Fire Regime Changes in La Michilía Biosphere Reserve, Durango, Mexico

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Abstract: *The ability of reserves to maintain natural ecosystem processes such as fire disturbance regimes is central to long-term conservation. Fire-scarred tree samples were used to reconstruct fire regimes at five study sites totaling approximately 230 ha in pine (*Pinus *spp.) and oak (*Quercus *spp.) forests of La Michilía Biosphere Reserve on the dry east slope of the Sierra Madre Occidental, Durango, Mexico. Study sites covered a 20-km environmental gradient of elevation, topography, and human land uses. Plant communities ranged from oak-pine to mixed conifer forests. Fires were frequent at all sites prior to 1930, when large-scale grazing of domestic livestock was initiated. Widespread fires have been excluded from four of the five sites since 1945, with an essentially uninterrupted regime of frequent fires continuing only in the reserve core. Xeric sites had many, smaller fires, whereas mesic sites had fewer but larger fires. On a reserve-wide scale, a fire burned on at least one site nearly every year, usually in the dry spring or early summer season, but fire years were rarely synchronous among the sites. Fire occurrence was weakly related to the Southern Oscillation climate pattern; major reserve-wide fire years almost never coincided with wet Southern Oscillation extremes but only occasionally matched dry extremes. Maintenance of the long-term frequent-fire regime in the reserve core is one indicator that the biosphere reserve model has been successful in conserving natural processes, but the protected area is small (7000 ha). Because of the key role of frequent-fire regimes in regulating ecosystem structure and function, restoration of the ecological role of fire disturbance is a desirable conservation strategy.*

Cambios en el Régimen de Incendios en la Reserva de la Biosfera de La Michilía, Durango, México

Resumen: *La habilidad de las reservas de mantener procesos naturales del ecosistema como son los regímenes de perturbaciones causadas por incendios es central en la conservación a largo plazo. Para reconstruir los regímenes de incendios usamos árboles con cicatrices causadas por fuego en cinco sitios de estudio totalizando aproximadamente 230 ha de bosques de pinos (*Pinus *spp.) y encinos (*Quercus *spp.) de la Reserva de la Biosfera de La Michilía localizada en la vertiente seca del Este de la Sierra Madre Occidental, Durango, México. Los sitios de estudio cubrieron un gradiente ambiental de elevación, topografía y uso humano del suelo de 20 km; las comunidades de plantas variaron de encino-pino a bosques mixtos de coníferas. Los incendios fueron frecuentes en todos lo sitios antes de 1930, cuando se inició un pastoreo de animales domésticos a gran escala. Los incendios de distribución amplia han sido excluídos de cuatro de cinco de los sitios desde 1945, con un régimen ininterrumpido de incendios escenciales continuando sólo en la zona núcleo de la reserva. Los sitios xéricos tuvieron muchos incendios pequeños, mientras que los sitios mésicos tuvieron pocos incendios pero prolongados. En una escala amplia de reserva, se presentó un incendio en por lo menos un sitio cada año, normalmente en la estación seca de primavera, o temprano durante el verano, pero los años con incendios estuvieron poco sincronizados entre sitios. La ocurrencia de incendios estuvo débilmente relacionada con el patrón de oscilación de clima del Sur; los incendios mayores de la reserva casi nunca coincidieron con oscilaciones del Sur extremamente húmedas, pero ocasionalmente armonizaron con oscilaciones del Sur extremadamente secas. El mantenimiento de regímenes de incendios frecuentes a largo plazo en el núcleo de la reserva es un indicador de que el modelo de la reserva de la biósfera ha sido exitoso en la con-*

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servación de procesos naturales, pero el área protegida es pequeña (7000 ha). Debido al papel clave de los regímenes de incendios frecuentes en la regulación de la estructura y función de ecosistemas, la restauración del papel de la perturbación por incendios es una estrategia deseable de conservación.

Introduction

The key role of frequent, low-intensity surface-fire regimes in regulating forest density, species composition, and dead biomass in long-needled pine forests (*Pinus* section Ponderosae) has been well established in western North America (Covington et al. 1994; Arno et al. 1995; Fulé & Covington 1996; Swetnam & Baisan 1996). But undisrupted frequent-fire regimes, those with fire-return intervals of 1–25 years (Pyne et al. 1996), continue in unharvested forests in only a few forests of northwestern Mexico, the southernmost range of Ponderosae ecosystems (Leopold 1937; Minnich et al. 1995; Fulé & Covington 1996). Because these areas represent rare examples of continuing, natural fire-disturbance regimes, they are valuable sites for the study of processes such as regeneration, mortality (Savage 1997), habitat use by wildlife (Minnich et al. 1995), and relationships between fire regime, forest structure, and spatial patterns of trees (Fulé & Covington 1997, 1998). The opportunity to learn from these sites may be limited in the future, however, because only a tiny fraction of forests in northern Mexico are protected, and many of these lands are degraded (Sánchez-Vélez 1987).

Frequent fires in northern Mexico appear to maintain relatively open forests by thinning small trees, limiting tree seedling establishment, and keeping fire-susceptible conifers (*Abies*, *Pseudotsuga*) from invading mesic pine sites (Barton 1995; Minnich et al. 1995; Fulé & Covington 1997, 1998). At sites in northwestern Durango, Mexico, where fire has been excluded for 30–50 years, Fulé and Covington (1997) found that densities of small trees increased together with forest floor depth and coarse woody debris loadings, leading to forest structural conditions that could support stand-replacing fire behavior. These changes parallel those in ponderosa pine (*Pinus ponderosa*) ecosystems of the United States, where a century or more of fire exclusion initiated by livestock grazing, fire suppression, and logging associated with EuroAmerican settlement has led to declines in ecosystem health (Kolb et al. 1994) as measured by imbalances in ecosystem processes (e.g., decomposition rates, tree mortality rates), loss of diversity, and reduced resistance to catastrophic change, especially high-intensity wildfire.

Fire-disturbance regimes are strongly influenced by local environmental differences associated with elevational gradients, topographic characteristics, and human influences. Environmental site factors can affect fire regimes in several ways: (1) production of vegetation (fuel) varies with site characteristics; (2) climatic factors that affect fire behavior, including windspeed and relative humidity, are related to site characteristics such as elevation and aspect; and (3) human activities, which are a predominant determining factor of most modern fire regimes, are usually associated with distinct site characteristics (e.g., lowlands are used primarily for agriculture and settlement, uplands for livestock grazing or forestry). Interactions of these factors can create complex patterns. For example, although the lower limits of species' distributions were regulated primarily by soil moisture in a coniferous Madrean forest in southeastern Arizona, fire disturbance appeared to be a strong force controlling plant distributions at elevations above the minimal physiological threshold (Barton 1993, 1994).

