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Fire ecology of Mexican pines and a fire management proposal

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Abstract. Many Mexican pine ecosystems are characterized by great biological diversity and are strongly influenced by fire. We summarize fire ecology information for 35 taxa (including infraspecific taxa) in terms of nine types of fire traits: serotiny, seed germination after fire, grass stage, fast initial growth, thick bark, protected buds, self-pruning capacity, resprouting, and canopy recovery from scorch. The majority of Mexican pine species appear to be adapted to a predictable, stand-thinning fire regime. Current fire regimes are often altered from long-term historical patterns due to a combination of natural fires plus anthropogenic fires. Human-caused fires are the most common and burning practices have deep historic and socioeconomic roots. As a consequence, there are three main categories of fire conditions: (1) pine forests endangered by excessive anthropogenic fire (eventually leading to deforestation); (2) pine forests maintained by an appropriate fire regime; and (3) pine forests with insufficient fire or fire exclusion due to fire protection. For managers, conservationists, and landowners concerned with maintaining the important benefits associated with fire, such as fuel hazard reduction and nutrient cycling, different approaches are needed. While recognizing the difficult social and economic factors that foster forest degradation, we recommend basing fire management in pine forests upon a site-specific and species-specific understanding of the historical and ecological role of fire, trying to reduce excessive anthropogenic burning, maintain appropriate burning, and restore fire into fire-excluded forests. The interaction of fire with other resource uses, such as timber harvesting and livestock grazing, should also be balanced in a holistic ecosystem management approach. These changes must be made in the context of seeking alternative economic options for rural residents and by thoughtful planning to obtain as many ecological and economic benefits from fire as possible while minimizing negative impacts.

Additional keywords: fire traits; fire management; fire regime; forest fires; Mexico; *Pinus*; Pinaceae; restoration ecology; wildfires.

Introduction

Forest fires are one of the most common disturbances on earth and a vital presence in many ecosystems. This is certainly the case with many of the pine forests of Mexico which are rife with natural and anthropogenic fires. In some areas, excessive burning has contributed to degradation and even outright deforestation. In other areas, frequent, low intensity fires facilitate regeneration and maintain an open structure. An understanding of fire's ecological role is essential to any program of restoration, conservation or management. Unfortunately, the quantity of research concerning fire ecology and fire impacts in Mexican pine ecosystems is not large and the majority of what exists is not known in international circles. This paper seeks to review and integrate the available information and to propose a strategy of fire use in resource management, considering both ecological and socioeconomic factors in order to help conserve and restore pine ecosystems.

Forest fires in Mexico

Most fires in Mexico occur during the spring before the summer rains and greenup of vegetation. In the Baja Peninsula, with a Mediterranean climate, fire season starts in summer. The average number of forest fires per year from 1995 to 2000 was 8877, with the area burned per year averaging 330 384 ha (Rodríguez-Galindo 2001), or 0.26% of the surface area covered by temperate and tropical forests plus shrublands. In 1998, under the influence of the strongest 'El Niño' on record by some measures (McPhaden 1999), Mexico experienced historic droughts and an extraordinary fire season (Rodríguez-Trejo and Pyne 1998). A total of 14 445 fires affected 849 632 ha (SEMARNAT, unpublished report,

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2000*a*) and the smoke reached the United States and other nations in the Caribbean.

According to SEMARNAT (2002*a*), only 6.2% of fires in Mexico start from lightning, illegal crops, and rare causes. However, we suggest that this figure underestimates the natural occurrence of fire, at least in northern Mexico. By way of comparison, 45% of wildland fires in Arizona and New Mexico, USA, are due to lightning (data 1992–2001, USDA Forest Service, Albuquerque, NM). Human-caused fires in Mexico are mostly due to agricultural and pastoral activities, accounting for 46% of ignitions for 2001 and 2002 (January–August 8) in the country (SEMARNAT 2002*a*). In northern Mexico, natural fires are more common. According to the same source, and for the same period of time, in northern Mexico (Baja California, Sonora, Chihuahua, Coahuila, Nuevo León and Tamaulipas), the causes related to agricultural and pastoral activities account for 20%, and other causes (including lightning), for 38%. In central Mexico (Distrito Federal, Estado de México, Puebla, Tlaxcala and Morelos), the figures are, respectively, 56% and 5%. Finally, in southern México (Yucatán, Quintana Roo, Campeche, Chiapas, Tabasco), the percentages are, respectively: 44% and 3%.

The reason for the predominance of human-caused ignition stems from the history and present socioeconomic situation of the country. Beginning thousands of years ago with the first inhabitants of present-day Mexico, the natural fire regimes were altered by anthropogenic fire with increasing frequency and effects on the ecosystems as the human population grew. The ancient cultures, such as Mayan, Aztec, and Texcocan, were concerned with sustaining forests; the Chichimec culture promulgated legislation to prevent forest fires (Rodríguez-Trejo and Sierra-Pineda 1992). After the Spanish conquest, the indigenous human population declined and livestock grazing started (Melville 1994; Pyne 1997*a*). The influence of the European pastoral economy led to the application of broadcast fire for range improvement; subsequent deforestation in parts of Mexico was a repetition of what happened in Spain (Pyne 1997*b*). After Mexican independence in the 19th Century, the government created the 'Secretaría de Fomento' (Gutiérrez-Palacio 1989), leading to the establishment of a Forest Service in 1861 (Esquinca 1950). Presently the Secretariat is named Secretaría de Medio Ambiente y Recursos Naturales (SEMARNAT).

Over time, this organization has gradually increased its size and capability to prevent, detect, and fight fires in collaboration with other federal, state, and private fire management agencies. The Mexican army and volunteers offer additional support during difficult fire seasons. Firefighters are working diligently at presuppression and suppression given the level of economic, human and material resources they have (Gonzales-Caban and Sandberg 1989). Recent improvements include better satellite and computer capability, as well as improved formal training of firefighters. But like many other countries in the world, and as demonstrated during the historic 1998 fire season (Rodríguez-Trejo 1998*a*, *b*), they cannot begin to detect or fight 100% of the wildfires. Contributing factors include the lack of resources and the common use and misuse of fire in agricultural activities across Mexico, practices with deep historic roots in which rural poverty plays a key role. For instance, econometric modeling showed that the most significant variables related with number of fires in different regions of Mexico in 1980, 1990 and 1994 were education level and the availability of land for cattle growing (Torres-Rojo and Hernández 1999).

