through 2005 (1998 and 2003 were El Niño years).

Relative to the rest of the state, the area burned inside the reserves in 1998 and 2003 was 18% and 50%, respectively, of the total area burned and was 8% for both years in buffer areas (Fig. 4).

Discussion

The fire situation in Chiapas from 1995 through 2005 illustrates how tropical protected areas are inefficient at mitigating fire impacts within their boundaries. This trend, however, was highly variable among years and reserves. In the only reserve in common with Bruner et al.'s (2001) analysis, Lagunas de Montebello National Park, 45% and 47% of total burnable area burned in TPA and buffer, respectively (Fig. 2c). These high values reinforce the importance of fire as a first-level pressure in most of Chiapas' reserves and show that less fire in TPAs than their buffers (e.g., 45 in TPA vs. 47 in buffer) does not mean parks are an effective means of conservation. Although methodological and scale differences prevent further comparisons with Bruner et al's (2001) report, two aspects of their methodology must be considered: (1) Because of the nature of global reviews, mean trends can leave unattended first-order conservation problems that may be important regionally, such as fire in Mesoamerican parks. And (2) methodological approaches can disguise tendencies that would be obvious at other scales. In Bruner et al.'s (2001) study, 10-km-wide buffers were chosen without considering the total burnable area of each reserve (all reserves were >5000 ha). Although methodologically acceptable, in our analyses 5,502-ha reserves of burnable land were related to 1.5-km buffers (Lagunas de Montebello) and 187,036-ha reserves were related to 8.5-km buffers (Sepultura). Because 67% (62 out of 93) of Bruner et al's (2001) reserves were under 15,000-ha, 10-km buffers are an excessive width that may dilute fire trends.

Our study has its own methodological limitations: (1) Small sample size ($n = 12$) and heterogeneous nature of areas examined (e.g., different reserve sizes, vegetation types, years of establishment). These limitations mean our focus was local, reducing the statistical power of our tests. However, fire trends observed in neighboring areas (e.g., Yucatan [Eastmond & Faust 2006]; Guatemala [Albacete 2003; Ramírez 2003]) favor the idea that Chiapas' trends could be extrapolated to the Mesoamerican Biological Corridor. (2) The selection of the control area as a surrounding concentric belt of land (buffer) is a frequently used approach but suffers from comparability limitations (e.g., topographic-vegetation-fire comparisons). (3) Spatial location of fires with a single GPS point limits vegetation results. And (4) further research is required to determine whether factors with statistical relationships to fire trends are causal.

Fire Incidence

Human pressures are responsible for the increased fire incidence in protected areas, with agrarian negligence, increased accessibility (higher road densities), and higher extensions of agrarian fields being among the significant trends. The importance of agrarian activities as fire sources in Mesoamerica and the tropics in general has been mentioned repeatedly (e.g., Fule & Covington 1999; Eastmond & Faust 2006). Moreover, Dean (1995) and Gascon et al. (2000) report enhanced matrix harshness (meaning enhanced damage) in agricultural landscapes surrounding tropical forest fragments (e.g., frequently burned sugar cane plantations in southern Brazil surrounding the Atlantic Forest). This would be the case for some reserves such as La Encrucijada, which are embedded in 96% anthropogenic land covers (pastures and agriculture fields), where burning is a routine procedure. Other reserves such as La Sepultura, Palenque, El Ocote, and Agua Azul have buffers with almost 50% anthropogenic land covers (Table 2), suggesting the importance of buffer conservation plans to preserve protected areas. In some TPAs, such as Palenque and Agua Azul, half their protected area corresponds to frequently burned land covers (55% pastures and 49% agriculture, respectively) (Table 2), which brings into question what these reserves are meant to preserve.

Several authors discuss the relationship between the opening of new roads and the enhanced presence of fire in tropical areas (Nepstad et al. 2001; Cochrane 2003; Du Toit et al. 2004). Roads favor land invasions and therefore fire incidence. Moreover, if roads are wide enough, they can also contribute to changes in microclimatic conditions and edge effects, which favor the spread of fire (Laurance et al. 1998; Cochrane 2001). As is the case in other tropical areas, such as Brazil (Nepstad et al. 2002), economic development is vital to the development of the state, and infrastructure investments seem inevitable. The major challenge therefore is to strengthen frontier management in the region, enhance institutional cooperation, and select the most sustainable development alternatives. Large macroeconomic projects (e.g., Plan Panama Puebla) must be considered carefully because they can jeopardize conservation efforts. In Chiapas the Plan Panamá Puebla threatens the integrity of several TPAs: La Sepultura will be crossed by a federal motorway and Yaxchilan and Montes Azules will be affected by a dam (Wilkerson & Jeffrey 2001).

