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Near zero mortality in juvenile *Pinus hartwegii* Lindl. after a prescribed burn and comparison with mortality after a wildfire

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Fire is considered a relevant ecological factor, however, human alterations of fire regime facilitate more destructive wildfires. The aims of this work were to model probability of tree mortality and to identify the factors associated with leader shoot growth in a prescribed burn area and in a nearby wildfire area in a juvenile *Pinus hartwegii* Lindl. stand in central Mexico. A prescribed burn was carried out in 10-ha stand in March 2012, and compared with a close area affected by a wildfire occurred one week later, as well as with a nearby unburned area taken as control. A logistic model was used to estimate the probability of mortality, and a linear regression model was employed to investigate factors related to leader shoot growth. No tree mortality was recorded in the unburned control. In contrast, mortality was 6% in the prescribed burn and 66.9% in the wildfire area. The probability of mortality was influenced by stem char height (positively, $p<0.0001$), tree height (negatively, $p=0.0443$), and diameter at breast height (negatively, $p<0.0001$). The variables that had more influence on leader shoot growth were stem char height (negatively, $p<0.0001$) and tree height (positively, $p<0.0001$). This work supports evidence of the feasibility of using low intensity prescribed burns in this ecosystem with minimum effects on young tree mortality.

Keywords: Fire Adaptations, Fire Ecology, Integral Fire Management, Prescribed Burning, Probability of Mortality, Logistic Regression, *Pinus hartwegii*

Introduction

Fire has been an ecological factor over 420 million years in many ecosystems (Scott et al. 2014). In Mexico, the oldest evidence of a wildfire dates back to 200 million years, a burned wood fossil found in Chiapas (Rodríguez-Trejo 2015), and the genus *Pinus*, specifically the subgenus *Pinus*, radiated into fire-prone environments leading to several fire adaptations (Keeley 2012). Mexico is the world's richest country in number of pine species: 47 species and 20 intraspecific taxa (Farjon et al. 1997). The vast majority of these species are fire-adapted, each species with different sets of fire adaptations, generally including three to six of the following: good regeneration in fire-created seed beds, thick bark, self-pruning, recovery from crown scorch, epicormic and basal resprouting, grass stage, serotinous cones, and fast initial growth (Rodríguez-Trejo & Fulé 2003, Rodríguez-Trejo 2014). *Pinus hartwegii* Lindl. is one of the Mexican pine species with more fire adaptations, showing all but the last two. Such adaptations to fire have been identified for pines of the USA (Agee 1993, Whelan 1997) and Europe (Fernandes et al. 2008). Fire increases understory diversity and richness in this type of forest (Martínez-Hernández & Rodríguez-Trejo 2008). This effect lasts no less than three years (Espinoza-Martínez et al. 2008). In this case, the higher the solar radiation (because of a reduction of tree canopy cover), the higher the presence of grasses (Islas-Madrid et al. 2013). Fire also reduces fuel load and fire danger and maintains these forest habitats. Low crown scorch (< 30%) benefits secondary and primary growth for one to two years after the fire when precipitation is not limiting (González-Rosales & Rodríguez-Trejo 2004, Vera-Vilchis & Rodríguez-Trejo 2007). The probability of mortality for this species one year after fire is higher when the burn occurs in May, as a heading fire (more intense and more severe fire), on a dense stand (the fuel bed is mostly needle litter, whose combustion transmits more heat to the surface roots) with small dbh trees (with thinner bark), than when this occurs in March, as a backing fire (less intense and less severe fire), in open stands (the fuel bed is mostly grasses; when it burns most heat is transmitted to crowns) with large dbh trees and thicker bark (Rodríguez-Trejo et al. 2007).

In Mexico, pine forests extend over 5,238,861 ha and this area increases to 16,176,825 ha when the vast pine-oak associations are included (SEMARNAP/ UACH 1999). *P. hartwegii* is found in 17 states in Mexico, as well as in Guatemala and Honduras. Frequently, it grows in pure stands at altitudes between 3000 and 3700 m a.s.l. and as high as 4300 m where it forms the timber line (Perry 1991, Farjon et al. 1997). This is the pine species reaching the highest altitude worldwide and is thus relevant for global warming issues.

