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Fire regime in a Mexican forest under indigenous resource management

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Abstract. The Rarámuri (Tarahumara) people live in the mountains and canyons of the Sierra Madre Occidental of Chihuahua, Mexico. They base their subsistence on multiple-use strategies of their natural resources, including agriculture, pastoralism, and harvesting of native plants and wildlife. Pino Gordo is a Rarámuri settlement in a remote location where the forest has not been commercially logged. We reconstructed the forest fire regime from fire-scarred trees, measured the structure of the never-logged forest, and interviewed community members about fire use. Fire occurrence was consistent throughout the 19th and 20th centuries up to our fire scar collection in 2004. This is the least interrupted surface-fire regime reported to date in North America. Studies from other relict sites such as nature reserves in Mexico or the USA have all shown some recent alterations associated with industrialized society. At Pino Gordo, fires recurred frequently at the three study sites, with a composite mean fire interval of 1.9 years (all fires) to 7.6 years (fires scarring 25% or more of samples). Per-sample fire intervals averaged 10–14 years at the three sites. Approximately two-thirds of fires burned in the season of cambial dormancy, probably during the pre-monsoonal drought. Forests were dominated by pines and contained many large living trees and snags, in contrast to two nearby similar forests that have been logged. Community residents reported using fire for many purposes, consistent with previous literature on fire use by indigenous people. Pino Gordo is a valuable example of a continuing frequent-fire regime in a never-harvested forest. The Rarámuri people have actively conserved this forest through their traditional livelihood and management techniques, as opposed to logging the forest, and have also facilitated the fire regime by burning. The data contribute to a better understanding of the interactions of humans who live in pine forests and the fire regimes of these ecosystems, a topic that has been controversial and difficult to assess from historical or paleoecological evidence.

Key words: dendrochronology; fire scars; human-caused ignition; pine–oak forest; Pino Gordo; Sierra Madre Occidental.

INTRODUCTION

The degree to which traditional human activities affected historical fire regimes and ecosystems is subject to considerable debate, as the assumption of "pristine" character in pre-industrialized environments has been questioned (Denevan 1992, Vale 2002). Aboriginal people practiced firing techniques to regulate burn severity in tropical north Australia (Lewis 1994), while Native Americans in California applied sophisticated burning techniques to produce food and basketry materials, using fires that affected broad landscapes and maintained characteristic vegetation types (Anderson 1999). In contrast, Baker (2002) argued that the low density of Native Americans in the Rocky Mountains barely affected fire regimes. In the neighboring Southwest, where pre-Columbian human populations were high and fires were frequent, Allen (2002) concurred that humans had little effect but for a different reason: the saturating density of lightning ignitions. Some sedimentary evidence of fire in central Mexico suggests that long-term human settlement substantially degraded landscapes (O'Hara et al. 1994), while other data in the region have been interpreted as showing little human influence on fire regimes or ecosystems (Figueroa-Rangel et al. 2008).

The complexity of past human relationships with fire regimes and the difficulty of interpreting paleoecological evidence are of more than theoretical interest, because contemporary resource management decisions are fraught with assumptions, often not explicit, about "naturalness" (Govender et al. 2006). For example, current policies in the United States and Mexico generally regard human-caused fire as nonnatural and subject to suppression (Stephens and Ruth 2005, Rodríguez-Trejo 2008). However, the disruption of fire disturbance regimes in many pine forest ecosystems coupled with climate warming has contributed to

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problems such as severe wildfires, pathogen outbreaks, or drought-facilitated tree mortality (Minnich et al. 1995), leading to calls for restoration of appropriate fire regimes (Allen et al. 2002, Millar et al. 2007). Detailed information about fire regimes in ecosystems where people maintain traditional practices would be valuable for designing fire management strategies. Unfortunately, the advent of modern forest land uses typically coincided with the removal of indigenous people or alteration of their traditional way of life (Anderson 1999).

The Sierra Tarahumara in northern Mexico is one of the few places in North America where questions about humans and fire can be examined in a landscape that is, in some areas, undisturbed by mechanical logging and road building. The Tarahumara, or Rarámuri as they refer to themselves, are an Uto-Aztecan-speaking people (Pennington 1963) whose population is estimated at 70 000. Their territory is currently recognized as covering an area of ~60 000 km^2, though not legally acknowledged by the land tenure structure in Mexico. This area comprises 17 municipalities on the southwestern border of the state of Chihuahua, generally known as the Sierra Tarahumara. Many Tarahumara live in *rancherías* (single or clustered family farm settlements), raising corn, beans, and squash and herding goats and sheep in ways very similar to their 17th-century ancestors (Pennington 1963). Many practice annual migrations, maintaining residences in the high mountains during the summer when forage for livestock and conditions for crop production are good, and moving to sheltered canyon bottoms during the harsh winters of the highlands (Hard and Merrill 1992).

Ethnographic literature records several uses of fire by Tarahumara that affected landscapes of the Sierra. In May 1894, explorer Carl Lumholtz (Lumholtz 1902) recorded the difficulty in finding forage for his mules because more than 100 miles of montane grasslands between the communities of Yoquivo and Guachochi had been burned, supposedly to bring rain. Other uses of fire include clearing brush from agricultural fields or stimulating growth of grass, and driving deer, rabbits, or foxes towards waiting hunters (Hartman 1897, Pennington 1963). Members of the community of Basíhuare maintain *kumerachi* (also known as *mawechi*), areas burned for shifting agriculture and oak coppice (Davidson-Hunt 2003). These disturbed areas also provide habitats for ruderal plants that are harvested for food (LaRochelle and Berkes 2003).