Burned Areas and El Niño Influence

Larger burned areas in protected areas than in their surroundings may relate to two different (but interacting) factors: fire-fighting practices and fuel variables. The remote location, steep slopes, and inaccessibility of many TPAs hamper fire-detection and fire-fighting activities. Those areas that are too remote or inaccessible are unwillingly, but irremediably, left to burn (P. Martínez, personal communication). Aerial supervision and several fire-fighting brigades are sent to these locations to supervise and control minor fronts. Moreover, severe fire seasons result in days when the number of simultaneously active fires exceeds fire-fighting capabilities (e.g., 56 active fires in Chiapas on 18 March 2003).

Fuel loads and fuel continuity play a key role in the total area burned. Thus, under severe drought (El Niño years), humid vegetation that is normally fire resistant becomes available to fire (Uhl & Kauffman 1990; Cochrane et al. 1999). The sudden availability of larger fuel loads and larger extensions of continuous forests inside TPAs than in their buffers, favor larger burned areas during El Niño events. Our results showed a significant correlation between natural habitat extent and burned area inside TPAs (Table 3) during El Niño years. The annual evolution of burned areas in TPAs and their buffers showed that TPAs were much more sensitive to El Niño events than their exteriors (Fig. 3). In these years, a few fires ran out of control and burned large areas (Román-Cuesta et al. 2003). Therefore, managers must concentrate on preventing and suppressing key fires where large fuel loads and fuel continuities exist.

Fires in La Selva El Ocote

Since the El Niño of 1982–1983, many parks have reported recurrent fire presence in areas already affected by previous fires (e.g., Giri & Shrestha 2000; Eldvidge et al. 2001; Cleary & Genner 2004). Despite this global awareness, when the 2003 El Niño fires affected the already burned areas of La Selva El Ocote (burned in one of the worst fire conflagrations of Chiapas in 1998; Asbjornsen et al. 2005) not much could be done. Thus, forests degraded by the previous El Niño resulted in available fuel loads up to 100 t/ha, which together with dry conditions, strong winds, inaccessibility to water, and extremely difficult access lead to the worst fire event in Chiapas in that year (Martínez et al. 2003). By the end of May, 20,000 ha had burned in the reserve. There was severe degradation of vegetation in some areas (Martínez et al. 2003) and complete vegetation removal in others (GFMC 2005), which represents a sound conservation failure in one of Mexico's top biodiversity areas. El Ocote forms part of the biological corridor Chimalapas-Uxpanapa-El Ocote (Selva Zoque), once one of the largest pristine extensions of cloud montane rainforests in North America (Asbjornsen et al. 2005).

Conclusions and Management Suggestions

Fire impacts in Chiapas were significantly higher in TPAs than in their buffers, meaning parks were not effective deterrents to fire. Differential fire trends between TPAs and their buffers were increased in El Niño years, meaning El-Niño-driven fires were more severe inside parks than in their buffers. Anthropogenic factors (agriculture and road density) played a major role in the enhanced fire incidence in TPAs, whereas natural habitat extents played a major role in the amount of area burned.

The problem of fire is not new in tropical areas, but the magnitude of its impacts is. Social and environmental synergisms have led to a complicated management situation, in which the knowledge gap in tropical fire ecology is an extra inconvenience. Although it is not possible to extrapolate our results to other tropical regions—especially out of the Mesoamerican area—tropical fires respond to similar factors, which can be analyzed to help determine potential management solutions: (1) the anthropogenic origin of fires, (2) sensitivity to El Niño, (3) large and available fuel loads and fuel continuity, and (4) lack of resources.

The management advantages and disadvantages of people in parks have been debated by Schwartzman et al. (2000) and Peres and Zimmerman (2001). In terms of fire reduction, people-free parks (categories I–IV of IUCN [World Conservation Union]) represent the ideal scenario. However, in highly populated areas such as Mesoamerica, few reserves can effectively control the incursion of people, and the social problems deriving from core-area protection frequently appear in the form of fire. Fagan et al. (2006) suggest that categories V and VI (people parks) can have significant conservation values as buffers or corridors, but the ability of these buffers and corridors to sustain biodiversity as stand-alone conservation units is uncertain. The fire situation in Chiapas and Guatemala's TPAs (Albacete 2003; Ramírez 2003) casts doubt on the conservation value of these categories and on the sustainability of the Mesoamerican Biological Corridor as a whole. Because people-free parks are not a realistic approach in Mesoamerica, projects have been developed to eliminate fire in parks and surrounding areas. The Pachuca Project, with the mucuna-maize green manure, is an interesting example (Eastmond & Faust 2006).