From 1998 to 2015, an average of 8198 recorded wildfires affected a mean surface area of 294,266 ha per year in Mexico. The main causes of wildfires in the country are

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agricultural activities and goat, sheep and cattle raising activities (36%), followed by campfires (13%) and smokers (12%). Officially only 2% of wildfires are caused by lightning (CONAFOR 2012a). However, 17% of fires have unknown causes, and some of them may be due to natural causes such as lightning. The agricultural and ranching group of wildfire causes is related to livelihood and poverty of the people living in rural areas.

Mexico is looking for what Myers (2005) called "integrated fire management", *i.e.*, the optimal combination of ecological and silvicultural use of fire with its rural communitary use, modern fire prevention and firefighting (Rodríguez-Trejo 2000). A key tool for this type of fire management is prescribed burning (Scott et al. 2014). However, in order to apply such a tool, one of the several challenges is to understand the effects of fire on ecosystems. Most Mexican pines resist fire (Rodríguez-Trejo & Fulé 2003), but one concern is the survival and growth of juvenile trees (<5 m height). A severe fire will kill pines smaller than 5 m, unless they have the ability to resprout.

Logistic regression is a useful approach to investigate the effects of fire on probability of tree mortality. Among the pioneer studies in this area are those of Ryan & Reinhardt (1988) and Ryan & Frandsen (1991) with North American conifers. In Mexico, there are studies that use this approach with *P. hartwegii* (Rodríguez-Trejo et al. 2007), but they do not focus on relatively extensive prescribed burns and young trees. Moreover, recent studies in Mexico have been conducted in small, uniform plots (1 ha or less per experimental unit) and not in relatively extensive management-ignited prescribed burns with more variable conditions, such as those existing in our study area.

In this study we attempted to answer the following questions: (i) does low severity prescribed burn affect juvenile tree survival? (ii) Which are the factors better explaining juvenile tree mortality in a severe fire? (iii) How is the primary height growth of the surviving juvenile trees (< 5 m) affected by fire?

The objectives of this work were to compare in a *P. hartwegii* stand: (a) the survival probability of trees of different heights, diameters and levels of fire damage; and (b) its leader shoot growth, after a relatively extensive management-ignited prescribed burn, after a wildfire and in an unburned control.

Materials and methods

Study area

The experiment was carried out in a *P. hartwegii* forest stand south of Mexico City, Mexico, on lands owned by the rural communities of San Miguel and Santo Tomás Ajusco, at an average altitude of 3250 m a.s.l. The main characteristics of the studied stand were: tree height ranging from 0.3 to 6.0 m (average: 3.1 m) and diameter at breast height (dbh) 1 to 19 cm (average: 10 cm), with an approximate stand age ranging from 2 to 25 years. These trees were growing under a low-density stand (50-80 trees ha^{-1}) of adult trees (average height: 20 m). To conduct this work a prescribed burn was carried out in a test area, and compared with a nearby wildfire-affected area as well as a non-affected area as control.

Plots and treatments

The experiment was conducted in three close plots, each with an approximate surface of 10 ha, at altitudes of 3215 to 3285 m a.s.l. (19° 09′ 55.55″ to 19° 10′ 19.06″ N, 99° 14′ 02.86″ to 99° 14′ 43.54″ W). One of the plots had not been burned for at least 6 years and was taken as control. The second plot underwent a prescribed burn in March 2012, while the third plot was affected by a wildfire one week later (Fig. 1). The local topography is quite irregular, very rocky, with small flatlands but also frequent small hills (5 to 40 m in height) with occasional steep hillsides (slope up to 50%).

The fuel complex was composed mostly of cured grasses. Needle litter was abundant in areas with high tree density, as well as light (1h timelag) or medium size (10 and 100 h timelag) woody litter (Weise et al. 2005). A fuel load of 3-12 t ha^{-1} was estimated in different parts of the plots. Fuel loads were the same for the prescribed burn and the wildfire areas.