Although similarities between fire-adapted forests in Mexico and the United States suggest that analogous patterns are likely to prevail across environmental gradients in northern Mexico, few or no contemporary studies exist (González-Cabán & Sandberg 1989). As Mexico recovers from the unprecedented wildfires of 1998, fire regime information is important for assessing wildfire behavior and selecting appropriate fire management strategies. We compared fire regimes at sites selected across an environmental gradient in La Michilía Biosphere Reserve on the dry eastern slope of the Sierra Madre Occidental. We asked the following questions: (1) What are the long-term fire-disturbance patterns (frequency, size, relationship to climate and environmental conditions)? (2) Have fire regimes been recently disrupted? (3) Has the conservation design, in this case a biosphere reserve, been effective in conserving fire as a natural ecological process?

Study Area

La Michilíla Biosphere Reserve is located on the eastern slopes of the Sierra Madre Occidental along the border of the states of Durango and Zacatecas, (lat 23°15′–23°35′N, long 104°–104°20′W, crossed by the Tropic of Cancer; Fig. 1). The reserve was established in 1975 for the conservation of genetic diversity and scientific investigation (Halffter 1978). As with other biosphere reserves around the world, La Michilía is not a preserve but is managed for sustainable uses compatible with

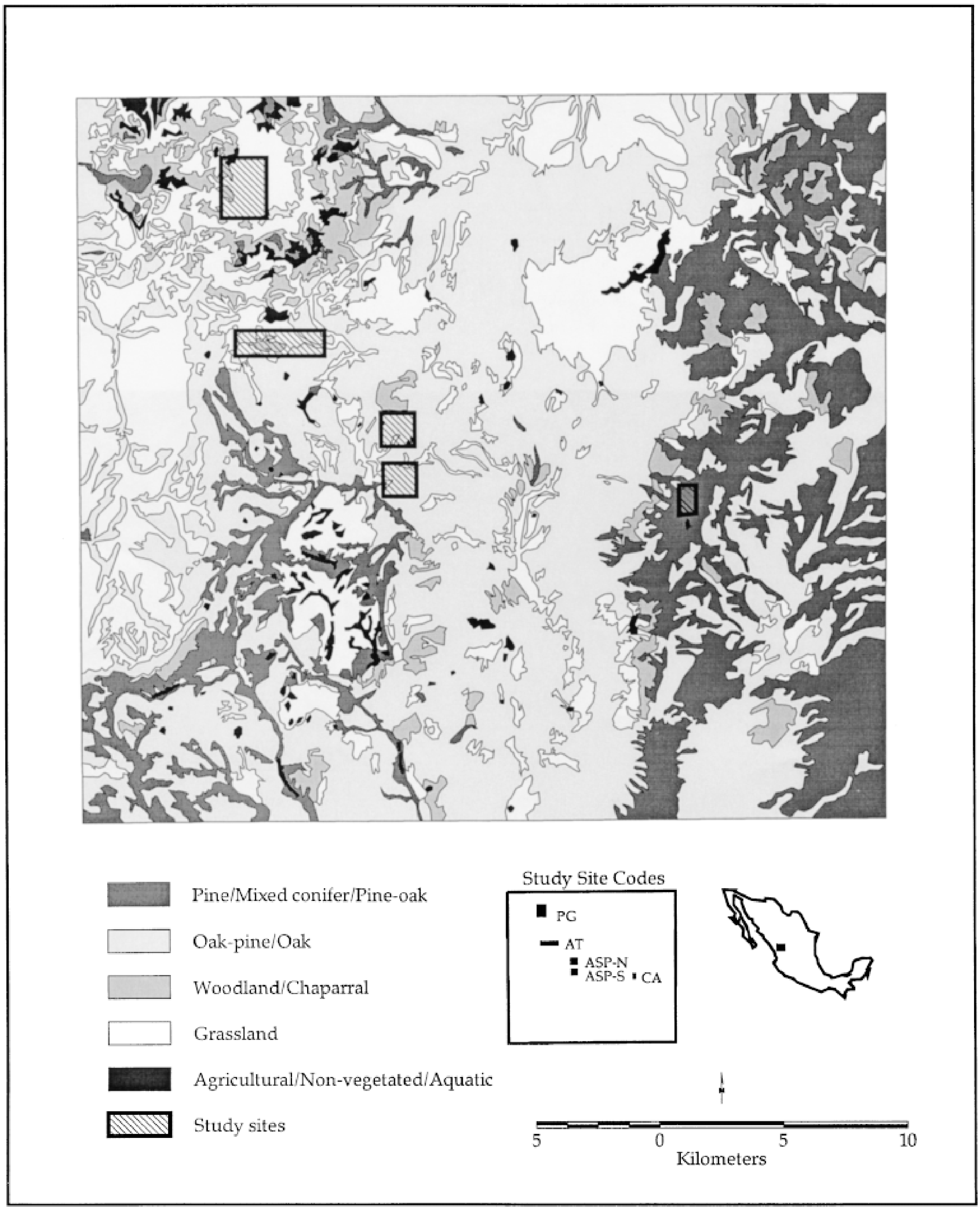

Figure 1. Study sites at La Michilía Biosphere Reserve (vegetation map from González-Elizondo et al. 1993).

long-term ecological conservation. The reserve site was selected because (1) it represents millions of hectares of dry pine-oak forests and grasslands in northern and central Mexico (in broader terms, even larger areas are represented: La Michilía is paired in the Man and the Biosphere system with Beaver Creek Biosphere Reserve in Arizona, approximately 1100 km to the north); (2) it contains an elevational range that includes communities from high desert to alpine, representing some of the wide biological diversity found in Mexico (Toledo & Ordóñez 1993); and (3) the geographic isolation and low human population density of the region has prevented extensive use of forest resources, leaving the reserve ecosystem "natural, rich, and gifted with a great capacity for auto-regulation" (Barbault 1978:51).

