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RESEARCH ARTICLE

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Modelling initial mortality of *Abies religiosa* in a crown fire in Mexico

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Abstract

Aim of study: The objectives of this work were to determine which morphological and fire severity variables may help explain the mortality of adult *Abies religiosa* (Kunth) Schltdl. & Cham., to model the probability of this species after being affected by crown fire, and to obtain more elements to classify the sacred fir in terms of fire resistance. This type of study is relevant to understand and estimate the impacts of crown fires on the climax forests formed by this species.

Area of study: The burned forest was located in the southern Mexico City, borough.

Material and methods: Morphological variables and fire severity indicators were collected for 335 *Abies religiosa* trees burned by a mixed severity fire. Logistic regression was used to analyze data and develop models that best explained tree mortality.

Main results: Survival was 26.9%. The models for height ($p \leq 0.0001$), diameter at breast height ($p=0.0082$), crown length ($p \leq 0.0001$) and crown base height ($p \leq 0.0001$) were significant, with a negative relationship between each one of these variables and probability of mortality. The significant severity variables were lethal scorch height ($p \leq 0.0001$) and crown kill ($p \leq 0.0001$), which have a direct relationship with probability of mortality.

Highlights: This species is moderately fire-resistant. Crown kill ≥ 70% markedly increases mortality. Silvicultural activities such as pruning, thinning and fuel management can reduce the risk of crown fires.

Keywords: Crown kill; crown scorch; forest fires; mixed fires; sacred fir; wildfire.

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Introduction

Abies religiosa (Kunth) (sacred fir) forms the climax vegetation in many temperate areas in Mexico. Factors like alteration of fire regimes have led to a decline in many populations. In central Mexico, sacred firs are a significant part of forest stands that provide invaluable ecosystem services to the Mexico City, part of the Distrito Federal. For the period 1996-2006, CORENA (2012) reports annual averages of 1,118 fires and 2,057 ha burned in the forests of the Distrito Federal. However, these forests are in the wildland urban interface, which places them at increased risk of burning (Rodríguez-Trejo, 2008).

During wet years the sacred fir forest serves as a barrier to fires spreading from more flammable vegetation, such as neighboring pine forests. Fir forests are characterized by low crown base height and dense canopies that readily support crown fires in dry years (Rodríguez-Trejo, 2008). Wildfires in sacred fir forests have had tragic results. For example, in the grand gully of the village of Texocuixpan, Puebla, in 1998, a crown fire swept through 400 ha of sacred fir and *Pinus patula* Schl. et Cham. forest. Tragically it took the lives of 19 volunteer firefighters (Rodríguez-Trejo *et al.,* 2000). That same year, the sacred fir forests in El Chico National Park, Hidalgo, and in the Desierto de los Leones Park, in Mexico City, also had crown fires over hundreds of hectares. In 2011, another extreme forest fire year for the country, the sacred fir forests in the Valley of Mexico once again experienced crown fires. Despite its evident relevance, research on crown fires in Mexico and many countries, including its effects, is very scarce. Because of that this study focuses on that type of fires.

Three factors are important to consider for understanding fire relationships of sacred fir: resistance to fire injury (e.g. bark thickness); resilience to fire injury, i.e., the ability to recover tissues and function; and regeneration on burned sites. Sacred fir forests are generally regarded as susceptible to fire. With the exception of studies by Rodríguez-Trejo (2007) and Ángeles & López (2009), respectively, relating moderate foliage resprouting from epicormic buds and prolific regeneration by seeds in areas moderately affected by crown fire, there is little published documentation of *Abies religiosa* fire adaptations.

Compared to angiosperms, gymnosperms generally exhibit less ability to sprout (Bond & Midgley, 2003; Burrows *et al.,* 2010; Meier *et al.,* 2012), but epicormic branching is an ancient gymnosperm trait (Creber & Collinson, 2006; Decombeix *et al.,* 2010) and a potential fire regime indicator (Burrows, 2002; Crisp *et al.,* 2011). Epicormic sprouting is a generalized response to canopy injury (Lanner 2002), including from fire (Burrows, 2002; Burrows *et al.,* 2010; Crisp *et al.,* 2011), exhibiting intra-specific variation in response to type and severity of disturbance (Meier *et al.,* 2012). Epicormic branching occurs in a number of species in the genus *Abies* (Meier *et al.,* 2012), including the closely related (Farjon, 2010) white fir (*Abies concolor* (Gordon) Lindley ex Hildebr.), which Hanson and North (2006) found produced epicormic sprouts from the stems 3-4 years after fire in the Sierra Nevada of California. Epicormic sprouting was more common in larger diameter trees and in moderate to high crown kill classes. A high, open crown character favors resistance to injury to foliage and buds. Conversely, a low, dense crown predisposes a tree to injury and crown-fire propagation. Sacred fir generally has the latter character, making it susceptible to high crown injury. However, the observed epicormic sprouting may contribute to increased survival.