Both the low-intensity prescribed burn and the wildfire at the studied site occurred in March 2012 (Fig. 1), though the fire danger index showed marked differences during the two events. During the prescribed burn, relative humidity was 30-50%, temperature 15-20 °C, and wind speed 0-15 km h^{-1}. In this case, the dead fine fuel moisture was 6% (temperature: 20 °C; relative humidity: 30%; 12:00 a.m., S aspect and slope <30%) to 11% (temperature: 15 °C; relative humidity: 50%; 8:00 a.m., N aspect and slope >30%), estimated with standard tables relating temperature and humidity to equilibrium moisture content. According to the Mexican System for the Prediction of Fire Danger (UJED 2018), the fire danger was medium to low the day the prescribed burn was applied (a hail storm occurred after mupping-up), while fire danger was high the day the wildfire occurred. The site is characterized by frequent changes in wind direction almost every day throughout the year. Because of both wind direction changes and irregular topography, a modified prescribed burn method was employed, a mix of the strip backing fire method (relative to the slope) and the

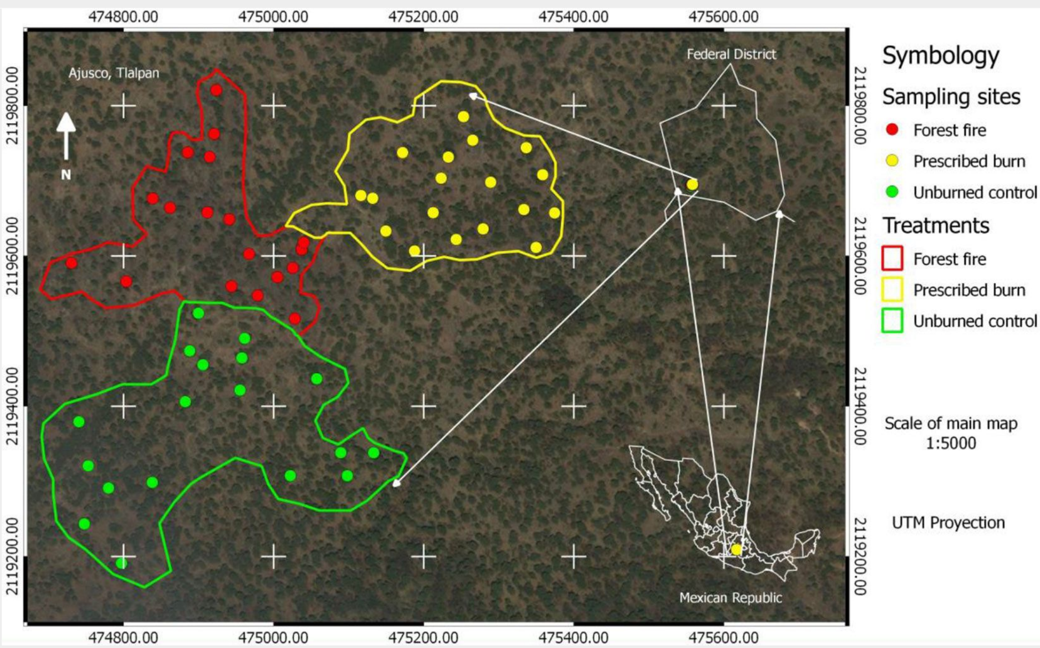

Fig. 1 - The study area (San Miguel and Santo Tomás Ajusco, Central Mexico). The yellow area was subjected to a prescribed burning in March 2012, the red area was affected by a wildfire one week later, while the green area had not been burned for at least 6 years and was taken as control.

Tab. 1 - Tree and fire severity measurements for each plot. (h): tree height; (bd): basal diameter; (dbh): diameter at breast height; (lc): live crown; (sc): scorched crown.