Pine ecosystems in Mexico

Mexico is one of the world's richest countries in number of pine species, with 47 species and 20 infraspecific taxa recognized by Farjon and Styles (1997), nearly 50% of the approximately 110 pine species worldwide. Other taxonomists have counted as many as 120 species for Mexico (see Farjon and Styles 1997, pp. 4–5). Appreciable confusion about species names exists among taxonomists, foresters, and ecologists. Throughout this article, we have used the nomenclature of Farjon and Styles (1997) and have provided synonyms wherever applicable.

Coniferous forests dominated by pines, mixed conifer hardwood forests, and hardwood forests cover 32.8 million ha in Mexico (SEMARNAT 2002*b*; note that other sources give differing numbers for various types of forest, e.g. Klooster and Masera 2000). Pines may form pure or mixed forests with other conifers and there are extensive pine–oak forests, but pines also associate with chaparral vegetation, juniper woodlands, deciduous forest and transitional and tropical vegetation (Farjon *et al.* 1997). Environmental conditions where pines occur are extraordinarily variable: elevations from sea level to >4000 m; mean annual temperature from 6°C to 28°C; mean annual precipitation from 350 to more than 1000 mm; from 1 to 7 dry months; commonly on soils formed from igneous parent material but also on sedimentary soils, acidic to neutral pH, rich in organic matter (Rzedowski 1978; Perry 1991; Farjon and Styles 1997).

In this paper, we review fire-related traits of 35 pine species or varieties (scientific names are given in Table 1). Where fire regime information is known, we applied the fire regime classification system used by Keeley and Zedler (1998): (1) fire predictable/unpredictable (2) stand-thinning/stand-replacing. The fire-related traits mentioned here are generally recognized as important in fire ecology, although there is debate regarding whether such traits evolved specifically as adaptations to fire (Mutch 1970; Bond and Midgley 1995; Whelan 1995). The traits listed in Table 2 include nine types (number of taxa in parentheses): serotinous cones (11), good regeneration on burned localities (25), resprouting capacity (8), grass stage (4), fast initial growth (4), thick bark (27), bud protected by heat resistant scales (1), self-pruning capacity (18), and recovery from crown scorch (3). Twelve taxa have four (*Pinus caribaea* var. *hondurensis*, *Pinus greggii*, *Pinus*

Table 1. Scientific names of pine taxa described in the text and Table 2

Nomenclature is from Farjon and Styles (1997); other names are given in parentheses. '=' indicates that the name is not recognized by Farjon and Styles (1997)

Species name and authority
P. arizonica Engelmann (=*P. ponderosa*)
P. arizonica Engelmann var. *cooperi* (C.E. Blanco) Farjon (=*P. cooperi* C.E. Blanco)
P. attenuata J.G. Lemmon
P. ayacahuite Ehrenberg ex Schlechtendal var. *veitchii* (Roezl) G.R. Shaw
P. caribaea Morelet var. *hondurensis* (Sénéclauze) W.H. Barrett & Golfari
P. cembroides Zuccarini
P. contorta D. Douglas ex J.C. Loudon var. *murrayana* (Balfour) Engelmann
P. cembroides Zuccarini ssp. *lagunae* (Robert-Passini) D.K. Bailey
P. coulteri D. Don
P. devoniana Lindley (= *P. michoacana* Martínez)
P. douglasiana Martínez
P. durangensis Martínez
P. engelmannii Carrière
P. greggii Engelmann ex Parlatore
P. herrerae Martínez
P. hartwegii Lindley (= *P. rudis* Endlicher)
P. jaliscana Pérez de la Rosa
P. jeffreyi J.H. Balfour
P. lambertiana D. Douglas
P. lawsonii Roezl ex G. Gordon & Glendinning
P. leiophylla Schiede ex Schlechtendal & Chamisso
P. leiophylla Schiede ex Schlechtendal & Chamisso var. *chihuahuana* (Engelmann) G.R. Shaw (=*P. chihuahuana* Engelm.)
P. monophylla J. Torrey & Frémont
P. montezumae A.B. Lambert
P. muricata D. Don var. *muricata* (=*P. remorata* H. Mason)
P. oocarpa Schiede ex Schlechtendal
P. oocarpa Schiede ex Schlechtendal var. *ochoterenae* Martínez
P. oocarpa Schiede ex Schlechtendal var. *trifoliata* Martínez
P. patula Schiede ex Schlechtendal & Chamisso
P. praetermissa Styles & McVaugh (=*P. oocarpa* Schiede ex Schlechtendal var. *microphylla* Shaw)
P. pringlei G.R. Shaw
P. pseudostrobus Lindley
P. pseudostrobus Lindley var. *apulcensis* (Lindley) G.R. Shaw (=*P. oaxacana* Mirov)
P. quadrifolia Parlatore ex Sudworth
P. radiata D. Don var. *binata* (Engelmann) J.G. Lemmon
P. teocote Schiede ex Schlechtendal & Chamisso

jeffreyi, *Pinus devoniana*, *Pinus muricata* var. *muricata*, *Pinus patula* and *Pinus teocote*), or five (*Pinus hartwegii*, *Pinus leiophylla*, *Pinus montezumae*, *Pinus oocarpa*, and *Pinus pringlei*) types of fire-related traits.

When summarizing the fire ecology literature, it must be stated clearly that research on Mexican ecosystems has been limited. Probably other traits and responses to fire are empirically known by foresters, biologists and people living in the rural areas. For instance, the profuse regeneration in burned sites of *Pinus patula*, as observed by Mirov (1967) for other pine species, was largely known before its technical documentation. Furthermore, even when information from a given region exists, the fire-related traits may vary in their manifestation over the entire range of the species. *Pinus hartweggii* (=*P. rudis*, Table 1) does not sprout at every site, for example, just as a serotinous species may not be always serotinous along all its range. Variation in serotiny has been documented in the USA in *Pinus contorta* (Lotan 1974), *P. muricata* (Zedler 1986), and *P. coulteri* (Borchert 1985). The three species are present in Mexico. Moreover, Myers (1992) reported that no consistent morphological differences besides serotiny were found between *Pinus clausa* var. *clausa* (serotinous) and *P. clausa* var. *immuginata* (non-serotinous) in south-eastern USA, suggesting that the degree of serotiny was likely a function of fire regime.