Pino Gordo-Choreachi (hereafter, "Pino Gordo") is a Rarámuri community formed of smaller rancherías, located in southwestern Chihuahua, and it contains one of the largest fragments of unharvested pine–oak forest remaining in the Sierra Madre Occidental (Lammertink et al. 1996). Since the beginning of mechanized logging in the late 19th century, >99% of the Madrean forest has been subject to one or more commercial timber harvests, which typically removed the largest diameter trees, and reduced stand age and structural diversity (Lammertink et al. 1996). Old-growth fragments that remain are often in inaccessible terrain, in territories controlled by indigenous communities, or are the subjects of land disputes, which have prevented them from being harvested. All of these factors have contributed to maintain the forest in Pino Gordo in an unharvested state with very limited road access. Approximately 800 Rarámuri people live in more than 48 small, isolated rancherías throughout the ejido of Pino Gordo (D. Curiel-Cante, R. W. Gingrich, A. M. Miller, and A.-B. Mancera-Valencia, *unpublished manuscript*). (An *ejido* is a communal landholding.) The local economy is based largely on subsistence crops (corn, beans, and squash) and livestock (goats, sheep, cows, and burros) production. Many residents of Pino Gordo maintain winter residences in the oak and tropical deciduous zones on the slopes and canyon bottoms of the Barranca de la Sinforosa, where they fish, graze their goat herds, and avoid the colder temperatures of the high elevations.

Pino Gordo is a remote area with substantial social, political, and economic problems, including violence, so research activities are limited by access and safety concerns (Miller and Chambers 2007). We took advantage of rare opportunities from 2003 to 2007 to visit Pino Gordo, in collaboration with local residents and governmental and nongovernmental organizations, to ask the following questions:

1) In an area under traditional management by indigenous people, what is the long-term fire regime, has it changed over time, and does it differ from those observed elsewhere in the Sierra Madre Occidental?
2) What are the characteristics and variability of forest composition and structure in a frequently burned, never commercially harvested forest?
3) Are fire uses reported by community members and in the literature consistent with measurements of fire regime and forest structure?

Materials and Methods

Study area

Three study sites were located within Pino Gordo (Fig. 1) in the Sierra Madre Occidental in the municipality of Guadalupe y Calvo, western Chihuahua (26°33′53″ N, 107°1′15″ W). Pino Gordo contains ~29 000 ha of high mesas and deep arroyos ranging in elevation from 2671 m above sea level to 915 m above sea level. The area between 1600 and 2600 m above sea level, ~15 000 ha, is pine–oak forest according to Rzedowski's (1978) classification of the vegetation of México. Tree species in this forest include pines such as *Pinus arizonica*, *P. durangensis*, *P. engelmannii*, *P. leiophylla* var. *chihuahuana*, *P. lumholtzii*, and *P. strobiformis* (pine taxonomy follows Farjon and Styles [1997]). Oaks include *Quercus rugosa*, *Q. hypoleucoides*

