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Modeling post-fire mortality of Turkish pine (*Pinus brutia* Ten.)

Coşkun Okan Güney [a,*], Aylin Güney [b], Abdullah Sarı [c], Ali Kavgacı [d], Kevin C. Ryan [e], Sharon M. Hood [f]

[a] Aegean Forestry Research Institute, Department of Forest Fires, Izmir 35430, Turkiye
[b] Izmir Katip Çelebi University, Faculty of Forestry, Izmir 35620, Turkiye
[c] Southwest Anatolian Forestry Research Institute, Department of Forest Fires, Antalya 07010, Turkiye
[d] Burdur Mehmet Akif Ersoy University, Burdur Food Agriculture and Livestock Vocational School, Burdur 15030, Turkiye
[e] FireTree Wildland Fire Sciences, Missoula, MT 59808, United States
[f] US Department of Agriculture, Forest Service, Rocky Mountain Research Station, Missoula, MT 59808, United States

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ABSTRACT

Turkish pine (*Pinus brutia*) is a widely distributed species in fire-prone regions of the eastern Mediterranean, where it is of economic and ecological importance. After wildfires, damaged trees are usually salvage logged out of concern that fire-injured individuals will eventually die. While fire is a major cause of Turkish pine mortality, the species has traits, such as thick bark, that should confer some resistance to low-intensity fire. The aim of this study is to develop post-fire tree mortality models for Turkish pine to support post-fire management decisions. We selected 510 Turkish pine trees from four wildfires that occurred in the Mediterranean region of Türkiye in 2018 and 2019. Only fire-damaged trees that had initially survived the fires were selected. We measured tree diameter, height, and bark thickness and fire-caused injuries (crown volume scorched, bark char height, bark char index, cambium kill rating, and ground char index) within two months after fire. Stem-related variables were measured at three different heights (0, 50, and 130 cm). We then quantified delayed mortality for two years after each fire and developed mixed effects logistic regression models to predict probability of mortality. Most Turkish pines (84 %) survived, with the majority of mortality occurring during the first year post-fire. Crown volume scorched and stem damage variables were the most important predictors of mortality. Models were selected based on their explanatory power and practical use in the field. Among these, the most explanatory model includes crown volume scorched and bark char index measured at 0 cm stem height. The suggested model for use in forestry includes crown volume scorched and diameter at breast height. Some trees were able to survive and flush new foliage during the first season after fire despite 100 % crown scorch due to low bud kill. Our results show that Turkish pine can survive fire when stem injury is low. The mortality models can assist managers in making more evidence-based decisions for post-fire management and developing more ecologically sustainable post-fire management operations.

1. Introduction

Wildfires drastically alter forest structure and composition by reducing plant biomass, affecting long-term forest dynamics and hydrological and biogeochemical processes (Catry et al., 2013; Keeley et al., 2012). In many regions across the world, such as the Mediterranean Basin, wildfires are the primary cause of tree mortality (Pausas and Keeley, 2009), resulting in forest area loss and subsequent forest management efforts to restore fire-affected areas. Tree mortality after fire is a common measure of fire severity (Keeley, 2009), with long-term consequences on ecosystem recovery and function (Huffman et al., 2017; Johnston et al., 2019). Understanding how trees respond to fire and accurately predicting fire-caused tree mortality is essential to inform pre- and post-fire management decisions, prescribed fire planning, risk assessment, and conservation efforts (Woolley et al., 2012).

Post-fire tree mortality depends on factors related to fire-caused injury, individual tree characteristics, edaphic-climatic conditions, and additional biotic (e.g., pest infestation) and abiotic stresses (Bär et al., 2019; Hood et al., 2018). Fire can cause injuries to tree stems and crowns, and these effects have been measured numerous ways. Bark

* Corresponding author.
E-mail address: coskunokanguney@ogm.gov.tr (C.O. Güney).

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char height, for example, correlates with fire intensity and flame size and provides information on potential injury to the underlying cambium of the main stem and/or foliage (Catry et al., 2013; Finney and Martin, 1993; Regelbrugge and Conard, 1993; Thies et al., 2006; Woolley et al., 2012). Morphological characteristics most commonly used to describe resistance to fire are bark thickness, stem diameter and tree height (Brando et al., 2012; Catry et al., 2009; Fernandes et al., 2008; Ryan et al., 1988; Woolley et al., 2012). These traits are species-specific and vary over space and time (Pellegrini et al., 2017; Stevens et al., 2020). Post-fire responses also depend on the physiological state of the trees at the time of the fire, such as carbohydrate and nutrient reserves needed for successful recovery (Moreira et al., 2012; Steuter and Whelan, 1997).

To accurately predict post-fire tree mortality, models are needed that describe the probability of tree death or survival. These models can be used for a variety of applications, such as post-fire salvage logging or for planning prescribed burns (Hood et al., 2018). As trees are usually recorded as either dead or alive (binary outcome), logistic regression models have been the most widely used tool in post-fire mortality studies. These models are typically based on predicted or observed fire-caused tree injuries to estimate the probability of tree mortality or survival over a given time period (usually 2–5 years) (Woolley et al., 2012). These models make it possible to determine variables most closely associated with tree mortality and/or to predict tree mortality at the stand-level as accurately as possible.