Fire ecology of Mexican pines

In this section we summarize fire ecology information by species for several of the taxa listed in Tables 1 and 2. Since most temperate Mexican forests are mixed, fire studies frequently include multiple species. Wherever possible, individual studies have been listed by the dominant pine species. As is frequently the case in fire ecology research (Whelan 1995), the majority of studies to date have been observational rather than experimental and the effects of fire have often been variable, if not even contradictory, between different studies and locations. Much of the fire ecology information in Mexico is in the 'gray literature': reports, proceedings, and theses.

P. arizonica (classified together with *P. ponderosa* in Mexico by Rzedowski 1978:294). Regenerates well on burned areas (Verduzco-Gutiérrez *et al.* 1962) and thick bark and good self-pruning capacity protect it from fire. However, in Durango, survival of *P. arizonica* and *P. durangensis* trees declined after burns with fuel loading ≥36–49 Mg/ha and pest susceptibility increased with fuel loading ≥22–35 Mg/ha (Zapata-Pérez 1991). Alanís-Morales (1995) tested successive fall or winter prescribed burns in *P. arizonica* stands in Chihuahua, finding increases in water flow, particularly on the second fall burn. In a cross-border comparison of the Sierra de los Ajos, Sonora, and Animas Mountains, New Mexico, Villanueva-Díaz (1996) found that total nitrogen and cation exchange capacity were lower in the Mexican site, consistent with the lower tree densities associated with the frequent fire history and logging activities in Sierra de los Ajos. In a *Pinus arizonica*-dominated stand in Chihuahua, Alanís-Morales *et al.* (2000) found increased runoff in prescribed-burned sites, with higher runoff associated with lower forest fuels loads and lower litter-layer depths.

P. devoniana. Regenerates well on burned sites (Vázquez and Pérez 1990) and its seedlings have a grass stage (Perry 1991; Keeley and Zedler 1998) (other Mexican species with a

Table 2. Fire traits and fire regimes for 35 species or varieties of Mexican pines

Nomenclature is from Farjon and Styles (1997). Data for serotiny, bark thickness, and self-pruning, from Martínez (1948), Eguiluz-Piedra (1988), Perry (1991), Farjon and Styles (1997), Farjon *et al.* (1997), and personal field observations, except if indicated. FL = frequent or relatively frequent and low intensity fires. NH = non-frequent high intensity fires. Numerals in parentheses refer to footnotes

Species	No. of states where found	Regenerates well in fire-created seed bed	Serotinous cones	Thick bark	Self-pruning (adult)	Recovery from crown scorch	Resprouts (young trees)	Grass stage	Fast initial growth	Bud protected by heat resistant scales	Fire regime / comments
P. arizonica	4	X (2,29,30)		X (31)	X(31)						FL 4–12 yrs. (32)
P. arizonica var. *cooperi*	3			X	X						Succession advances w/o fire
P. attenuata	1	X(1)	X		X						NH, predictable stand replacing (39)
P. ayacahuite var. *veitchii*	9			X	X				X		
P. caribaea var. *hondurensis*	1(3)	X(4)		X		X(4)	X(5)				Frequent (4)
P. cembroides	18	X(6)		X							Non predictable. Absence of fire displaces it (39,7). 10–30 years in Texas (42)
P. contorta var. *murrayana*	1	X(45)									
P. coulteri	1	X(8)	X(9)	X							At its lower limit merges in chaparral with destructive fire regime (10)
P. devoniana	17	X(11,21)		X	X(39)			X			FL
P. douglasiana	10	X(11)			X						
P. durangensis	5	X(20)			X						FL, 4 yrs. (12) succession advances w/o fire
P. engelmannii	6			X				X(13)			Predictable, stand thinning (39), FL, 4 yrs. (12). In Arizona, 1–38 years (44)
P. greggii	6	X?	X	X					X		
P. herrerae	5			X	X						Succession advances w/o fire
P. hartwegii	17	X(33)		X	X	X(34)	X(14,35)				FL, succession, advances w/o fire (15,19)
P. jaliscana	1		X(18)	X	X(39)						
P. jeffreyi	1	X(16)		X(6, 39)	X(39)					X(43)	FL, predictable, stand thinning (39)
P. lambertiana	1	X(40,41)		X(40,41)							Resistant to low to moderate severity fires (40,41)
P. lawsonii	7	X(11)		X	X						
P. leiophylla	16	X	X(17)	X(38)	X(39)		X(18)				Predictable stand replacing (39), LF, NH, succession, advances w/o fire (19)
P. leiophylla var. *chihuahuana*	6			X	X		X(37)				
P. monophylla	1										Non predictable (39)
P. montezumae	17	X(22)		X	X		X(7,23)	X			FL, succession advances w/o fire (7,19)
P. muricata var. *muricata*	1	X(10)	X	X					X(46,47)		NH, predictable stand replacing (39). 6–9 years—puntual analysis or 20–30 years—composite data analysis in California (48)

Table 3.

P. oocarpa	17	X(18)	X	X	X		X(7,18)		
P. praetermisa	4	X?	X						
P. oocarpa var. *ochoterenae*	3						X(24)		
P. oocarpa var. *trifoliata*	2	X?	X						
P. patula	11	X(25)	X(25)	X				X	FL and NH. Succesion advances w/o fire (26)
P. pringlei	6	X?	X	X	X		X(27)		
P. pseudostrobus	12			X	X	X(28)			FL
P. pseudostrobus var. *apulcensis*	8			X					FL, succession advances w/o fire (19)
P. quadrifolia	1	X(16)		X					Non predictable (39), with a frequency of 100 years or more (16)
P. radiata var. *binata*	1	X?	X	X					
P. teocote	23	X(20,36)		X	X		X		FL, succession advances w/o fire (19)