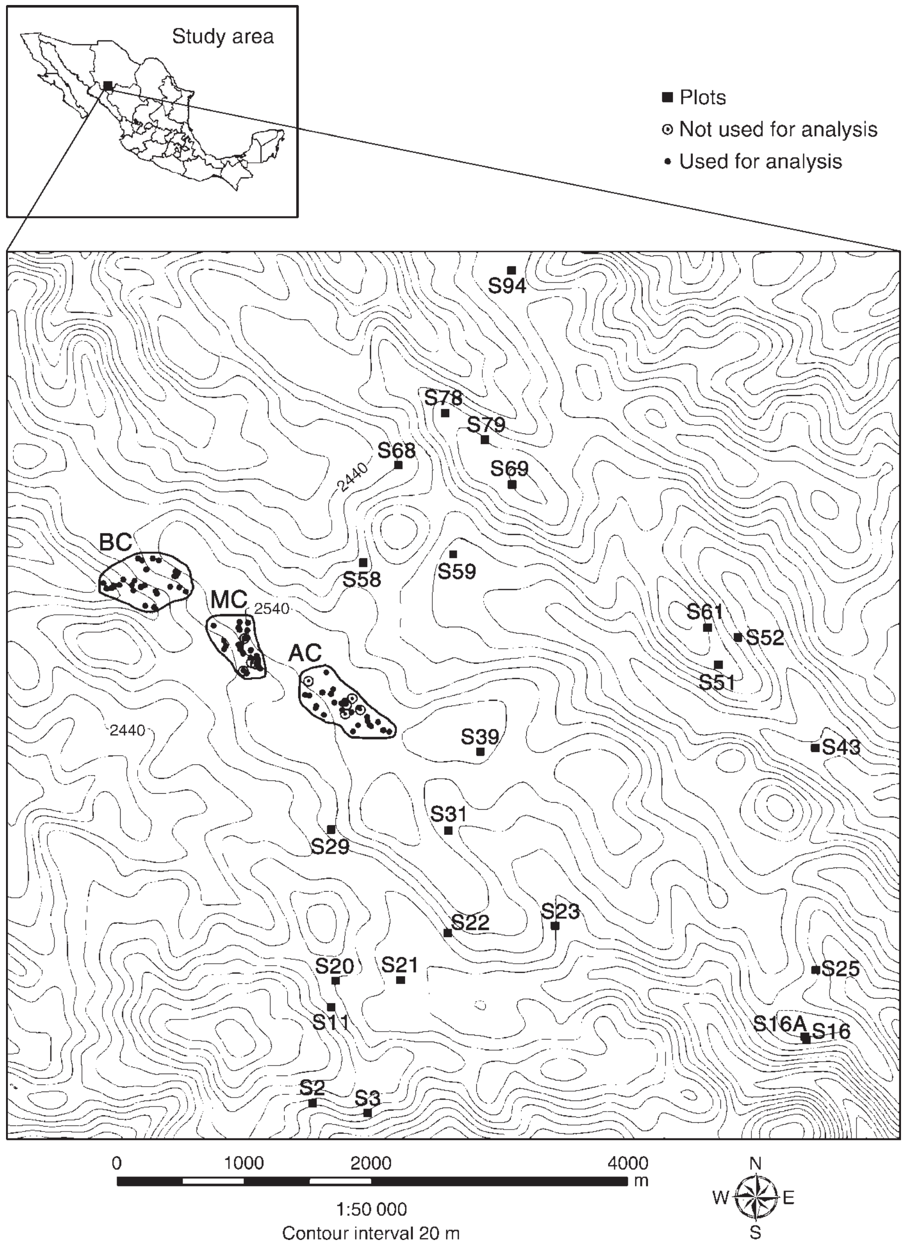

FIG. 1. Study sites in the ejido of Pino Gordo in the Sierra Madre Occidental, western Chihuahua, Mexico. Fire-scarred samples used in the analysis are indicated with solid circles. Fire-scarred samples that could not be cross dated are shown with open circles. From southeast to northwest, the sites are Arriba Coyachi (AC), Medio Coyachi (MC), and Bajo Coyachi (BC). The Cerro Grande (CG) site is ~39 km northwest (not shown).

and *Q. emoryii*. Mexican manzanita (*Arctostaphylos pungens*) and yucca (*Yucca* sp.) are common understory plants, especially on exposed south-facing slopes and in forest gaps.

The average annual temperature in Pino Gordo is between 15° and 20°C, with a maximum below 22°C and annual minimum above −10°C (Aguilar-Uranga 1959). Annual average precipitation is <60 cm (Pase and Brown 1994). The monsoon season begins from mid to late June and lasts until September. Approximately 70% of the annual precipitation occurs during this period, and lightning storms can occur almost daily. The majority of the remaining 30% occurs as rain or snow between November and January.

Fire scar sampling and analysis

We established three fire scar sampling sites in the upper (AC), middle (MC), and lower (BC) portions of the Arroyo Coyachi to characterize fire regimes (Fig. 1). Each site was ~15 ha in size. Fire-scarred tree sampling

TABLE 1. Fire-scarred tree study site characteristics.

Study site	Site code	Elevation (m)	Slope (%)	No. samples collected/ cross dated	Average diameter (cm) of sampled trees (all species)
Arriba Coyachi	AC	2565	21	31/25	49.8
Medio Coyachi	MC	2528	24	32/28	39.0
Bajo Coyachi	BC	2480	25	29/29	54.3

Note: Each site was ~15 ha in extent.

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 2008). Samples were mapped when collected and were well distributed throughout the study sites (Fig. 1). Characteristics of the sampled trees are summarized in Table 1.

In the laboratory, samples were mounted and surfaced until cell structure could be seen clearly under a microscope. Samples were cross dated using characteristic patterns of narrow marker years (Stokes and Smiley 1968). A master tree-ring chronology developed in Bisaloachic (Tutuaca), ~200 km north of Pino Gordo, was also used in cross dating (J. Villanueva-Díaz, *unpublished data*). After dating, ring widths of all samples were measured in order to check dating with the Cofecha program (Holmes 1983). The 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: EE (early earlywood), ME (middle earlywood), LE (late earlywood), L (latewood), and D (dormant or ring boundary). Dormant season scars were assigned to the year of the following earlywood (i.e., spring fires) (Heyerdahl and Alvarado 2003, Fulé et al. 2005). The season was listed as "not determined" when it could not be distinguished clearly.

Fire history data were analyzed with the FHX2 software, version 2.05 (Grissino-Mayer 2001). Analysis at each site began in the first year with an adequate sample depth, defined as the first fire year recorded by 10% or more of the total number 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*b*). Beginning dates were 1847 (AC), 1816 (MC), and 1813 (BC). The period of analysis for all Pino Gordo fire scars combined began in 1835. A common fire history ending date of 2003 was used.

Fire return intervals were filtered for analysis. The statistical distribution of fire intervals using all fire years was assessed. Then only those fire years were included in which 10% or more, or 25% or more, of the recording samples were scarred. After assessing the Pino Gordo study sites individually, all the data were combined, representing 45 ha in total, and the complete distribution of fire return intervals was described using the same three filters: all scars, 10%-scarred, and 25%-scarred. These filters were used because the all-scar filter shows every single fire year, but in some years only one or two trees were scarred. The 10% filter eliminates the years with the most minimal scarring, but still represents a relatively high estimate of fire frequency. The 25% filter is widely used as an estimate of fire frequency considering those fires that were relatively large and/or intense (Swetnam and Baisan 1996*b*).

Forest structure

We determined a sampling area of approximately 7 × 6 km, representative of the forests of Pino Gordo. We generated a map with 100 random sampling points. Since the terrain is so rugged and access is mostly by walking trails, every morning we selected a direction in which to walk and located nearby sampling points with a GPS unit. At 26 sampling points, we established 1000-m^2 circular plots (17.85 m radius) centered on the coordinates of the random points (Fig. 1).

