# Scorch height and volume modeling in prescribed fires: Effects of canopy gaps in *Pinus pinaster* stands in Southern Europe

## Abstract

The use of prescribed fire has been on the rise in recent years owing to its effectiveness in surface fuel reduction, its implementation cost, and the possibility of firefighter training. However, greater knowledge regarding the effects of fire on woodlands is required by forest managers. Scorch height and scorch volume are the most widely used variables for evaluating the effects of burning on trees. This study proposes a scorch height model for the prescribed fires of pine stands in Southern Europe. Although the two main variables of the existing models (fire-line intensity and air temperature) were considered, our model achieved a coefficient of determination of 89% with the incorporation of the canopy base height. A decision tree for scorch volume was also developed using the three independent variables. The presence of canopy gaps in the lower, mid-, and upper slopes resulted in significant differences in the scorch height. The scorch height increased between 0.33 m and 2.08 m because of the canopy gaps in the upper slope. These findings can play an important role in the implementation and improvement of prescribed burn windows.

**Keywords:** fire behavior, fire management, fire impact, fuel treatment, thermal pruning, canopy gaps

## 1. Introduction

Greater accumulation of woody biomass, increasing socio-economic activities, and climate change have caused changes in large fire regimes (Flannigan et al., 2009; Pausas and Fernández-Muñoz, 2012; Rogers et al., 2020). Fuel treatments can help mitigate the spread rate and intensity of fires (Stephens et al., 2012; Piqué and Domènech, 2018). In addition, fuel treatments can be used as a supporting tool within the operational firefighting systems (Alcasena et al., 2019). A wide variety of manual and mechanical fuel treatments can be used in the case of surface and/or ladder fuels to reduce fire hazards (Agee and Skinner, 2005). Prescribed fire represents a highly useful method of fuel treatment owing to its low cost (Hesseln, 2000), its ability to reduce dead fuel load (Knapp et al., 2011; Molina et al., 2018), and its potential application for training firefighters (McCaw, 2013). Although the use of prescribed fires has received significant attention globally, this fuel treatment is not yet sufficiently understood to be effective against large forest fires (Fernandes et al., 2013).

Prescribed fires involve short- and medium-term changes in the fuel load and continuity, reducing the risk of fires (Stephens et al., 2012; Fernandes, 2015). Fire managers should estimate fire intensity by integrating the objectives of surface fuel reduction with the mitigation of crown scorch height (Valor et al., 2015). Some researchers (Methven, 1971) have suggested that the probability of tree survival is 50%, with 75% of the crown volume being scorched. For *Pinus pinaster* Ait., Vega et al. (2011) predicted tree mortality based on the crown volume that was scorched. However, they included other variables, such as the attack of pine beetles and the region of provenance, as well.

The scorch height is observed shortly after burning, and it manifests as a change in the color of the needles to a yellowish-brown hue, which is a result of the temperature reached by the leaves. It has been reported that pine needles can tolerate heat stress up to a temperature of 60 °C (Methven, 1971). Therefore, crown scorch height is a reliable variable for monitoring the post-burning effects on trees (Fernandes et al., 2000). A potential function of fire intensity developed by Van Wagner (1973) has been widely used to model scorch height. In some models, the scorch height directly depends on the fire-line intensity (Van Wagner, 1973; Burrows et al., 1989; Fernandes, 2002), while in other models, it is also associated with air temperature and wind speed (Van Wagner, 1973). In addition, yet other scorch height models (Albini, 1976; Gould, 1994) are related to the flame height or flame length, which provide the chance to record "in situ" observations. Another example involves the model described by Botelho (1999), which included canopy base height as an independent variable in the scorch height equation, together with wind speed and air temperature.

There are several tools (Reinhardt et al., 1997; Andrews et al., 2008; Fernandes et al., 2012) that allow us to estimate the crown scorch height from the models of Van Wagner (1973) and Fernandes (2002). Some researchers (Alexander and Cruz, 2012) have suggested that the scorch height may be underestimated due to fuel consumption. A higher fuel consumption could increase flame length and fire intensity, and therefore, scorch height. Other researchers (Knapp et al., 2011) have reported that the presence of a high load of masticated fuel from biomass harvesting may have resulted in underestimations of scorch height. The higher scorch height in masticated fuels could be related to flame residence time and heat being produced even though flame length was apparently suppressed. Significant differences have also been observed depending upon the prescribed fire season (McHugh and Kolb, 2003; McHugh et al., 2003) and species characteristics (canopy characteristics), which may result in different values of vertical heat transfer (Michaletz and Johnson, 2006a).

This research aims to: (ⅰ) propose a scorch height model for prescribed fires in Southern Europe; (ⅱ) propose a decision tree analysis for crown scorch volume; and (ⅲ) identify the effects of canopy gaps on crown scorch height. The third objective (that is, identifying whether canopy gaps affect the crown scorch height) is based on the hypothesis that the presence of canopy gaps causes an increase in air flow (Duan et al., 2008; Ma et al., 2010; Keifer et al., 2016) and a chimney effect of the convective plume. The novelty of this research lies in the identification of scorch height differences based on the presence and size of canopy gaps. The identification of the factors (meteorological variables, stand characteristics, burning conditions, and fuel availability) that can affect the scorch height is essential for efficient planning of prescribed burn windows. Instances involving the use of prescribed fires as a fuel management tool have been increasing rapidly; thus, it is necessary to harmonize the effects of surface fuel reduction with the mitigation of ecological impacts and tree mortality.

## 2. Material and methods

### *2.1. Study area*

This study was carried out in three provinces (Almería, Ciudad Real, and Córdoba), which belong to two autonomous communities of Spain (Andalusia and Castilla la Mancha) located in the south of the Iberian Peninsula (Figure 1). The average annual number of fires (2009–2019 period) in the three provinces is between 61 and 69 fires, and the average annual burned area is between 497.42 ha and 885.52 ha. Although prescribed fires continue to encounter administrative limitations in the study area, fire use has increased considerably in the last few years.

