Fire regime in a conservation reserve in Chihuahua, Mexico

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Abstract: Fire regime characteristics were reconstructed from fire-scarred trees in the Tutuaca reserve, a newly designated protected area in the Sierra Madre Occidental of western Chihuahua. The reserve was created to protect thick-billed parrot nesting habitat (large snags) and a relict forest of Chihuahua spruce (*Picea chihuahuana* Martínez). We collected fire-scarred samples from conifers (*Pinus ayacahuite* Ehrenb., *Pinus durangensis* Martínez, and *Pseudotsuga menziesii* (Mirb.) Franco) in three 25-ha sites arrayed at different watershed positions, from a low site adjacent to the spruce trees up to the watershed divide. Fire analysis periods began in 1702, 1704, or 1761 and continued through the final fire in 1955 (two sites) or 1995. All sites had frequent fire regimes (mean fire interval (MFI) 3.9–5.2 years; MFI for years in which 25% or more of the samples were scarred: 6.9–8.4 years). Almost all fires occurred before cambial growth began or early during the season of cambial growth. Fire years were significantly dry, and the years immediately preceding fire were significantly wet. After 1955, no further fires occurred at two of the three study sites, a pattern similar to that observed elsewhere in northern Mexico. The third site had fires in 1987 and 1995. The extended fire-free period in portions of the Tutuaca landscape may result in fuel accumulation and eventually in severe wildfire. For effective conservation of fire-susceptible habitat features, managers should seek to incorporate surface fire as a management tool.

Résumé : Les caractéristiques du régime des feux ont été reconstituées à partir des arbres portant des cicatrices de feu dans la réserve de Tutuaca, une nouvelle aire protégée dans la Sierra Madre occidentale de l'ouest de l'État de Chihuahua. La réserve a été créée pour protéger l'habitat de nidification (chicots de forte dimension) de la conure à gros bec ainsi qu'une forêt ancienne d'épinette de Chihuahua (*Picea chihuahuana* Martínez). Les auteurs ont collecté des échantillons de cicatrices de feu chez des conifères (*Pinus ayacahuite* Ehrenb., *Pinus durangensis* Martínez et *Pseudotsuga menziesii* (Mirb.) Franco) dans trois sites de 25 ha établis dans différentes parties d'un bassin versant; allant d'un site situé au bas, adjacent aux épinettes, jusqu'à la ligne de partage des eaux. La période d'analyse des feux a débuté en 1702, 1704 ou 1761 et continué jusqu'au dernier feu en 1955 (deux sites) ou 1995. Les feux étaient fréquents dans tous les sites (l'intervalle moyen entre les feux est de 3,9 à 5,2 ans; l'intervalle moyen entre les feux où 25 % ou plus des échantillons portaient des cicatrices de feu est de 6,9 à 8,4 ans). Presque tous les feux sont survenus avant que débute la croissance du cambium ou tôt dans la saison de croissance du cambium. Les années où il y a eu des feux ont été particulièrement sèches et celles qui ont immédiatement précédé ces années ont été particulièrement humides. Après 1955, aucun autre feu n'est survenu dans deux des trois sites étudiés, une situation qui a été observée ailleurs dans le nord du Mexique. Le troisième site a subi des feux en 1987 et 1995. La longue période sans feux dans des portions du paysage de Tutuaca pourrait entraîner l'accumulation de combustibles et éventuellement de sévères feux de forêt. Les aménagistes devraient chercher à incorporer le brûlage dirigé comme outil d'aménagement pour réussir à conserver les caractéristiques des habitats sensibles au feu.

[Traduit par la Rédaction]

Introduction

The Sierra Madre Occidental, the mountain range that stretches from central Mexico to the southwestern United States, supports ecosystems of extraordinary biological diversity (Rzedowski 1992; Bye 1995). The mountains repeatedly served as glacial refugia and migration corridors (Axelrod 1986); remnants from the most recent cold epoch still persist in the form of rare relict forests of Chihuahua spruce (*Picea chiahuahuana* Martínez) (Ledig et al. 2000). Though humans have lived in the Sierra Madre Occidental for thousands of years, the impacts of roads, livestock, and industrial-scale logging only became widespread in the mid-20th century. But by 1996, Lammertink and coworkers found that old-growth

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forests persisted only in isolated fragments representing <1% of the landscape. Fire and other disturbances, logging, overgrazing, overhunting, erosion, population growth, have lead to identification of these regions as a critical conservation priority (Biodiversity Support Program 1995; Consejo Nacional para el Conocimiento y Uso de la Biodiversidad 2002).

Fire ecology has been little studied in northern Mexico, but changes in fire regimes have been quantified at a few sites in the Sierra Madre Occidental (Fulé and Covington 1997, 1999; Kaib 1998; Swetnam et al. 2001; Heyerdahl and Alvarado 2003). These forests had frequent surface fire regimes, in some cases continuing up to the present. At most sites, however, fire regimes were disrupted in the mid-20th century, and forests entered extended fire-free periods, primarily because of heavy livestock grazing. Fire exclusion can threaten forest sustainability, because accumulated fuels can support uncharacteristically severe wildfires. Recent 40- to 70-year periods of fire exclusion in the Sierra Madre Occidental were associated with increased tree regeneration and tree density, changes in species composition and tree spatial patterns, and forest floor fuel buildup (Fulé and Covington 1994; Fulé et al. 2000). Two such sites recently burned with high-intensity fires (Fulé and Covington 1998; Fulé et al. 2000), a distinct change from predisruption fire behavior, altering or even supplanting natural successional trajectories (Romme et al. 1999). Severe fires killed many or all overstory trees, exposed soils to erosion, and altered successional pathways to favor sprouting species and shrubs (Fulé et al. 2000; Barton 2002).