Numerous models have been developed to predict post-fire mortality for many tree species and regions following wildfire and prescribed fire (Butler and Dickinson, 2010; Fowler and Sieg, 2004; Hood and Bentz, 2007; Hood et al., 2010; Rigolot, 2004). The explanatory variables that are most commonly used in these models are measures of crown (e.g., crown volume scorched) and stem (e.g., bark char height) injury that are easily observable (Peterson, 1985; Ryan, 1982b; Stephens and Finney, 2002). Crown injury was identified as the primary cause of mortality after fire in most conifers (Hood et al., 2018; Varner et al., 2021). In particular bud mortality is a more critical issue than foliage mortality, as portions of the crown with killed meristems cannot recover (Ryan, 1982a; Varner et al., 2021). Stem injury may include impacts to phloem, cambium and functional xylem (Bär et al., 2019). Other explanatory variables often included are indirect assessments of actual injury, such as bark char height and bark char severity (Ryan, 1982b; Thies et al., 2006), or resistance to heating, such as stem diameter and bark thickness (Hood et al., 2007; Ryan and Reinhardt, 1988); however, some models include direct quantification of stem injury, such as cambium kill rating (Hood et al., 2010; Vega et al., 2011). Since small differences in bark thickness result in large differences in fire resistance, bark thickness has become a widely used morphological variable to explain fire resistance (Bond and Van Wilgen, 1996; Pausas, 1997; Rigolot, 2004).

Models that include both variables of stem and crown damage have a higher prediction accuracy (Woolley et al., 2012). Overall, these models provide a basis for a simple and rapid prediction of tree mortality. In addition to predicting tree or stand-level mortality, models can improve our understanding of fire effects on post-fire plant community structure and composition (Agee, 1993), and thus ecosystem processes and function (Regelbrugge and Conard, 1993; Woolley et al., 2012). This is particularly important in ecosystems with recurring wildfires, such as the Mediterranean Basin, where studies of post-fire responses in terms of fire and plant characteristics are rare (Catry et al., 2013).

Pine species are an important component of forests and wooded areas in the Mediterranean region (Moreno et al., 2021). After shrublands, pine forests are the second most burned vegetation type (Dimitrakopoulos et al., 2011). In the lower and middle elevation ranges, Turkish pine (*Pinus brutia* Ten.), Aleppo pine (*Pinus halepensis* Mill.), and maritime pine (*Pinus pinaster* Aiton) are typically subjected to high-intensity crown fires within the natural fire regime. In contrast, at upper elevations, species such as black pine (*Pinus nigra* J.F.Arnold) are mainly exposed to low-intensity surface fires (Ne'eman and Arianoutsou, 2021). Following high-intensity fires, Turkish pine, Aleppo pine and maritime pine show a mass renewal and subsequently re-dominate the vegetation due to their serotinous cones (Pausas et al., 2002, Kazanis and Arianoutsou, 2004, Tavşanoğlu and Gürkan, 2009). Changes in the natural fire regime, especially the increase in fire frequency resulting from human activity and climate change, have a negative impact on the re-occurrence of these species and cause ecosystem degradation (Pausas et al., 2004). As they are all are obligate seeders, they require a sufficient crown seed bank for post-fire regeneration. Turkish pine forests, which represents the most characteristic Mediterranean-type ecosystem in the Eastern Mediterranean Basin, are also adversely affected by alterations in the fire regime, resulting in degradation (Kavgacı et al. 2016). This demonstrates the need for new approaches to forest management that are compatible with the changing conditions.

In Türkiye, the vast majority of forest fires occur in Turkish pine forests, which are mainly found in the Mediterranean and Aegean regions (Kavgacı and Tavşanoğlu, 2010). It is the most economically important tree species in Türkiye, accounting for 23.8 % of the total forest area (Turkish General Directorate of Forestry, 2022). This species is a relatively fire adapted-tree as it shows traits that confer resistance and resilience to fire: relatively thick bark, serotinous cones, self-pruning branches, and hard seed coats (Kavgacı et al., 2016; Kazancı, 2021; Keeley and Zedler, 1998; Tavşanoğlu and Gürkan, 2004). However, in Türkiye, forest managers generally assume that Turkish pine trees affected by a wildfire, even if the fire injury is very low, will die (personal observation). It is further believed that trees that sustain partial post-fire injuries are prone to bark beetle attacks, which can lead to outbreaks and the subsequent spread to unburned, healthy trees. Therefore, the vast majority of trees that show signs of fire damage are felled soon after fires and concern about tree mortality is one of the reasons why prescribed burning is not used as a forest management practice in Türkiye.

The objective of this study was to develop post-fire tree mortality models for Turkish pine for use in post-fire management. These models can be used to evaluate options for the management and conservation of valuable areas (e.g., reforestation areas, natural habitats) affected by wildfire (Regelbrugge and Conard, 1993; Von Gadow, 2000). Secondly, we examined morphological characteristics and stem height to assess which ones most influenced post-fire mortality. On the basis of these models, tree characteristics and fire-injury variables can be determined to inform decision making and post-fire planning to ensure that trees with a high probability of survival are identified immediately after fire for possible retention.

2. Materials and methods

2.1. Study sites

For this study, four wildfires (two in 2018 and two in 2019) were selected within the Antalya Regional Directorate of Forestry in Türkiye that had surviving trees within the burn perimeter (Fig. 1). The burned area of the fires varied between 4 and 46.9 ha (Table 1). Of the four selected wildfires, the Serik fire was the only one that was a surface fire only, while all other fires were both surface and crown fires. Turkish pine was the dominant tree species at all sites.