The prescribed burns were conducted at six locations: Velefique (VEL), Sierro (SIE), San Lorenzo de Calatrava (SLO), Puebla de Don Rodrigo (PUE), Viso del Marqués (VIS), and La Lozana (LOZ). It is important to highlight that the SLO burnings were located within the “Valle de Alcudia and Sierra Madrona Natural Park”. In each location (Table 1), prescribed burns were implemented during different days and years to ensure that a comparative analysis of the meteorological conditions could be conducted for the same characteristics of surface and crown fuels.

The climate of the six locations is characterized as Mediterranean, with cold and rainy winters and hot and dry summers. Summer precipitation is usually less than 20 mm per month. Prescribed burns are located between 735 m and 1,650 m above sea level, with slopes between 1% and 28%.

Maritime pine (*Pinus pinaster*) covers more than four million hectares in Europe (Fernandes and Rigolot, 2007). Maritime pine is the tree species most affected by wildfire in the Iberian Peninsula. As an example, 48% of the burned area in the 1990s consisted of *P.pinaster* forests (Fernandes and Rigolot, 2007). According to maritime pine importance, the vegetation of our six locations is dominated by *P. pinaster* reforestations in flat terraces. The dispersed understory is dominated by *Quercus ilex* L. and *Cistus* spp. in SLO, PUE, VIS, and LOZ, and by *Macrocholoa tenacissima* (L.) Kunth and *Erinacea* spp. in VEL and SIE.

### *2.2. Field sampling*

a) Pre-burning sampling

Prescribed burns were conducted over an 18-day period, spread over seven years (Table 1); 1–5 ha of forest area was burned daily. Forest fuel inventories were carried out in rectangular sampling units using a stratified random inventory. The inventory included a total of 69 sampling units (40 m × 50 m). Sampling units were staked out in advance to achieve the most similar fuel characteristics, preventing the edge effect of ways, streams, fuel-breaks, and other sampling units. Each sampling unit and its surrounding area were burned under the same fire ignition patterns (strip-heading, flanking, and spot-heading fires).

The field inventory collected data regarding canopy or ladder fuels and surface fuel. The canopy fuel inventory included variables such as stand density, diameter at breast height, stand height, canopy base height, and crown diameter. Basal area was easily calculated using the diameter at breast height and stand density. Two approaches were used to estimate canopy cover (proportion of the forest floor covered by the projection of the tree crowns) and canopy gaps. Firstly, the canopy cover was calculated as the sum of tree crown vertical projection divided by the area of the sampling unit. Vertical crown projection was modelled by a circular shape using orthogonal diameter measurements. The second approach was based on supervised classification of a binary image of the sampling unit (white and black). Canopy cover was estimated as the percentage of black pixels to the total area.

The characterization of surface fuel was conducted through line transect sampling (Rodríguez y Silva and Molina, 2012). The surface fuel load was destructively sampled from 1 $m^2$ square plots. At each sampling unit, the total fuel load, fuel depth, and dead fuel categories were identified by size or timelag (1 h-, 10 h- and 100 h-timelag), and live fuel load was identified by species. Samples of the different fuel categories (dead fuel by timelag and live fuel by species) were oven-dried (110ºC for 48 h until constant weight). The differences in weight before and after drying constituted the moisture content of the sample. Fuel load was expressed as dead fuel after the percentage of moisture was eliminated.

b) Monitoring of the prescribed burning

Fire behavior was monitored in each sampling unit using k-type thermocouples (with a wire diameter of 1 mm), a thermal camera, and photographic and video cameras. Spatiotemporal monitoring of fire behavior was carried out using rectangular sampling units. A matrix of 64-84 thermocouples was used for each sampling unit according to the total number of sampling units for each prescribed burn (Molina et al., 2021). Thermal camera and video cameras were installed with camera lens at right angle to fire spread. Temperature, relative humidity, and wind speed 2 m about ground were measured at 10 s intervals using a weather station (SkyWatch Geo 11). Average values of meteorological conditions for each sampling unit (Table 2) were used to perform scorch height model.

Even though this study does not attempt to provide an in-depth analysis of the surface fire behavior, the monitoring of the prescribed burning allowed us to estimate fire behavior parameters, such as the spread rate, flame length and flame residence time. While spread rate was estimated based on the distance between the thermocouples and the arrival times of the fire, flame length was estimated with the support of photographs and videos, using two video cameras (SONY HDR-CX240) and a thermal camera (FLIR ThermaCAM SC640). The fire-line intensity (Byram, 1959) was estimated based on the spread rate estimated by the thermocouples, the available fuel load, and the heat of combustion (Equation 1). Finally, flame residence time was calculated using thermocouples (seconds above 285ºC) due to its importance on the generation of a water repellent layer in Mediterranean ecosystems (García-Chevesich et al., 2019).

$$I = H * w * ros, \quad (1)$$

where, *I* is the fire-line intensity (kW/m), *H* is the heat of combustion (established at 18,500 kJ/kg for the Mediterranean vegetation), *w* is fuel load consumed per unit area that is calculated as the difference between the pre-burning fuel load and the post-burning fuel load (kg/m$^2$), and *ros* is the spread rate (m/s).

### c) Post-burning sampling

The stake-out of the sampling units required GPS and the use of treated wooden posts. Trees inside of each sampling unit were marked with permanent paint for easy identification by fuel consumption and scorch heigh inventories. Immediately after burning, the fuel consumption (t/ha) was estimated as the difference between the pre-burning fuel load and the post-burning fuel load. The post-burning fuel load was calculated as dry matter content using destructive square plots of 1 m$^2$, in a similar way to the pre-burning inventory. Before the prescribed burning, nail heads (12 cm) were set flush with the litter, next to the thermocouples. In this sense, the consumed fuel bed depth (cm) was also estimated as the difference between the pre-burning depth and post-burning depth with the help of the nails. The consumed surface fuel was classified by six categories (<15%, 15-35%, 35-50%, 50-75%, 75-90%, > 90%) based on the proposed severity field indicators for Mediterranean vegetation (Castillo et al., 2017).