(1) Vogl (1973)
(2) Verduzco-Gutiérrez *et al.* (1962).
(3) Only a small population present in Mexico. In Central America represents a fire climax.
(4) In Central America, according to Hudson and Salazar (1981).
(5) In forest plantations in Oaxaca (R Bonilla Beas, personal communication, 1992).
(6) Verduzco-Gutiérrez (1976).
(7) Rzedowski *et al.* (1977).
(8) Borchert (1985)
(9) Partial serotiny, Keeley and Zedler (1998).
(10) Farjon and Styles (1997).
(11) Flores-Garnica and Benavides (1993).
(12) Fire frequency for a *P. durangensis*, *P. engelmannii* mixed stand in Sonora (Dieterich 1983, 1985).
(13) Barton (1993)
(14) Benítez-Badillo (1988).
(15) At the lowest altitudes in range, Rzedowski (1978).
(16) Minnich and Franco-Vizcaíno (1998).
(17) Low degree of serotiny.
(18) Perry (1991).
(19) Rzedowski (1978).
(20) Park (2001).
(21) Vázquez and Pérez (1990).
(22) Zendejas and Villarreal (1971).
(23) Becerra-Luna (1992).
(24) In Honduras resprouts when young (Hudson and Salazar 1981).
(25) Vela-Gálvez (1980).
(26) Jardel and Sánchez (1989).
(27) Dvorak and Donahue (1992), cited by Farjon and Styles (1997).
(28) M Rodríguez-Aguilar, personal communication, 1998.
(29) Kilgore (1987).
(30) In the USA, Wright and Bailey (1982).
(31) In the USA, Keeley and Zedler (1998).
(32) In Arizona and New Mexico (Kilgore 1987).
(33) González *et al.* (1991)
(34) Rodríguez-Trejo (1996).
(35) R Bonilla-Beas, personal communication (1992).
(36) M Rodríguez-Aguilar, personal communication, 1991.
(37) Fulé *et al.* (2000).
(38) Very persistent (Martínez 1948; Little 1962), opening partially in different times (Martínez 1948), low degree of serotiny.
(39) Keely and Zedler (1998)
(40) Arno and Hammerly (1977)
(41) Atzet and Wheeler (1982)
(42) Koniac (1985)
(43) Wagener (1961)
(44) Swetnam *et al.* (1992)
(45) Agee (1981)
(46) Agee (1974)
(47) Krugman and Jenkinson (1974)
(48) Finney and Martin (1989)

grass stage include *P. montezumae* [below] and *P. engelmannii* [Barton 1993]). Thick bark and a self-pruning habit protect adults from fire. In Jalisco, Flores-Garnica and Benavides (1993) recorded 161 seedlings/ha in control areas, 1257/ha in areas burned with heading fires and 1394/ha in areas burned with backing fires. They also found an increase in soil cations, mainly Ca, after fire.

P. durangensis. The fire regimes of *P. durangensis* (usually in mixed-species stands) are perhaps the best-studied of Mexican pines. The categorization of the fire regime for this species as predictable and stand-thinning (Keeley and Zedler 1998) is supported by several fire history reconstructions. In the Sierra de los Ajos of northern Sonora, Dieterich (1983, 1985) found a fire frequency of 3.8 years for stands of *P. durangensis*, mixed with *P. engelmannii* and other species, a fire regime that probably reflected human influences. Fulé and Covington (1994, 1996, 1997) compared the fire regimes of three stands in north-western Durango dominated by *P. durangensis* with other conifers and *Quercus* spp. The pine stands had fire return intervals ranging from 3.8 to 4.7 years (counting all fire scars) or 6.6 to 9.0 years (counting only fires that scarred 25% or more of the fire-recording sample trees, presumably fires that were larger and/or more intense). A mesic stand nearby with *Pseudotsuga* and *Abies* had similar fire frequency statistics (5.0 years for all scars, 8.6 years for 25%-scarred samples). Only one of the four stands maintained the frequent fire regime up to the present; the others entered extended periods of fire exclusion beginning after 1945–1955. Stands without recent fire had higher tree densities and greater forest floor fuels, suggesting that fire exclusion contributed to increasing the hazard of severe fire (Fulé and Covington 1997). Similar patterns of frequent fire were observed in *P. durangensis*-dominated forests of Durango and Chihuahua (Heyerdahl and Alvarado-Celestino, in press) and south-eastern Durango (Fulé and Covington 1999) until the establishment of ejidos (a form of community-based ownership created after the Mexican Revolution [1910–1915]) led to increased livestock grazing in the 20th Century. According to Park (2001), the regeneration of *Pinus durangensis*, *Pinus teocote* and *Quercus crassifolia* was more abundant in localities recently affected by surface fires in Durango.

A winter-season prescribed burn in Chihuahua killed 87% of *P. durangensis* trees shorter than 30 cm in height, while 54% were killed by a fall prescribed burn (Sánchez-Córdova and Dieterich 1983). Winter-season prescribed burning did not significantly affect chemical or physical soil properties but increased the frequency of two forb species, *Pteridium aquilinum* and *Lupinus mashallianus* (Sánchez-Córdova and Dieterich 1983). Fire-caused mortality of mature trees of *P. durangensis* and *P. arizonica* in Durango increased when fuel loads ≥36–49 Mg/ha and susceptibility to forest pests increased in burned areas with fuel loads ≥22–35 Mg/ha (Zapata-Pérez 1991).

P. hartwegii. Historically *P. hartwegii* and *P. rudis* have been considered distinct species (e.g. Perry 1991). However, Matos (1995) and Farjon and Styles (1997) recognized only *P. hartwegii*. We adopt their nomenclature but the reader should recognize that the authors of several of the following studies referred to the species as *P. rudis*.

Probably this species is the best studied, among Mexican pines, in terms of fire ecology. *P. hartwegii* reaches the upper altitudinal limit for trees, 4300 m above sea level on the volcanoes in central Mexico. *P. hartwegii* forms monospecific stands with a grass understory including *Muhlenbergia macroura* and *Festuca tolucensis*. The fire regime apparently is characterized by frequent low intensity fires (Rodríguez-Trejo, in press). On the highest sites, changes in the fire frequency would not change the tree species composition: *P. hartwegii* is the pioneer and also the climax tree because is the only one that can reach such altitudes. According to Rzedowski (1978) and Miranda and Hernández-Xolocotzi (1985), however, very frequent fires will favor grasses to the detriment of this pine. Grasses propagate fire and fire facilitates sprouting from the rhizomatous grasses (Rzedowski 1978). Fire also affects the timing and amount of flowering in grasses (Benítez-Badillo 1988). Seeds find favorable conditions for establishment in burned areas, as shown by González *et al*. (1991) in Tlaxcala, where seedling survival was higher on burned areas than in unburned areas.