Plot	Stat	Stem char height (m)	h (m)	Leader shoot growth (m)	bd (cm)	dbh (cm)	Tree-density (n ha^{-1})	lc (%)	sc (%)
Control	Min	-	0.31	0.06	3.0	2.0	1000	10	-
	Max	-	5.98	0.62	35.0	14.0	3400	95	-
	Avg	-	2.32	0.26	9.0	5.0	2224	50	-
Prescribed burn	Min	0	1.10	0.04	3.0	1.0	900	0	0
	Max	1.80	6.00	0.7	26.0	17.0	3800	100	100
	Avg	0.48	2.66	0.25	8.0	5.0	2253	40.5	14.8
Wildfire	Min	0.30	0.95	0.08	2.5	1.0	1600	0	0
	Max	4.80	5.70	0.6	22.0	19.0	3900	80	100
	Avg	1.67	2.53	0.25	8.0	5.0	2714	8.0	87.0

Chevron method that was denominated the Ajusco method (Rodríguez-Trejo 2015). The fire started in parallel lines, beginning at the ridges of the small hills, thus it was a backing fire with respect to slope. Because of changes in the wind direction, the descendent fire sometimes advanced favored by the wind and sometimes against the wind, even perpendicular to wind direction. The prescribed burn was planned, directed and conducted by personnel of the *Comisión Nacional Forestal* (National Forestry Comission), the *Comisión de Recursos Naturales* (Natural Resources Commission of the Mexico City government), and the *Universidad Autónoma Chapingo* (Autonomous Chapingo University), as part of the Ajusco Research Project of the *Universidad Autónoma Chapingo* on fire ecology, integrated fire management and restoration of burned areas. In general, flame length was lower than 1 m, and the rate of fire propagation was less than 1 m min^{-1} for these backing fires, though in some cases they reached 1.0-1.5 m and 3-5 m min^{-1} when the wind blew down the slope.

The wildfire occurred in March 2012, affecting an area of about 10 ha. It reached high intensity, with flame lengths >5 m in some sectors (CONAFOR 2012b) causing high severity and high mortality among the juvenile trees. Crown scorch in trees smaller than 5 m was 100%, and stem char height was up to 5 m on some adult trees.

By September 2012, six months after the prescribed burn, a randomized sampling in each plot was conducted with square-shaped sampling units of 100 m^2, 18 per treatment, for a total of 54 sampling units and a sampling intensity of 1.8%. A total of 1148 young trees were sampled.

For each tree in all plots we recorded the tree vitality (a tree was considered alive when showing any amount of green foliage), diameter at breast height (1.3 m), basal diameter at the root collar, tree height, length of the leader shoot, stem char height, percent of live crown, percentage of scorched crown (lethal for the buds). For each sampling unit, tree density of live and dead trees was also calculated.

Statistical analysis

Logistic regression (Hosmer & Lemeshow 2000) was performed to obtain the probability of juvenile tree mortality (P – eqn. 1):

$$P=\frac{1}{1+e^{-(\alpha+\beta_1 X_1+\beta_2 X_2+\beta_3 X_3)}} \tag{1}$$

where *e* is the Euler number, α the intercept, and β the constants associated with the independent variables X.

To consider a model significant, all variable included must show $p < 0.05$, an odds confidence interval lower or higher than 1, and a high concordance ratio (number of concordant pairs divided by the total number of pairs). Models including each individual variable and all the combinations of individual variables were tested, and the more significant model was finally chosen.

A linear multiple regression model was used to find the variables mostly related to the leader shoot growth (Ls – eqn. 2):

$$Ls=\beta_0+\beta_1 X_1+\cdots+\beta_n X_n \tag{2}$$

where $\beta_{0,\dots,n}$ are constants and $X_{1,\dots,n}$ are the independent variables.

The statistical analysis for the logistic model was carried out using the PROC LOGISTIC of the SAS® ver. 9.0 package (SAS Institute 2002). The regression model was obtained using the procedure PROC GLM.

Results

Tree characteristics and fire severity

The sampled trees were young, with an average height of 2.66 and 2.53 m in the areas treated with prescribed fire or those affected by wildfire, respectively. In both areas, the mean dbh was 5 cm. Severity of the prescribed fire was low and satisfactory, with a mean stem char height of 0.48 m and an average crown scorch of 14.8%, while the wildfire resulted in high severity, reaching 1.67 m for average stem char height and 87% for crown scorch (Tab. 1).