We used metric tapes and ropes to lay down radii and mark subsections within each plot. We collected the following data for all living trees >5 cm in diameter at breast height (dbh): species; dbh; heights for representative trees in the following canopy classes, emergent, dominant, codominant, intermediate, suppressed; and damage type if applicable (fire scar or char on trunk, topped, lightning scar). We also measured dbh for the standing dead trees (snags) in each plot.

Forest data were grouped by vegetation type (20 pine–oak forest plots, 1 juniper woodland plot, 5 open/disturbed plots). We analyzed forest structure for the pine–oak forest, calculating species composition, tree density, and basal area. We estimated biomass using allometric equations (Návar 2009).

For comparison to the Pino Gordo forest structure, we measured a site that had been heavily and repeatedly harvested 39 km to the north on the other side of a deep canyon, the Barranca de la Sinforosa, at Cerro Grande (CG), Municipio Guachochi, 26°53′56.01″ N, 107°10′24.07″ W, in April 1997. Field sampling was conducted over an ~15-ha study area. We measured trees at the Cerro Grande site (CG) on 20 circular plots

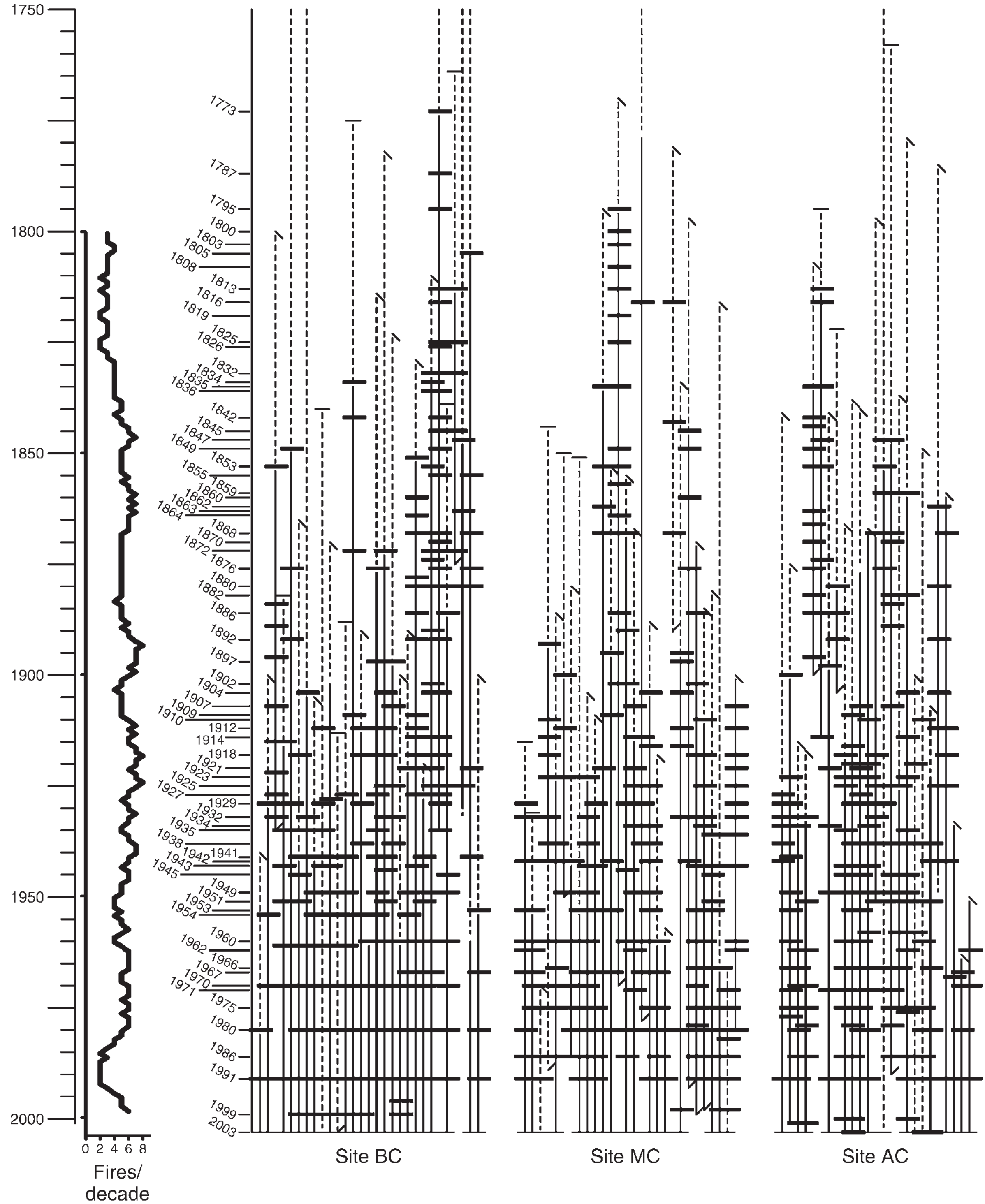

FIG. 2. Fire history charts at three sites in Ejido Pino Gordo. Vertical lines represent trees, and thick horizontal lines represent fire scars. The composite fire history, filtered to fires that scarred at least 10% of recording trees in all three sites, is shown. The software used was FHX2 v. 2.05 (Grissino-Mayer 2001). At the top of some of the dashed lines, the short horizontal bar means that the data begin at the pith (center) of the tree; the slash means that the data begin at a tree ring, not at the pith. The moving window average of the number of fires per decade is shown at the left.

TABLE 2. Fire intervals (years) at the study sites.