Seedlings were able to survive very low intensity fires, after winter prescribed burns at −3°C in the Distrito Federal. After 2 weeks, the *P. hartwegii* seedlings between 0.5 and 1.2 m in height had 97.5% survival (Cedeño-Sánchez 1989). Over 84% of *P. hartwegii* seedlings survived a low intensity prescribed burn conducted on flat land, but survival was reduced to 8% when burning was conducted on steep slopes (Velázquez-Martínez *et al*. 1986). Susano (1990) suggested that seedling mortality could exceed 50% when the fuel load is greater than 4 Mg/ha. Fuel loads ranged from 5.6 to 22.6 Mg/ha (COCODER 1988; Rodríguez-Trejo and Sierra Pineda 1995), with grasses and woody fuels commonly accounting for the largest proportion.

Regeneration (sprouting) dynamics of a *P. harwegii* stand in central Mexico under the influence of frequent surface fires were reported by Rodríguez-Trejo (1996), following a synchronic (Pickett 1989; Whelan 1995) approach. The density of seedlings <1.3 m in height was 2764 trees/ha; 97% of these trees had sprouts, averaging 7.8 sprouts/tree. Density declined to 1190 trees/ha for stems taller than 1.3 m. Sprouting rate also declined to 28%, averaging 3.3 sprouts/tree. Sprouting capacity was progressively reduced as the trees grew older. In time, competition led to the death of all the stems, with exception of one or two. Eventually given a period of approximately 5–10 years without fire, the stems grew tall enough that the terminal bud could survive low intensity fires and the bark became thick enough to protect the cambium (Fig. 1). *P. hartwegii* on the borders of the

Fig. 1. Old sprout in a *Pinus hartwegii* tree in the Park Ajusco, Distrito Federal, Mexico.

Estado de México and Tlaxcala recovered from 100% crown scorch, regaining 40% of the original crown after 16 months, as long as the terminal bud survived (Rodríguez-Trejo 1996). Crown scorch greater than 50% led to a 32.2% reduction in diameter growth during the following growing season in the 35-year-old *P. rudis* stand (Rodríguez-Trejo 1996) (Fig. 2). Fire effects on *P. hartwegi* growth were studied by González-Rosales (2001) and González-Rosales and Rodríguez-Trejo (in review). They found that light crown scorch ($<30\%$) was associated with 32% greater radial growth than an unburned control. Trees with medium crown scorch (30–60%) had radial growth similar to the control, while intense crown scorch ($>60\%$) was associated with reduced radial growth.

The effects of fire on soil were studied in stands with *P. hartwegii*, *Quercus* spp. and *Alnus firmifolia*, on deep soils with abundant organic matter, pH from 5.5 to 7.1, high levels of N, fertile, classified as Eutrandpets. After low intensity prescribed burns, Aguirre-Bravo and Rey (1980) found no changes in pH, a slight loss of N by volatilization, and increases in P, Ca, K, Mg and Na levels. Erosion levels per year were low, 560 kg/ha in the burned sites, and 140 kg/ha in the controls. Runoff per year in burned sites averaged 200 m^3/ha versus 70 m^3/ha on controls.

The fuel complex in forests of the Distrito Federal was dominated by tall sprouting grasses plus needles and woody fuels. The average fuel load in pine forests (*P. rudis*, *P. hartwegii*, *P. montezumae*, *P. teocote* and pine–broadleaf forest) was 23 Mg/ha, reaching a maximum of 76 Mg/ha (Rodríguez-Trejo and Sierra-Pineda 1995). As these forests are open and occur on high mountains (around 3000 m above sea level), strong winds are also common. Even on gentle slopes, fire rate of spread may reach 36 m/min or more under dry conditions (Rodríguez-Trejo, in press). Smoke has been studied for this stands of this species in Central Mexico. Contreras-Moctezuma (2002) and Contreras-Moctezuma *et al.* (in review), reported emissions of 4.07 kg NO/ha, 3.65 kg NO_2/ha, 198.69 kg CO/ha and 2.84 kg SO_2/ha.

P. leiophylla. Cones are very persistent (Little 1962), the species regenerates well on burned sites, and burned trees may resprout from the root collar, a rare trait among pines (Perry 1991). Adult trees have thick bark that isolates the cambium from lethal temperatures. Keeley and Zedler (1998) grouped this species in the stand-replacing fire regime category. However, Fulé *et al*. (2000) found that a xeric forest at La Michilia Biosphere Reserve in south-eastern Durango, with *P. leiophylla*, *P. leiophylla* var. *chihuahuana*, and *P. teocote*, had a surface fire regime (mean fire interval 4.1–6.3 years) until heavy livestock grazing began in 1932. Similar forests further north, in the borderlands region of Sonora, Chihuahua, Arizona, and New Mexico, generally also had frequent surface regimes in the past (Kaib 1998; Swetnam *et al*. 2001). Barton (1995) suggested that the weak sprouting capability of *P. leiophylla* made it a weak competitor against vigorous oak sprouts following severe fire. In Michoacán, *P. leiophylla* trees affected by forest fires are more susceptible to attack by bark beetles (Pérez-Chávez 1981).

P. montezumae. This species regenerates with a grass-stage strategy (Perry 1991; Becerra-Luna 1995) and mature trees have thick bark and a self-pruning habit. Fire favors the liberation and dispersion of seeds (Zendejas and Villarreal 1971), but González *et al*. (1991) did not find differences in seedling survival between burned and unburned areas.

Fig. 2. Sixteen months after a crown fire in surrounding shrubs, this adult *Pinus hartwegii* regenerated 40% of its crown in central Mexico.