2.2. Field sampling

Sampling was carried out within two months following each fire. We selected all trees in the burned area with crowns not completely consumed. We also selected some trees within the burn perimeters that had no visible signs of fire-injury (i.e., no bark char or crown scorch) to ensure we had a wide range of fire severities in our sample for model development. Each tree was tagged with a number and the following parameters were recorded: tree height, stem diameter, bark thickness, crown volume scorched, bark char height, bark char severity, cambium

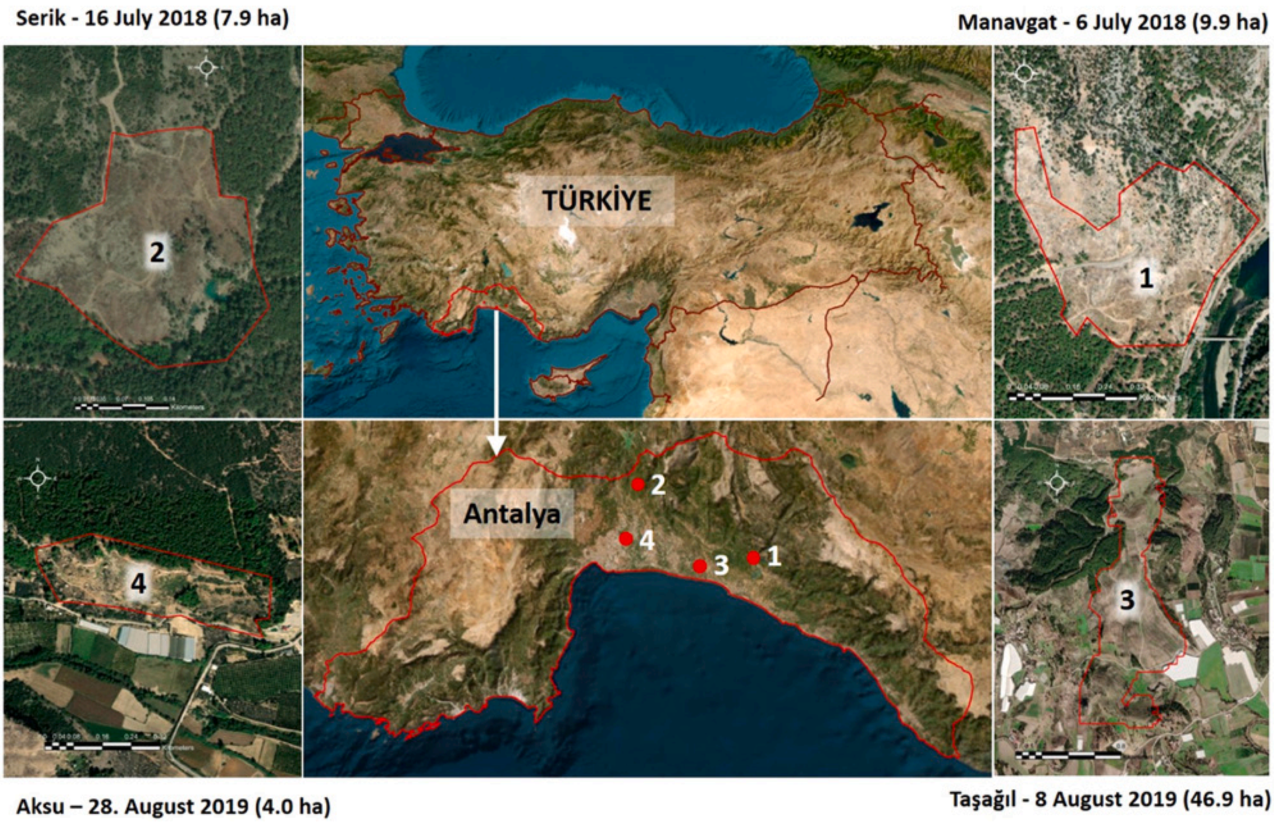

Fig. 1. Map showing the location and perimeters of the four wildfires selected for this study within the Antalya Regional Directorate of Forestry, Türkiye.

Table 1
Site characteristics of the selected wildfires and the number of trees selected at each site with the number of dead trees two years post-fire.

Fire	Date	Area (ha)	Location (UTM 36 N WGS84)		Altitude (m)	Aspect	Slope (%)	Number of trees	
			E	N				Selected	Dead
Manavgat	6 July 2018	9.9	368680	4085271	90–150	South-east	40	65	14
Serik	16 July 2018	7.9	314185	4119068	240–265	South-east	30	235	18
Taşağıl	8 August 2019	46.9	342999	4082032	100	South	42	104	28
Aksu	28 August 2019	4.0	309052	4094313	90	-	0	106	20

kill rating, and ground char severity. Bark thickness and stem diameter (diameter at breast height= DBH) are typically measured at 130 cm by forest operators and in studies. In contrast, stem injury variables, such as cambium kill rating and bark char severity, are normally recorded close to the ground line (0 cm). We therefore measured stem diameter, bark thickness, bark char severity, and cambium kill rating at three different stem heights - 0 cm (close to the ground line), 50 cm, and 130 cm (red arrows in Fig. 2A) - to determine at which stem height fire-injury or morphological variables would give the most accurate result in the models.

Bark char height (white arrows in Fig. 2A) in four quadrants oriented in the cardinal directions of each stem (Fig. 2E) was recorded and then averaged (BCH_{mean}). Crown volume scorched (CVS, %) was determined by visually assessing the volume of pre-fire crown foliage that was killed by either direct flame contact or convective heating (Hood and Bentz, 2007; Ryan, 1982a). Bark char and ground char severities were visually assessed for the same four quadrants of the stem as char height (Fig. 2E) as unburned (0), light (1), moderate (2), or deep (3) (Hood et al., 2008; Ryan, 1982b; Ryan et al., 2012). Bark char was considered as light (1) when bark was not completely blackened but the edges of the bark plates were charred, as moderate (2) when bark was uniformly black but bark characteristics still discernable, and deep (3) when outer bark species characteristics were lost. Ground char was considered as light (1) when litter was charred but only partially consumed and the surface appeared black, as moderate (2) when litter was mostly or entirely consumed, leaving coarse, light-colored ash, and as deep (3) when litter and duff were completely consumed leaving fine white ash. The four ground char codes and four bark char codes for each quadrant were summed and divided by 4, creating indices with possible ranges from 0 to 3 (ground-char index (GCI) and bark-char index (BCI)) (Hood and Bentz, 2007). GCI and BCI ranged between 0 and 2 for our sampled trees.