Larger burned areas during El Niño years are not new phenomena in Chiapas. In the 1986–1987 El Niño, more hectares were burned than in the 1997–1998 El Niño, and more mature forest was affected (Román-Cuesta et al. 2004). If climate change increases the frequency and magnitude of extreme events (IPCC 2001), fires in TPAs may emerge as an even greater problem in the future. Fire management and fire planning are among the conservation alternatives. Fire prevention is a key factor because it concentrates on fire causality (both human and environmental). The Climate Prediction Center (NOAA 2005) has an on line El Niño-La Niña diagnosis that helps track the ENSO evolution and intensity.

Fuel management reduces fuel loads, fuel flammability, and fuel continuity to avoid the start and spread of fire. Fuel management strategies are discussed in Agee et al. (2000), Gascon et al. (2000), and Finney (2001). Although fire management should benefit from fuel modification, a problem occurs when deciding which fuel modification practices best fit the various tropical ecosystems. Thus, in fire-intolerant humid forests, common fuel management practices, such as firebreaks or prescribed burning, can have the paradoxical effect of increasing fuel loads and fire risk (Martínez et al. 2003; Barlow & Peres 2004).

Funding for fire-related activities has increased in Chiapas since the 1998 El Niño. However, equipment, logistics, staff training, and restoration activities always require more money than the budget allows. Reinforcing institutional cooperation and strengthening the local social networks are among the most important strategies to obtain meaningful results (Martínez et al. 2003). Although still seriously underdeveloped, a well-managed local ecotourism network could benefit the conservation efforts of Chiapa's parks.

It is important to frame the problem of fire within a larger sociopolitical context in which development decisions have a direct influence on conservation efforts. Because the roots of the fire problem belong to the social and macroeconomic realm (Rodríguez-Trejo & Fulé 2003), any political decision and their derived activities will affect people's access to land and population redistributions, which will, in turn, affect fire. Protection and fire management planning, although important, will not fully address the problem of fire in tropical protected areas.

Acknowledgments

This work was been done under the financial support of the Secretaria de Relaciones Exteriores de Mexico. We thank M. Cochrane, D. McKenzie, D. Rodríguez-Trejo, and J. Retana for their comments on earlier versions of this manuscript. We thank the friendly and hardworking fire-fighting personal and dedicated fire managers of CONAFOR-Chiapas and the friends of CONANP for their help. Our gratitude to ECOSUR for offering their facilities and scientific discussions.

Literature Cited

Agee, J., B. Bahro, M. Finney, P. Omi, D. Sapsis, C. Skinner, J. van Wagtendonk, and C. Weatherspoon. 2000. The use of fuel breaks in landscape fire management. Forest Ecology and Management **127:**55-66.

Albacete, C. 2003. Guatemala: deliberate fires raze tropical forest and serve logging interests. Bulletin 70. World Rainforest Movement, Montevideo, Uruguay.

Asbjorsen, H., N. Velázquez-Rosas, R. García-Soriano, and C. Gallardo-Hernández. 2005. Deep ground fires cause massive above and below-ground biomass losses in Tropical Montane Cloud Forests in Oaxaca, Mexico. Journal of Tropical Ecology **21:**427-434.

Barlow, J., and C. Peres. 2004. Ecological responses to El Nino-induced surface fires in central Brazilian Amazonia: management implications for flammable tropical forests. Philosophical Transactions of the Royal Society of London B. **359:**367-380.

Brito, D., L. Oliveira, and M. Mello. 2004. An overview of mammalian conservation at Poço das Antas Biological Reserve, southeastern Brazil. Journal of Nature Conservation **12:**219-228.

Bruner, A., R. Gullison, R. Rice, and G. da Fonseca. 2001. Effectiveness of parks in protecting tropical biodiversity. Science **291:**125-128.

Cantú, C., R. Wright, J. Scott, and E. Strand. 2004. Assessment of current and proposed nature reserves of Mexico based on their capacity to protect geophysical features and biodiversity. Biological Conservation **115:**411-417.

Castillo-Santiago, M. A. 2002. Qué está pasando con los bosques y las selvas en Chiapas? Ecofronteras **17:**16-18.

Cleary, D., and M. Genner. 2004. Changes in rain forest butterfly diversity following major ENSO-induced fires in Borneo. Global Ecology and Biogeography **13:**129-140.

Cochrane, M. A. 2001. Synergistic interactions between habitat fragmentation and fire in evergreen tropical forests. Conservation Biology **15:**1515-1521.

Cochrane, M. A. 2003. Fire science for rainforests. Nature **421:**913-919.