Site/ analysis period†	Category of analysis	No. intervals	Mean fire interval, MFI	Minimum	Maximum	Average fire interval per sample‡	Weibull median probability interval (WMPI)§
AC 1847–2003	all scars	62	2.5	1	9	10.2	§
	10% scarred	53	2.9	1	9		§
	25% scarred	23	6.8	2	36		5.5
MC 1816–2003	all scars	56	3.3	1	10	10.2	§
	10% scarred	49	3.7	1	10		3.5
	25% scarred	29	6.0	1	18		5.4
BC 1813–2003	all scars	63	3.0	1	11	13.6	§
	10% scarred	54	3.4	1	11		§
	25% scarred	29	6.4	1	19		5.9
ALL 1835–2003	all scars	91	1.9	1	6	not applicable	§
	10% scarred	58	2.9	1	8		§
	25% scarred	22	7.6	2	38		6.3

Notes: Analysis was carried out from the first fire date with a depth of recording samples equal to 10% of total sample size or a minimum of three recording samples (site CG), until the final fire date. 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.

† The three fire scar sampling sites were in the upper (AC), middle (MC), and lower (BC) portions of the Arroyo Coyachi.

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

§ WMPI values are not shown where the Weibull model did not fit the fire interval data adequately (Kolmogorov-Smirnov test, $\alpha = 0.05$).

200 m^2 in size (7.98 m radius). Plots were located on a 100-m grid. Measurements included species, condition (living/snag decay class/cut stump), dbh, and height. We also compared the Pino Gordo forest data to tree data reported by Miller and Chambers (2007) from Ejido Cabórachi, close to the CG site, ~40 km north of Pino Gordo on the north side of the Barranca de la Sinforosa. Forests in the Ejido Cabórachi and Cerro Grande were similar in elevation and species composition to Pino Gordo, but had been heavily harvested.

Community interviews

In spring 2003, three local indigenous field assistants (two men and one woman) assisted us in collecting standardized interviews from 21 Pino Gordo residents on their use of and understanding of the effects of fire. Their fluency in Rarámuri allowed us to collect information from monolingual informants. Questions focused on: fire uses at home, around the ranch and away from residences; frequency with which informants used fire to clear fields and other agricultural practices; how they perceived fire to benefit soil, animals, and plants; if and when people chose to suppress fire; and how fire practices of previous generations may have differed from those currently in use. The interview component of this study is limited because none of the investigators have formal training in interviews or other social science techniques, nor did we wish to be intrusive toward the residents. Therefore we constrained our questioning to a brief list.

RESULTS

Fire regime

A continuous pattern of frequent surface fires was observed at all three Pino Gordo study sites from the earliest reliable dates (1813–1847) up to the present (Fig. 2), based on 82 cross-dated specimens out of a total of 92 samples collected (Table 1). The final fire occurred at site AC in 2003, MC in 1998, and BC in 1999, respectively 1, 6, and 5 years before the field sampling in 2004. Fire frequency calculated in a 10-year moving window averaged 4.97 fires per decade (Fig. 2). The fire frequency dropped to a low of 2.30 fires per decade in 1984–1994, before rising back to 6 fires per decade by 1998. Fire occurrence at the lowest-elevation site, BC, changed to a pattern of less frequent but more consistently scarring fires beginning around 1960. Mean fire intervals (MFI) ranged from 2.5 to 3.3 yr at individual 15-ha sites, considering all fire dates, and from 6.0 to 6.8 yr when data were filtered to include only fire years in which 25% or more of the recording samples were scarred (Table 2). Combining all sites, the overall MFI dropped to 1.9 yr for all fires but increased to 7.6 yr for the 25%-scarred category. Minimum fire intervals were 1 or 2 years for all sites and categories; maximum intervals between fires were all below 20 yr except for the 25%-scarred category in site AC and the combined data from all sites (Table 2). Average per-sample (or "point") fire intervals ranged from 10.2 to 13.6 yr. The Weibull model generally fit the data only in the 25%-scarred category; Weibull median probability intervals were similar to MFI values (<1.5 yr difference) (Table 2).

Seasonal position of fire lesions could be determined on 481 out the 652 fire scars (74%) (Table 3). Approximately two-thirds of the scars occurred in the dormant season. Early and middle earlywood made up an additional 44.7%. Only an average of 1.7% of scars formed in the late earlywood and no latewood scars were found, indicating that the assignment of dormant-season scars to the year of the following earlywood (i.e., spring fires) was justified.

TABLE 3. Distribution of fire scars (number and percentage) based on season and the position of the fire lesion within the scarred ring.

Site	Season determined	Season not determined	Dormant	Early earlywood	Middle earlywood	Late earlywood	Latewood
AC	160 (78%)	46 (22%)	109 (68%)	35 (22%)	15 (9%)	1 (1%)	0
MC	161 (76%)	52 (24%)	102 (63%)	33 (21%)	24 (15%)	2 (1%)	0
BC	160 (69%)	73 (31%)	109 (68%)	24 (15%)	22 (14%)	5 (3%)	0

Note: The three fire scar sampling sites were in the upper (AC), middle (MC), and lower (BC) portions of the Arroyo Coyachi.