Bark thickness is considered a major factor in determining resistance to fire injury (Peterson & Ryan 1986, van Mantgem & Schwartz, 2003) Bark thickness generally increases linearly with stem diameter, but resistance to cambial injury increases with the square of bark thickness. Van Mantgem & Schwartz (2003) found *A. concolor* had a greater proportion of inner bark, which appeared to have higher insulating value, particularly in smaller diameter stems. One author (DART) has observed 80 cm diameter sacred fir with 3.5 cm thick bark (Fig. 1). Such bark thickness is three times thicker than the fire-sensitive subalpine fir (*Abies lasiocarpa* (Hooker) Nuttall) (Ryan, 1982) and comparable to white fir (*A. concolor*) (Larsen & Hann, 1985). This would rank *A. religiosa* as moderately fire resistant. A deep rooting habit confers resistance to root injury (Ryan, 1982; 1990; Ryan *et al.,* 2010; Fowler & Sieg, 2004). Little is known of sacred fir's rooting habit, but late successional/climax species tend toward a shallow rooting habit (Ryan, 1990).

Figure 1. Thick bark in the stump of an old sacred fir, Estado de México, 2013. Photograph by Dante Arturo Rodríguez-Trejo.

The modeling of post-fire tree mortality in forest species began in the United States (Bevins, 1980; Peterson & Ryan, 1986; see Woolley *et al.,* 2012 for review). Ryan & Reinhardt (1988) used binary logistic models to estimate the mortality of seven conifers, including *A. lasiocarpa*, in the western United States. They found crown volume killed and bark thickness were the best predictors of mortality. van Mantgem *et al.* (2003) studied the interaction between crown scorch and pre-fire growth rate in *A. concolor* in the Sierra Nevada of California. They found crown scorch to be the most important determinant of mortality but pre-fire growth rate significantly improved prediction. The effect was especially pronounced in moderately injured trees (crown scorch 50% to 90%). Also in the Sierra Nevada, Stephens and Finney (2002) modeled fire-caused mortality of five species including *A. concolor*. They found crown scorch and a forest floor consumption best predicted mortality. Sieg *et al.* (2006) monitored *Pinus ponderosa* mortality across four widely distributed, biophysically diverse sites from Montana to Arizona. Their logistic models indicated that crown scorch or crown consumption accounted for most of the variability in their predicted mortality. Fowler & Sieg

(2004) developed methods for estimating mortality in *Pinus ponderosa* Douglas ex C. Lawson and *Pseudotsuga menziesii* (Mirb.) Franco. In Mexico, the probability of mortality of *Pinus hartwegii* Lindl. is influenced by season of burn, fire intensity, tree density (that influences the fuel complex) and tree diameter, according to logistic models (Rodríguez-Trejo *et al.,* 2007).

In the sacred fir stands of central Mexico, as is to be expected when crown fires occur, tree mortality is very high. Fire behavior commonly transitions between surface fire and crown fires in response to local variations in the stand density, surface fuels, terrain, and wind. In some sectors the crown fire is active, but in others passive and in yet others it does not reach crowning. Such mixed-severity fires result in a diversity of effects on residual trees. The objectives of this work are: a) to determine quantitatively which morphological and fire severity variables may help explain the mortality of adult *A. religiosa*, b) to model the probability of mortality of sacred fir affected by crown fire, and c) obtain more elements to classify the sacred fir in terms of fire resistance.

Material and Methods

Study area

The study area was in a place known as Rincones de la Viga, which belongs to the community of San Miguel Topilejo in the Mexico City borough of Tlalpan, within a previously burned area. In this area there are abundant large rock outcrops, product of the eruption of the nearby Xitle volcano in 300 AD. The forests in this area are dominated by *Abies religiosa.* but there are also other less abundant species, namely *Pinus hartwegii*, *Arbutus xalapensis* Kunth and *Buddleia cordata* Kunth. Part of the affected area is near flat terrain.

The diversity of trees in these forests is low, although *A. religiosa* is associated with *Pinus*, *Quercus* and others. However, these forests have high species diversity at the understory and fauna level (Rzedowski, 1978). Although they cover slightly less than 1% of forested land in Mexico, sacred fir (*A. religiosa*) forests are the climax vegetation in cold-temperate areas. *Abies* forests are located between 2,400 and 3,600 masl, in areas with a mean annual temperature of 7-15 °C and where mean annual precipitation exceeds 1,000 mm. Normally there are only four dry months and snowfalls occur almost every year. Sacred fir are mainly located on deep, dark brown soils with sandy loam or loamy texture, abundant organic matter and slightly acidic pH (Rzedowski, 1978). The species is primarily found in the Trans-Mexican Volcanic Belt and in the mountains of southern Mexico, where they form large stands, although they are also found in the north, albeit to a lesser degree (Challenger & Soberón, 2008). In the Valley of Mexico sacred fir prefers wetter exposures, from the NW to NE (Madrigal-Sánchez, 1967). However, in the Cofre de Perote, near the Sierra Madre Oriental, it commonly occurs on SW, W, NW, N and NE exposures (Sánchez *et al.,* 1991).