González-Elizondo et al. (1993) summarized the physical characteristics of the reserve. Located between two small mountain ranges, the Sierra de Michis and Sierra de Urica, which form an eastward extension of the Sierra Madre Occidental, the reserve ranges between 2000 and 2985 m in elevation. Soils and geologic formations are of igneous origin, predominantly rhyolitic. Annual precipitation fluctuates between 600 and 860 mm, with a rainy season from May to September, a period of occasional rains from October to January, and a dry period from February to April. The average annual temperature is 11.6° C, with an average high temperature in June of 23.8° C and an average low temperature in January of −2.7° C. Ownership of the reserve is mixed, with a 7000-ha government-owned central core and approximately 70,000 ha in the "buffer zone" under private ownership or communally owned lands called *ejidos.*

Five study sites totaling approximately 230 ha were selected to represent an environmental gradient crossing the reserve (Table 1), including the major forest communities of oak-pine (low elevation, xeric), pine-oak (low elevation, intermediate), pine-oak (high elevation, mesic), and mixed conifer (high elevation, mesic). Tree species are listed in Table 2. The study sites were chosen as representative areas following review of previous studies and a reconnaissance of the reserve. The gradient also coincides with human settlement and land-use patterns, as represented in the biosphere reserve management scheme: the low-elevation sites, Arroyo San Pedro (ASP) and Arroyo Taray (AT) are in the reserve buffer zone, where human land use is most intense. Human impact is more limited at the higher sites, Cerro Almagre (CA) and Playa Grande (PG). The CA site is remote, steep, and far from water, but the land is communally owned and seasonally available for grazing. The PG forest is in the core area, the only part of the biosphere reserve officially protected from extractive uses.

Methods

We sampled fire-scarred trees in June 1996 at all sites except Playa Grande (April 1997). Partial cross-sections were cut from scarred "catfaces" on trees, logs, and stumps of conifers apparently containing the oldest and/or most extensive fire records. Several oak samples were collected but proved to be unusable due to rot in the scarred areas. We attempted to collect 30–40 fire-scarred samples per site, but sample size was limited at the ASP sites due to the predominance of oaks and the low density of old pine trees. Samples were mapped when collected and were well distributed throughout the study areas, except for the ASP-S site, where fire-scarred pines were found primarily along the western and eastern sides of the 30-ha area.

In the lab, samples were mounted and surfaced with fine-grit sandpaper. A total of 112 samples was crossdated (Stokes & Smiley 1968) by means of characteristic patterns of narrow marker years: 1789, 90, 1805, 26, 28, 30, 36, 38, 57, 82, 87, 93, 1904, 25 (thin latewood), 29, 32, 57, 80, 82, and 89. Master tree-ring chronologies developed elsewhere in Durango by Harlan (1973) and D. W. Stahle (personal communication) also were used in crossdating. After initial dating, ring widths of all samples were measured in order to check dating with the Cofecha program (Grissino-Mayer & Holmes 1993), and all dates were independently visually confirmed by another dendrochronologist. The season of fire occurrence (Baisan & Swetnam 1990) was estimated based on the

Table 1. Summary of study-site characteristics in the La Michilía Biosphere Reserve listed on an environmental gradient from most xeric to most mesic.

Study site	*Code*	*Area (ha)*	*Elevation (m)*	*Slope (%)*	*Aspect*	*Vegetation type/land use history*
Arroyo San Pedro (north)	ASP-N	30	2450	5	flat	oak-pine/continual grazing, wood products, charcoal/communal ownership (ejido). ASP-N site completely burned by wildfire, May 1996.
Arroyo San Pedro (south)	ASP-S	30	2450	5	flat	similar to ASP-N, but not burned in 1996.
Arroyo Taray	AT	70	2375	30	north	pine-oak/continual grazing, some wood products/private.
Playa Grande	PG	70	2720	20	west	pine-oak/scientific and recreational use/government ownership (biosphere reserve core area).
Cerro Almagre	CA	30	2850	40	north	mixed conifer (Douglas-fir, pine-oak)/seasonal grazing/communal ownership (ejido).

Table 2. Tree species encountered on the study sites in La Michilía Biosphere Reserve.

Family	*Species**
Cupressaceae	*Juniperus deppeana* var. *zacatecensis* Steud. *J. durangensis* Mtz.
Ericaceae	*Arbutus arizonica* (Gray) Sarg. *A. tessellata* Sorensen *A. xalapensis* HBK. *A.* spp. *Arctostaphylos pungens* HBK.
Fagaceae	*Quercus arizonica* Sarg. *Q. coccolobifolia* Trel. *Q. crassifolia* H. & B. *Q. eduardii* Trel. *Q. hartwegii* Benth. *Q. rugosa* Neé *Q. sideroxyla* H. & B. *Q. urbanii* Trel. *Q.* spp.
Oleaceae	*Fraxinus* sp.
Pinaceae	*Pinus arizonica* Engelm. *P. ayacahuite* var. *brachyptera* Shaw *P. cembroides* Zucc. *P. chihuahuana* Engelm. *P. durangensis* Martínez *P. engelmanii* Carr. *P. leiophylla* Schl. *et* Cham. *P. lumholtzii* Rob. *et* Fern. *P. teocote* Schl. *et* Cham. *P.* spp. *Pseudotsuga menziesii* (Mirb.) Franco

**Scientific names of deciduous species are from González-Elizondo et al. (1991) and González-Elizondo et al. (1993); conifer names are from Rentería-Arrieta and García-Arévalo (1997).*

relative position of each fire lesion within the annual ring according to the following categories: EE (early earlywood), ME (middle earlywood), LE (late earlywood), L (latewood), and D (dormant). Dormant season scars were assigned to the year of the following earlywood (i.e., spring fires), a convention that appears valid for the spring drought–summer monsoon climate pattern of northern Mexico (Fulé & Covington 1996, 1997) and the southwestern United States (Baisan & Swetnam 1990). Phenological data exist for ponderosa pine (*Pinus ponderosa*) in southern Arizona, permitting calendar dates to be assigned to these within-ring positions (Baisan & Swetnam 1990). Because we have no such information for the species and region studied here, fires were divided only into "spring" (D + EE) and "summer" (ME + LE + L) groups.

Fire-history data were analyzed with the FHX2 software (Grissino-Mayer 1995). Analysis at each site began with the first year with an adequate sample depth (Grissino-Mayer et al. 1994), defined as the first fire year recorded by 10% or more of the total sample size of "recording" trees at each site. Recording trees are those with open fire scars or other injuries (e.g., lightning scars), leaving them susceptible to repeated scarring by fire (Swetnam & Baisan 1996). A common fire-history ending date of 1996 was used (sites measured in June 1996 were revisited in April 1997 to check for fires later in 1996; no evidence was found).