Post-burning inventories were carried out in all plots where prescribed burnings were conducted after one month and after six months. These inventories included crown scorch height, crown scorched volume, bole charring, and tree mortality. While crown scorch height was identified by the yellowish-brown color of the needles using a Vertex IV-360 and telescopic milestone, bole charring was identified by the black color of the trunk using telescopic milestone and tape measures. Crown scorch volume (percentage of the pre-fire crown volume that was scorched) was visually estimated by viewing the tree from all sides. The scorch height, crown scorched volume, and bole charring were estimated by taking the average value of these parameters for all the trees measured in each sampling unit.

### *2.3. Scorch height and scorch volume modeling*

First, a test was carried out on some of the existing models of crown scorch height: Van Wagner (1973), Gould (1994), Botelho (1999), and Fernandes (2002). Subsequently, we tried to identify linear and non-linear models of crown scorch height based on the following independent variables: air temperature, relative humidity, wind speed, dead fine fuel moisture content, decomposed litter moisture content, foliar moisture content, total fuel load, fine fuel load (1-h timelag dead fuel), fuel consumption (%), consumed fuel bed depth, stand density, canopy closure, stand height, canopy base height, spread rate, flame length, fire-line intensity, flame residence time, and bole charring height. The ranges of the variables used are listed in Table 2. We incorporated new parameters to obtain a better fit using the SPSS software. Multivariable analysis requires a previous correlation study to remove the strongly correlated variables ($r > 0.7$). This research used 80% of the dataset for model generation (training data) and 20% of the dataset for validation (test data). The coefficient of determination ($R^2$), root-mean-square error (RMSE), and mean absolute error (MAE) were used to identify the most reliable models.

Classification and regression tree (CART) analysis was used to determine the crown scorch volume. This method identifies the best factors that can be integrated into a given scorch volume dataset. CART and their breakpoints. CART analysis results in a decision tree diagram utilizing the breakpoints of the independent variables. The criteria used for CART were 10-fold cross-validation, a value of 10 for minimum parent node, and a value of 3 for minimum child node.

### *2.4. Effects of canopy gaps in scorch height*

Twelve sampling units from the SLO were used to identify the effects of canopy gaps on scorch height. In this case, the prescribed fire was conducted over one day to homogenize the sample. The density of the control stand was 502(±10.65) trees/ha. Canopy gaps were characterized by the mean distance between the trees or the percentage reduction in stand density. Based on the field inventory, the gaps or tree distances ranged from 4.61(±0.19) m to 7.30(±0.37) m. The reduction in stand density was between 15.5% and 62.35% of the control stand density. Analysis of variance (ANOVA) was used to identify whether the gap size resulted in significant differences in the scorch height.

Some researchers (Cheney et al., 1992; Vélez, 2009) have already pointed out important differences in wind speed based on the topographic position on the slope: lower- and mid-slope (> 25% of distance to creek) and upper slope (< 25% of distance to creek). Wilcoxon test (non-normal data) was performed to identify significant differences between the presence of gaps in the lower- and mid-slope and upper-slope.

## **3. Results**

### *3.1. Scorch height and scorch volume modeling*

We measured a total of 1,255 trees, with scorch height varying between 0 and 9.2 m. For the existing models, RMSE ranged from 1.21 m to 4.94 m and MAE was between 1.39

m and 5.85 m (Table 3). The lower error was obtained using the Van Wagner model (equation 6), which includes three independent variables: fire-line intensity, wind speed, and air temperature.

The fire-line intensity or flame length, by themselves, were both good estimators of scorch height. In the classical potential modeling of the scorch height based on the fire intensity, the coefficient of determination reached a value of 0.73 (equation 8 in Table 4). The incorporation of air temperature and canopy base height (equations 10 and 11) increased the coefficient of determination, reducing the RMSE and MAE (Table 4) and improving the goodness-of-fit (Figure 2). Although flame length was the second variable in normalized importance for scorch height (Figure 3), flame length and fire intensity were strongly correlated variables ($r > 0.7$). In this sense, fire intensity exhibited the most normalized importance (100%), followed by temperature (34.6%) and canopy base height (32.7%) (Figure 3). All independent variables were positively related to crown scorch height (Table 4). It is important to note that a suitable model or correlation between scorch height and charring height was not observed.

Fire-line intensity (100%), canopy base height (91.2%), and temperature (33.6%) were the most important variables in explaining crown scorch volume (Figure 3). The CATR analysis identified three decision nodes and five terminal nodes (Figure 4). The first decision node depended on the fire intensity, showing its high importance. In prescribed burns with fire intensities higher than 362.8 kW/m, scorch height differences were found based on air temperature. When the temperature was higher than 18.8 ºC, significant differences were observed in the crown scorch volume (Figure 4). Therefore, canopy base height became the most important variable when the fire intensity was higher than 362.8 kW/m and the temperature was higher than 18.8 ºC.

### *3.3. Effects of canopy gaps in scorch height*

The scorch height showed a significant increase ($t = - 2{,}291$, $p < 0.05$) for canopy gaps that were characterized by a distance greater than 6.68 m between the trees and a reduction of 56.07% compared with the control stand density. In the case of canopy gaps of a smaller size, there was an increase in the scorch height; however, it was not significant. There was a positive logarithmic trend, reaching a maximum increase of 3.54 m for a gap with 7.22 m between the trees. This maximum scorch height was associated with a 62.35% reduction of trees in the upper slope. Furthermore, significant differences ($Z = -2.12$, $p < 0.05$) were observed between similar gaps located in the upper slope and in the mid- and lower slopes. Two predictive equations for the increase in the scorch height were obtained based on the topographical position of the gap.

$$y_1 = 6.822 \ln(x) - 10.36 \qquad (R^2 = 92.2\%) \qquad (2)$$

$$y_2 = 1.595 \ln(x) - 2{,}278 \qquad (R^2 = 90.2\%), \qquad (3)$$

where, $y_1$ is the increase in the scorch height in the upper slope (m), x is the distance between the trees (m), and $y_2$ is the increase in scorch height in the mid- and lower slopes (m). When a canopy gap is observed, this increase ($y_1$ or $y_2$), which is based on its topographic location, should be added to the mean scorch height.