Probability of mortality

No dead trees were recorded in the control plot, while in the prescribed burn plot mortality was 6%, mostly affecting trees with height < 1 m. In the wildfire plot, mortality reached 66.9% and most of the dead trees were ≤ 3 m tall.

The regression model for probability of mortality obtained from both the prescribed burn and the wildfire plots (eqn. 3) was significant ($\chi^2 = 552.1133$, $p < 0.0001$). The significance of each of the explanatory variables is shown in Tab. 2. Concordance of the model reached 94.5% (eqn. 3):

$$P=\frac{1}{1+\exp^{-(1.1025+4.4095 X_1-0.5213 X_2-88.4305 X_3)}} \tag{3}$$

where P is the probability of mortality for juvenile *P. hartwegii*, X_1 is the stem char height, X_2 is the tree height, X_3 is the diameter at breast height.

The confidence intervals for the variables in the model did not include the value 1 in any case. As expected, the model predicts a higher probability of mortality for the wildfire area. P maximizes when the dbh is small and stem char height is high, which is associated with large crown damage (Fig. 2).

Based on the model obtained, a tree 1.3 m

Tab. 2 - Significance of the parameters for the logistic regression model to predict mortality probability of *Pinus hartwegii* in the prescribed burn and wildfire treatments.

Parameter	DF	Estimation	Standard error	χ^2	P
Intercept	1	1.1025	0.3025	13.2881	0.0003
Stem char height	1	4.4095	0.3576	152.0642	<0.0001
Height	1	-0.5213	0.2592	4.0445	0.0443
Diameter at breast height	1	-88.4305	10.9090	65.7100	<0.0001

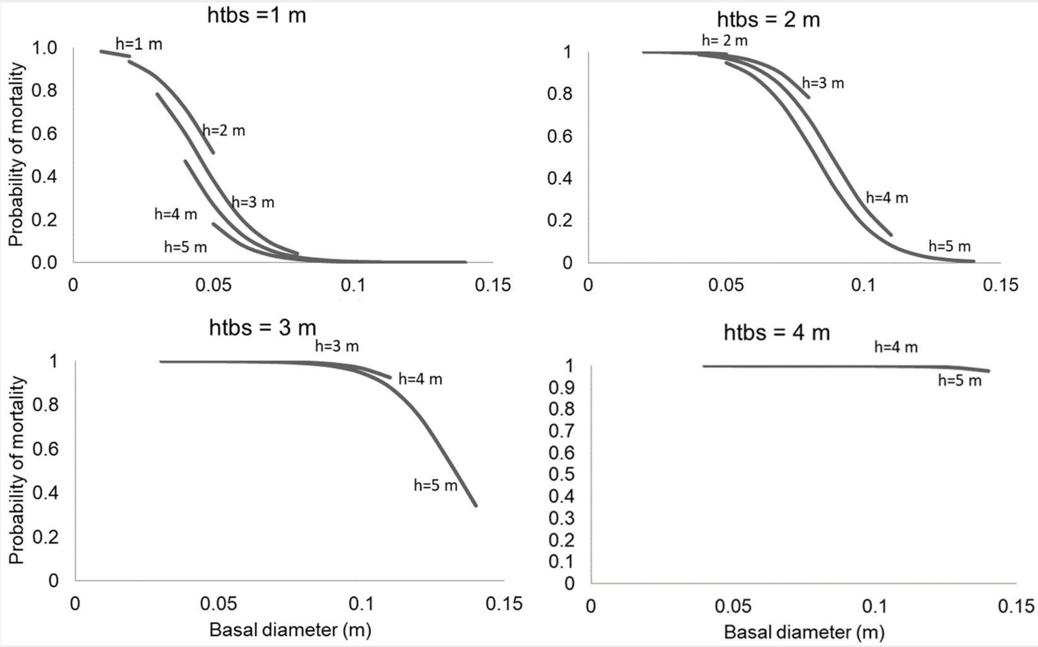

Fig. 2 - Probability of mortality as a function of the explanatory variables. (htbs): stem char heigth; (h): tree height.

tall, with a stem char height of 1.2 m and a basal diameter of 4 cm has an 89.8% probability of mortality, while another tree 3.8 m tall, with a stem char height of 0.6 m and a basal diameter of 15 cm, has a 0.0001% probability of mortality.