Intermediate stand density conditions appear to favor *P. montezumae*. Becerra-Luna (1995) reported that germination and early survival of *P. montezumae* seedlings was better under a partial canopy than either full shade or exposure of bare mineral soil. Either fire exclusion or excessive fire can be detrimental to this species. In the absence of fire and cattle grazing (fires are often set to stimulate forage production for livestock), *P. montezumae* in Puebla was displaced by successional change toward *Abies religiosa* and *P. ayacahuite* var. *veitchii* (Rzedowski *et al*. 1977). Frequent fires made *P. montezumae* stands more susceptible to forest insects in the Estado de México, where Espinosa and Muñoz (1988) found a direct relationship between fire-affected area in one year and *P. montezumae* and *P. leiophylla* forest area affected by the bark beetle *Dendroctonus mexicanus* during the next year. *P. montezumae* can sprout from the root collar when the main leader is damaged, a capacity that reduces with age from more than 90% of seedlings in the grass stage to 65% 3 years after the elongation of the epicotyl (Becerra-Luna 1992). *P. montezumae* seedlings remain in a grass stage for 2–12 years in central Mexico. Emergence seems to take place when the cotyledonary node reaches 2 cm in diameter (Becerra-Luna 1995). Seedlings that had developed secondary needle fascicles could sprout after the tops were killed by fire or clipped (Becerra-Luna 1995).

P. oocarpa. Fire favors the opening of the serotinous cones of some varieties and the burned sites are a good seed bed for its seeds. Seedlings 2–4 years old and young trees are able to sprout if fire kills the shoot (Rzedowski *et al*. 1977; Perry 1991). Mature trees have thick bark and a self-pruning habit.

P. patula. This species of mesic sites, around 1000 mm mean annual precipitation, is one of the most conspicuous examples of fire-adapted species among Mexican pines. Fire stimulates its serotinous cones to open (Vela-Gálvez 1980; Keeley and Zedler 1998). The seed bed created after the passage of fire allows hundreds of thousand of seeds per hectare to germinate during good seed years. When in the seedling stage the tree is susceptible to fire, but its growth rate allows it to reach the minimum height to survive low intensity fires relatively soon and a thick bark develops to protect the cambium. Epicormic sprouts appear in the lower stem in some adult individuals.

P. patula often forms pure stands or dominates stands, but can be codominant in a forest undergoing successional change. In the absence of recent fire, on deep and fertile soils with abundant precipitation in Puebla, *P. patula* was found mixed with *P. ayacahuite* var. *veitchii*, *Abies religiosa* and several *Quercus* species. The fuel load was high and vertically continuous, including herbs, shrubs, several tree strata and dead woody fuels of every size. This structure appears likely to support infrequent, high intensity crown fires that may favor the re-establishment of *P. patula* from seed protected in its serotinous cones, as observed by Mirov (1967) for other serotinous pine species.

In contrast, on rocky soils with less precipitation, *P. patula* is found mixed with oaks and the fuel load is lower because of the reduced site productivity. Jardel and Sánchez (1989) found an example of a predictable, stand-thinning fire regime where fire prevented the replacement of *P. patula* by broadleaf species in the Sierra de Juárez, Oaxaca.

P. pseudostrobus. This species exhibits fire traits such as thick bark, self-pruning capacity, and recovery of scorched or partially burned crown, at least when young. Along the border of Tlaxcala and Puebla, *P. patula* and *P. pseudostrobus* coexist in some stands but the former is less fire-resilient when young. In an area burned in 1998, crowns of some young pines 2 m tall of both species were completely scorched or even needle consumption, but after a few months only the *P. pseudostrobus* produced new foliage, starting from the terminal bud (M. Rodríguez-Aguilar, personal communication, 1998). This case study suggested that the species might have contrasting ecological strategies: *P. patula* is better suited to colonize burned areas than *P. pseudostrobus*, a fire-resilient response, because the latter species is not serotinous. But when young, *P. pseudostrobus* has a better capacity to restore its scorched foliage, a fire-resistant response that may be better adapted than *P. patula* to intense surface fires.

In mixed conifer forests including *P. pseudostrobus* in Jalisco, soil erosion per year in burned areas was 86–170 Mg/ha (Hernández 1990). In a pine-oak forest in Michoacán, erosion and water runoff were 0.02 Mg/ha and 1.7 m^3/ha, respectively, on control areas, versus 15.6 Mg/ha and 77.1 m^3/ha on burned areas. The burned area values declined 99% and 95% respectively by the second year post-fire, due to increased understory growth (Chávez and Carmona 1994).

Pinyon pines. *P. cembroides*, *P. monophylla* and *P. quadrifolia* do not appear to have a predictable fire regime (Keeley and Zedler 1998). The limited studies of fire ecology in Mexican pinyons have also not suggested consistent effects. Fire was believed by Verduzco-Gutiérrez (1976) to favor the regeneration of pinyon pines and *P. quadrifolia* recruited quickly after burns (Minnich and Franco-Vizcaíno 1998). These authors noted that the fire ecology of this pine has not been investigated formally, but field observations suggested that the rapid establishment of seedlings was related to efficient seed caching from living stands by birds and mammals. Díaz *et al*. (2000) suggested that a wave-like age distribution in *Pinus cembroides* ssp. *lagunae*, an endemic species of Baja California Sur, was probably related to hurricanes and fires. Several *P. cembroides* forests were considered a fire-maintained climax by Rzedowski *et al*. (1977) but excessive fire degraded pinyon forests in Coahuila (López-Reyna and Gómez-Mendoza 1989; Perry 1991).

Summary of pine fire ecology

Fire trait and fire regime relationships in Mexican pines are consistent with the general categorizations of Keeley and Zedler (1998). The most common fire traits are regeneration on burned sites and thick bark. Most of the pines (33 out of 35, or 94%) exhibit one or both of these traits, and the documented examples correspond to both stand-thinning or stand-replacing fires. Of the 12 species with serotinous cones, 5 (42%) have been documented to correspond with stand-replacing fire regimes and none were documented with frequent, low-intensity fire regimes. Also, 11 out of 12 serotinous species (92%) show good regeneration on burned sites. Self pruning is present in 19 species (54%), and 11 out of 19 (58%) of these correspond to low-intensity fire regimes or where there is evidence of a fire-maintained successional stage. Of the 19 species with self pruning, 13 (68%) also exhibit good regeneration on burned sites. The majority of resprouter species (7 out of 8, 88%) also have thick bark. Most of the resprouter species (75%) have non-serotinous cones. Finally, the species with grass stage correspond to low-intensity fire regimes. As future research focuses on pine fire ecology in Mexico, more data will become available to assess the links between fire traits and evolutionary relationships.