Cambium was sampled in the center of each quadrant (Fig. 2D) using a small increment puncher (Trephor ©, Fig. 2B). This procedure caused less damage to the tree than removing larger parts of the bark. The status of the cambium (dead or live) was determined visually and tested by application of ortho-tolidine hydrogen peroxide solution (Ryan, 1982b). The solution tests for the peroxidase enzyme and causes a blue reaction (Fig. 2C) when applied to live plant tissue and remains unreactive (no color change) when applied to dead tissue. Cambium-kill rating (CKR) was then calculated by summing the dead cambium samples per tree (0–4). We then reassessed each tree's status (i.e., live, dead) at the end of the first and second growing season post-fire. Trees were considered dead if no green foliage remained.

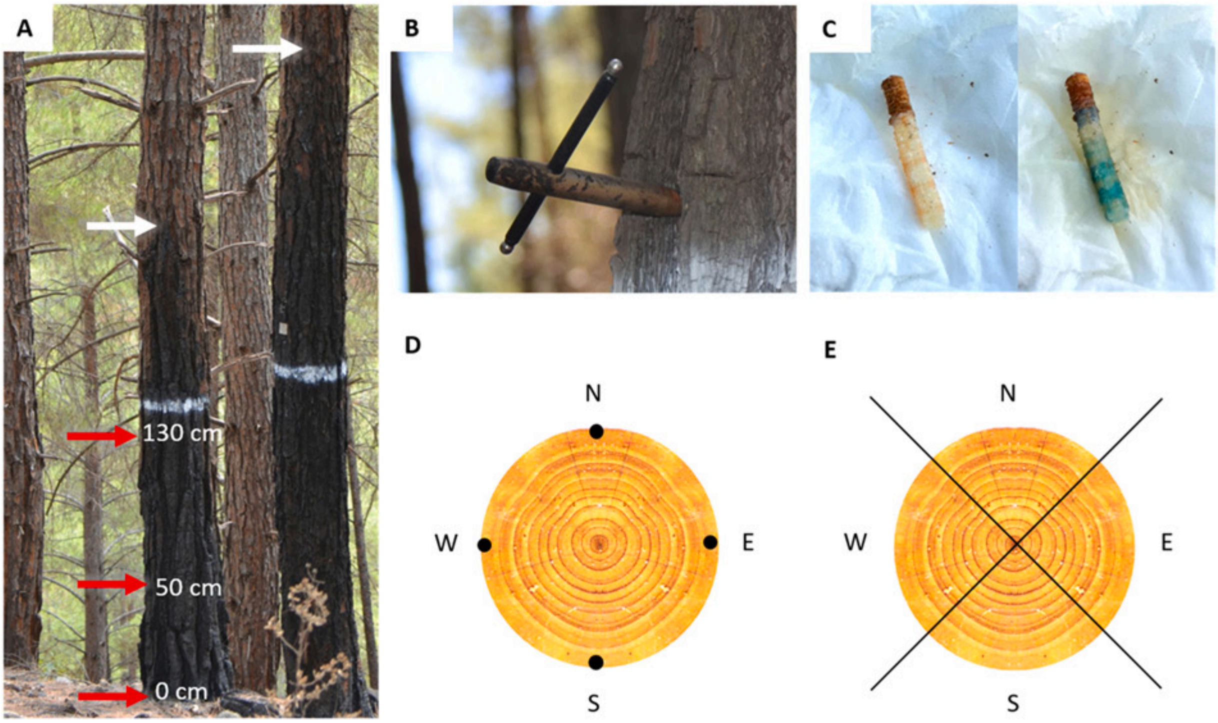

Fig. 2. Some of the parameters measured for assessing fire-caused injuries and Turkish pine traits. A) Heights (red arrows) at which stem diameter, bark char, cambium kill rating, and bark thickness were measured. Bark char height (white arrow) was measured for all four quadrants. B) Increment puncher for extracting small wood samples. C) The extracted wood samples contained parts of living bark, cambium and wood. The application of an ortho-tolidine hydrogen peroxide solution causes living tissue to turn blue. Sampling schemes for D) extracting wood samples and measuring bark thickness, and for E) assessing bark char height, bark char severity, and ground char severity.

2.3. Data analysis

Trees were coded as either 0 (live) or dead (1) based on their status two years after each fire. Average values of the measured variables (DBH, CKR, BT, etc.) between live and dead trees were compared using the Mann-Whitney Test for independent-sample (U-Test) since the data did not fit a normal distribution (Kolmogorov-Smirnov test, $p < 0.05$). The probability of tree mortality was modeled using mixed effects logistic regression, which is a type of generalized linear mixed model (GLMM) (Botequim et al., 2017). The logistic model has the form

$$P_m = 1/[1 + \exp(-((\beta_1 * X_1) + (\beta_2 * -X_2) + \ldots\ldots + (\beta_k * -X_k) + \beta_0))]$$

where P_m is the probability of mortality, β are regression coefficients and X are independent fixed variables. Distance correlation was used to check for linear or non-linear relationships between variables. As some parameters were significantly correlated (Tables A1-A4), we included only one of them at a time in the model. For instance, we included either diameter or bark thickness. Furthermore, based on the results of the distance correlation analysis, only variables with a value ≤ 0.3 were introduced into the same model (Grayson et al., 2017).

The GLMM analysis was performed using "binomial distribution" and the "logit link function" in SPSS including the measured variables as fixed effects and fire as the random effect. First, we performed univariate GLMM analyses retaining variables for the multivariate models if the p-value was < 0.1 (Table A5). CKR_{50} and CKR_{130} were the only variables with a p-value > 0.1 and therefore excluded from further analysis. We then performed GLMM analysis with different variable combinations. For the multivariate models only variables with a p-value < 0.05 were retained. We then calculated ROC, AIC and BIC values, which describe how well the model predicts the outcome and how well the model fits the data, respectively (Grayson et al., 2017). Further, residual diagnostics were conducted for each GLMM to test the goodness of fit of each model using the package "DHARMa" in R (Hartig, 2022). Classification tables were generated using a cut-off level of 0.5, where $P_m \geq 0.5$ = dead and $P_m < 0.5$ = alive, to report model accuracy in classifying trees based on negative predictive value and positive predictive value (Cansler et al., 2020).