In this area on March 3, 2011, a forest fire occurred in a sacred fir forest, affecting 197 ha. The fire was mostly a crown fire with varying intensity but it occassionally spread as surface and ground fires as well. The ground fire was due to the accumulation of combustible materials in the cracks between rocks. The cause of the fire was human activity (CORENA, 2012) (Fig. 2).

Field sampling

The sampling included 335 *Abies religiosa* trees (≥ 1.5 m tall), selected on a transect in the fire affected area. Field data collection began six months after the fire, in the months of September and October 2011. The variables considered were qualitative and quantitative. The former included the following: substrate where the tree grew (soil, rocky, or natural rock pot filled with earth), damage on the trunk caused by an agent unrelated to fire, and whether the tree was alive or dead. Quantitative variables included: total height, crown base height (height from ground to the base of the original crown), crown length (length from the base of the original crown to the tip of it), lethal scorch height (height from ground to the top of the crown zone with leaf and bud mortality, without resprouting of leaves), crown kill percentage ((length of dead crown/original crown length)(100)), height of the visible scar on the trunk bark and diameter at breast height. The material used included rope, metric and diametric measuring tapes, a Haga height-measurer, a clinometer, a global positioning system (GPS) and a digital camera.

Figure 2. Photograph of the study area six months after the fire. Photograph by Dante Arturo Rodríguez Trejo, 2011.

Statistical analysis

For the statistical analysis, we used logistic regression (Hosmer & Lemeshow, 2000), used individually or in combinations the explanatory variables obtained in the field. The dependent variable was the probability of tree mortality (P):

$$P = 1/\left(1+e^{-(\alpha+\beta_1 X_1+\beta_2 X_2+\ldots+\beta_n X_n)}\right) \quad (1)$$

Where e is Euler's number (=2.7183), α is the intercept, β_1 the constant associated with the explanatory variable X_1, β_2 the constant associated with the explanatory variable X_2, and β_n the regression constant associated with the explanatory variable X_n.

Numerical variables were expressed directly, for qualitative variables the value 0 was used when they were absent and the value 1 when they were present. This is how to incorporate such variables into logistic models. The significance of the models was set at $p \leq 0.05$ for the explanatory variables, and the value 1 would not be within the 95% confidence interval. A regular to high concordance was also sought. These analyses were conducted in SAS software v. 6.1. for microcomputers.

Results

Stand structure

The sacred fir stand had an average height of 11.3 m, with a maximum of 32 m, and an average DBH equal to 36.7 cm and a maximum of 92 cm. As is typical of the species, crown base height was low (average of 2.1 m, minimum of 0 m), but with high crown length and crown length/height ratio (the latter was 0.79) (Table 1, Fig. 3). Although not sampled, abundant regeneration of *A. religiosa* was observed in various areas of high mortality. However, three years later, it was observed that most of them did not survive.

Fig. 4 shows a slight trend, with low R^2, where the tallest trees have the largest diameters. However, more notable is the large variation in heights that each diameter class presents. A closer correlation is presented by crown length and tree height (Fig. 5). That was not the case for crown base height and lethal scorch height (Fig. 6).

Fire severity

As is to be expected from an intense, predominantly crown fire, the severity in the sacred fir forest was high, as mortality reached 73.1% and is likely to increase by some degree in the first 2-3 years after the fire. Such delayed mortality is a response to stem and root injuries, as well to insect attacks (McHugh *et al.*, 2003). Another measure of the high severity is 83.9% of crown kill (Fig. 3). There is not a strong direct relationship between crown length and lethal scorch height. The opposite was expected, for longer and lower crowns can catch surface fire easily. However, if values with 0 lethal scorch height are removed, of trees with non fire-affected crowns due to variation in the intensity and severity of the fire, the relationship would undoubtedly be more direct.

Models for estimating the probability of mortality

After running the regressions for all variables, both one-by-one and using combinations of them, there was

Table 1. Indicators of stand structure and fire severity

Abies religiosa			
Variable	**Mean**	**Maximum**	**Minimum**
Structure indicators			
Height (m)	11.3	32.0	1.8
Diameter at breast height (cm)	36.7	92.0	6.0
Crown height (m)	2.1	7.0	0
Crown length (m)	9.1	30.4	0
Crown length/height	0.79	1.00	0
Severity indicators			
Mortality (%)	73.1	–	–
Lethal scorch height (m)	9.1	27.0	0
Crown kill (%)	83.9	100	0
Scar on trunk (m)*	2.5	14.5	0.2

*This could only be identified in 25% of the *Abies* sampled.