Fire-return intervals were analyzed statistically in different subcategories related to the size and/or intensity of past fires. The size of past fires in frequent-fire ecosystems cannot be precisely reconstructed because most overstory trees survive such fires (Swetnam & Baisan 1996), precluding fire-history methods based on stand ages and stand mapping (e.g., Heinselman 1973). Swetnam and Baisan (1996), argue, however, that fire years in which only one or two samples were scarred probably represent relatively small fires, whereas fire years in which a greater proportion of samples were scarred represent relatively larger fires. Accordingly, the fire data were filtered to look at progressively greater proportional scarring. First, all fire years, even those represented by a single scar, were considered. Then only those fire years were included in which, respectively, 10% or more and 25% or more of the recording samples were scarred. Comparing study areas of different sizes may be misleading because larger study areas may encompass more small fires, leading to an artificially high fire frequency compared to that of smaller study areas. Therefore we divided the two larger study areas (AT and PG, 70 ha each) in half geographically and compared fire regime results on an approximately equal-area basis (approximately 35 ha versus 30 ha each for the smaller study areas of ASP-S, ASP-N, and CA).

The statistical analysis of fire-return intervals includes several measures of central tendency: the mean fire interval (MFI, average number of years between fires), the median, and the Weibull median probability interval (WMPI). This last statistic is a central measure in the Weibull distribution, used to model asymmetric fire-interval distributions and to express fire-return intervals in probabilistic terms (Grissino-Mayer et al. 1994; Swetnam & Baisan 1996). Because fire-return intervals are rarely normally distributed, the WMPI is preferred over the MFI, although the values are often numerically similar. Reserve-wide fire occurrence among sites was analyzed over the 108 years (1837–1945) during which all five sites shared recording samples. The three longer-record sites were analyzed separately for reserve-wide fire occurrence over the longer period of 166 years (1779–1945). During both periods, fires *within* sites were analyzed in the all-scar and 25%-scar categories to examine possible differences in fire regime between smaller and larger fires. Finally, to investigate the occurrence of simultaneous fires across the Michilía landscape, fires *between* sites were compared in three categories: all fire years (fire at any site), fire years at 50% or more of the sites, and fire years represented at 75% or more of the sites.

To see whether pre-exclusion fire-return intervals and percentage of scarring had changed over time, the fire records prior to recent fire exclusion were divided into earlier and later halves at each study site and compared. Fire distributions were tested for significantly different means (*t* test), variances (*F* test), and distributions (Kolmogorov-Smirnov test). The alpha level for all tests was 0.05. In addition, the spatial homogeneity of fires in the two nearby Arroyo San Pedro study sites was investigated by testing the synchroneity of fire years (chi-square tests, 2 × 2 and 2 × 1 contingency tables [Grissino-Mayer 1995]). Additional detail on statistical procedures is presented by Swetnam and Baisan (1996) and Grissino-Mayer (1995).

Results

Low-Elevation Oak-Pine Forest

Numerous fires burned in the past in these dry forests, but both sites entered an extended period of fire exclusion beginning in the early 1930s (Fig. 2). The fire-free period at ASP-N lasted 64 years, except for a 1966 scar on a single sample tree, until an intense 1996 wildfire caused substantial tree mortality ($n = 15$ fire-scarred samples). The ASP-S site had fire exclusion since 1930, except for a single sample scarred in 1949 ($n = 6$ fire-scarred samples). Before fire exclusion (1837–1932), the ASP-N site had a Weibull median probability interval (WMPI) of 3.7 years, including all scars (Table 3). The 10%-scarred category was nearly identical to the all-scar category, indicating that most fire years are represented by at least two scarred samples. But the WMPI of the 25% category, 5.5 years, is about 50% higher, suggesting that a number of fires may not have grown large enough to cross the entire study area (30 ha). Fire patterns and pre-exclusion WMPI values were similar at ASP-S. (The all-scar and 10%-scarred categories were identical to each other at ASP-S due to the small sample size.)

The effect of fire exclusion was most striking in comparing the pre-exclusion fire frequencies to the post-exclusion fire records: only one fire in 66 years at ASP-S (scarring only 1 sample tree in 1949) and two fires in 64 years at ASP-N (scarring 1 sample tree in 1966, crossing the entire area in 1996), in contrast to pre-exclusion WMPI values of 4.7 and 3.7 years, respectively.

Fire years were highly asynchronous between the two sites, even though the two ASP sites were close together, had similar vegetation types and land-use patterns, and had nearly identical fire regimes in statistical terms (Tables 3 & 4). The fire chronologies were not statistically independent between the two sites (chi-square contingency test, 2 × 2 contingency table, $p < 0.005$), but the number of synchronous fire dates was smaller than asynchronous dates (chi-square contingency test, 2 × 1 contingency table, $p < 0.05$).

Low- and High-Elevation Pine-Oak Forest

Fire frequency at AT was highest of all the sites until 1945 ($n = 33$ fire-scarred samples; Table 3, Fig. 2). The difference between the all-scar WMPI and the 25%-scarred WMPI was nearly 75%, the highest of the study sites, but both WMPI values were the lowest of all sites in their respective categories, suggesting that AT had the greatest total number of small as well as large fires. Division of the AT samples into two geographic halves, representing approximately 35 ha each, caused no significant difference in fire frequency in any category (all, 10%, or 25% scarred), except for an increase in the all-scar MFI to 4.95 for the western half of site AT. Thus, fire frequency results were robust when converted to approximately equal-area terms with the 30-ha study sites, supporting the direct cross-site comparison presented in Table 3. No fires at all were recorded in the 51 years since 1945, making AT the only site of the five with such an abrupt and well-defined disruption of the frequent-fire regime.

Widespread frequent fires continued up to the present in the reserve core at PG, the only site with a relatively undisrupted fire regime ($n = 32$ fire-scarred samples; Fig. 2). Even at PG, fire frequency declined after 1945. A long fire-free period occurred between 1945 and 1971, but this 26-year interval is only about twice as long as the maximum pre-1945 fire-free period of 16–17 years (Table 3). In contrast, the recent 51 years of fire exclusion at AT is about five times longer than the maximum predisruption interval. The post-1945 fires at PG, in 1971 and 1989, scarred nearly all of the sample trees, apparently similar in extent and effects on forest structure to the pre-1945 fires (P.Z.F., unpublished data).

Fire-return intervals were longer (7–9.5 years) at PG than the pre-exclusion fire intervals at the lower sites, and most fires appear to have been relatively large: the 25%-scarred WMPI is only about 20% higher than the all-scar WMPI (Table 3). There was low variability (standard deviation) in the fire-interval distribution (Table 3). Only one pair of fires occurred in subsequent years (1944 and 1945), showing a clear geographic demarcation between the fires. The 1944 fire burned approximately 20 ha of the study site (based on the mapped locations of the fire-scarred sample trees), whereas the 1945 fire covered the remaining 50 ha. Division of the PG samples into two halves, representing approximately 35 ha each, caused no significant difference in fire frequency in any category (all, 10%, or 25% scarred), again supporting the direct cross-site comparison presented in Table 3.