## 4. Discussion

Prescribed fires play a significant role in reducing the fuel load and the risk of forest fires (Knapp et al., 2011; Stephens et al., 2012; Fernandes, 2015; Molina et al., 2018; Morgan et al., 2020). In pine stands, fuel load reduction lowers the probability of a surface fire transitioning into a crown fire (Van Wagner, 1977; Agee and Skinner, 2005; Roccaforte et al., 2008). However, excess fire-line intensity can cause damage to the trees (Reinhardt and Ryan, 1989; Zeleznik and Dickmann, 2004; Espinosa et al., 2020). The scorch height is an easy variable for monitoring the burning effects or damages on trees (Fernandes et al., 2000). One study (Burrows, 1997) has reported that a scorch height above 6 m could cause damage to the trees. The scorch height observed in our sampling units was greater than this threshold, reaching a maximum of 9.2 m. In this sense, some indicators or estimators of the scorch height should be integrated in the “burn window”.

Equation 8 with two independent variables (fire intensity and air temperature) achieved a reliable fit for scorch height in the study area. On the one hand, the relationship between scorch height and fire intensity has already been explored by other researchers (Van Wagner, 1973; Fernandes, 2002). The fire intensity depends directly on the availability of fuel and the season of the year in which the burning occurs (Burrows, 1997). Some researchers have tried to replace the fire-line intensity with flame height (Gould, 1994) or flame length (Fernandes, 2002) because these variables are easier to identify in situ. Cheney et al. (1992) reported that the scorch height was approximately nine times higher than the flame height under dry fuel conditions. This result is consistent with our findings, which indicated that the scorch height was 9.18 (± 2.93) times higher than the flame length. On the other hand, air temperature is exponentially related to scorch height, which increases rapidly at temperatures above 25 °C (Cheney et al., 1992).

The improvement observed in the scorch height equations (10 and 11) with the incorporation of canopy base height can help to mitigate the ecological impacts associated with tree mortality. The positive relation between the scorch height and the canopy base height was similar to that obtained by Botelho (1999) for *P. pinaster*. This relation may be due to the structure of the foliage and the arrangement of the branches of *P.pinaster* and, consequently, the convective heat transfer (Michaletz and Johnson 2006a). In this sense, this study only considered reforested *P.pinaster* stands, because of the high variability in the canopy architecture of natural stands (Molina et al., 2014). Further studies should provide additional information of the scorch height in other species with different canopy characteristics.

The highest differences in observed versus predicted values of scorch height (Figure 2) were mainly associated with rainy seasons (Espinosa et al., 2020) and plots that had a concentration of masticated fuel load (Knapp et al., 2011). Some studies (Van Wagner, 1973; Botelho, 1999; Fernandes, 2002) have suggested that the scorch height is related to wind speed. While wind speed had a negative effect in the equations developed by some authors (Botelho, 1999; Fernandes, 2002), other researchers (Van Wagner, 1973) showed a positive effect in the equation. The positive effect can be expected by the effect of turbulence generated by the fire (Michaletz and Johnson, 2006b; Alexander and Cruz, 2012), as well as to the effect of no wind on a vertical fire plume. However, wind speed did not have either a negative or positive significant effect in our equations (8, 9, 10 and 11). This lack of correlation could be associated with the limited wind speed range (0–9.5 km/h) of our prescribed burn windows.

The scorch height showed great variability between prescribed burns and even between trees within the same sampling unit. In this sense, no significant relationship was found between the charring height and the scorch height for our dataset. This fact may be associated with the higher load and dryness of the surface fuel in sheltered areas close to the boles (Wotton et al., 2005). Additionally, some studies (Alexander and Cruz, 2012) have shown significant differences in scorch height based on the fire ignition pattern. Spatial ignition patterns can increase or decrease the spread rate, flame length and fire intensity (Molina et al., 2021) and, therefore, the scorch height. Further studies should also consider that the influence of fire ignition pattern in the scorch height due to fire interaction (Finney and McAllister, 2011). Other limitation of the model developed in this study is that it did not consider ignition lines longer than 50 m. Therefore, more research needs to be conducted to achieve a trade-off between fire intensity and the impacts of fire on trees.

Many studies have attributed the probability of tree survival to the scorch volume (Methven, 1971; Swezy and Agee, 1991). The scorch volume observed in our study varied significantly, ranging from 0% to 88.3%. In many trees, the scorch volume was higher than 68%, which is the volume recommended for the survival of *P. pinaster* in the Iberian Peninsula (Vega et al., 2011). In our prescribed burns, the scorch volume was especially high in prescribed burns with fire intensity higher than 362.8 kW/m, flame length higher than 1.15 m, and air temperature higher than 18.8ºC. If it is necessary, fire managers could reduce scorch height based on a modification of the prescribed burn windows. In this sense, the season of the burning and, therefore, the air temperature could have been modified to reduce the scorch height. It must not be forgotten that the burn window requires the consideration of both the surface fuel and the scorch height.

The wind speed used for the models was 2 m above ground in-forest, which is the one used by other existing models (Van Wagner, 1973). The drag coefficient (relation between wind speed 2 m above ground in-forest and wind speed 10 m above ground in the open) ranged between 0.16 and 0.55 for our prescribed burns, with the values closest to 0 associated with the lower slopes. These values are consistent with those described in previous studies, which ranged from 0.15 to 0.4 (Cheney et al., 1992). Some researchers (Duan et al., 2008) have reported increases of up to 1.82 times the wind speed (with respect to the control stand density) in canopy gaps due to the Venturi effect. In addition, the 2 m in-forest wind speed increased by 2.66–3.75 times between the upper slope and the mid- and lower slope when the 10 m wind speed in the open was between 5–10 km/h (Cheney et al., 1992).