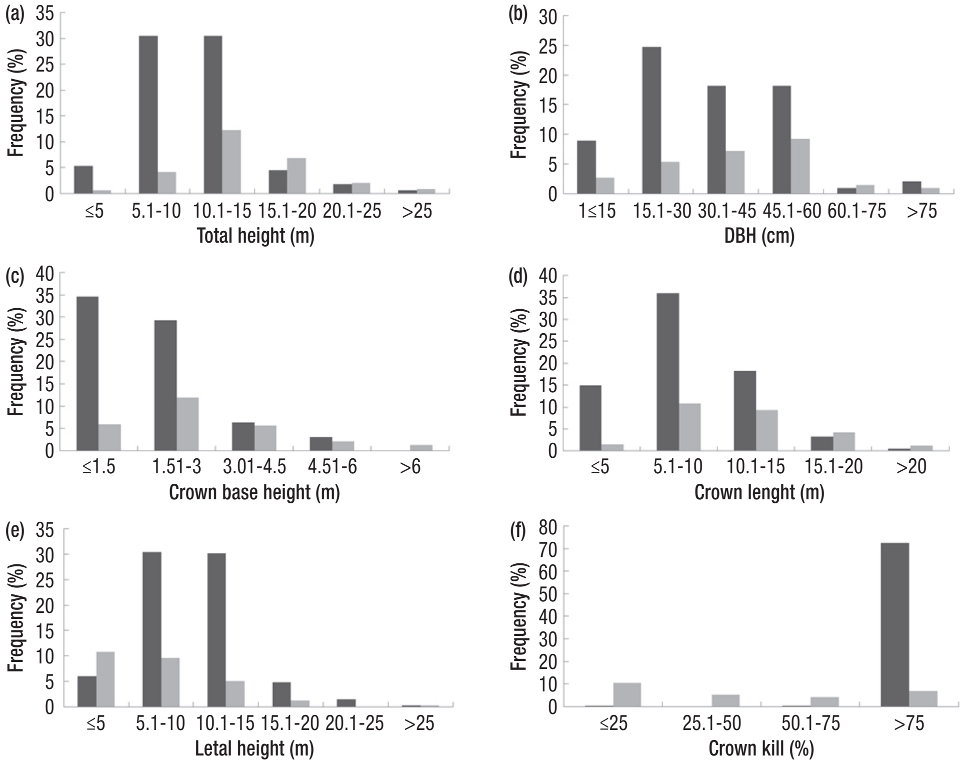

Figure 3. Frequency distribution of living and dead trees (*Abies religiosa*), for the significant variables in the logistic models. a) height, b) diameter at breast height, c) crown height, d) crown length, e) lethal scorch height, f) crown kill. Dead trees in black, living ones in gray. n=335.

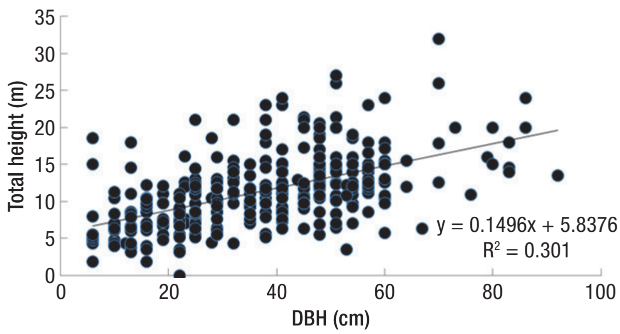

Figure 4. Diameter at breast height-height relationship for the sample obtained.

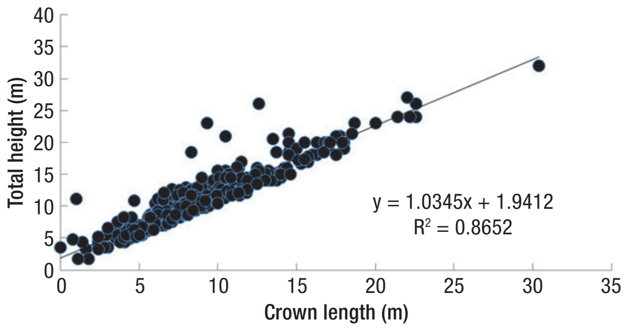

Figure 5. Crown length-height relationship.

only significance for estimating the probability of tree mortality (P) when individual variables such as crown base height (CH), diameter at breast height (DBH), lethal scorch height (LH), total height (TH), crown length (CL) and crown kill (CS) were used. Below is a list of the models, and Table 2 provides data on the significance.