Forest composition and structure

The unharvested forest at Pino Gordo was dominated in basal area and density by pines (Table 4). Oaks were less dense than pines (190 vs. 498 trees/ha) and made up less basal area (5.93 vs. 17.75 m^2/ha) (Table 4). Other species, junipers, madrones, and hardwoods, made up <7% of the total basal area. Pines were relatively large, with quadratic mean diameter equal to 21.3 cm; the largest individual had a dbh = 69.1 cm. The quadratic mean diameter of oaks was 19.9 cm and the largest oak was also the largest tree encountered in the forest, with dbh = 79.7 cm. The overall diameter distribution of the forest was unimodal with a peak in the 10.1–30 cm class (Fig. 3). Trees >30 cm dbh made up 13% of the total density; trees >50 cm made up 2% of the distribution. Pine stumps, reflecting cutting by residents for domestic uses, averaged 0.5 stumps/ha. Total aboveground biomass averaged 132 Mg/ha, of which pines made up 89 Mg/ha.

In contrast to Pino Gordo, both of the harvested forest sites had less pine basal area, smaller trees, and many pine stumps. The total basal area at Cerro Grande was approximately equal to that of Pino Gordo, but the pine basal area was only 65% that of the unharvested site; at Ejido Cabórachi, total basal area was 32% and pine basal area was 33% that of Pino Gordo (Table 4). Quadratic mean diameters of pines and oaks were 18.5 cm and 14.5 cm at Cerro Grande and 15.3 cm and 23.2 cm at Ejido Cabórachi, respectively. Diameter distributions at both harvested sites were strongly dominated by the smallest trees (Fig. 3). Trees >30 cm dbh made up 5% and 8% of the total density at Cerro Grande and Ejido Cabórachi, respectively. Trees >50 cm made up 2% of the distribution at Ejido Cabórachi; there were no trees >50 cm at Cerro Grande. Pine stumps from past harvests averaged 17.5 and 26.0 stumps/ha at Cerro Grande and Ejido Cabórachi, respectively. Total aboveground biomass at Cerro Grande averaged 108 Mg/ha, of which pines made up 57 Mg/ha.

Densities of large snags also differed between Pino Gordo and the harvested sites. The Pino Gordo forest had 11.5 snags/ha with dbh > 30 cm and 2.0 snags/ha with dbh > 50 cm. Only 2.5 snags/ha > 30 cm were encountered at Cerro Grande and 0.5 snags/ha with dbh > 30 cm at Ejido Cabórachi. Neither of the harvested sites had any snags >50 cm.

Fire use in the community

Several uses of wildland fire were reported by 21 Pino Gordo residents from seven rancherías (Table 5). Two uses were related to agricultural cultivation: clearing new fields and fertilizing fields. Other uses, such as improving livestock forage, hunting, and managing areas for firewood, are consistent with previous reports in the literature. Domestic uses included lighting, heat, firing pottery, and cooking. The final fire use mentioned was bringing rain. Ecological effects of fire mentioned by residents included causing sprouting, nourishing vegetation, and increasing growth, and attracting animals to fresh browse and birds to live in snags. Improved growth of medicinal plants and fungi following fire was noted by several people.

DISCUSSION

The frequent surface-fire regime at Pino Gordo is the least interrupted sequence of fires up to the present reported to date in North America. There is no evidence of fire regime disruption from the early 19th century

TABLE 4. Pine–oak forest structure at Pino Gordo (never harvested), Cerro Grande (harvested), and Ejido Cabórachi (harvested).

	Pino Gordo		Cerro Grande		Ejido Cabórachi	
Forest type	Basal area (m^2/ha)	Density (trees/ha)	Basal area (m^2/ha)	Density (trees/ha)	Basal area (m^2/ha)	Density (trees/ha)
Hardwood	0.13	12.0	0	0	0	0
Juniper	0.84	35.0	2.09	155.0	0.38	23.8
Madrone	0.81	45.5	2.61	255.0	0.20	3.5
Oak	5.93	190.0	9.45	570.0	1.64	38.7
Pine	17.75	497.5	11.5	427.5	5.86	317.3
Total	25.46	780.0	25.64	1612.5	8.19	588.5

Notes: Data are from Miller and Chambers (2007). At Pino Gordo, trees measured were ≥5 cm dbh.

(1813–1847) into the first decade of the 21st century (2004), except at site BC, which showed reduced frequency and increased synchrony of fires beginning around 1960. During the same time period elsewhere in North America and locally in northern Mexico, fire regime disruption has been associated with events such as the introduction of sheep to the Navajo in Arizona circa 1820 (Savage and Swetnam 1990); widespread livestock grazing across the southwest USA beginning around 1860 in California and 1880 in Arizona and New Mexico, coincident with the completion of transcontinental railroads (Swetnam and Baisan 2003); and the formation of ejidos in northern Mexico between 1930 and 1950 (Heyerdahl and Alvarado 2003). The Sierra Tarahumara in general was unaffected by industrialized society until the latter half of the 20th century. The mountains were crossed by a railroad to the Pacific in 1961 and harvesting accelerated to "massive" proportions in the subsequent decades; in 2001 the municipalities of the Sierra Tarahumara accounted for 97% of the timber production in Chihuahua (Davidson-Hunt 2003). However, the inaccessible location of Pino Gordo on the southern side of the Barranca de la Sinforosa, as well as internal political conflicts, have kept logging at bay. Several other isolated forests in northern Mexico maintained relatively frequent fire regimes even after the 1950s, including the Sierra San Pedro Mártir (Baja California) (Stephens et al. 2003), Sierra de los Ajos (Sonora) (Swetnam and Baisan 1996), Cerro Mohinora (Chihuahua) (Cerano-Paredes 2008), and Cerro Blanco in La Michilía Biosphere Reserve (Fulé and Covington 1999). All those sites, however, displayed lengthening fire-free intervals beginning circa 1970. The pattern of fewer but more synchronous fires in the late twentieth century that we observed at site BC resembles fire regime changes in the Sierra San Pedro Mártir (Stephens et al. 2003). At Pino Gordo, however, the neighboring upslope sites MC and AC did not reflect the BC pattern; the reason for the difference at BC is unknown.