To ensure adequate sample size and increase the power of our models, we retained all data for model development and did not use any of the data to independently test the predictive accuracy of the models (Hosmer and Lemeshow, 2000). This follows the approach used in most post-fire tree mortality models (Hood et al., 2010; Kobziar et al., 2006; Regelbrugge and Conard, 1993; Schwilk et al., 2006).

Only models with a high degree of explanatory power, few variables, and no time-consuming requirements for post-fire operations were selected. For post-fire forestry management, only the DBH of each tree is measured to determine trunk volume. Subsequently, standing sales are prepared based on these measurements. The models that will help to decide which tree to cut or not should therefore be easily measurable, contain variables that will save time and have a good prediction percentage.

Finally, assessment rubrics were created according to the selected models to be used in situations that practitioners will encounter when working in the field. These rubrics present the probabilities of trees dying across various values of the selected models' variables (Hood et al., 2020).

3. Results

3.1. Tree responses

We monitored 510 Turkish pines for two consecutive years, with 96 % of the trees having visible fire injury and 19 individuals without visible fire damage. Two years after fire, 80 (16 %) of the sampled trees had died (Table 1); 75 (94 %) of these trees died in the first year after the fires. No signs of insect attack were observed during the 2-year study period. All measured variables (Table 2) showed significant differences between live and dead trees, except for DBH (Mann-Whitney U test, $p=$ 0.062).

While diameter at 0 cm and 50 cm and bark thickness were significantly lower in dead trees compared to live trees, all other variables were significantly higher in dead trees. A decreasing trend in the number of dead trees was observed with increasing DBH, while the number of dead trees increased with increasing BCH_{mean} (Fig. 3). Even in the absence of crown scorch, some small trees died due to thin bark and cambium kill. Overall, an increase in tree mortality was observed with increasing CVS and cambium damage.

3.2. Mortality models

A total of 26 models were created to predict post-fire mortality of Turkish pine using different combinations of variables. The only variables that were not included in the models were CKR_{50} and CKR_{130}, as they were not significant in the univariate analyses (Table A5). The models were ranked for their accuracy and explanatory power by evaluating ROC, AIC and BIC values (Table A6). All models included CVS, often accompanied by stem injury variables (BCH_{mean}, CKR and BCI). Some models additionally included diameter, height or bark thickness as morphological variables. The classification accuracies of the models ranged from 85.3 % to 88.4 % (Table A7). A higher percentage of prediction accuracy was obtained for live trees (94.9–97.7 %) than for dead trees (32.5–45.0 %). Based on our model criteria (i.e., variables that are easily measured and used in standard forestry practices; model parsimony and accuracy), three models were selected (Table 3). Although it ranked last, we also selected a fourth model (model 26) that included CKR_0, as this variable is a direct measure of cambium damage. Model accuracy ranged from 85.5 % to 88.4 %, with predictive accuracy of surviving trees much higher than for dead trees (Table 4). Assessment rubrics for predicted probability of mortality based on a range of cutoff values were created for the four selected models (Table A8-A11).

Three of the selected models included CVS and stem damage variables (BCI_0, BCH_{mean} or CKR_0), one included CVS and DBH (model 5). Model 1 was the most accurate model and included CVS and BCI_0 as explanatory variables (Fig. 4A). According to this model, if BCI_0 is low, P_m remains low even if CVS is high (Fig. 4A). According to model 5 (Fig. 4B), P_m is low if DBH is higher than 35 cm and CVS less than 90 %. Model 7 shows that P_m is low when CVS and BCH_{mean} are less than 80 % and 200 cm, respectively (Fig. 4C). However, with a BCH_{mean} of 700 cm or higher a tree dies regardless of the percentage of CVS. According to model 26, P_m increases significantly with increasing CKR_0 (Fig. 4D). CKR_0 must be less than 3 for a tree to have a probability of survival.

The models show that stem damage plays a dominating role in Turkish pine mortality. In most cases P_m is low as long as stem damage is low even if CVS is high (Fig. 4). Several trees survived despite high crown injury when CKR was low (Figs. 5b, 6). During field visits new foliage was observed on some trees with the onset of the first post-fire growing season and then most of the crown recovered via surviving buds.

In this study, diameter, bark thickness, BCI and CKR were measured at three different stem heights (0, 50, and 130 cm). Regarding CKR, the models did not provide outputs for comparing different stem heights using the same set of variables (such as CVS and CKR_0, CVS and CKR_{50}, CVS and CKR_{130}). However, the models including BCI in combination with CVS showed the following order of decreasing significance: BCI_0, BCI_{130}, and BCI_{50}. Bark thickness in combination with CVS and BCH_{mean} demonstrated the following order of decreasing significance: BT_{130}, BT_{50}, and BT_0. Diameter in combination with CVS and BCH_{mean} demonstrated the following order of decreasing significance: DBH, D_{50}, and D_0.