$$P = 1/\left(1+e^{-(3.2639-0.1870TH)}\right) \quad (2)$$

$$P = 1/\left(1+e^{-(1.7033-0.0185DBH)}\right) \quad (3)$$

$$P = 1/\left(1+e^{-(1.9762-0.4354CH)}\right) \quad (4)$$

$$P = 1/\left(1+e^{-(2.5914-0.1646CL)}\right) \quad (5)$$

$$P = 1/\left(1+e^{-(-0.6042+0.1957LH)}\right) \quad (6)$$

$$P = 1/\left(1+e^{-(-14.3417+0.1718CS)}\right) \quad (7)$$

The resulting graphs of the probabilistic models are given in Fig. 7. They show that sacred fir mortality tended to decrease with higher crown base heights, diameter at breast height, total height, and crown length. By contrast, its mortality increased with higher crown kill levels and lethal scorch height. In the case of dead trees, it is clear that the class of >

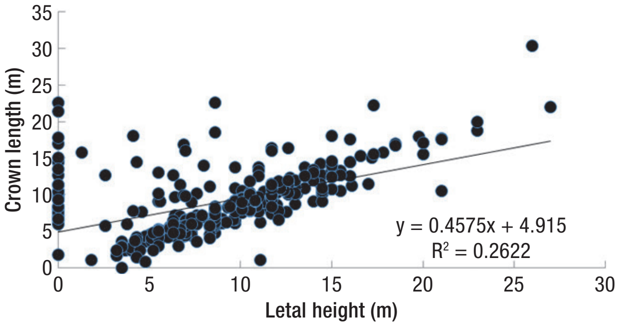

Figure 6. Lethal scorch height-crown length relationship.

75% kill contains only trees with total kill of their crowns.

Discussion

Structural and severity variables

Height. Shorter individuals generally have even thinner bark and less protection against fire than tall trees, so they have higher mortality. Such trees also incur more crown injury due to a greater portion of their foliage and buds being killed because they are closer to the surface flaming. Fig. 4 showing the relationship between height and diameter of the sample, demonstrates that almost all diameter categories have a significant proportion of individuals up to 15 m high; according to Model 2 and Fig. 7a, trees 15 m high have a 61% probability of mortality. The great variability of heights, with values ranging from 2-32 m, helps explain the vertical continuity of fuels.

Diameter. Sacred firs with a DBH of 20 cm have a close to 80% probability of mortality. By contrast, that probability for *P. hartwegii* with the same diameter in high-intensity prescribed fire treatments is only 10% (Rodríguez-Trejo *et al.,* 2007). The larger diameter is associated with thicker bark that better protects the vascular cambium from lethal temperatures. In seven conifers in the U.S. and Europe, greater bark thicknesses delayed the time to kill the cambium. For example, in *Pseudotsuga menziesii*, with a DBH of 30 cm this time was 10 min, but with a DBH of 60 it was delayed by 43 min (Ryan *et al.,* 2010). However, in the U.S., *Abies lasiocarpa* has very thin bark, while *Abies grandis* (Dougl. ex D. Don) Lindl., *A. procera* Rehder, *A. amabilis* Douglas ex J. Forbes, *A. magnifica* A. Murray and *A. concolor* all have medium-thick bark (Miller, 2000; van Mantgem & Schwartz, 2003). *A. religiosa* bark is considered to be medium-thick.

Crown base height. Lower crown base heights are related to higher levels of mortality in the sacred fir, evidence that the lower they are the greater the possibility that the fire will transit from surface flaming to torching or crowning and damage the photosynthetic,