Cochrane, M. A., and W. F. Laurance. 2002. Fire as a large-scale edge effect in Amazonian forests. Journal of Tropical Ecology **18:**311-325.

Cochrane, M. A., A. Alencar, M. D. Schulze, C. M. Souza, D. C. Nepstad, P. Lefebvre, and E. Davidson. 1999. Positive feedback in the fire dynamic of closed canopy tropical forests. Science **284:**1832-1835.

CONANP (Comisión Nacional de Areas Naturales Protegidas). 2003. Incendios Forestales 2003. Frontera Sur, Región X. México, D.F

CONANP (Comisión Nacional de Areas Naturales Protegidas). 2005. Categories of natural protected areas in Mexico. CONANP, Tuxtla, Chiapas. Available from http://www.conanp.gob.mx/anp/ (accessed June 2003).

Crutzen, P., and M. O. Andreae. 1990. Biomass burning in the tropics: impact on atmospheric chemistry and biogeochemical cycles. Science **250:**1669-1678.

Dean, W. 1995. With Broadax and firebrand: the destruction of the Atlantic Forest. University of California Press, Berkeley.

Deininger, K., and B. Minten. 2002. Determinants of deforestation and the economics of protection: an application to Mexico. American Journal of Agrarian Economy **84:**943-960.

Du Toit, J., B. Walker, and B. Campbell. 2004. Conserving tropical nature: current challenges for ecologists. Trends in Ecology & Evolution **19:**12-17.

Eastmond, A., and B. Faust. 2006. Farmers, fires and forests: a green alternative to shifting cultivation for conservation of the Maya forest? Landscape and Urban Planning **74:**267-284.

Elvidge, C., V. Hobson, K. Baugh, K. Dietz, Y. Shimabukuro, T. Krug, E. Novo, and F. Echavarria. 2001. DMSP-OLS estimation of tropical forest area impacted by surface fires in Roraima, Brazil: 1995 versus 1998. International Journal of Remote Sensing **22:**2661-2673.

Fagan, C., C. A. Peres, and J. Terborgh. 2006. Tropical forests: a protected-area strategy for the twenty-first century. In press in W. F. Laurance and C. Peres, editors. Emerging threats to tropical forests. University of Chicago Press, Chicago.

Finney, M. A. 2001. Design of regular landscape fuel treatment patterns for modifying fire growth and behavior. Forest Science **47:**219-228.

Foster, D., M. Fluet, and E. Boose. 1999. Human or natural disturbance: landscape-scale dynamics of tropical forests of Puerto Rico. Ecological Applications **9:**555-572.

Fule, P., and W. Covington. 1999. Fire regime changes in La Michilía Biosphere Reserve, Durango, México. Conservation Biology **13:**640-652.

Gascon, C., B. Williamson, and G. da Fonseca. 2000. Receding forest edges and vanishing reserves. Science **288:**1356-1358.

Giri, C., and S. Shrestha. 2000. Forest fire mapping in Huay Kha Khaeng Wildlife Sanctuary, Thailand. International Journal of Remote Sensing **21:**2023-2030

GFMC (Global Fire Monitoring Center). 2005. Pictures of El Ocote 2003 fires. GFMC, Freiburg, Germany. Available from http://www.fire.uni-freiburg.de/photos/mx/mx_1.htm (accessed March 2005).

Goldammer, J. 1993. Fire management. Pages 1221-1268 in L. Pancel, editor. The tropical forestry handbook. Springer-Verlag, Berlin.

Goldammer, J. 1999. Forests on fire. Science **284:**1782-1783.

Goldammer, J., and B. Seibert. 1990. The impact of droughts and forest fires on tropical lowland rain forest of Eastern Borneo. Pages 11-31 in J. G. Goldammer, editor. Fire in the tropical biota. Ecosystem processes and global challenges. Ecological Studies 84. Springer-Verlag, Berlin.

Holdsworth, A., and C. Uhl. 1997. Fire in the Amazonian selectively logged rain forest and the potential for fire reduction. Ecological Applications **7:**713-725.

IHN (Instituto Historia Natural). 2004. Proyecto protección y desarrollo sustentable en áreas naturales protegidas. Incendios forestales período 2000. IHN, México D.F.

INEGI (Instituto Nacional de Estadística y Geografía). 2000. Anales de estadística para el Estado de Chiapas, 2000. Instituto Nacional de Estadística, Geografía e Informática, Gobierno del Estado de Chiapas, Tuxtla Gutiérrez, Chiapas, México.