The Tutuaca reserve, established in pine–oak forests in western Chihuahua in 2000, is a prototype of a new approach to forest protection. Rather than a government-funded National Park or Biosphere Reserve (e.g., Halffter 1978), the Tutuaca reserve was created through a civil agreement to defer timber harvesting and manage for long-term conservation; landowners were compensated with funds contributed by several nongovernmental organizations (Enkerlin-Hoeflich 2000). Two critical ecosystem elements protected at Tutuaca are vulnerable to fire: the large old snags that serve as nest sites for thick-billed parrots and a relict Chihuahua spruce forest.

We selected a watershed of pine–Douglas-fir forest in the center of the Tutuaca reserve, next to the relict spruce stand, as a study area to answer the following questions: (1) What were the characteristics of the past fire regime (fire frequency, seasonality, synchrony) across sites located in different watershed positions and elevations? We expected fires to move readily up the drainage, but that the site at the top of the watershed would capture additional fires burning up from the adjacent watershed. (2) Have fire patterns changed, especially through recent fire exclusion? (3) What is the strength and pattern of the influence of climate on fire? Finally, we sought to suggest ways in which this information could be applied to management for long-term conservation of the reserve.

Materials and methods

Study area

The study sites were located within the Tutuaca Natural Protected Area, also referred to as “Cebadillas” or “Bisaloachic”. The reserve is located in the Sierra Madre Occidental in Municipio Temosachic, western Chihuahua (28°39′N, 108°17′W). Soils are of volcanic origin with parent materials of rhyolite and pyroclastic rock, shallow, and rocky except in valley bottoms (Instituto Nacional de Estadística, Geografía, e Informática 1999). Climate was classified as temperate, semicold, subhumid climate with summer rains (Dirección General de Geografia del Territorio Nacional 1981). Dominant tree species include *Pinus durangensis* Martínez, *Pinus ayacahuite* Ehrenb., *Pseudotsuga menziesii* (Mirb.) Franco, *Quercus* spp., and *Arbutus* spp.

The Tutuaca reserve was selected from among the few areas identified by Lammertink et al. (1996) and field surveys as an active breeding site for the endangered thick-billed parrot or *guacamaya* (*Rhynchopsitta pachyrhyncha*) (Monterrubio-Rico and Enkerlin-Hoeflich 2004). It includes the key nesting site for an international partnership between the Species Survival Plan Management Group in the United States, and several institutions in Mexico (Lamberski and Healy 2002). The land is owned by two “ejidos”, civil organizations with communal land tenure, the ejidos Tutuaca and Conoachic. The forest has been selectively harvested in the past, but the area retains more large trees and large snags than most Madrean forests. A relict stand of Chihuahua spruce, also an endangered species, is located along the bottom and northeast-facing slopes of Arroyo Piceas in the Tutuaca reserve. By creating the reserve, conservationists hoped to protect these habitats and eventually develop a nonconsumptive economy supported by ecotourism and scientific studies.

We established three fire scar sampling sites on the north slope of the Arroyo Piceas to characterize fire regimes in the vicinity of the spruce forest. Each site was 25 ha in size, to have a common basis of sampled area for consistent comparisons (Falk and Swetnam 2003), and the sites represented a range in elevation and slope position (Table 1). The LOW site was at the bottom of the drainage and next to a forest road. The HIGH site was located on steep slopes at the top of the drainage, adjacent to the TOP site, which lay atop the watershed divide.

Field and laboratory methods

Fire-scarred tree sampling was done in August 2003. Each study site was thoroughly searched for fire-scarred trees. Partial cross-sections were cut from scarred “catfaces” on trees, snags, logs, and stumps of conifers apparently containing the oldest and (or) most extensive fire records. Samples from living trees were collected as partial cross-sections, a method that does not require felling the tree and that rarely causes lasting damage to large pine trees, such as those we sampled (Heyerdahl and McKay 2001). Samples were mapped when collected and were well distributed throughout the study sites (Fig. 1). Characteristics of the sampled trees are summarized in Table 2.

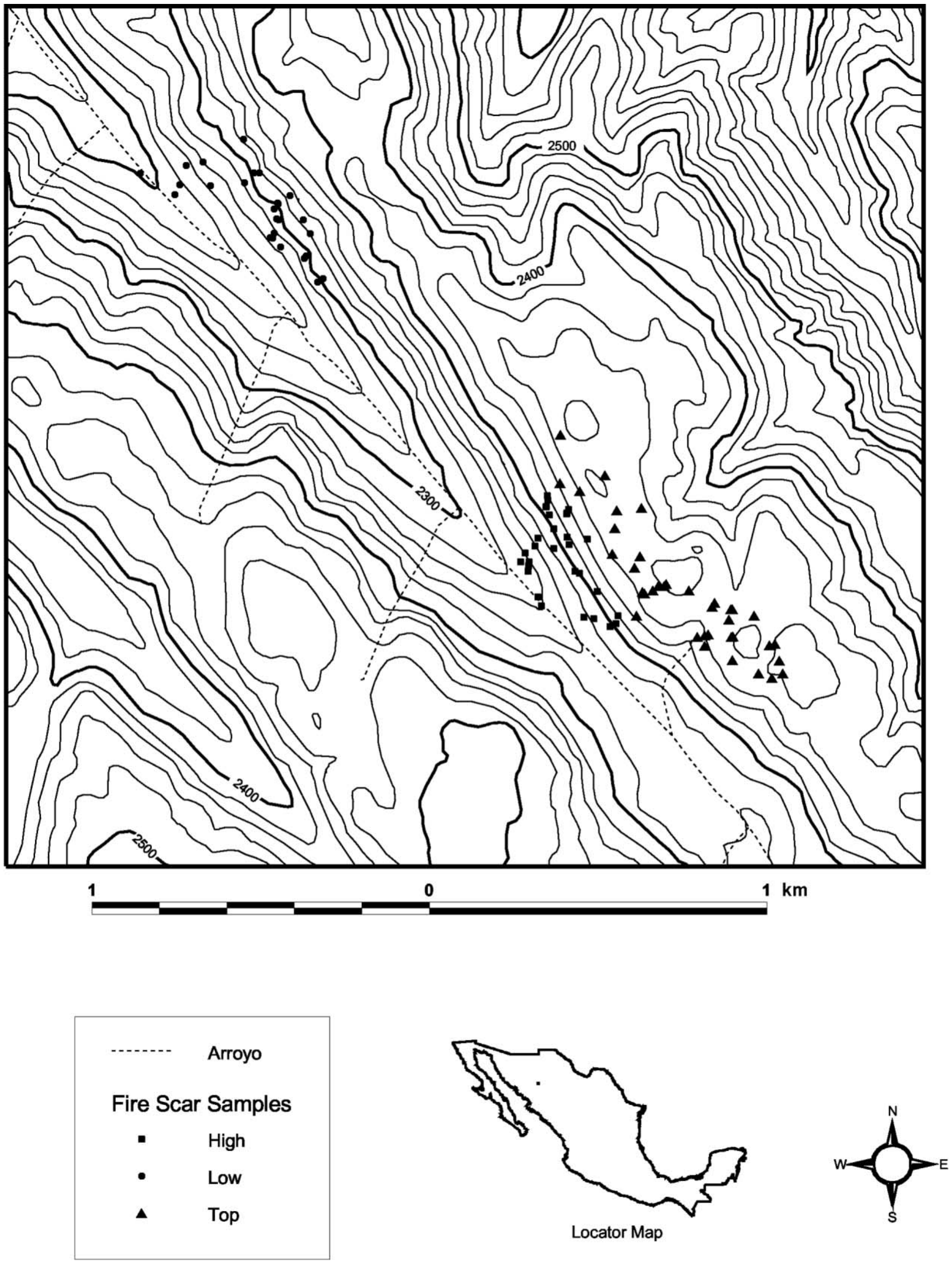
In the lab, samples were mounted and surfaced until cell structure could be seen clearly under a microscope. Samples were crossdated (Stokes and Smiley 1968) using characteristic patterns of narrow marker years. A master tree-ring chronology developed in Bisaloachic (Tutuaca) was also used in crossdating (J. Villanueva-Diaz, unpublished data). After initial dating, ring widths of all samples were measured to check dating with the Cofecha program (Holmes 1983). The