Apart from the persistence of frequent fires to the present, the statistical characteristics of the Pino Gordo fire regime are similar to those of other pine forests in Chihuahua and nearby areas of Mexico and the United States. The all-scar MFI values (2.4–3.3 yr) and 25%-scarred MFI values (6.0–6.8 yr) are at the lower end of the range encountered elsewhere. The other published studies in Chihuahua reported these values respectively as 3.5–4.9 yr/6.9–8.4 yr (study sites 25 ha in size [Fulé et al. 2005]), 5.1–8.8 yr/13.3–13.8 yr (study sites 40–60 ha [Cerano-Paredes 2008]), and ~4 yr (all scars only, study sites 2–6 ha) (Heyerdahl and Alvarado 2003). The next nearest studies in northern Durango reported 3.8–5.0 yr/6.5–8.6 yr (Fulé and Covington 1997) and ~3 and 6 years (all scars only) (study sites 2–6 ha [Heyerdahl and Alvarado 2003]). In the Sierra de los Ajos of Sonora, Swetnam and Baisan (1996*a*) found 3.8–4.0 yr/5.5–9.1 yr (study sites 10–100 ha). Taking all three Pino Gordo sites together, the overall composite interval of 1.9 yr

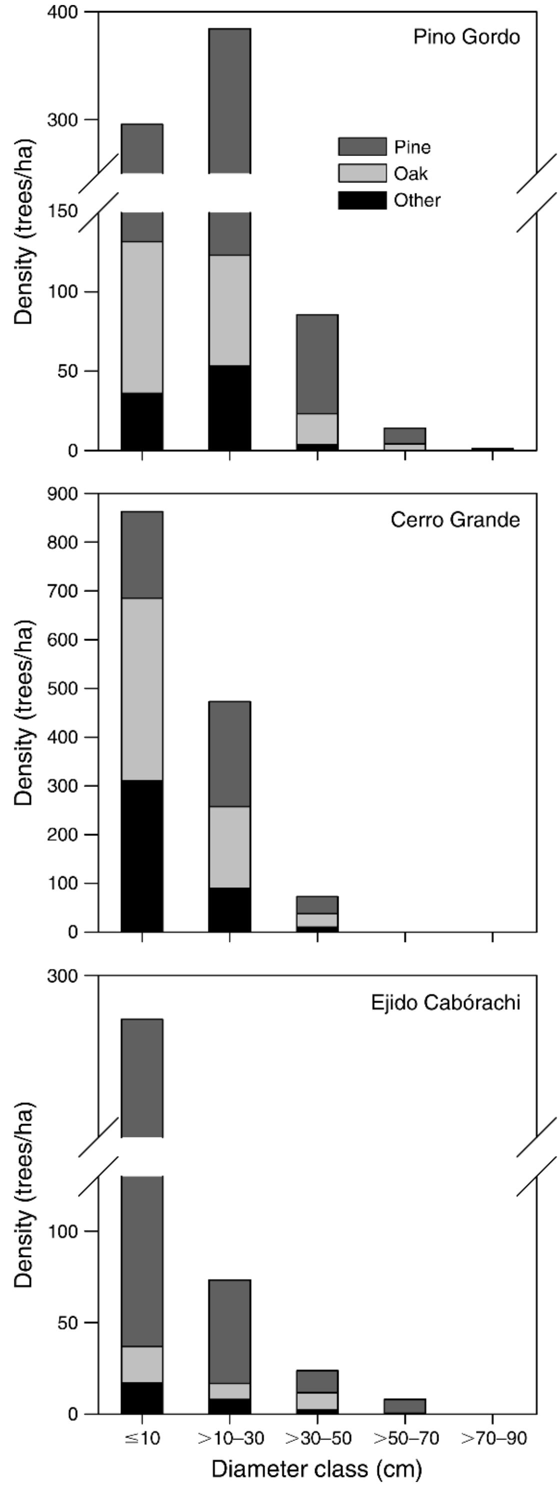

Fig. 3. Diameter distributions of trees at Pino Gordo (never harvested, top), Cerro Grande (harvested, middle), and Ejido Cabórachi (harvested, bottom). Ejido Cabórachi data are from Miller and Chambers (2007).

TABLE 5. Indigenous Rarámuri uses of fire from interviews in the community of Pino Gordo and from literature.

Purpose	Use of fire: At Pino Gordo	Use of fire: In the literature
Clear brush and trees from new fields	X	Pennington (1963)
Fertilize fields	X	Pennington (1963)
Improve grass/forage for livestock	X	Pennington (1963)
Hunting	X	Mares-Flores (1974), Pennington (1963)
Manage firewood collecting sites	X	Davidson-Hunt (2003)
Bring rain	X	Pennington (1963), Lumholtz (1902)

(over 45 ha) has been matched only by studies ~9° latitude north on the Mogollon Rim, Arizona, at Limestone Flat (1.8 yr, 16 ha) (Dieterich 1980) and Yellow Flat (1.7 yr, 100 ha) (Van Horne and Fulé 2006). However, surface fires ceased at the Arizona sites 110–129 years ago. Fire seasonality also followed similar patterns at Pino Gordo as in the other forests, with dormant-season scars predominant followed by early-earlywood scars; almost no late earlywood or latewood scars were reported. Elsewhere, fires burning in different seasons have been suggested as a means of separating human-caused from lightning ignitions (Kaye and Swetnam 1999, Skinner et al. 2009). However, we did not observe differences at Pino Gordo compared to other sites. Overall, the Pino Gordo fire history is similar to those of other forests in southwestern North America, except that the Pino Gordo fire regime has continued up to the present.