IPCC (International Panel on Climate Change). 2001. Climate change 2001: the scientific basis. Pages 6, 28 in F. Roos, L. Ramírez-Rojas, P. Stone and J. Zillman, editors. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental (IPCC). IPCC, Geneva, Switzerland.

Kinnaird, M., and T. O'Brien. 1998. Ecological effects of wildfire on lowland rainforest in Sumatra. Conservation Biology **12:**954-956.

Laurance, W. F., L. V. Ferreira, J. M. Rankin-de Merona, and S. G. Laurance. 1998. Rainforest fragmentation and the dynamics of Amazonian tree communities. Ecology **79:**2033-2040.

Malingreau, J. G., G. Stephens, and L. Fellows. 1985. Remote sensing of forest fires in Kalimantan and Northern Borneo in 1982-1983. Ambio **14:**314-321.

Martínez, P., J. Velázquez, and R. M. Román-Cuesta. 2003. Versión preliminar del plan de manejo del fuego Selva El Ocote, Chiapas, México. Available as Fire management plan, Selva El Ocote, Chiapas from http://www.fire.uni-freiburg.de/GlobalNetworks/MesoAmerica/MesoAmerica_3_b.html (accessed September 2004).

NFI (National Forestry Inventory). 2000. Inventario de los recursos forestales en Mexico, 1:250,000. NFI, México, D.F.

Nepstad, D. C., A. Veríssimo, A. Alencar, C. Nobre, E. Lima, P. Lefebvre, P. Schlesinger, C. S. Potter, P. Moutinho, and E. Mendoza. 1999. Large-scale impoverishment of Amazonian forests by logging and fire. Nature **398:**505-508.

Nepstad, D. C., G. O. Carvalho, A. C. Barros, A. Alencar, J. P. Capobianco, J. Bishop, P. Moutinho, P. A. Lefebvre, U. L. Silva, and E. Prins. 2001. Road paving, fire regime feedbacks, and the future of Amazon forests. Forest Ecology and Management **5524:**1-13.

Nepstad, D., D. McGrath, A. Alencar, A. Barros, G. Carvalho, M. Santilli, and C. Vera Díaz. 2002. Frontier governance in Amazonia. Science **295:**629-630.

NOAA (National Oceanic and Atmospheric Administrations). 2005. El Niño diagnostic discussion. Climate Prediction Center, Camp Springs, Maryland. Available from http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/enso_advisory/ (accessed March 2005).

Peres, C. A., and B. Zimmerman. 2001. Perils in parks or parks in peril? Conservation Biology **15:**793-797.

Pons, X. 2000. MiraMon. Sistema d'Informació Geogràfica i software de Teledetecció. Centre de Recerca Ecològica i Aplicacions Forestals, Bellaterra, Spain.

Ramírez, A. 2003. Guatemala fire emergency. GFMC, Freiburg, Germany. Available from http://www.fire.uni-freiburg.de/GFMCnew/2003/0509/20030509_gt.htm (accessed March 2005).

Rodríguez-Trejo, D., and P. Fulé. 2003. Fire ecology of Mexican pines and a fire management proposal. International Journal of Wildland Fire **12:**23-37.

Román-Cuesta, R. M., M. Gracia, and J. Retana. 2003. Environmental and human factors influencing fire trends in ENSO and non-ENSO years in tropical Mexico. Ecological Applications **13:**1177-1192.

Román-Cuesta, R. M., J. Retana, and M. Gràcia. 2004. Fire trends in tropical Mexico: a case study of Chiapas. Journal of Forestry **102:**26-32.

Sanford, R., J. Saldarriaga, K. Clark, C. Uhl, and R. Herrera. 1985. Amazon rain-forest fires. Science **227:**53-55.

SEMARNAT (Secretaría de Medio Ambiente y Recursos Naturales). 2002. Entidades federativas con mayor superficie afectada. SEMARNAT, México, D.F.

SMN (Servicio Meteorológico Nacional). 2000. Precipitación media, máxima y mínima de la República Mexicana. SMN, México, D.F.

Soulé, M., and M. A. Sanjayan. 1998. Conservation targets: do they help? Science **279:**2060-2061.

Schwartzman, S., A. Moreira, and D. Nepstad. 2000. Rethinking tropical forest conservation: perils in parks. Conservation Biology **14:**1351-1357.

Uhl, C., and J. B. Kauffman. 1990. Deforestation effects on fire susceptibility and the potential response of the tree species to fire in the rainforest of the eastern Amazon. Ecology **71:**437-449.

Wilkerson, S., and K. Jeffrey. 2001. Usumacinta River Dam Project. Pages 791-792 in S. Evans and D. Webster, editors. Archaeology of Ancient Mexico and Central America: an encyclopedia. Garland, New York.