A fire use proposal

The fire situation in Mexican pine forests can be summarized in three broad categories: (1) excessive fire; (2) appropriate fire; and (3) insufficient fire.

(1) Excessive fire

Pine ecosystems adapted to fire are resilient to certain amounts of anthropogenic fire; in fact, human-caused fires may have played important roles over evolutionary time (e.g. see descriptions of indigenous fire practices in Chihuahua [Pennington 1969] and California [Anderson 1996]). When the frequency of human-originated fires increases, however, long-lasting changes may occur in forest structure (e.g. fire-resistant species invade or increase, changes in age-distribution in pines with demographic implications [Rzedowski 1978]). When excessive human-originated fire is applied, usually accompanied by heavy resource extraction, degradation occurs. Anthropogenic fire is a contributor to the 769 350 ha of temperate and tropical forests annually deforested in the country (Masera *et al*. 1995; SEMARNAT 2002*b*) and an important factor endangering directly or indirectly 11 pine taxa, according to Perry (1991). Forest fires are threats to endangered pine species such as *P. culminicola*, *P. maximartinezii*, *P. rzedowskii*, *P. cembroides* ssp. *lagunae*, *P. jaliscana* and *P. nelsoni* (Perry 1991). Anthropogenic fires have been a major factor contributing to the loss of more common pine species as well, including *P. flexilis* var. *reflexa*, *P. arizonica*, *P. lumholtzii*, and *P. ayacahuite* in the Sierra Madre Occidental (DeBano *et al*. 1998).

The obvious management option in the case of excessive fire is to reduce the fire frequency to allow the pine forest to recover. Throughout Mexico, attempts to control excessive burning have included public education campaigns (Fig. 3) and increasing the ability of foresters to prevent or suppress fire by providing (limited) funds for personnel, training, tools, and vehicles. But these activities are unlikely to be sufficient, for the root of the problem is, and historically has been, socioeconomic. Rural residents farm and graze livestock in forests and pine savannahs. Fire is applied because it is cheap, relatively easy to use, and an efficient tool to dispose of crop residues and weeds, add nutrients to the soil, control agricultural pests, and promote sprouting in grasslands. Agricultural fires are often allowed to spread through forestlands. For example, fewer than 10% of the farmers who own lands contiguous to forest in the eastern part of the state of México create a fire break around their property when burning (Rodríguez-Trejo and Mendoza-Briseño 1992). Many forest owners lack the resources to develop productive forests and many forest types are poorly suited for sustainable profitable resource use.

If forests are to be conserved in the face of growing pressure on rural lands, then the challenge for Mexico—as in much of the world—is at the macroeconomic scale,

Fig. 3. A substantial investment has been made in educating people about the importance of fire prevention, as in this sign from the Sierra Madre Occidental, Durango. However, more complex messages about the ecological role of fire and its beneficial as well as deleterious effects will be needed in order for the public to understand a transition to the use of fire as a management tool where ecologically and socially desirable.

to provide better economic opportunities to the campesinos (rural residents) so they could use their natural resources in a more economically and ecologically sustainable way, thereby reducing deforestation and the misuse of fire. Approximately 70% of Mexico's forest lands are in communal ownership (Masera *et al*. 1995). Despite liberalization of land tenure laws in 1992, Barbier (2002) found that formal and informal institutions such as ejido ownership still served as a constraint on land conversion from forests to agriculture. Klooster and Masera (2000) argued that the international community should support community forest management, perhaps through the clean development mechanism (CDM) of the 1997 Kyoto Protocol, because of the global benefit of mitigating carbon emissions. An analysis by Masera *et al*. (1995) found that afforestation and forest conservation could have significant positive effects on both carbon sequestration and economic returns to landowners, as long as national and international policies were adjusted to support sustainable forest management.

(2) Appropriate fire

Few Mexican pine ecosystems appear to be maintained by the prevailing anthropogenic and/or natural fire regimes. For example, Minnich and Franco-Vizcaíno (1998) suggested that *P. jeffreyi* dominance of mixed-conifer forests in Baja California may be due to its thick bark, high canopy, and good regeneration following surface fires, in contrast to competing species of *Abies* and *Calocedrus* that are more fire-susceptible. Forest sites where modern fire regimes remain relatively similar to those of past centuries have been identified in the Sierra de los Ajos, Sonora (Swetnam *et al*. 2001), Sierra San Pedro Mártir, Baja California (Minnich *et al*. 2000), and the Sierra Madre Occidental of Durango and Chihuahua (Fulé and Covington 1997, 1999; Kaib 1998). However, sites with undisrupted fire regimes appear to comprise relatively small, rare fragments within heavily disturbed landscapes (Fulé and Covington 1997, 1999; Kaib 1998). In several managed forests, prescribed fire is used as a silvicultural tool (e.g. Chihuahua, Alanís-Morales 1995; Durango, Rentería-Anima 2001).

Where fire appears to be playing an appropriate ecological role, a good approach is to maintain the present fire regimes while refining management practices to achieve multiple objectives from fire, such as forage production, wood production or recreational opportunities. Particular care must be taken in finding an appropriate point of equilibrium between fire frequency to sustain the pine forest and cattle growing, because a preference toward livestock has historically been a major factor in deforestation in Mexico (Melville 1994). Here universities and research centers have an opportunity and challenge to evaluate the effects of fire on different ecosystem components, structure, and processes.

However, it must be mentioned that in some cases frequent fires sustain pine forests, preventing successional change to more biologically diverse and endangered ecosystems, such as the cloud forest in the Sierra de Manatlán, Jalisco (Saldaña and Jardel 1991; Jardel *et al*. 2001). Similarly, anthropogenic disturbance in montane rain forests of Chiapas, including fire, increases the dominance of pines and reduces the floristic richness of mixed forests (e.g. *Pinus–Quercus–Liquidambar* forest) (Ramírez-Marcial *et al*. 2001).