Tree leader shoot growth

The variables most closely associated with leader shoot growth in the linear model were stem char height ($p < 0.0001$) and tree height ($p < 0.0001$ – Tab. 3). The higher the stem char height, the lower the leader shoot growth, but the taller the tree, the higher the leader shoot growth (Fig. 3). The resulting model was (eqn. 4):

$$Ls = 0.0716 - 0.1037 X_1 + 0.0774 X_2 \tag{4}$$

where Ls is the leader shoot growth (m), X_1 the stem char height (m), and X_2 the tree height (m).

Tab. 3 - Significance of the parameters for the multiple regression model to predict the leader shoot growth of juvenile *Pinus hartwegii.*

Parameter	Estimation	Standard Error	*t*	P
Intercept	0.07163	0.00643	11.13	<0.0001
Stem char height	-0.10365	0.00479	-21.65	<0.0001
Tree height	0.07740	0.00296	26.12	<0.0001

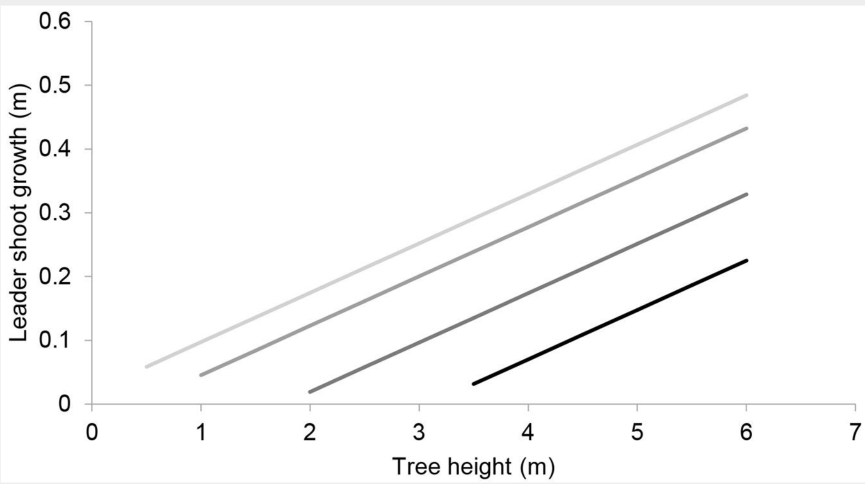

Fig. 3 - Relationship between total tree height and leader shoot growth at different stem char heights, wildfire and prescribed burn treatments. Progressively darker lines (left to right) represent stem char heights of 0.5, 1, 2 and 3 m.

According to this model, a 3.10 m tall tree with a stem char height of 0.8 m had a leader shoot growth of 0.23 m, and the same tree with a stem char height of 2.0 m would have an increment of only 0.10 m.

Discussion

In a low-intensity prescribed burn carried out in small (1 ha) and uniform plots of *P. hartwegii* under less variable wind and topographic conditions, Rodríguez-Trejo et al. (2007) found a mortality of 4.4% one year after the treatment application. In this study, a similar low mortality and a high juvenile tree survival was observed, despite the irregular topography and the changes in wind direction during the experiment. A small increase in mortality is expected one or two years after wildfire, while such increase is expected to be negligible for the prescribed burn. For the same experimental area, Vera-Vilchis & Rodríguez-Trejo et al. (2007) found no mortality increase two year after the prescribed burns. However, in the case of a high intensity prescribed burn in May (emulating a wildfire), mortality was 52% one year later and rose to 67.3% two years after the treatment.

Older trees have thicker bark that isolates the vascular cambium from lethal temperatures and higher crowns less subjected to damage from fire (Ryan & Frandsen 1991, Miller 2000); therefore, the probability of mortality tends to be lower. However, with higher damage, *i.e.*, higher stem char height or higher crown scorch, more photosynthetic tissue is affected in the crown, and the vascular tissue receives more damage, resulting in higher mortality (Ryan & Reinhardt 1988, Woolley et al. 2012, Robles-Gutiérrez et al. 2015). Mchugh & Kolb (2003) reported that mortality of *Pinus ponderosa* is influenced by the interaction between crown damage and severity of trunk damage, as well as by differences in fire resistance among trees.