Table 1. Study site characteristics.

Study site	Site code	Elevation (m)	Slope position	Slope (%)	Aspect
Tutuaca low	LOW	2517	Lower slope	32.6	South
Tutuaca high	HIGH	2611	Upper slope	33.2	South
Tutuaca top	TOP	2686	Watershed divide	19.3	Slope to N and S

Note: The sites are listed on an environmental gradient from lowest to highest elevation and slope position. Each site was approximately 25 ha in extent.

Fig. 1. Study sites in the Arroyo Piceas, Tutuaca Reserve, in the Sierra Madre Occidental, western Chihuahua, Mexico.



season of fire occurrence (Baisan and Swetnam 1990) was estimated based on the relative position of each fire lesion within the annual ring according to the following categories: early earlywood, middle earlywood, late earlywood, latewood, and 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 monsoonal climate pattern of northern Mexico (Fulé and Covington 1997, 1999; Heyerdahl and Alvarado 2003). The season was listed as "not determined" when it could not be distinguished clearly.

Fire history data were analyzed with the FHX2 software (Grissino-Mayer 2001). Analysis at each site began with the

Table 2. Characteristics of sampled trees.

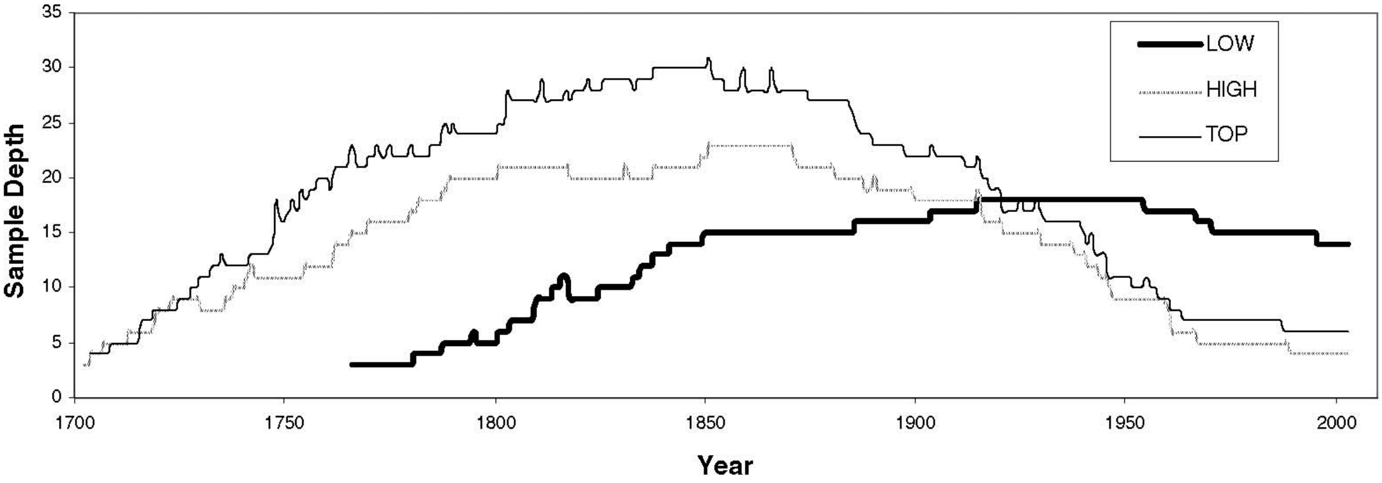
Study site	No. of samples collected	No. used in study	Living	Snag or log	Cut stump	Species	Avg. diameter of sampled trees (all species) (cm)
LOW	26	21	15	7	4	PIDU 15, PIAY 9, Unk. 1	43.5
HIGH	30	25	9	9	12	PIDU 21, PIAY 9	46.6
TOP	37	33	11	10	16	PIDU 27, PIAY 8, PSME, Unk. 1	44.3

Note: Tree species are *Pinus durangensis* (PIDU), *Pinus ayacahuite* (PIAY), and *Psuedotsuga menziesii* (PSME). Unknown (Unk.) species were samples collected from deteriorated pine stumps.