(3) Insufficient fire

In many areas, fire exclusion has allowed successional change or fuel accumulation to progress to a high hazard for severe wildfire. For example, some pine forests in the states of Estado de México and Puebla show dramatic fuel increases (Rodríguez-Trejo 1996), as do some forests with heavy surface fuels and dense regeneration in the Sierra Madre Occidental (Fulé and Covington 1997). This case is typical of preserves, parks, forests in which heavy grazing has eliminated herbaceous fuels, and several managed and/or well fire-protected forests in which fire is used little or not at all. Managers may be averse to fire use simply because it is feared and its ecological relevance, complicated by human-caused wildfires, is not well understood. In managed forests, silvicultural treatments may be used to maintain pine dominance by thinning fire-susceptible species from advanced successional stages, such as oaks. Nonetheless, in the absence of fire the fuel load still increases every year. Where fire has been excluded, it would be advantageous to use prescribed burning to reduce the fuel load in general, to reduce activity (slash) fuels, to promote nutrient recycling, and to prepare seed beds for future pine regeneration (Alanís-Morales 1995; Alanís-Morales *et al*. 2000).

No single or simple formula for fire management can be applied to the diversity of Mexican pine forests. All three fire categories can be considered as part of a human and/or natural fire-gradient (Rodríguez-Trejo 1998*a*, 1999) and each may require a variety of different responses depending on the land's ownership, managers' goals, economic value, and ecological situation. As a guiding principle, however, we assume that it is in Mexico's best interest to preserve the ecosystems that it presently has and to restore those ecosystems that have been modified or have lost their original composition, structure, and function. In all three fire categories discussed above, the point of reference for the use of fire should be an understanding of the long-term, historical fire regime. A starting point for management would be mimicking natural fire as much as possible and applying it to reach clear and specific objectives at well-defined times. Fire management plans, tiered to broader forest management plans, should consider such factors as fire frequency (considering both the average return period and variability), intensity, areal extent, and season of burning. Potential benefits of fire use, such as enhancing regeneration, maintaining biodiversity and habitats, or fire hazard reduction, must be balanced against the negative effects of fire, such as higher erosion, smoke emissions, and the possibility of escaped fires (Rodríguez-Trejo 2000*a*,*b*, 2001).

A fire management example

There is no uniform approach to fire management because every forest has a unique ecological and social environment, but here we present an example to illustrate concerns and suggest management approaches for a specific place: La Michilía biosphere reserve, on the Durango/Zacatecas border (latitude ~ 23° 20′ N, longitude ~ 104° 10′ W). The site was established as a biosphere reserve because it is representative of millions of hectares of temperate forest in central and northern Mexico (Barbault 1978). The reserve consists of a 7000 ha core area managed for biological conservation and an approximately 70 000 ha 'buffer zone' under private or communal ownership. Forests range from dry oak-pine woodlands around 2000 m elevation, pine–oak forests at mid-elevations, to pine and mixed-conifer forests at elevations up to 2985 m (González-Elizondo *et al*. 1993).

Prior to the 20th Century, surface fires recurred frequently in all these forests, with fire return intervals averaging 3.2–7.2 years (Fulé and Covington 1999). Between 1932 and 1945, however, fires ceased over most the landscape as a result of intensive livestock grazing; only the high-elevation core area maintained a surface fire regime throughout the 20th Century (Fulé and Covington 1999). The current management policy of wildfire suppression has not been successful. An intense fire burned about 10 000 ha of low-elevation forest in 1996 with substantial tree mortality (Fulé *et al*. 2000), an event likely to foster long-term degradation (Barton 2002), while a high-elevation forest fire in 1998 caused little environmental damage but resulted in the death of a firefighter (A. García-Arévalo, personal communication, 1999).

An analysis of the fire situation at La Michilía suggests that 'excessive fire' does not appear to be a problem here, unlike many other regions of Mexico. 'Appropriate fire' is a good description of the high-elevation core area, a small but important natural site. Currently, reserve managers feel obligated to fight fires in order to demonstrate that they are protecting the site. With documentation that the historic fire regime is relatively undisrupted (Fulé and Covington 1999) and evidence of fire-resistant forest structure (P.Z. Fulé, unpublished data), managers may be able to design and defend an alternative policy of allowing wildland fires to burn under certain conditions. This approach would save money, avoid subjecting firefighters to unnecessary risk, and maintain a key disturbance regime in the core. The largest portion of La Michilía falls into the 'insufficient fire' category, where accumulated living and dead fuels present a high hazard of severe fire (Fulé *et al*. 2000). Allowing wildfires to burn in the low-elevation forests would be inappropriate because of the threat of crown fire, damage to trees and soils, and danger for people and livestock. Instead, fire could serve as one of several restoration tools. A combination of tree thinning and well-designed harvest, with rapid burning of activity fuels, could produce some economic benefit while creating fuelbreaks to reduce future wildfire losses (Agee *et al*. 2000). Broadcast prescribed fire could play a role in reducing forest floor material and spurring understory growth. Ultimately, La Michilía and similar regions will probably remain dominated by human influences indefinitely, but a management approach closely aligned with the natural fire ecology of the forests is more likely than a simplistic fire suppression approach to favor a sustainable and economically beneficial social/ecosystem.

Future challenges

Previously, fire was not broadly considered as an ecological factor in Mexico, but this started to change in the past two decades. The use of prescribed burns has been growing gradually, and support for fire management has been strengthened. In some respects, the historic 1998 fire season was a setback for the incorporation of fire into management, because of the traumatic impact that the wildfires had on the public and even on foresters, biologists, and government officials. But the 1998 fire season also increased awareness of wildfires and fire management among Mexicans (Rodríguez-Trejo 1998*b*). The initial social responses to the 1998 fires appear to be mixed. A reaction to increase protection from fire may benefit pine forests in the short term but simply exacerbate the severity of future fires. Another reaction is increased support for fire-related research, although such gains might not last long.

We suggest that a useful approach would be the application of fire where appropriate, based on thoughtful consideration of the ecological and social circumstances of specific forest lands. There are several challenges to confront:

- Promote more fire-ecology research on fire regimes, fire effects, and management alternatives; research should include long-term monitoring and experimental comparisons.
- Increase the economic, human and material resources to manage wildfire and prescribed burning.
- Educate society about the natural role of fire, including an honest presentation of the risks and benefits of alternative fire management approaches.

Perhaps the most fundamental challenge is to seek innovative means and international support to reduce the economic constraints that currently contribute to degradation of forests in Mexico and much of the world. Because of the social and economic aspects of the fire problem in Mexico, conservation and ecological restoration of pine forests, and in general of all ecosystems, are likely to be reached only if the owners of the land have access to more education and economic opportunities.

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