The scorch height is directly related to the gap size and its topographic position on the slope (Latif and Blackburn, 2010). In our study, the differences in scorch height were significant in the case of gaps with distances of 6.68 m between the trees, that is, canopy gaps between 38.64 $m^2$ and 44.62 $m^2$. However, it is also necessary to highlight the significant differences in the scorch height based on the topographic position of the gap. The scorch height increased from 0.33 m (for gaps with 5 m spacing between trees) to 2.08 m (for gaps with 7 m spacing between trees) between the upper and lower slopes (Figure 5). This phenomenon may be due to the Venturi effect created by the canopy opening and the generation of the convective plume, mainly in the upper slope.

Given the uncertain conditions and the existing administrative limitations in southern Europe (Fernandes et al., 2013; Fernandes, 2015), the use of prescribed fires requires high efficiency. One of the main demands of fire managers is knowledge of the fire intensity, which would allow an efficient reduction in surface fuel without causing damage to the trees (Fernandes and Loureiro, 2010; Fernandes et al., 2012). The fire intensity can be managed based on the burning season and the fire ignition pattern. The correct implementation of the prescribed burn window is required for both surface fuel reduction and mitigation of scorch height and scorch volume. However, scorch height equations are standard, and managers should pay attention to the presence of gaps in the upper slope. The results of this study introduce a novel approach. However, the proposed method needs to be refined further by experimenting with a higher range of fuel availability and a wider number of woodland ecosystems. The configuration of the branches, physiology, morphology, and bark of each species modifies the convection heat transfer to the canopies (Michaletz and Johnson, 2006a) and, consequently, the scorch height and scorch volume.

## Conclusions

Prescribed fire is a useful tool based on its demonstrated fire hazard reduction benefits and reduced costs with respect to mechanical fuel treatments. Prescribed fire requires both the reduction of surface fuel load and the minimization of scorch height on trees. Despite fire behavior and canopy architecture limitations, the proposed scorch height equation plays a keystone role in the implementation and improvement of prescribed burn windows. Fire intensity, air temperature, and canopy base height were identified as the most important variables for scorch height and scorch volume modeling. However, large differences were observed inside the same sampling unit because of the presence of gaps in upper slopes. Before burning, fire manager can test scorch height in lower- and upper slopes and with and without canopy gaps presence. If it is necessary, fire managers could reduce scorch height based on a modification of the prescribed burn windows. Therefore, managers seek criteria and tools, like this, which allow a simple evaluation of potential scorch height under different meteorological and fire ignition scenarios.

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Figure 1. Study area location and sampling design of one location (VIS)

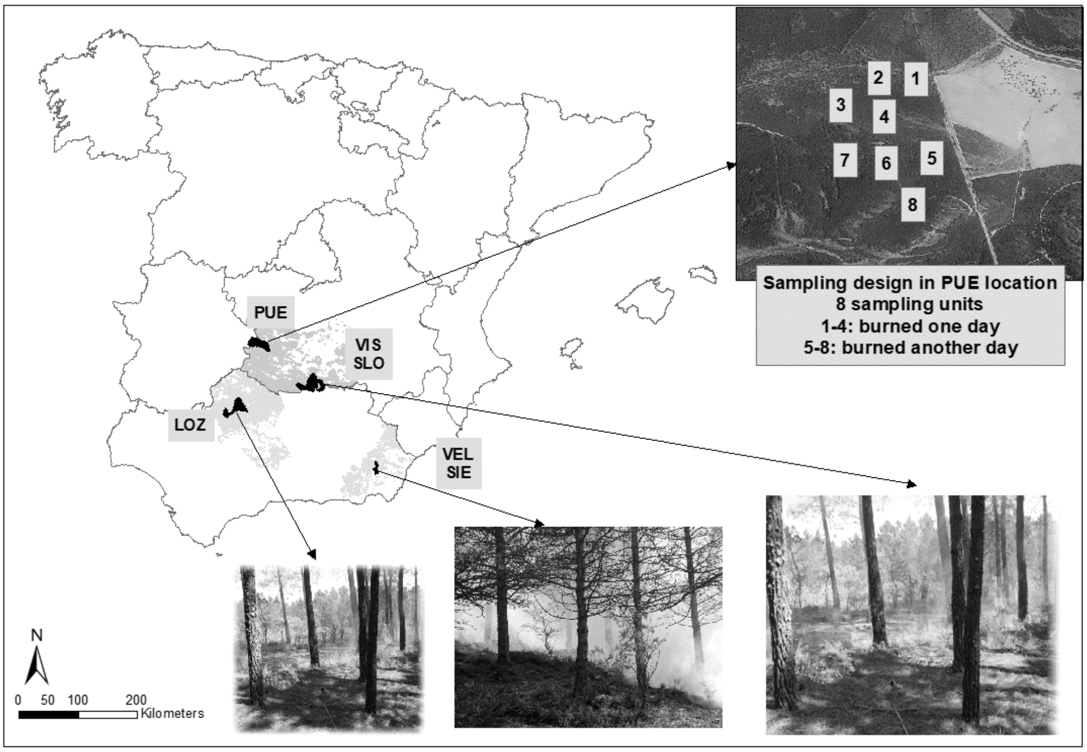


Figure 2. Sampling units of observed versus predicted values of scorch height using Equation 10