Table 3. Seasonal distribution (number and percent) of fire scars based on the position of the fire lesion within the scarred ring.

Site	Season determined	Season not determined	Dormant	Early earlywood	Middle earlywood	Late earlywood	Latewood
LOW	112(58%)	80(42%)	47(42%)	30(27%)	34(30%)	1(1%)	0
HIGH	115(56%)	91(44%)	56(49%)	30(26%)	25(22%)	4(4%)	0
TOP	191(59%)	135(41%)	93(49%)	46(24%)	50(26%)	2(1%)	0

Fig. 2. Sample depth at the three study sites.

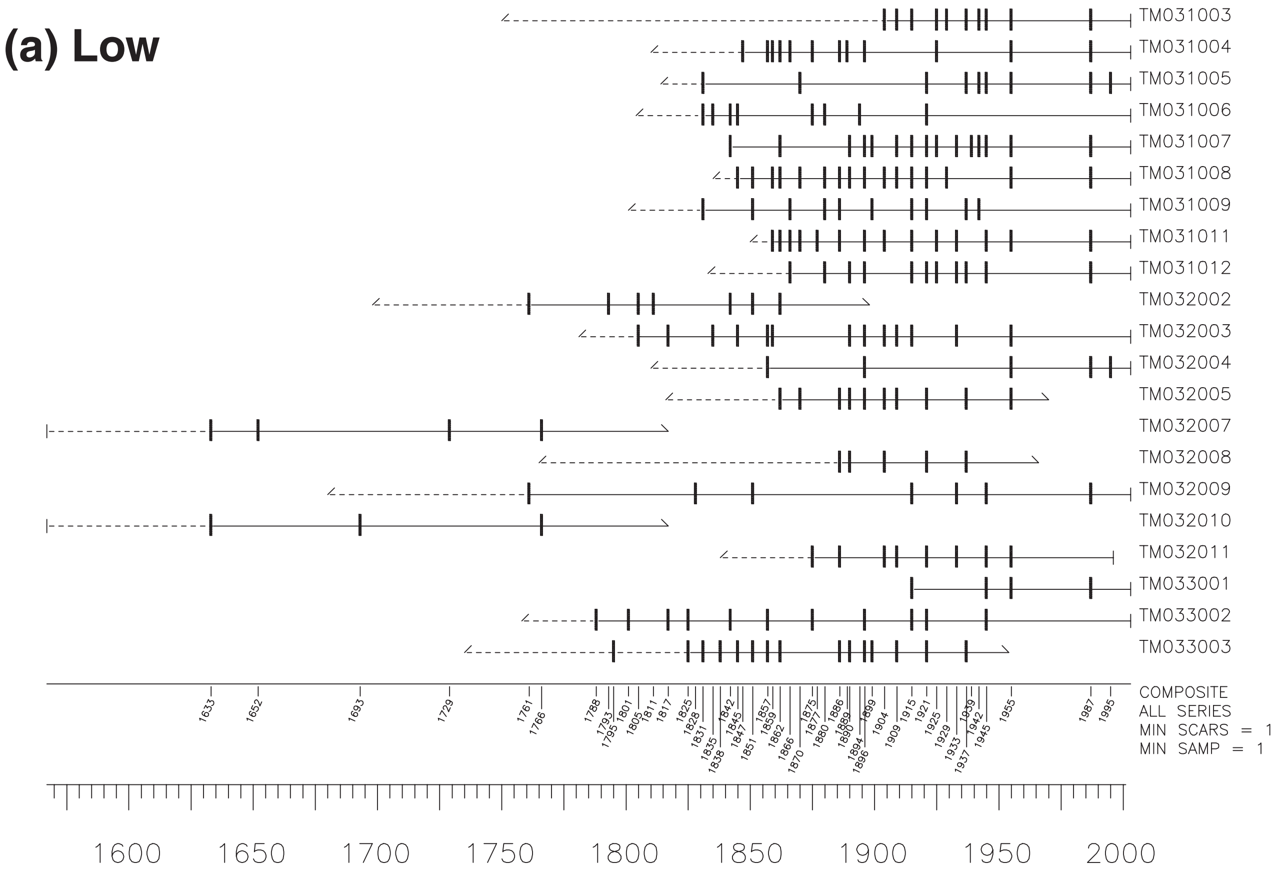


first year with an adequate sample depth (Grissino-Mayer et al. 1994), defined as the first fire year recorded by 10% or more of the total sample size of recording trees at each site. "Recording" trees are those with open fire scars or other injuries (e.g., lightning scars), leaving them susceptible to repeated scarring by fire (Swetnam and Baisan 1996). Beginning dates were 1761 (LOW), 1702 (HIGH), and 1704 (TOP). A common fire-history end-date of 2003 was used.

Fire-return intervals were analyzed statistically in different subcategories or "filters". First, the statistical distribution of fire intervals using all fire years, even those represented by a single scar, was assessed. Then only those fire years were included in which, respectively, 10% or more, and 25% or more, of the recording samples were scarred. In contrast with the all-scarred category, these filters capture fires that were relatively larger and (or) more intense than those fires that scarred only one or a few trees (Swetnam and Baisan 1996, 2003). The 25% scarred category has been shown to agree relatively closely with point-based fire interval analysis (Baker and Ehle 2001), perhaps better reflecting the ecological impact of the fire regime at any given point within a study area. The statistical analysis of fire-return intervals included the minimum, maximum, and mean fire intervals (MFI, average number of years between fires) and the Weibull median probability interval (WMPI), used to model asymmetric fire interval distributions and to express fire-return intervals in probabilistic terms (Grissino-Mayer 1999). After assessing each study site individually, all the data were combined, and the complete distribution of fire-return intervals was described using the same three filters: all scars, 10% scarred, and 25% scarred.