High-Elevation Mixed Conifer Forest

Fire regime changes at site CA, at the crest of the Sierra Urica on the border between Durango and Zacatecas, were the most complex of all the sites ($n = 26$ fire-scarred samples; Fig. 2). Frequent fires occurred up to 1893, fol-

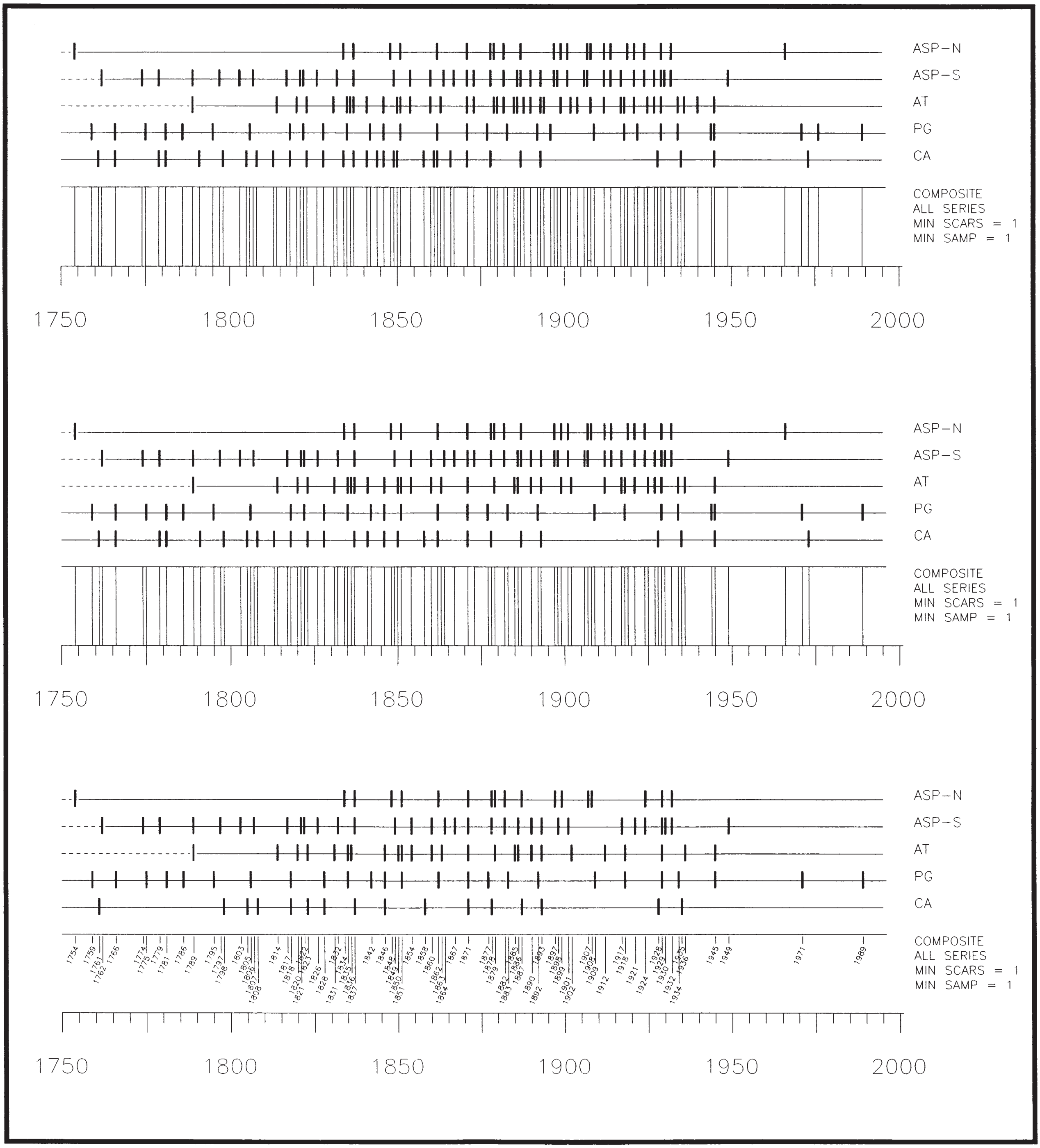

Figure 2. Comparison of fire regimes at the study sites in three categories: all fires, those that scarred only a single sample tree (top); fires scarring 10% or more of the sample trees on each site (middle); and fires scarring 25% or more of the sample trees (bottom). ASP-N, ASP-S, AT, PG, CA are site codes (see Table 1 and Fig. 1).

lowed by a 35-year break and then the return of widespread fires in 1928 and 1935. Most recently, a 51-year fire-exclusion period has prevailed up to the present, except for apparently localized fires in the same portion of the site, near the top of the mountain, in 1945 and 1973. Before 1893 the fire regime at CA was most similar to those of the lower-elevation sites: the WMPI (all scar) was 4.8 years and the WMPI (25% scarred) was about twice as long (Table 3). The 35-year, fire-free period between 1893 and 1928 was nearly three times longer than the maximum pre-1893 interval for the all-scar and 10%-scar distributions, but it was actually shorter than the 37-year maxi-

Table 3. Fire return intervals at the study sites in La Michilía Biosphere Reserve.*