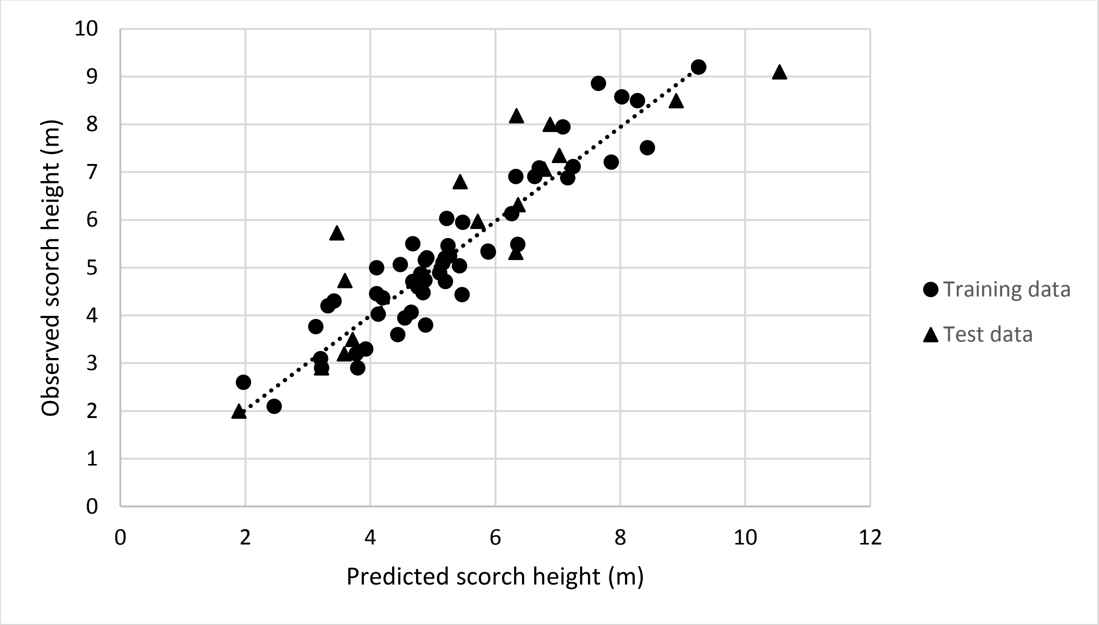
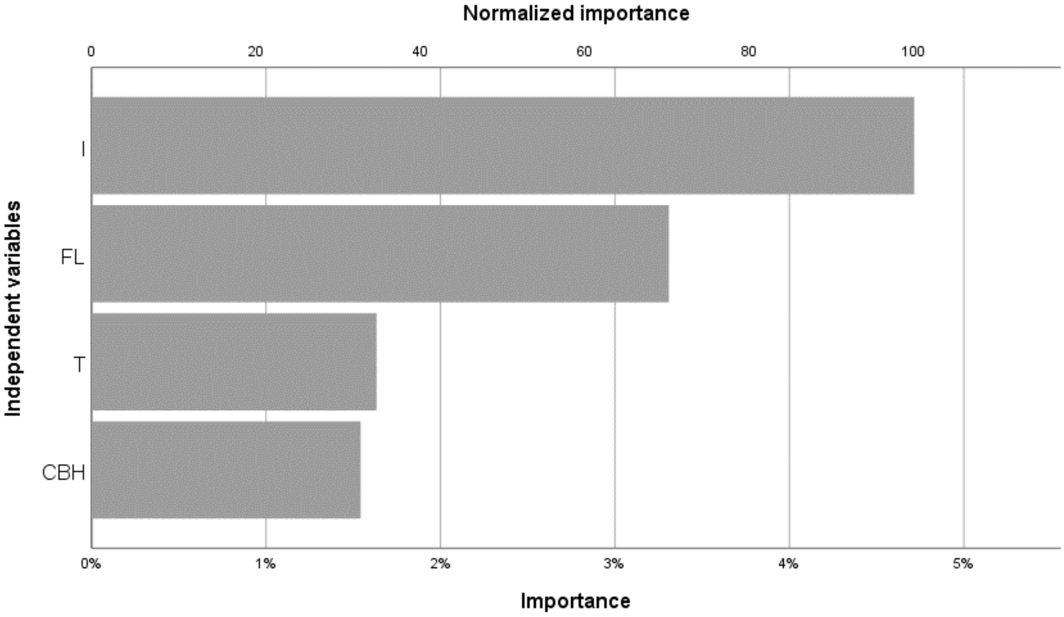
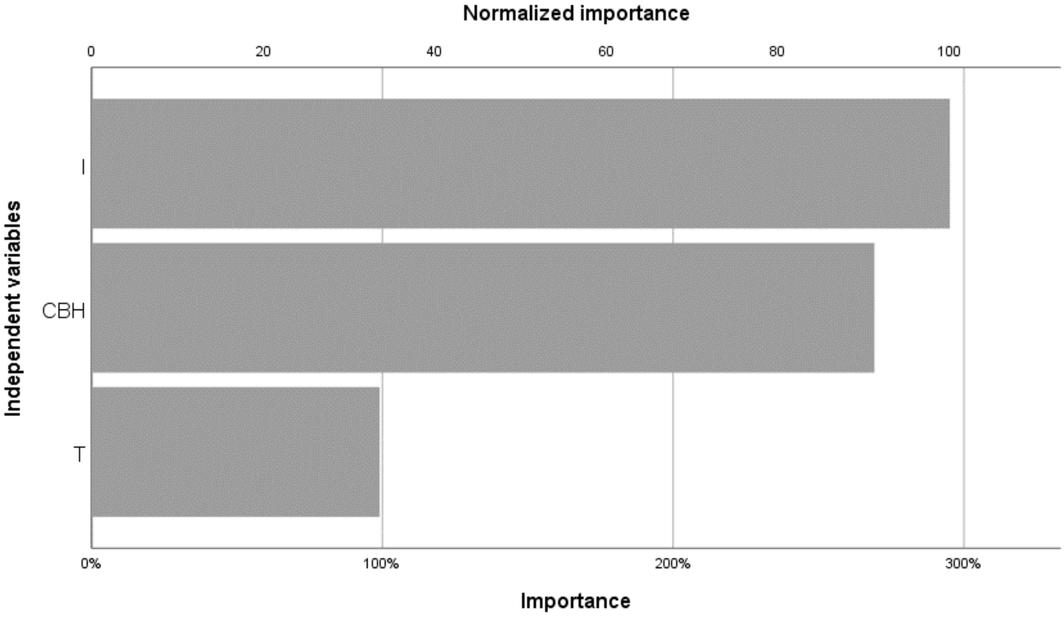