The relationship between climatic fluctuations and fire occurrence was evaluated with superposed epoch analysis, using software developed by Grissino-Mayer (2001). A locally developed Douglas-fir tree-ring chronology served as a proxy for climate. The residual earlywood chronology explained 51% of the winter–spring (October–May) precipitation variance of climatic stations for northwestern Chihuahua and northeastern Sonora for the period 1950–1990. The precipitation reconstruction covers the 1472–2002 period and shows the presence of extreme droughts, especially in the 1860s, 1550s, and 1490s (J. Villanueva-Diaz, unpublished data).

Fig. 3. Fire-history charts at three sites in the Tutuaca Reserve: (*a*) LOW slope position, (*b*) HIGH slope position, and (*c*) the TOP of the watershed.



The power spectrum for the reconstructed precipitation indicated a significant variance concentration at 4 years, which is related to the warm phase of the El Niño - Southern Oscillation (ENSO) influence on this part of Mexico (Stahle et al. 1998). In the superposed epoch analysis, the climate values in all fire years (81 fire events) were averaged and compared with the average climate values in a window of 5 preceding and 2 succeeding years. Bootstrapped distributions of climate data in 1000 random windows were used to create confidence intervals.

Results

We collected a total of 93 fire-scarred samples, 79 of which were crossdated and used for analysis (Table 2). Nearly two-thirds of the samples were collected from dead trees, mostly downed logs and stumps. Most samples were from *Pinus durangensis*, some from *Pinus ayacahuite* and *Pseudotsuga menziesii*. There was little difference in average sample tree diameter between sites, with an overall average of 44.8 cm.

A total of 724 fire scars was dated, and the season of fire occurrence was estimated on 58% of the scars (Table 3). Dormant-season scarring was the most common (47% overall). Early-earlywood and middle-earlywood scarring occurred nearly equally, representing 25% and 26% of the fire scars, respectively. Fewer than 2% of the scars occurred in the late earlywood and none were found in latewood.

Fires were frequent at all three sites from the onset of adequate sample depth (Fig. 2) through the mid-20th century (Fig. 3). Although each site contained sample trees predating 1600 A.D., with the earliest fire date in 1572, adequate sample depth for statistical analysis was only reached in 1702 and 1704 at the HIGH and TOP sites and not until 1761 at the LOW site. Fires recurred at mean intervals of 3.9–4.5 years, using all scars (Table 4). The filtered fire scar data, using the 25% scarred criterion, averaged 1.5–2.2 times longer, with MFI values ranging from 6.9 to 8.4 years. Weibull median probability interval (WMPI) values were very similar to MFI values; the greatest discrepancy at any site or filter category was a 1.0-year difference. All sites had a minimum of only 1 year between fires, but fire-free maxima ranged from 10 to 22 years (all scars) or 20 to 39 years (25% scarred). The average per-sample fire intervals (or "point" fire intervals; Baker and Ehle 2001) were roughly twice as long as the 25% scarred MFI, ranging from 13.8 to 15.2 years.

In ponderosa pine forests, Baker and Ehle (2001) suggested that the interval between the tree pith and the first scar should be considered a true fire-free interval, analyzed in the same manner as the intervals between subsequent scars on a recording sample. This concept is not widely accepted (for discussion, see Fulé et al. 2003; Stephens et al. 2003; Swetnam and Baisan 2003), but the data on pith to first-scar intervals are presented here to contribute to the minimal existing data on this topic. Twenty-one of the 79 crossdated samples (27%) included the tree pith. The average

Fig. 3 (*concluded*).