The unharvested forest of Pino Gordo differed from the two harvested forests in three key ways: larger trees, higher proportion of pines, and the presence of large snags. The abundant stumps of large pines in the harvested forests attested to the cutting of the largest, most valuable pines. If all three forests were assumed to have been roughly similar in structure prior to harvesting, the two harvested forests have lost 35–67% of their original pine basal area. Aboveground biomass at Pino Gordo was 22% higher than at Cerro Grande and pine biomass was 56% higher. Forest biomass at Pino Gordo (132 Mg/ha) was similar to the average in south-central Durango (130 Mg/ha), a relatively productive region of Mexico (Návar 2009). Not only does the Pino Gordo forest support more aboveground biomass and carbon than the nearby harvested forests, it is likely to be more resistant to severe disturbance from fire. Frequently burned pine forests in Mexico have relatively low surface and canopy fuels (Fulé and Covington 1998, Stephens et al. 2007), resulting in limited fire intensity (Stephens et al. 2008). Unlike some other frequently burned Mexican forests, the Pino Gordo forest was fairly dense (Table 4, Fig. 4), but the mode of the diameter distribution was in the 10.1–30 cm class (Fig. 3). Diameter distributions of the two harvested forests were strongly skewed to the smallest diameter class (<10 cm); a high density of small trees indicates a greater vulnerability to fire transition into the canopy (Scott and Reinhardt 2001).

Structural features of the old forest are linked to conservation of biological diversity. Miller and Chambers (2007) encountered 30 bird species on systematic transects at Pino Gordo, as compared with 19 species at Cabórachi, despite having fewer transects at Pino Gordo. Consistent with the striking difference in densities of large snags between Pino Gordo (13.5 snags with dbh > 30 cm/ha) and Cabórachi (0.5 snags > 30 cm/ha), twice as many primary cavity nesters were observed at Pino Gordo (Miller and Chambers 2007). The Acorn Woodpecker (*Melanerpes formicivorus*), which uses large (50+ cm) snags for nest sites and granaries, was far more frequent at Pino Gordo (Miller and Chambers 2007). However, generalist and ground-nesting birds were also observed, suggesting that human activity was contributing to maintaining habitat diversity (Miller and Chambers 2007); this hypothesis was supported at the landscape scale by the fact that 12% of our random plot locations were classified as open or disturbed.

Human uses of fire reported by Pino Gordo residents are consistent with indigenous fire use documented nearby in the Sierra Tarahumara (Pennington 1963, Davidson-Hunt 2003) and similar to traditional fire uses in indigenous communities elsewhere (Lewis and Ferguson 1988) (Fig. 4). Davidson-Hunt (2003) studied fire use by Rarámuri people in Basíhuare, describing a practice of burning called *kumerachi* in which residents made clearings for farming in oak-dominated areas of forest, either removing the wood for firewood or leaving it to dry and then igniting a fire coincident with the onset of summer monsoon rains in June. Key points of *kumerachi* included a sophisticated selection of field sites mostly on east and southeast-facing slopes, timing of ignition when early rains had reduced fire danger but fuels were not yet saturated, and retention of mature pine, juniper, and oak trees within the cleared area; resprouting oaks produced multiple stems of good size for firewood (Davidson-Hunt 2003). The effects of such a management regime appear to be consistent with our observations of the forest at Pino Gordo: primarily a surface-fire regime with numerous mature, fire-scarred trees; individual trees allowed to reach mature age and

FIG. 4. (Upper photo) Open forest with charred trees, and higher forest density in background. (Lower photo) Corn growing in a swale adjacent to pine forest. Fires lit for agricultural clearing can spread into forest lands.

size even in the perturbed sites; and undisturbed patches interspersed with parcels used for agriculture.

While our survey with Pino Gordo fire users does provide an overview of some of the ways they continue to use it as a land management tool, our understanding of how they relate to fire and their management preferences remains rudimentary. Insiders' understandings of the ideal role for fire in maintaining land health, indigenous institutions for its use, and indicators for its successful use may not be transparent to a cultural outsider (Miller and Davidson-Hunt 2010). These understandings, while outside the scope of the current work, will be important for crafting a cooperative management regime for Pino Gordo that both protects this important ecological learning opportunity while respecting local peoples' culture and aspirations.

Certain questions about the role of human activities in the fire regime cannot be addressed by this study. For example, while it is clear that the Tarahumara ignite many fires, we cannot disprove the hypothesis of Allen (Allen 2002) that there are sufficient lightning ignitions to maintain the frequent fire regime. However, Pino Gordo is a valuable example of a continuing frequent-fire regime in a never-harvested forest. The Rarámuri of Pino Gordo have conserved their forests up to the present because of their emphasis on maintaining a traditional life, as opposed to logging the forest. They also facilitate the fire regime by burning. The presence of large trees, high forest biomass, large snags, and birds dependent on old forest indicate that these ecosystem elements are compatible with frequent surface fire as well as with the current level of human resource use. These findings suggest that conservationists should recognize that the presence of native peoples may be a key reason why valued resources, such as old-growth forests, are still present. Conservation planning should incorporate traditional knowledge and resource management practices of indigenous peoples, especially when these practices are found to have ecologically as well as socially beneficial outcomes.

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