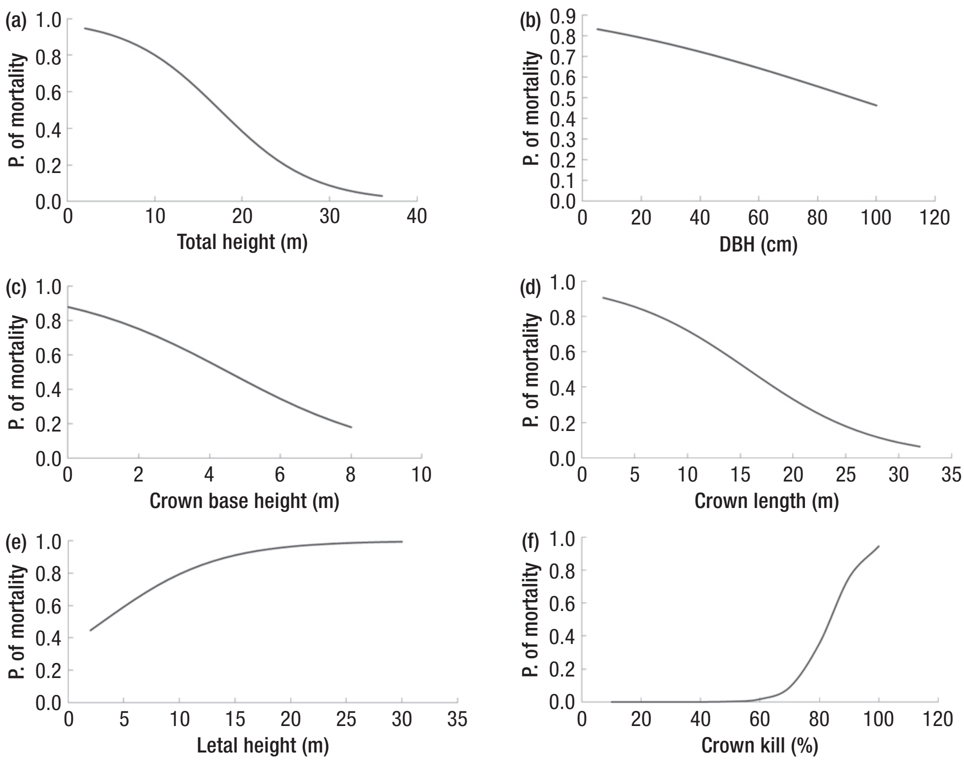

Figure 7. Graphical representation of the logistic models that were significant. a) total height, b) diameter at breast height, c) crown base height, d) crown length, e) lethal scorch height and f) crown kill.

Table 2. Significance of the variables in the logistic models used

Variable	p	CI (95%)	Concordance	Discordance	Linked
Total height	≤0.0001	0.782-0.880	72.6	25.7	1.8
Intercept	≤0.0001				
DBH	0.0082	0.968-0.995	57.4	37.9	4.6
Intercept	≤0.0001				
Crown height	≤0.0001	0.540-0.775	64.3	31.6	4.1
Intercept	≤0.0001				
Crown length	≤0.0001	0.798-0.902	68.3	31.1	0.6
Intercept	≤0.0001				
Lethal scorch height	≤0.0001	1.141-1.296	70.8	27.5	1.7
Intercept	0.0289				
Crown kill	≤0.0001	1.124-1.255	95.0	4.4	0.6
Intercept	≤0.0001				

conductive and supporting tissues. Alexander (1988, after Van Wagner, 1977) proposed a model to determine the critical intensity (I_O) that a ground fire must have to start a crown fire as a function of live crown base height (LCBH) and foliar moisture content (FMC):

$$I_O = \left(0.01 \text{ LCBH}\left(460 + 25.9\text{FMC}\right)\right)^{1.5} \quad (10)$$

From the direct relationship that exists between flame length and fire intensity, given by Byram (1959), Van Wagner (1977) and Alexander (1988), the relationship between critical flame length to start a crown fire and crown base height, in different foliar moisture scenarios, was established. For 100% foliar moisture content, a crown base height of 2.1 m, the average found in this study, would require the following critical intensity for the fire to crown:

$$I_O = \left(0.01(2.1)\left(460 + 25.9(100)\right)\right)^{1.5} = 512.6 \text{ kW m}^{-1}$$

The flame length (L) required to generate such intensity was estimated as follows with the Byram (1959) model, that uses Byram's intensity (kW m^{-1}):

$$L = 0.0775\left(I_B\right)^{0.46} \quad (11)$$

$$L = 0.0775(512.6)^{0.46} = 1.37 \text{ m}$$

This flame length is easily achievable by surface fire, particularly in an understory with abundant shrub cover, such as that of the sacred firs. Because many trees had lower than average crowns and low foliar moisture content, the crown fire was facilitated in the study site.

Crown length and lethal scorch height

When a surface fire severely affects tree crowns, the bottom of the crown is burned (without foliage). Above this section is another zone called the scorch area (with dehydrated foliage), above which there is another zone, not significantly affected, with green foliage. The scorch area is divided, in turn, into two, because the lower part includes dead buds, while the upper has living buds and has the potential to regrow (Hood, 2010; Ryan *et al.,* 2010; Fowler & Sieg, 2004).

Crown kill. The highest levels of crown kill and thinnest bark thicknesses are related to higher mortality in *Abies lasiocarpa* and six other North American conifers, *Pseudotsuga menziesii, Larix occidentalis* Nutt*., Picea engelmannii* Parry ex Engelm*., Pinus contorta* Douglas*, Thuja plicata* Donn ex D. Don and *Tsuga heterophylla* (Raf.) Sarg. (Ryan & Reinhardt, 1988). If the crown kill is total or near total, non-fire-tolerant trees will lack living buds and carbohydrates stored by twigs and stems that can allow recovery. The greater the crown area left unaffected or affected at low severity, the more buds will have survived and there will be some carbohydrate reserves to supply their activation and growth. In addition, severe damage to the tree increases the possibility of pest attack.