Site/analysis period, scar category	*Number of intervals*	*Mean (MFI)*	*Median*	*SD*	*Minimum*	*Maximum*	*Weibull median probability interval*
Site ASP-N/1837–1996 (FULL)							
all scars	25	6.36	3	8.23	1	34	4.63
10% scarred	22	7.23	5	8.54	1	34	5.43
25% scarred	16	9.94	5	15.38	2	64	6.67
Site ASP-N/1837–1932 (PRE)							
all scars	23	4.13	3	2.93	1	11	3.73
10% scarred	20	4.75	4.5	3.02	1	11	4.33
25% scarred	15	6.33	5	5.55	2	23	5.47
Site ASP-S/1779–1996 (FULL)							
all scars	33	6.58	4	8.04	1	47	5.41
10% scarred	33	6.58	4	8.04	1	47	5.41
25% scarred	30	7.23	5	8.29	1	47	6.08
Site ASP-S/1779–1930 (PRE)							
all scars	31	4.87	4	2.50	1	12	4.68
10% scarred	31	4.87	4	2.50	1	12	4.68
25% scarred	28	5.39	4.5	2.56	1	12	5.24
Site AT/1831–1996 (FULL)							
all scars	37	4.46	3	8.05	1	51	3.30
10% scarred	29	5.69	4	9.06	1	51	4.17
25% scarred	21	7.86	6	10.37	1	51	5.95
Site AT/1831–1945 (PRE)							
all scars	36	3.17	3	1.73	1	8	2.97
10% scarred	28	4.07	4	2.51	1	10	3.70
25% scarred	20	5.70	6	3.21	1	11	5.18
Site PG/1759–1996 (FULL)							
all scars	30	7.90	7	4.50	1	26	7.54
10% scarred	27	8.78	7	5.07	1	26	8.31
25% scarred	25	9.48	9	4.87	4	26	9.22
Site PG/1759–1945 (PRE?)							
all scars	26	7.15	7	2.89	1	13	7.03
10% scarred	24	7.75	7	3.35	1	17	7.57
25% scarred	22	9.48	9	3.05	4	17	8.44
Site CA/1761–1996 (FULL)							
all scars	31	7.58	5	7.69	1	35	6.15
10% scarred	26	9.04	7	7.83	2	35	7.93
25% scarred	16	14.69	9	15.84	3	61	11.65
Site CA/1761–1935 (PRE 1)							
all scars	28	6.21	5	6.27	1	35	5.31
10% scarred	23	7.57	6	6.49	2	35	6.89
25% scarred	15	11.60	9	10.26	3	37	10.12
Site CA/1761–1893 (PRE 2)							
all scars	26	5.08	5	2.83	1	13	4.76
10% scarred	21	6.29	5	2.65	2	13	6.19
25% scarred	13	10.15	9	8.55	3	37	9.19

**Statistical analysis was carried out in three categories: (1) all fire years, including those represented by a single fire scar; (2) fire years in which 10% or more of the recording sample trees were scarred; and (3) fire years in which 25% or more of the recording sample trees were scarred. For sites where an apparent disruption of the long-term frequent-fire regime was identified, fire-return intervals are calculated for the predisruption period (PRE) as well as the full sampling period (FULL). Evidence of two possible dates of fire-regime change was noted at site CA, so it has three analysis periods. In addition to the fire-scar data, site ASP-N was burned over by a wildfire in May 1996.*

mum in the 25%-scar distribution, suggesting that the 35-year gap may not have been excessively long for this site.

Reserve-Wide Fire Analysis

About 80% of fires for which season could be determined occurred in the spring at all sites (Table 4). Seasons could be determined on 50–80% of the fire scars at each site. The large number of early earlywood fires and the general lack of late-season scars supports the assumption that dormant-season fires burned in the spring, before earlywood formation. Because narrow tree rings were the most common reason for failure to identify the season, the determination of seasonal distribution might be biased toward years in which relatively good conditions for tree growth produced wider rings.

Including all the study sites, fires burned in at least some portion of the reserve at least every 2 years until

Table 4. Seasonal distribution (number and percent) of fire scars based on the position of the fire lesion within the scarred ring.*

Site	*Season determined*	*Season undetermined*	*Dormant (D)*	*Early earlywood (EE)*	*Middle earlywood (M)*	*Late earlywood (LE)*	*Latewood (L)*	*D+EE (spring)*	*M+LE+L (summer)*
ASP-N	41 (67)	20 (33)	27 (66)	6 (15)	8 (20)	0	0	33 (81)	8 (19)
ASP-S	55 (80)	14 (20)	26 (47)	22 (40)	7 (13)	0	0	47 (87)	7 (13)
AT	147 (64)	84 (36)	81 (55)	26 (18)	36 (25)	4 (3)	0	107 (73)	40 (27)
PG	182 (60)	124 (40)	101 (56)	50 (28)	31 (17)	0	0	151 (83)	31 (17)
CA	83 (52)	77 (48)	48 (58)	24 (29)	9 (11)	2 (2)	0	72 (87)	11 (13)

**Percentages in parentheses. Site codes defined in Table 1 and Fig. 1.*

widespread disruption of frequent-fire regimes after 1945 (Fig. 2), but reserve-wide fire occurrence was highly variable depending on the categories of analysis (Table 5). Including any fire, even those scarring a single sample tree, at any site, the reserve-wide WMPI was only 1.6 years between 1837 and 1945. The WMPI was approximately 30% longer (2.1 years between 1837 and 1945) for fire years limited to those scarring 25% or more of the sample trees. But fire intervals increased by a factor of 5–6 for fire years burning in 50% or more of the sites and increased by a factor of 16–25 for fires burning in 75% or more of the sites. Only 1 fire year (1871) is recorded at all five sites. Thus, although fires were frequent at La Michilía before 1945, fire sizes appear to have remained relatively small and fires were rarely synchronous between sites.

The WMPI values (Table 5) were approximately 30% shorter in the five-site analysis period (1837–1945) than in the three-site analysis period (1779–1945). This result could be due either to fire frequency increasing over time or to the effect of adding more sites. Two lines of evidence suggest that the difference is due primarily to the additional sites. First, several sites showed decreases in fire frequency toward the end of the analysis periods (site CA, no fires between 1893 and 1928; ASP sites, last widespread fire in early 1930s), and no site evidenced increasing fire frequency. Second, because the generally asynchronous pattern of fire occurrence between sites suggests that small, local fires were common, the addition of more sites is likely to add new fire dates.

Discussion

Environmental Gradient and Fire Regimes

The gradient of environmental conditions appears to be related to the four main trends observed in fire regimes across La Michilía Reserve: (1) numerous fires, many of them small in area; (2) higher fire frequency at lower el-

Table 5. Reserve-wide fire-interval analysis comparing predisruption fire years over multiple study sites.

*Site/analysis period, scar category**	*Number of intervals*	*Mean (MFI)*	*Median*	*SD*	*Minimum*	*Maximum*	*Weibull median probability interval*
All 5 sites/1837–1945							
all scars within sites							
all fire years	64	1.69	1	0.94	1	4	1.61
50% years	12	9.00	8.5	4.51	4	19	8.76
75% years	3	36.0	34	21.07	16	58	35.14
25% scarred within sites							
all fire years	46	2.35	2	1.73	1	9	2.09
50% years	7	15.43	15	10.53	5	36	14.23
75% years	2	37.00	37	29.70	16	58	na
Long record sites (ASP-S, PG, CA)/ 1779–1945							
all scars within sites							
all fire years	73	2.27	2	1.46	1	9	2.10
50% years	14	11.86	9	11.08	2	37	9.78
75% years	1	74.00	74	na	74	74	na
25% scarred within sites							
all fire years	55	3.02	3	2.14	1	10	2.70
50% years	8	15.88	12.5	9.98	7	36	15.01
75% years	1	74.00	74	na	74	74	na