4. Discussion

In this study, only trees that were not completely burned and were considered to have a chance of surviving the fire were selected. After two years, 84 % of the selected trees were still alive. The mortality models included crown damage (CVS), stem damage (BCI, GCI, BCH_{mean}, CKR_0) and morphological variables (diameter, BT, H). No univariate models were generated. The majority of the models included three variables; however, when compared to the bivariate models, the additional variable did not improve the models enough to justify their use. We selected four out of the 26 models based on their accuracy, ranking, applicability in the field, and the presence of variables that account for the causes of tree mortality. Out of these four models we recommend model 5 which includes a visual estimate of crown damage (CVS) and a variable (DBH) that is typically measured in post-fire management operations. In many studies, DBH has been included in post-fire tree mortality models (Woolley et al., 2012; Rigolot, 2004). Although model 1 (CVS and BCI_0) is the most explanatory model, visual assessment of BCI_0 requires experience and, being a more subjective measure, can vary from person to person. In contrast, BCH_{mean} and CKR_0 are variables that require more time and effort from the practitioner to obtain. In order to measure variables such as BCI, BCH_{mean} and CKR, practitioners would need to be trained and a standard to be established, however model 5 could be easily introduced in post-fire management operations, as CVS is easy to assess and DBH is already a standard

Table 2
Mean, standard error (SE), and range of post-fire characteristics of Turkish pine sampled within the first two months following the wildfires. Live and dead status is two years post-fire. Different letters after mean live and dead values denote significant differences ($p < 0.05$). Abbreviations (abbr.) of the measured variables are given as used in the analyses.

		All trees ($n=$ 510)			**Live trees ($n=$ 430)**			**Dead trees ($n=$ 80)**		
Measured variable	Abbr.	Mean	SE	Range	Mean	SE	Range	Mean	SE	Range
Height (m)	H	15.0	0.28	7.2—24.6	15.2a	0.13	8.0—24.6	13.6b	0.40	7.2—24.4
DBH (diameter at 130 cm)	DBH	25.2	0.95	8.0—66.2	25.5a	0.48	8.0—66.2	23.5a	1.16	8.6—54.9
Diameter at 50 cm (cm)	D_{50}	27.8	0.98	7.3—74.0	28.3a	0.50	9.5—74.0	25.4b	1.23	7.3—59.1
Diameter at 0 cm (cm)	D_0	32.7	1.03	11.9—78.0	33.2a	0.52	11.9—78.0	30.0b	1.31	13.4—68.0
Bark thickness at 130 cm (cm)	BT_{130}	2.1	0.09	0.3—8.1	2.2a	0.05	0.6—8.1	1.7b	0.09	0.3—5.0
Bark thickness at 50 cm (cm)	BT_{50}	3.0	0.10	0.9—11.3	3.1a	0.05	1.0—11.3	2.5b	0.11	0.9—5.9
Bark thickness at 0 cm (cm)	BT_0	3.8	0.11	1.1—10.7	4.0a	0.06	1.5—10.7	3.2b	0.12	1.1—7.0
Crown volume scorched (%)	CVS	30.5	3.62	0—100	23.8a	1.65	0—100	66.3b	4.65	0—100
Ground char index	GCI	1.1	0.06	0—2	1.0a	0.03	0—2	1.5b	0.07	0—2
Mean bark char height (cm)	BCH_{mean}	114	11.5	0—777	92a	4.74	0—761	231.8b	18.45	0—777.3
Bark char index at 130 cm	BCI_{130}	0.5	0.06	0—2	0.4a	0.03	0—2	1.2b	0.08	0—2
Bark char index at 50 cm	BCI_{50}	1.1	0.07	0—2	1.0a	0.03	0—2	1.5b	0.08	0—2
Bark char index at 0 cm	BCI_0	1.5	0.07	0—2	1.4a	0.04	0—2	1.7b	0.07	0—2
Cambium kill rating at 130 cm	CKR_{130}	0.4	0.08	0—4	0.2a	0.03	0—3	1.3b	0.15	0—4
Cambium kill rating at 50 cm	CKR_{50}	0.6	0.10	0—4	0.4a	0.04	0—4	1.7b	0.17	0—4
Cambium kill rating at 0 cm	CKR_0	0.9	0.12	0—4	0.8a	0.05	0—4	1.8b	0.17	0—4