However, there is not a direct relationship for all species between crown scorch level and mortality or adverse effects. In fire-adapted species, a low level of crown scorch (up to 1/3 of it) improves secondary growth the next year, as has been found in *P. elliottii* Engelm. (Johansen, 1975), *P. palustris* Mill. (Wade, 1983) in North America, *P. pinaster* Ait. (Botelho *et al.,* 1998) in Europe, and *P. hartwegii* in Mexico (Rodríguez-Trejo *et al.*, 2007). According to the logistic model obtained for this study, the sacred fir tolerates up to 60% crown scorch. From that point on mortality increases. According to Ryan & Reinhardt (1988), different conifers with a high level of crown kill have a high probability of mortality. Both, fire-resistant species such as most hard pines (Keeley, 2012), and fire-susceptible species characteristic of late successional stages, like sacred fir, increase their mortality with high levels of crown kill.

Fire adaptations

Foliage sprouting. Characteristics that increase the likelihood of a crown fire, such as a low crown base height and high crown bulk density (VanWagner, 1977), or high stand density are generally considered to be deleterious to tree survival. However, regeneration of new crown from epicormic buds is an important fire adaptation to the damage inflicted by fires occurring in such stands (Bond & Midgley, 2001, 2003; Hanson & North, 2006). Likewise, fire tolerance is evidenced by basal sprouting or if there is consistent sexual regeneration to recolonize burned sites. Sacred fir has the stand characteristics that make it prone to crown fires when the environment is dry enough, yet it has foliage sprouting when the fire is not very intense.

Sexual regeneration. There is evidence that under intermediate levels of damage by crown fire in El Chico Park, Hidalgo, Mexico, sacred fir regeneration is more abundant than with high levels of damage in the crowns or ground fire areas or unburned sites, so there fire is part of the sacred fir regeneration niche (Ángeles & López, 2009). Lara *et al.* (2009), have documented that *A. religiosa* regeneration is best in small gaps (most with between 44 and 88 m^2 and an average age of 7.6 years) than under canopy, with densities of 4,239 ha^{-1}, in the Cofre de Perote, Veracruz. In Japan, Narakawa & Yamamoto (2001) have reported that the regeneration of other species of *Abies* is favored in gaps. Other researchers have typically denoted *A. religiosa* as a shade-tolerant species. González *et al.* (1991) note that in Zoquiapan, State of Mexico, the seeds of this species germinate better under a closed canopy (87.3%) than under open canopy (76.9%) or intermediate canopy (60.2%). They also included prescribed ground burn treatments in intermediate and open canopies, obtaining germination of 61.1 and 48.5% respectively.

Bark thickness. The authors know of no comparative analysis of the morphological characteristics of the genus *Abies*. However, a synthesis for 25 *Abies* species grown in a common setting at the Arnold Arboretum in Massachusetts indicates several species develop moderately thick, furrowed bark at maturity (Warren & Johnson, 1988). This is particularly evident for species habiting cool mountain areas proximal to more fire-adapted pines (*Pinus* sp.) and oaks (*Quercus* sp.), in contrast to those from cold, boreal regions. In North America *Abies concolor*, *Abies grandis*, *A. magnifica*, and *A. procera* are moderately resistant (Miller, 2000; Stephens & Finney, 2002; van Mantgem & Schwartz, 2003; Schwilk *et al.,* 2006; van Mantgem *et al.,* 2013), mainly due to their bark thickness. These species grow in cool temperate forests in the Sierra Nevada and Rocky Mountains, with *A. concolor* extending into northern Mexico. They experience a pronounced dry season where lightning is common and fires frequent pine and oak forests lower on mountain slopes. In contrast *A. balsamea*, *A. amabilis* and *A. lasiocarpa* are fire-sensitive. These boreal and subalpine species burn predominantly in long fire return interval stand replacing fires (Miller, 2000).

Comparison with a fire-adapted species. *Pinus hartwegii*, a species with which the sacred fir forms some associations and ecotones, and which succeeds it on the next altitudinal level, is one of the better fire-adapted pines. This pine has resistance mechanisms (thick bark) and even a fire tolerance level (it recovers much of its crown when it is affected by fire and some populations are able to emit abundant basal resprouts), in addition to recolonizing burned areas (winged seed, the bed generated by fire is suitable for the germination of its seeds, and it is a shade-intolerant species); thus, many populations present a grass stage (Rodríguez-Trejo, 1996, 2001, 2006; Rodríguez-Trejo & Fulé, 2003). Even crown scorch not exceeding one third of the crown generate greater secondary growth than that of unburned controls during the year following a prescribed fire (González-Rosales & Rodríguez-Trejo, 2004). With a low-intensity fire applied mid-season, young pine survival is very high, in both the first and second year (Rodríguez-Trejo *et al.,* 2007; Vera-Vilchis & Rodríguez-Trejo, 2007). Also the comparison among a pine and a true fir, both from North America, may be useful. Van Mantgem *et al.* (2013) found similar mortality rates for large (DBH > 50 cm) ponderosa pine (*Pinus ponderosa*) and white fir (*Abies concolor*) five years after prescribed burning in the Southwestern United States. For smaller trees (DBH < 50 cm) white fir was more likely to die. Prescribed fires are commonly less intense than wildfires, but not necessarily. These authors accounted for actual fire injuries (crown volume scorched and stem char height), so results should be broadly applicable to these species. In general surface fuels can be expected to burn out before lethal heat can penetrate to cambia beneath bark thicker than about 1 cm (Ryan, 1990).