**The analysis includes fire years represented* within *sites by the all-scar and 25%-scarred categories. Within these categories, fire years are analyzed* between *sites in three groups: (1) all fire years, (2) fire years represented on 50% or more of the sites, and (3) fire years represented on 75% or more of the sites. Site codes defined in Table 1 and Fig. 1.*

evations than higher elevations; (3) asynchrony in fire occurrence between sites, with few years in which a large fraction of the landscape burned; and (4) extended fire-free periods beginning in the twentieth century at four of the five sites. The strength of inferences or generalizability of the fire regime data differs: the strongest data are the fire histories of the study sites, which are precisely dated, to the temporal extent supported by sampling and allowing for the possibility of additional fires that left no scars. Based on the review of previous studies and reconnaissance, the study sites appear to be reasonably representative of similar forests in and around La Michilía. Less conclusive are any causal relationships between fire regime changes and environmental characteristics and human activities such as livestock grazing. Nevertheless, the positive and negative links between fire-regime characteristics and three important environmental factors—site characteristics, climate, and human influences—can suggest possible explanations for changing ecological patterns, especially where these correlations are biologically logical and consistent with results elsewhere.

SITE CHARACTERISTICS

Forest communities at La Michilía are distributed along a moisture gradient determined by various combinations of elevation, slope, aspect, and soils (González-Elizondo et al. 1993; Rentería-Arrieta & García-Arévalo 1997). Mesic sites (PG and CA: high elevation, northern aspect) support more biomass (i.e., fuel) than the drier sites (ASP and AT: low elevation, other aspects) (P.Z.F. et al., unpublished data). Steep slopes would tend to encourage the spread of heading fires, and high-elevation areas may be more frequently struck by lightning. The remote mesic sites also present a greater challenge to limited firefighting resources. The fire regime results show that mesic-site fires were more likely than dry-site fires to become widespread, as measured by the relatively smaller difference between the all-scar and 25%-scarred fire-return intervals (Table 3). Because fire recurrence at the mesic sites was limited to approximately every 7–10 years, however, either humid weather conditions or infrequent ignitions appear to have forestalled fires in most years.

In contrast, the xeric sites (ASP-N and ASP-S) had gentle to flat slopes, slowing fire spread, although drier weather conditions probably could support wildfires almost every year. Lightning strikes might be relatively less likely at the xeric sites because of their lower elevation, but the probability of human-caused ignitions is high. But fire suppression efforts are more feasible at the xeric sites due to their proximity to communities, farmlands, and roads, which also serve as firebreaks.

The shortest fire-return intervals in the entire reserve were observed at the intermediate site AT. This site may have the overall mix of characteristics most suited for fire: (1) mesic enough to support more biomass and more continuous fuels than the xeric sites; (2) relatively low in elevation for more reliable warm, dry weather than the mesic sites, with steep slopes that permit fast fire spread; and (3) close to human populations, thereby receiving both lightning and human-caused ignitions.

CLIMATE

Seasonal climate patterns appear to be an important factor in promoting fire occurrence from the spring to midsummer, corresponding with the typical spring drought and the lightning associated with the onset of the monsoon. Human-caused ignitions may also be higher in the spring due to burning of agricultural fields. Few fires burned in the humid late summer and fall, despite the continuing possibility of human-caused ignitions.

Inter-annual regulation of fire occurrence is less clear. The El Niño–Southern Oscillation climate pattern, the major source of inter-annual variation in climate, is well correlated with tree growth in the Sierra Madre Occidental (Stahle & Cleaveland 1993), but climatic factors appear to have been less correlated with reserve-wide fire occurrence at La Michilía than at sites in northwestern Durango. Major reserve-wide fire years, defined as those in which fires were recorded at 60% or more of the study sites, occurred about every 10 years between 1779 and 1945 (Table 6; mean 9.77 years, minimum 2 years, maximum 37 years, SD 8.22 years). Reserve-wide fire years based on widespread fires (25%-scarred cate-

Table 6. Major reserve-wide fire years based on the percentage of fire occurrence (all fires) at all study sites.

Year	*Sites burned*	*Recording sites*	*Sites burned (%)*	*Fire interval (years)*
1779	2	3	67	
1781	2	3	67	2
1818^{a}	2	3	67	37
1822	2	3	67	4
1828^{a}	2	3	67	6
1837^{a}	4	5	80	9
1846^{a}	3	5	60	9
1851^{a}	3	5	60	5
1862^{b}	3	5	60	11
1871^{a}	5	5	100	9
1878^{a}	3	5	60	7
1882	3	5	60	4
1887^{b}	3	5	60	5
1893^{a}	3	5	60	6
1912^{c}	3	5	60	19
1921^{b}	3	5	60	9
1929^{a,b}	4	5	80	8
1945	3	5	60	16

^{a}*Also a major reserve-wide fire in the 25%-scarred category.*
^{b}*Dry, cold conditions: positive Southern Oscillation Index extreme year (Stahle & Cleaveland 1993).*
^{c}*Wet, warm conditions: negative Southern Oscillation Index extreme year (Stahle & Cleaveland 1993).*

gory) occurred half as frequently as all reserve-wide fires. Positive Southern Oscillation Index (SOI) extremes are characterized by cold, dry conditions. But only 4 of the 18 major reserve-wide fire years (22%) and only one of the reserve-wide fire years using the 25%-scarred criterion (1929) corresponded to 1 of the 29 positive SOI extremes during the 1779–1945 period. In contrast, 7 of 10 major regional fire years (70%) at four sites in northwestern Durango occurred during positive SOI extremes (Fulé & Covington 1997). Negative SOI extremes, when generally warmer but moister conditions may have retarded fire ignition and spread, occurred 17 times between 1779 and 1945 but coincided with only one reserve-wide fire year at La Michilía (1912) and none in northwestern Durango (Fulé & Covington 1997). Although the number of study sites remains small, the data suggest that negative SOI extremes are consistently associated with relatively low-fire years, but the association between positive SOI extremes and high-fire years may be weak.

HUMAN INFLUENCES

Humans have been present in ecosystems of the Michilía region for tens of thousands of years (Gerhard 1982). Much of Durango was populated by Tepehuán people, who traditionally used fire for agriculture and hunting (Pennington 1969), although indigenous populations dropped rapidly following European contact (Gerhard 1982). The first permanent Spanish settlement in Durango, Nombre de Dios, was established about 1560 (Jones 1988) approximately 45 km northwest of the present-day Michilía Reserve.