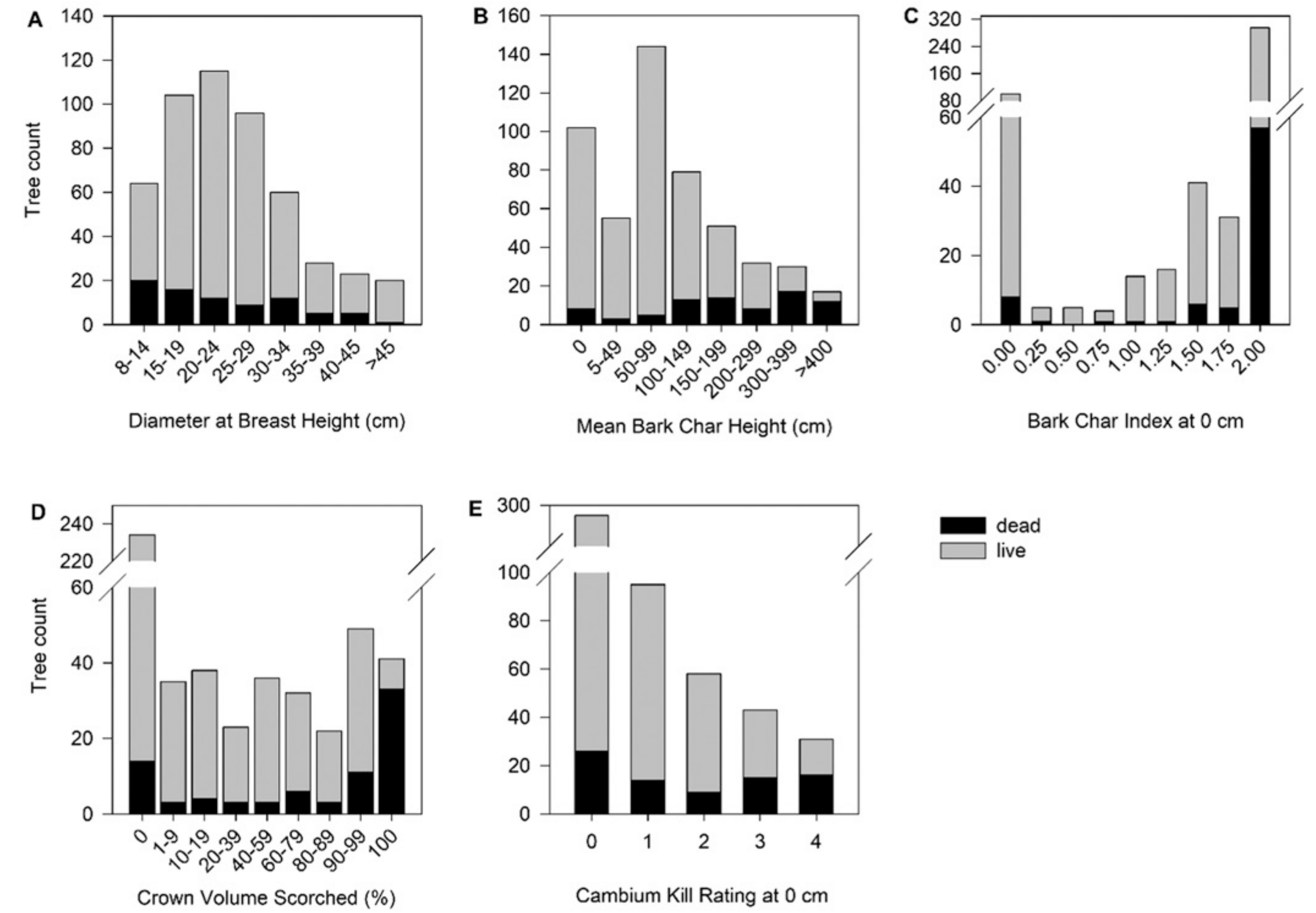

Fig. 3. Distribution of tree counts for A) diameter at breast height, B) bark char height, C) bark char index, D) crown volume scorched, and E) cambium kill rating for sampled Turkish pines. Stacked bars indicate the number of dead (black) and live (gray) trees. Total number of trees n=510.

Table 3
Selected generalized linear mixed models for predicting the probability of post-fire mortality (P_m) in Turkish pine based on accuracy and parsimony. ROC = receiver operating characteristic curve; AIC = Akaike's information criterion; CVS = crown volume scorched (%); DBH= diameter at breast height (cm); BCH = bark char height (cm); BCI_0 = bark char index at 0 cm; CKR_0 = cambium kill rating at 0 cm.

Model No	Logistic model with explanatory variables	ROC RANK	AIC RANK	BIC RANK	ROC+AIC +BIC
1	$P_m = 1/[1 + \exp(-((CVS * 0.042) + (BCI_0 * 1.078) + (-5.232))]$	22	1	1	24
5	$P_m = 1/[1 + \exp(-((CVS * 0.044) + (DBH * -0.073) + (-1.710))]$	25	5	5	35
7	$P_m = 1/[1 + \exp(-((CVS * 0.044) + (BCH_{mean} * 0.007) + (-4.882))]$	4	7	7	18
26	$P_m = 1/[1 + \exp(-((CVS * 0.046) + (CKR_{0i} * X_i) + (-5.091))]$ $i = 0, 1,2,3,4$ and X_i= 0, 1.289, 1.677, 3.284, 4.430	1	26	26	53

In the equation of model 26, i refers to the CKR_0 categories and X_i represents the respective regression coefficients

Table 4
Predictive accuracy of the selected Turkish pine mortality models using cutoff = 0.5. Each tree is placed in one of four categories (live/live-live/dead-dead/live-dead/dead) based on the observed versus predicted event. The overall accuracy percentage is calculated based on the weighted mean of both sub-accuracies (dead and live).

Model No	Observed	Predicted		
		dead (n)	live (n)	**Percentage correct**
1	dead (n)	35	45	43.8
	live (n)	22	408	94.9
	Overall Percentage			86.9
5	dead (n)	26	54	32.5
	live (n)	20	410	95.3
	Overall Percentage			85.5
7	dead (n)	31	49	38.8
	live (n)	13	417	97.0
	Overall Percentage			87.8
26	dead (n)	31	49	38.8
	live (n)	10	420	97.7
	Overall Percentage			88.4

measure.

Evaluating the models for their ability to explain tree mortality showed that, while CVS was included in all models, stem damage variables stood out as dominant predictors of Turkish pine mortality. Our results show that if stem damage is low, Turkish pines are likely to survive even if CVS is high. Some trees in our study had crowns where almost all needles were completely scorched by convective heating but