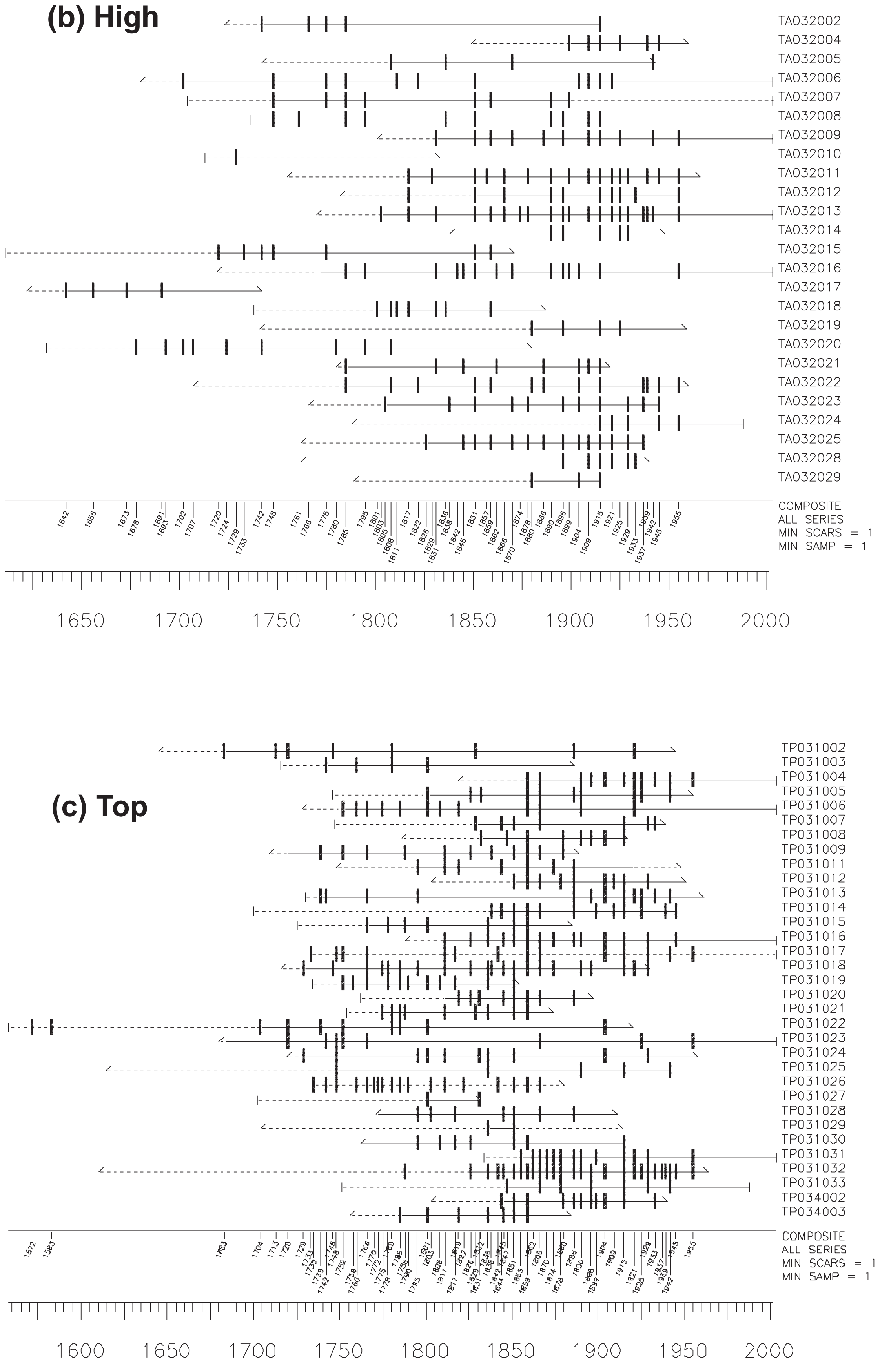


Table 4. Fire intervals (in years) at the study sites.

Site (analysis period)	Category of analysis	No. of intervals	MFI	Min.	Max.	Average per-sample fire interval*	WMPI[†]	Interval since last fire[‡]
LOW (1761–1955)	All scars	43	4.5	1	22	13.8	4.1	Gap 1955–1987
	10% scarred	38	5.1	2	22		4.7	
	25% scarred	28	6.9	2	39		5.9	
LOW 1761–1995	All scars	45	5.2	1	32	14.0	—[†]	7 years
	10% scarred	38	5.9	2	32		—	
	25% scarred	30	7.8	2	39		—	
HIGH 1702–1955	All scars	52	4.9	2	13	15.2	4.6	48 years
	10% scarred	44	5.8	2	13		5.6	
	25% scarred	30	8.4	2	27		7.7	
TOP 1704–1955	All scars	64	3.9	1	10	15.8	—	48 years
	10% scarred	53	4.7	1	11		4.5	
	25% scarred	33	7.6	2	20		7.2	
ALL 1761–1995	All scars	62	3.1	1	10	15.8	3.0	
	10% scarred	43	4.5	2	10		4.0	
	25% scarred	25	7.6	3	20		7.1	

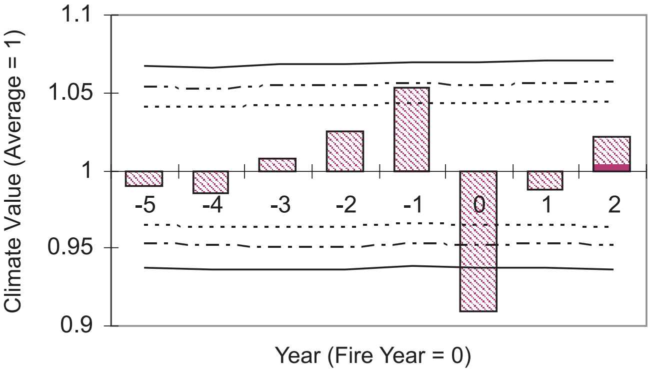
Note: Analysis was carried out from the first fire date with a depth of recording samples of 10% of total sample size, until the final fire date. All three sites recorded fires in 1955; thereafter only the LOW site recorded fires. Statistical analysis was carried out in three categories: (1) all fire 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. MFI, mean fire interval.

*Average per-sample intervals are calculated for the analysis period.

[†] Weibull median probability interval: WMPI values are not shown (—) where the Weibull model did not fit the fire interval data adequately (Kolmogorov–Smirnov test, $\alpha = 0.05$).

[‡] Interval between the last fire and the sampling date, August 2003.

Fig. 4. Superposed epoch analysis showing the relationship between local climate (tree-ring width index) and fire occurrence (81 fire dates, 1702–1995). Bootstrapping procedures were used to assess the statistical significance of climate departures above the mean ("wet years") and below the mean ("dry years"). The three lines above and below the *x*-axis represent confidence intervals of 90%, 95%, and 99%.



interval from pith to the first recorded scar was 52.3 years, minimum 9 years, maximum 138 years. Eleven of the 21 samples had pith to first-scar intervals <50 years, ranging from 9 to 46 years.

Fire events were commonly recorded on numerous samples, leading to the relatively small difference between the all-scar MFI and the 25% scarred MFI. In addition, fires were often synchronous across sites (Fig. 3). Since there were relatively few fire dates that did not appear in all sites, the MFI for ALL sites, shown in the lower section of Table 4, was only slightly lower than the individual-site MFI values: 3.1-year all-scar MFI and 7.6-year 25% scarred MFI. Thus the fire history of the entire study area, 75 ha, was very similar to the fire histories of each individual 25-ha site.

Unique fire dates were assessed by comparing fire events between sites. Of the 63 fire dates in the period 1761–1955, 30 fires (48%) were recorded at all three sites. The LOW and TOP sites each had 8 unique fire dates, each representing 13% of the total number of events. No unique fire dates were found at the HIGH site. Three fires (5%) burned only at the LOW + HIGH sites, 12 fires (19%) burned only at the HIGH + TOP sites, and 2 fire dates (3%) were recorded only at the LOW + TOP sites.

The pattern of frequent, synchronous fires was broken in the mid-20th century. All three sites burned in 1945, followed by a 10-year fire-free gap and another synchronous fire in 1955. No fires were recorded in the HIGH or TOP sites after 1955, creating a 48-year interval (1955–2003) that is approximately 1.8–4.8 times longer than any previous fire-free period since the beginning of the 18th century. In contrast, a fire at the LOW site in 1987 scarred two-thirds of the sample trees, and another fire in 1995 scarred 2 trees. The longest fire-free period at the LOW site was 32 years (1955–1987), and the interval since the most recent fire was only 7 years (1995–2003).