Although human presence was already longstanding in the region by the earliest dates of the fire regimes reconstructed in the present study (mid-1700s), fire patterns were generally relatively stable until the mid-twentieth century. These frequent-fire regimes may have been due to a mix of lightning and human-caused ignitions. Human-caused ignitions are popularly believed to be the major cause of forest fires in Mexico (González-Cabán & Sandberg 1989; Fulé & Covington 1996), but reliable statistical data do not exist. Because population density was low before the mid-twentieth century (J. Medina Flores, personal communication), lightning probably has been and remains an important ignition source at Michilía, as in similar monsoonal climates with high lightning density (Baisan & Swetnam 1997). The asynchrony of fire years between lowland fires, presumably more likely to be of human origin, and upland fires also suggests that at least the latter sites were independently ignited, probably by lightning.

The greatest human influence on the fire-disturbance regime is seen in the post-1930 period of fire exclusion. Between 1932 and 1962, a North American rancher, Raymond Bell, owned the hacienda that later formed La Michilía (A. Morales and C. Galindo, unpublished manuscript, Instituto de Ecología, Durango, Mexico). Large numbers of livestock were purchased, grazed on the range, and then sold on the Mexican and U.S. markets. Bell maintained about 7,000 head of cattle, taking full advantage of the excellent condition of the pastures. His ranch manager noted that supplemental feeding was not necessary because of the high quality of the grasses. Census data in 1940 for the municipio of Suchil, including Bell's approximately 50,000-ha ranch, listed 9,771 cattle, 14,946 horses, mules, and donkeys, 3,337 sheep, 2,866 goats, and 4,877 swine (J. F. Nieto, personal communication). Heavy grazing and foraging by domestic livestock, breaking the continuity of herbaceous fuels, is likely the primary cause of the exclusion of widespread fire from four of the five study sites beginning around 1930. Only the Playa Grande site continued to burn, probably due to its remoteness and lack of water, although the relatively long 26-year, fire-free period suggests that grazing had an effect even here.

The Bell hacienda was divided in the late 1960s, forming several private ranches and the ejido of San Juan de Michis. Contemporary livestock numbers are somewhat lower, but grazing has been identified as a contemporary management problem in buffer zones of the reserve (Galindo-Leal et al. 1993). Gallina et al. (1978) compared photographs of forest openings in the dry and wet seasons, showing that the herbaceous biomass produced in summer was absent by the following spring. Most herbaceous forage was probably consumed by livestock because fecal analysis indicated that the largest native herbivore, the white-tailed deer (*Odocoileus virginianus*), primarily ate shrub and tree vegetation (Gallina et al. 1978).

Heavy livestock grazing has been identified as a major factor initiating fire exclusion throughout frequent-fire ecosystems of North America (Covington et al. 1994). Apart from grazing, the fire-exclusion period at La Michilía does not coincide with any major change in climate (Stahle & Cleaveland 1993), large-scale forest harvesting (P.Z.F. et al., unpublished data), or other apparent landscape change. Deliberate fire suppression is practiced but consists mainly of local landowners with hand tools and pickup trucks, sometimes supplemented by army troops.

Conservation and Restoration of Ecosystems

The maintenance of a frequent-fire regime in the core is a striking confirmation of the value of the biosphere reserve at this site. We don't know how many frequently burning sites remain in the Sierra Madre Occidental; so far only two such sites have been documented in addition to site PG (the others are Arroyo Laureles, Durango [Fulé & Covington 1996, 1997], and Sierra Ajo, Sonora [Baisan & Swetnam 1995]). Site PG is the only documented site under protected management, underscoring the importance of continued conservation of La Michilía. (The possibility was recently raised of trading the government-owned reserve core to meet other state commitments.) The past preservation of the frequent-fire regime and unharvested forest structure of Cerro Blanco, the mountain that includes site PG, was an unintentional consequence of the remote, rugged nature of the mountain. In contrast to the current broad recognition of the ecological role of fire, no particular consideration appears to have been given to fire when the reserve was designed in the 1970s by a team of biologists, ecologists, and anthropologists (Barbault 1978; Gallina et al. 1978; Halffter 1978), supporting the idea that conserving ecosystems in relatively natural conditions will help sustain important ecological elements that are presently unknown or unappreciated. In some cases these unknown critical elements, perhaps a particular microorganism or rare plant, may be easy to overlook. But in the present case the unrecognized element appears obvious in hindsight: fires crossing the landscape, even low-intensity fires, tend to be fairly conspicuous.

A primary application of detailed fire-regime data is to assist managers to maintain or restore natural disturbance regimes into the future. But regimes can probably be maintained only in reserves that are several times the maximum disturbance size and that are located to contain disturbances within their borders (Baker 1992). The 7000-ha core area of La Michilía is small compared to large-scale ecological processes such as contagious disturbances (e.g., fire) and ranges of larger animals (e.g., mountain lion [*Puma concolor*]), it doesn't represent the major lower-elevation ecological types such as oak-pine forest or grassland, and this small reserve constitutes the only protected forest area for hundreds of kilometers. The reserve core is unlikely to maintain a frequent-fire regime—or many other natural ecosystem attributes—indefinitely. Furthermore, exclusively protected areas in Mexico, such as national parks and biosphere reserve cores, are unlikely to increase because of the strong pressure for lands to meet the needs of growing human populations.

Expanding the effectiveness of small reserves by actively restoring ecosystems surrounding and connecting protected lands offers promise for sustaining natural biological diversity at far larger scales (Hobbs & Norton 1996) and may be the only hope for ecosystem conservation at the scales required to sustain large predator species (Noss et al. 1996). Ecological restoration is not a panacea for the pressing problems of social inequity that contribute to ecosystem degradation in northern Mexico. Management plans for this region, including conservation and restoration strategies, can be designed only in a local context. Speaking as outsiders, however, we suggest that the following points may merit consideration in restoration initiatives. First, because many important ecological factors are imperfectly understood, reserves themselves should be managed conservatively (Dellasalla et al. 1996), with scientifically based restorative actions initiated first in buffer areas. The greatest learning opportunity exists where restoration treatments are designed as experiments. Second, given the many social challenges facing conservation in Mexico (Simonian 1995), management plans are most likely to succeed if landowners see direct benefits to their natural resources. In the case of forests adapted to frequent fire, thinning and burning treatments designed to restore natural ecosystem structure and function can improve forage production, soil moisture relations, and tree growth while reducing the risk of high-intensity wildfire (e.g., Covington et al. 1997). Not every restoration treatment will be beneficial to conservation and resource extraction goals simultaneously, of course, but even moderate steps favoring natural ecological processes are likely to be an improvement over the status quo. Considering the relatively short period of fire exclusion in forests of the Sierra Madre Occidental, some of these ecosystems may escape the more deleterious effects of fire-regime disruption if conservation and restoration activities succeed.

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