It is the sacred fir fire-adapted? *Abies religiosa* has no marked fire adaptations, except for the following evidence: the foliage of *A. religiosa* resprouts after a fire of moderate severity (Rodríguez-Trejo, 2007); it regenerates well in partially shaded burned areas (Ángeles & López, 2009); and has a thick bark when old. Based on the evidence of this study and in the literature review, *A. religiosa* is considered to be a moderately fire-resistant species adapted to mixed-severity fire regimes.

Management implications

Sacred fir forests are critical habitat for wintering Monarch butterflies. Logging and other land use changes threaten these forests (Ramírez *et al.,* 2003; Toone & Hanscom, 2003). Forest fires originating from land clearing, charcoal production, and other activities increasingly damage these forests (Brower & Malcolm, 1991; Brower *et al.,* 2012). The most critical years in terms of forest fires for Mexico have been 1998 and 2011. In both years crown fires in sacred fir forests were relatively common. Various global climate change predictions indicate drying trends for Mexico (Magaña *et al.,* 1997; Villers-Ruiz & Trejo-Vazquez, 1997, 1998; Karmalkar *et al.,* 2011; Sáenz-Romero *et al.,* 2012) with anticipated increases in fire, which could have a major impact on Monarch butterflies (Villers-Ruiz & Trejo-Vazquez, 1998; Peterson *et al.,* 2002). Longer and stronger dry seasons (Karmalkar *et al.,* 2011) coupled with the structural characteristics of sacred fir, leads to the conclusion that crown fires will become more common in sacred fir forests, as well as in adjacent forest types. In light of this situation, the silvicultural practices of pruning low branches to raise crown base height, thinning and managing forest fuels where they are excessive, including materials resulting from silvicultural treatments, are factors that can help to reduce the incidence of fires in the vicinity of sacred fir forests. There may be a roll for judicious use of prescribed burning under mild weather conditions to effectively treat fuels, raise crown base height, and create fire-resilient sacred fir forests. However, fire use should be timed such that the butterflies are not directly affected, i.e., scheduled for times when butterflies are not present. Air pollution in general, and smoke in particular, is known to adversely affect Monarch butterflies (Mayerle, 1992; Toone & Hanscom, 2003). Given the critical importance of sacred fir forests for Monarch butterflies, these forests should be managed in a landscape context, particularly in the face of climate change and increased land use pressure (Peterson *et al.,* 2002; Vos *et al.,* 2008; Sáenz-Romero *et al.,* 2012). Management should attempt to develop a fire resilient landscape where the risks of major habitat loss due to fire are reduced. Research on the role and use of fire in managing these landscapes is critical to the development of informed policy and management. Such research should integrate Monarch butterfly ecology and monitoring to reduce the risks.

Conclusions

In the study area, initial mortality of *A. religiosa* 6 months after a crown fire was high (73.1%). This allowed for quantitatively analyzing the relationship between morphological variables and mortality. As tree dimensions (DBH, height, crown length, crown base height) increase, the probability of mortality tends to decrease, whereas the more intense and severe the fire, represented by increased lethal scorch heights and crown kill percentage, the greater the probability of mortality.

Abies religiosa is considered moderately fire-resistant, as it can lose half its crown and not die, for at least the first six months after the fire, and trees with larger dimensions have somewhat reduced mortality. Crown kill ≥ 70% markedly increases mortality.

Assuming 100% foliar moisture content at the time of the fire and using the Van Wagner model, the flame length required to reach the average crown height (2.1 m) to generate the crown fire was estimated at 1.37 m. This flame length is easily attainable in this type of forest, which has leaf litter, woody material, herbaceous and shrub species and a range of tree heights, thereby providing vertical continuity to the forest fuel bed. In addition, the lower branches of many trees are 50 cm above the ground or at its level.

Crown fires in sacred fir forests tend to occur in very dry years, such as 1998 and 2011, years of extreme fires in Mexico. It is estimated that as a result of global climate change, crown fires in sacred fir forests and other forest types will be more common in the country in the near future. A variable useful for estimating the possibility of crown fire, besides foliar moisture content and the flame length that the ground fire may produce, is crown base height.

Pruning, reducing density and managing forest fuels, including those produced by pruning and thinning, would reduce the risk of crown fire.

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