Several studies demonstrated that when fire causes low crown scorch, primary and secondary growth during the following growth season is higher than in unburned controls, unless a severe drought occurs. This has been found for species such as *P. palustris* Mill. (Grelen 1983), *P. lambertiana* Dougl. (Mutch & Parsons 1998), and *P. hartwegii* (González-Rosales & Rodríguez-Trejo 2004). This response is related to the ashes produced by fire which are rich in cations and to the higher solar radiation on burned sites, as well as to the pruning of lower and older branches that have less photosyntetically efficient needles than younger and higher branches.

The wildfire occurred in the study area was severe because an important part of the forest fuels was represented by dead needles. Indeed, the burning of such fuel causes lethal temperatures for the surface roots, greater damage and mortality, as demonstrated for *P. palustris* (Brockway & Outcalt 1998) and *P. hartwegii* (Rodríguez-Trejo et al. 2007). Vera-Vilchis & Rodríguez-Trejo (2007), found that after low intensity prescribed burns carried out in May on high density juvenile stands, tree leader shoots had a growth of 8.2 cm m^{-1} y^{-1}, *i.e.*, 32% higher than the unburned control (6.2 cm m^{-1} y^{-1}). In the same study, the probability of mortality was higher at high density than at low density, but it apparently enlarged the growing space and favored height growth of surviving trees.

In this study stem char height and tree height, which were associated with tree leader shoot growth in the linear model, also affect tree survival. The higher the stem char height, the smaller the tree leader shoot growth, as damages on the trunk usually lead to a reduction of sap and water flux to the crown. Other types of damage have been associated with lower primary growth. For instance, Chambers et al. (1986) found a reduction in height growth of 0.73 m in conifer trees with a crown scorch of 30 to 40%; the reduction reached 1.71 m when the crown scorch was 85 to 99%, in a 4.5-year period.

Tree leader shoot growth was positively influenced by tree height because, in general, taller trees have thicker trunk and thicker bark, and leaf tissue may be far from fire lethal temperatures. However, even higher fire resistance in older trees becomes useless when the forest accumulates more fuels due to fire exclusion, and then intentional or accidental fires are more intense and severe. Thus, older trees have a higher probability of mortality than younger ones, as found for *P. ponderosa* in Montana (Ryan & Frandsen 1991), *Calocedrus decurrens* (Torr.) Florin, *Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr., *P. lambertiana* Douglas, *P. jeffreyi* Balf., and *P. ponderosa* in California (Hood et al. 2010). Conversely, Pollet & Omi (2002), in *P. ponderosa* Laws forests, found that clearing and prescribed burning significantly reduce crown scorch, so that severity of future fires was lowered.

Conclusions

The main concern of the application of extensive prescribed burning is its effect on young trees. This study provides evidence of the advantages of low intensity and low severity prescribed burning carried out in March, since it does not cause significant mortality and can favor the growth of juveniles of the studied tree species. The smaller the tree diameter the higher the probability of mortality, particularly with high severity wildfires in dense stands. If the stem char height is high, the probability of mortality will also increase. Fire damage on trees, as evidenced by stem char height, is inversely related to shoot leader growth. However, old stands may have high accumulations of forest fuels, causing high mortality in old trees in the case of wildfire occurrence.

In pursuing the objectives of prescribed burning in the studied ecosystem, it is mandatory to prevent significant mortality of trees, particularly the young ones. We demonstrated that this can be achieved with extensive prescribed burns, using the Ajusco method and following the prescription. If other objectives, such as resprouting from grasses to feed cattle and sheep (main cause of wildfires in Mexico), are fitted into this type of prescribed burns, together with the prevention of wildfires (through fuel reduction), an integrated fire management can be achieved. This is a useful fire management option for Mexico to be combined with traditional fire prevention measures and the firefighting.

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