Fire years were significantly dry (<99% confidence interval), as shown by superposed epoch analysis (Fig. 4). The years immediately preceding fire were also significantly wet (>90% confidence interval). Eight fire years coincided with positive extremes of the Southern Oscillation Index, as reconstructed from tree rings in the Sierra Madre Occidental by Stahle and Cleaveland (1993), indicating cool, dry conditions. In six of these years, fires occurred at all the three sites (1801, 1862, 1904, 1909, 1921, 1925). In 1805, fire occurred at the LOW and HIGH sites; in 1855, fire was recorded only at the TOP site. Only one fire event occurred in a year with a negative Southern Oscillation extreme (warm, moist conditions; Stahle and Cleaveland 1993): 1844, when a fire occurred at the TOP site.

Discussion

Fire frequency and spread

Surface fires recurred frequently in the Arroyo Piceas and adjacent watershed. The MFI values and minimum–maximum fire intervals at the Tutuaca reserve were similar to fire regime characteristics across several other sites in the Sierra Madre Occidental (Fulé and Covington 1997, 1999; Kaib 1998; Swetnam et al. 2001; Heyerdahl and Alvarado 2003) and elsewhere in the greater Southwest, defined as the southwestern United States, and northwestern Mexico (Stephens et al. 2003; Swetnam and Baisan 2003). Fires appeared to have spread readily across all three study sites in most years, as shown by the fact that there was little difference (generally <1 year) between the MFI values at any individual site (25 ha each) versus the MFI calculated for all sites together (75 ha). Although fires were relatively synchronous, with nearly 50% of fire dates recorded at all three sites, the TOP site did not reflect an unusual number of unique dates, even though its position at the watershed divide would seem to be suitable for importing fires from two drainages. Because the LOW site had an equal number of unique dates as the TOP site (8 fires), we interpret the overall pattern as approximately one-half large synchronous fires and one-half smaller fires, apparently affecting all the watershed positions in similar ways.

Fire regime disruption

All three Tutuaca sites showed a change in fire frequency after 1955, with fire ceasing entirely at two sites. Throughout western North America, frequent-fire regimes in long-needled pine forests have been interrupted by extended fire exclusion, beginning in the 19th century in the southwestern United States (Swetnam and Baisan 2003), and extending to northwestern Mexico by the mid-20th century. Heyerdahl and Alvarado (2003) found MFI <4 years and fire cessation beginning around 1950 at Salsipuedes (Ejido Largo). This site is the only previously published fire history from Chihuahua, near Madera, approximately 100 km north of the Tutuaca study area (Heyerdahl and Alvarado 2003). At three sites in the Sierra de los Ajos, Sonora, Dieterich (1983) and Swetnam et al. (2001) reported MFI values of 4.0–5.9 years (all scars), increasing to 5.9–9.6 years for the 25% scarred distribution. The onset of fire exclusion crossed a range of dates in the Ajos, from 1916 to 1972. In the Sierra San Pedro Mártir, Baja California, MFI values ranged from 3.9 to 9.2 years in the 1700s and 1800s (all scars), from 9.6 to 22 years (25% scarred); widespread fires ceased after 1946, although a few individual trees were scarred in apparently small fires thereafter (Stephens et al. 2003). Further south in Durango, seven sites studied by Heyerdahl and Alvarado (2003) and nine sites studied by Fulé and Covington (1997, 1999) displayed strikingly similar MFI values (almost all within 3–6 years) but a broad range of fire exclusion dates. Four sites ceased burning in the 1930s, three in the 1940s, two in the 1950s, two in the 1970s–1980s, and surface fires essentially continued up to the present at the remaining five sites.

The primary reason for fire exclusion in northern Mexico is believed to be land-use change, especially increased livestock grazing, associated with land redistribution following the Mexican Revolution. Heyerdahl and Alvarado (2003) graphically illustrated the juxtaposition of widespread grants of land for ejidos with steep decline in sites with fires between 1930 and 1960. Historical records document increased grazing coincident with fire exclusion at both the Sierra San Pedro Mártir in Baja California (Stephens et al. 2003) and La Michilía Biosphere Reserve in Durango (Fulé and Covington 1999). Even in the United States, where active fire suppression has played a greater role than in Mexico in eliminating fire (Rodríguez-Trejo and Sierra-Pineda 1992), fire exclusion associated with grazing began as early as the 1820s in Arizona (Savage and Swetnam 1990).

Fire and climate

Fire years were significantly dry, as reflected in the superposed epoch analysis and the correspondence with the dry phase of ENSO, but the years immediately before fires were significantly wet. Observing the same phenomenon in the southwestern United States, Swetnam and Baisan (2003) suggested that fire spread was favored when a dry year followed a moist year, with high fine fuel production. A similar mechanism is possible at Tutuaca, where perennial grasses were the predominant understory vegetation. Northern Mexico is strongly affected by the ENSO climate pattern (Stahle and Cleaveland 1993; Stahle et al. 1998; Villanueva-Díaz and McPherson 2002), and fire occurrence in northern Mexico has been linked to ENSO (Fulé and Covington 1997, 1999; Heyerdahl and Alvarado 2003; Stephens et al. 2003), as in the southwestern United States (Swetnam and Betancourt 1998) and southern South America (Kitzberger et al. 2001). Extreme fire weather conditions were associated with El Niño in 1998 in central and southern Mexico, when nearly 600 000 ha burned in uncontrollable wildfires (Rodríguez-Trejo and Pyne 1998).