Figure 3. Normalized importance of the independent variables on (a) scorch height model and (b) scorch volume

**a)**



**b)**



Note: I is the fire intensity, FL is the flame length, T is the air temperature, CBH is the canopy base height

Figure 4. Decision tree for crown scorch volume based on fire intensity, air temperature and canopy base height

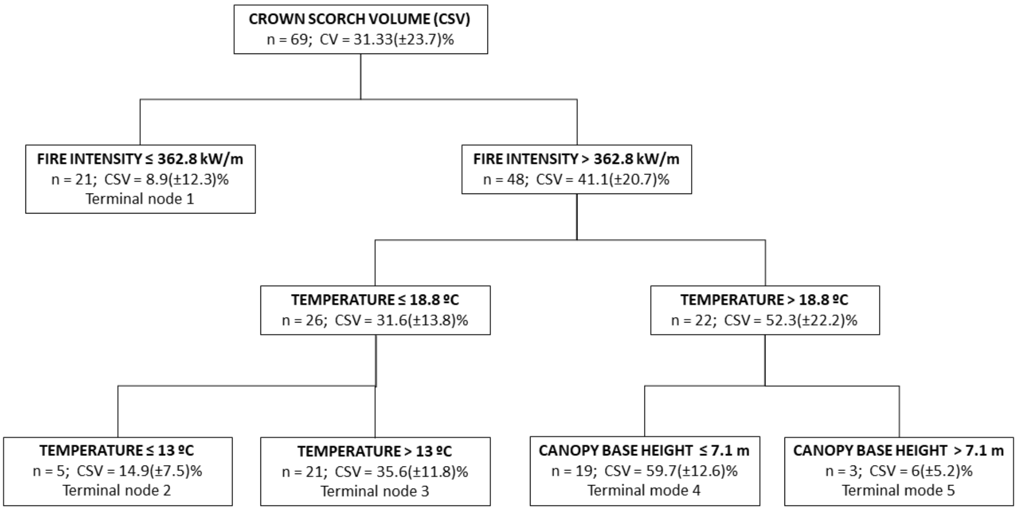


Figure 5. Comparative analysis of the scorch height based on the topographic position and the distance between trees

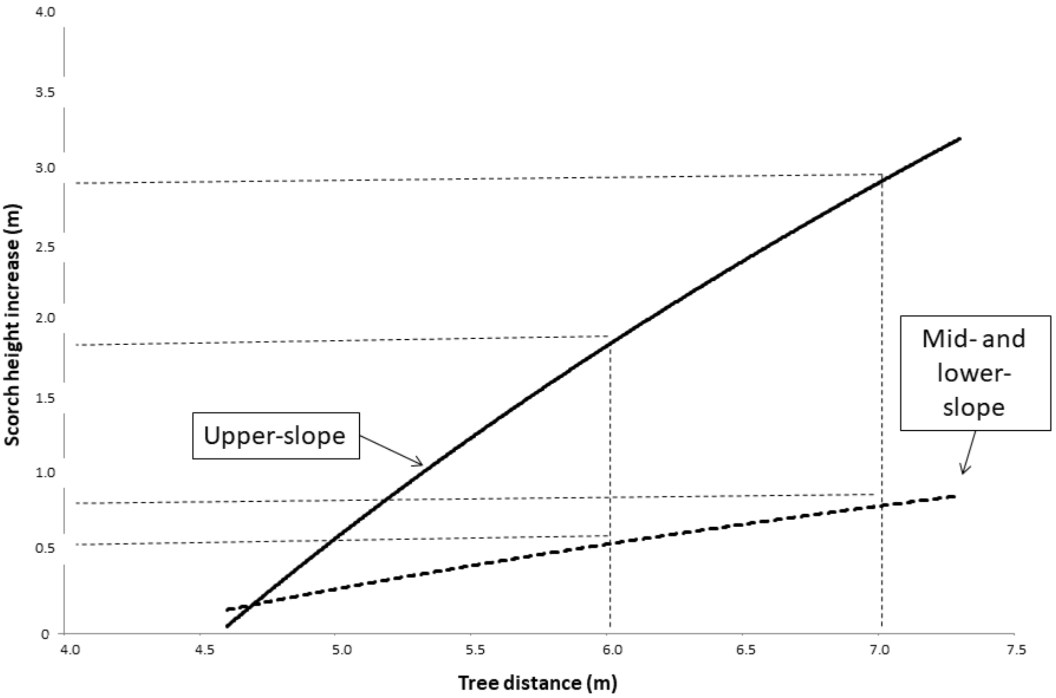


Table 1. Characterization of the prescribed burn in the six study locations

| Location | VEL | SIE | SLO | PUE | VIS | LOZ |
|---|---|---|---|---|---|---|
| Location (ETRS89 30N)* | X: 555703<br>Y: 4119852 | X: 555721<br>Y: 4123096 | X: 428100<br>Y: 4252922 | X: 371900<br>Y: 4329600 | X: 462758<br>Y: 4251550 | X: 462758<br>Y: 4251550 |
| Area burnt (ha) | 1 | 3.55 | 6.6 | 7.5 | 15.3 | 12.1 |
| Number of burning days | 1 | 2 | 3 | 2 | 3 | 7 |
| Number of sampling units | 2 | 11 | 24 | 8 | 17 | 19 |
| Altitude (m) | 1751 | 1562 | 1090 | 780 | 1094 | 735 |
| Fine dead fuel moisture (%) | 13.5-14 | 9.2-11.3 | 9.9-14 | 13.7-14.8 | 8.2-12.2 | |
| Wind speed (km/h) | 3-5 | 1.5-8 | 2.5-5.9 | 3-6 | 4-14.5 | |
| Fuel load (t/ha) | 28.55(±7.50) | 25.51(±7.67) | 29,48(±7.37) | 16.59(±3.39) | 21.9(±8.61) | |
| Fire ignition patterns | Strip heading fire (1 sampling unit), flanking fire (1 sampling unit) | Strip heading fire (4 sampling units), flanking fire (4 sampling units), spot heading fire (3 sampling units) | Strip heading fire, flanking fire, spot heading fire | Strip heading fire (6 sampling units), flanking fire (2 sampling units) | Strip heading fire, flanking fire, spot heading fire | Strip heading fire, flanking fire, spot heading fire |