In much of the greater Southwest (southestern United States, and northwestern Mexico) and in southern South America, fire frequency was reduced in a period from the late eighteenth to the early nineteenth centuries (LEENT, roughly 1790–1830) (Grissino-Mayer and Swetnam 2000; Stephens et al. 2003). This reduction may be related to low-frequency changes in ENSO variability (Kitzberger and Veblen 2003) that resulted in a decrease in Southern Oscillation Index extremes in the Sierra Madre Occidental (Stahle and Cleaveland 1993). For example, in northern Baja California, the fire regime appeared to change from one of relatively frequent but patchy fires before 1790, to an extended gap that was nearly fire-free till around 1830, followed by less frequent but widespread fires until the mid-19th century (Stephens et al. 2003). In contrast, at Tutuaca there is no evidence of a gap in fire occurrence in LEENT (Fig. 3). However, fires did become highly synchronous beginning about 66 years later in the record: from 1896 to 1955, every fire date was recorded at every site. No obvious gap or change in synchrony around LEENT is evident in the small number of fire histories from Chihuahua and Durango (Fulé and Covington 1997, 1999;

Heyerdahl and Alvarado 2003), though few sites have adequate sampling depth before 1800. It would be valuable to assemble additional fire regime reconstructions across the latitudinal and elevational ranges of northern Mexico to determine the extent and scale of climatic teleconnections with fire regimes.

Management implications

The main implications arising from this study are that frequent fire played a long-term role in the ecosystem, the pattern of fire occurrence has changed in recent decades, and it will be important for managers to develop strategies for managing future fires. These observations are not only relevant for the Tutuaca reserve but are likely to be useful in related sites in Mexico, the western United States, and Central America, as pine–oak forests adapted to surface fire regimes are among the most common, and most threatened, forest ecosystems in these regions (Biodiversity Support Program 1995).

Not enough is known about the fire ecology of Madrean forests, as is true of Mexican forests in general (Rodríguez-Trejo and Fulé 2003), and the sites in this study do not comprise a comprehensive sampling of the reserve or the region. Nonetheless, the trends observed here are a useful starting point. The three study sites in the Arroyo Piceas were quite similar to each other in their pre-1955 fire regime characteristics. While they may not fully represent the range of fire regimes in the reserve, they provide a detailed picture of the fire disturbance regime in the landscape surrounding the spruce forest. It would probably be safe to consider the other pine–oak forests in the vicinity as being similar in fire regime, at least until additional sites can be studied.

The variability in post-1955 fire patterns indicates that some areas of the reserve have not burned for as long as 48 years, much longer than any previous fire-free interval in the fire-scar record. This extended fire-free interval raises the possibility that fuels are accumulating in several ways. At the stand level, forest floor, coarse woody debris, ladder fuels (small trees under taller trees), and canopy fuels have been shown to build up in Madrean forests under fire exclusion, leading to severe wildfires (Fulé et al. 2000; Barton 2002). Perhaps more importantly, these types of changes in individual stands can have a cumulative impact of increasing the continuity of high and homogeneous fuel loads across landscapes (e.g., White and Vankat 1993), leading to broad-scale burning. Even assuming that stand-replacing fire occurred previously to some extent in the spruce stands, the fire-susceptible spruce trees that survived centuries of surface burning all around them could succumb to a larger fire that carries through their mesic habitat. As an isolated population, even one fire event could permanently remove the spruce from the reserve.

Climate change forecasts for northern Mexico, while far from uniform in their predictions, are consistent in suggesting that future conditions will be warmer and drier (Magaña et al. 1997; Villers-Ruiz and Trejo-Vázquez 1998), causing vegetation to shift northward and upward in elevation (Villers-Ruíz and Trejo-Vázquez 1998; Shafer et al. 2001) and increasing the frequency and severity of extreme drought years. If the duration and severity of fire seasons also increases (Flannigan et al. 2000, 2001), it may be very difficult not only for spruce but for all the temperate forests to persist in their current elevational ranges. However, dense forests with heavy fuel loads will be especially vulnerable to these changes, whereas open pine–oak forests undergoing frequent burning are likely to be more resistant.

To conserve the most options for the future, managers should seek to reduce the probability of catastrophic loss of the reserve's forest. Fire should be actively suppressed in the spruce forest and wherever intense burning threatens the large snags and trees that are required by the thick-billed parrots. But fire should be used wherever possible to begin to restore a frequent surface regime to gain ecological benefits and reduce risk of stand-replacing fire (e.g., Wagle and Eakle 1979; Pollet and Omi 2002). The use of fire, whether ignited by managers or through accidental or lightning ignition, should be accomplished within the context of a fire management plan (Rodríguez-Trejo 1996). It may be necessary to protect valuable snags with firelines. Expertise in prescribed burning is available nearby, through research at the Madera experimental station (Alanís-Morales et al. 2000). Conservationists and scientists associated with the reserve may also be able to offer assistance. Thinning of small trees, together with burning, can help create a fire-resistant landscape as well (Agee et al. 2000).

There are caveats associated with the reintroduction of fire. First, prescribed fires that escape because of poor planning or inexperience can have devastating ecological consequences, just like a wildfire, but even more severe social consequences, since the managers would be perceived to be at fault. Second, historical information such as the fire regime statistics presented in this study should be interpreted in the context of modern management goals. A historical average fire-return interval every 4–5 years does not necessarily mean that managers should emulate this pattern (Tiedemann et al. 2000); it may be the case that desirable ecological conditions could be maintained with a longer interval (e.g., Fulé et al. 2003). Finally, Baker and Ehle (2001) called attention to the fact that historical fires did not burn every square metre of ground; neither should fire managers seek to create a uniformly blackened landscape.

Protected lands around the world serve multiple objectives and are impacted by numerous biological and social forces. The Tutuaca site serves as one example of the interconnection between disturbance and habitat, because recent anthropogenic fire exclusion and future fire management decisions are important factors affecting sustainability. The importance of the Tutuaca reserve extends beyond its boundaries and even beyond the rare species it conserves. The reserve represents a new approach to conservation in Mexico that bypasses limited governmental funding to foster direct, mutually beneficial interactions between conservationists and landowners. A variety of ecological and social research initiatives should be developed to support this important advance. Because of the powerful role of fire, additional studies of forest structure, fuels, and fire patterns should complement experimental forest restoration studies to develop the base of knowledge needed for long-term conservation at Tutuaca and other fire-adapted forest reserves around the world.

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