Table 2. Range of the different independent and dependent variables

| Variable | Range |
|---|---|
| Response variables | |
| Scorch height (m) | 0 – 9.2 |
| Scorch volume (%) | 0 – 88.3 |
| Predictor variables | |
| Meteorological variables | |
| Temperature (ºC) | 10.7 – 26 |
| Relative humidity (%) | 20.8 - 85 |
| Wind speed 2 m above ground (km/h) | 0.50 – 9.5 |
| Fine dead fuel moisture (%)* | 8.2 – 14.8 |
| Decomposed litter moisture content (%)* | 28.6 – 76.9 |
| Foliar moisture content (%) | 91.7 – 134.8 |
| Fuel characteristics | |
| Total fuel load (t/ha) * | 13.1 – 32.3 |
| Fine fuel load (t/ha) * | 8.8 – 25.41 |
| Stand density (trees/ha) | 288 - 875 |
| Canopy cover (%) | 40 - 100 |
| Stand height (m) | 6.5 – 14.1 |
| Canopy base height (m) | 1.62 – 8.1 |
| Fire behavior | |
| Spread rate (m/min) | 0.1 – 4.3 |
| Flame length (m) | 0.2 – 1.8 |
| Fire-line intensity (kW/m) | 55.8 – 1609 |
| Flame residence time (s) | 62 - 260 |
| Fuel consumption (%) | 63.5 – 95 |
| Consumed fuelbed depth (cm) | 2.45 – 5.68 |
| Charring height (m) | 0.4 – 4.2 |

Note:

Fine dead fuel was related to 1-hour timelag dead fuel (less than 0.25 inch in diameter).

Decomposed litter was related to the organic horizon found beneath the litter characterized by accumulation of partly decomposed organic matter.

Fuel load was calculated as the sum of dead fuel load (1-, 10- and 100-h timelag) and live fuel (leaves and fine stems).

Table 3. Test of the existing crown scorch height models.

| Equation | Existing model | Source | MAE | RMSE |
|---|---|---|---|---|
| 1 | $h_s$= 0.1483 $I^{2/3}$ | Van Wagner, 1973 | 3.27 | 3.94 |
| 2 | $h_s$= 0.125 $I^{0.724}$ | Fernandes, 2002 | 4.94 | 5.85 |
| 3 | $h_s$= 4.4713 $I^{2/3}$/(60-T) | Van Wagner, 1973 | 1.62 | 2.39 |
| 4 | $h_s$=5.232$H^{0.756}$ | Gould, 1993 | 1.86 | 2.10 |
| 5 | $h_s$= 0.544+0.102 T – 0.28$U^2$+1.053CBH | Botelho, 1996 | 2.53 | 3.0 |
| 6 | $h_s$=0.74183 $I^{7/6}$/(0.02557 I+0.02143$U^3$)$^{1/2}$ (60-T) | Van Wagner, 1973 | 1.12 | 1.39 |
| 7 | $h_s$= 3.770L+0.171T-0.231U | Fernandes, 2002 | 1.21 | 1.42 |

Note: hs is the scorch height (m), I is the fire intensity (kW/m), T is the air temperature (ºC), H is the flame height (m), U is the wind speed (m/s), CBH is the canopy base height (m).

Table 4. Scorch height models for our study area

| Equation | Model form | Parameter | Estimation | Standard error | $R^2$ | MAE | RMSE |
|---|---|---|---|---|---|---|---|
| 8 | $h_s=a\ I^b$ | a | 0.215 | 0.065 | 0.73 | 0.87 | 1.24 |
| | | b | 0.510 | 0.046 | | | |
| 9 | $h_s=a\ FL^b$ | a | 6.931 | 0.205 | 0.67 | 0.93 | 1.24 |
| | | b | 0.556 | 0.053 | | | |
| 10 | $h_s= a * I^b * T^c * CBH^d$ | a | 0.072 | 0.017 | 0.89 | 0.61 | 0.83 |
| | | b | 0.437 | 0.033 | | | |
| | | c | 0.501 | 0.070 | | | |
| | | d | 0.102 | 0.036 | | | |
| 11 | $h_s= a * FL^b * T^c * CBH^d$ | a | 1.567 | 0.547 | 0.76 | 0.75 | 0.92 |
| | | b | 0.428 | 0.055 | | | |
| | | c | 0.505 | 0.117 | | | |
| | | d | -0.017 | 0.050 | | | |

Note: hs is the scorch height (m), I is the fire intensity (kW/m), FL is the flame length (m), T is the air temperature (ºC), CBH is the canopy base height (m).

**Declaration of interests**

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

# Author Statement

The first author contributed to the methodology, formal analysis, data curation and original draft preparation. The second author participated in conceptualization, formal analysis, data curation and writing—review. The last author contributed to the methodology, formal analysis, supervision and funding acquisition.

## Appendix A. Photographs of the different study locations.

Prescribed fire implementation in the different sampling units

Scorch height in the mid slope (left image) and in the upper slope (right image) in the same prescribed burn

Scorch height differences based on the presence of canopy gaps in the upper slope