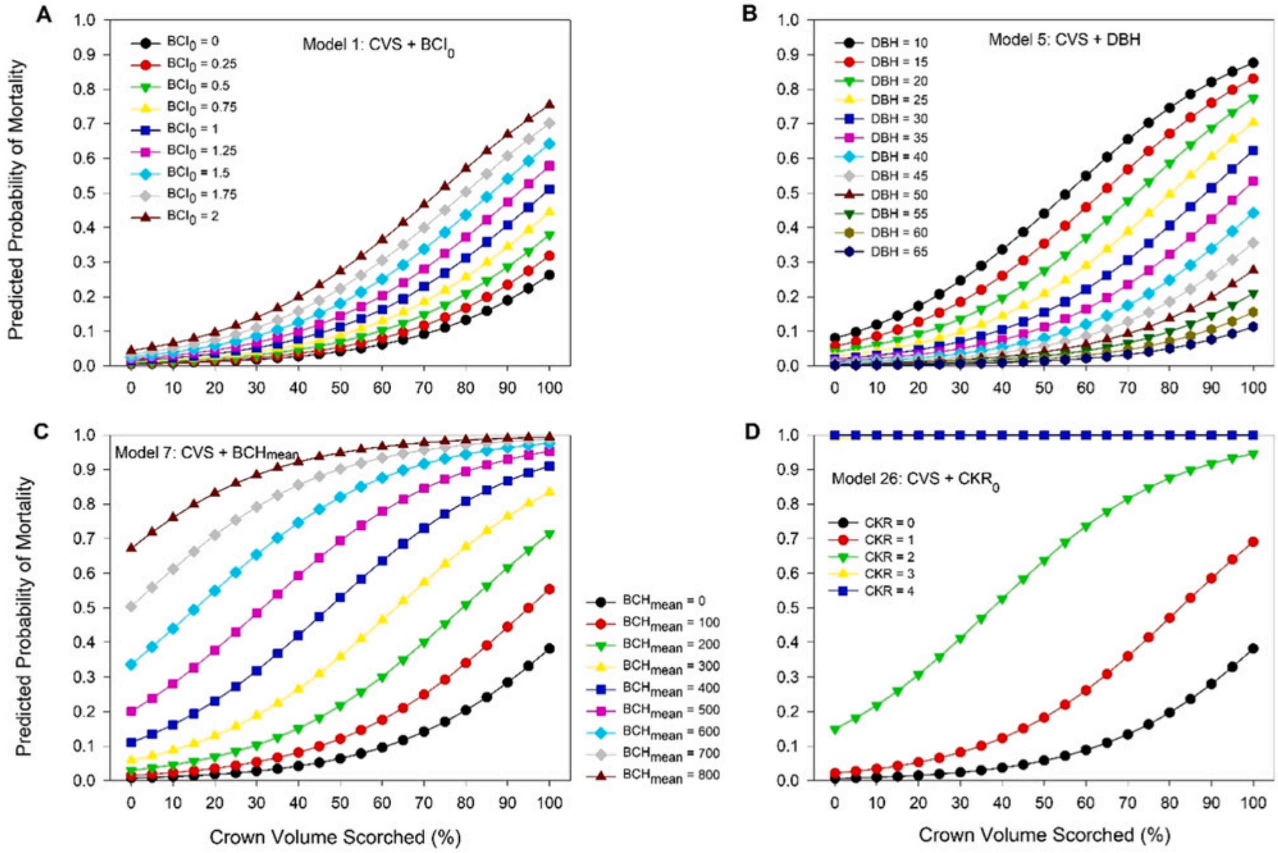

Fig. 4. Predicted probability of Turkish pine mortality as a function of A) crown volume scorched (CVS) and bark char index at 0 cm stem height (BCI_0), B) CVS and diameter at breast height (DBH, cm), C) CVS and mean bark char height (BCH_{mean}, cm), and D) CVS and cambium kill rating at 0 cm stem height (CKR_0). CKR=3 (yellow line) is hardly visible as it overlaps with CKR=4 (blue line).

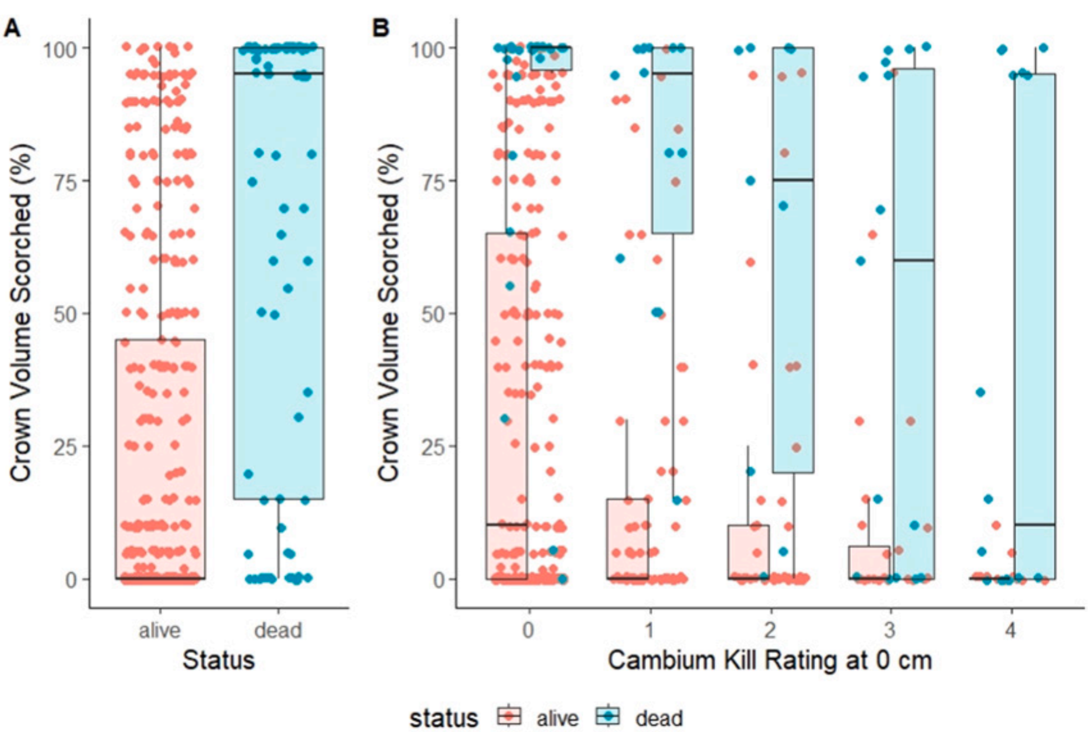

Fig. 5. Boxplots showing A) distribution of crown volume scorched (CVS) for alive and dead trees and B) distribution of CVS for alive and dead trees along the observed cambium kill ratings at 0 cm stem height (CKR_0). Boxes denote first and third quartiles, black lines the median, whiskers the 1.5 interquartile range (IQR). Dots are jittered values of individual trees.

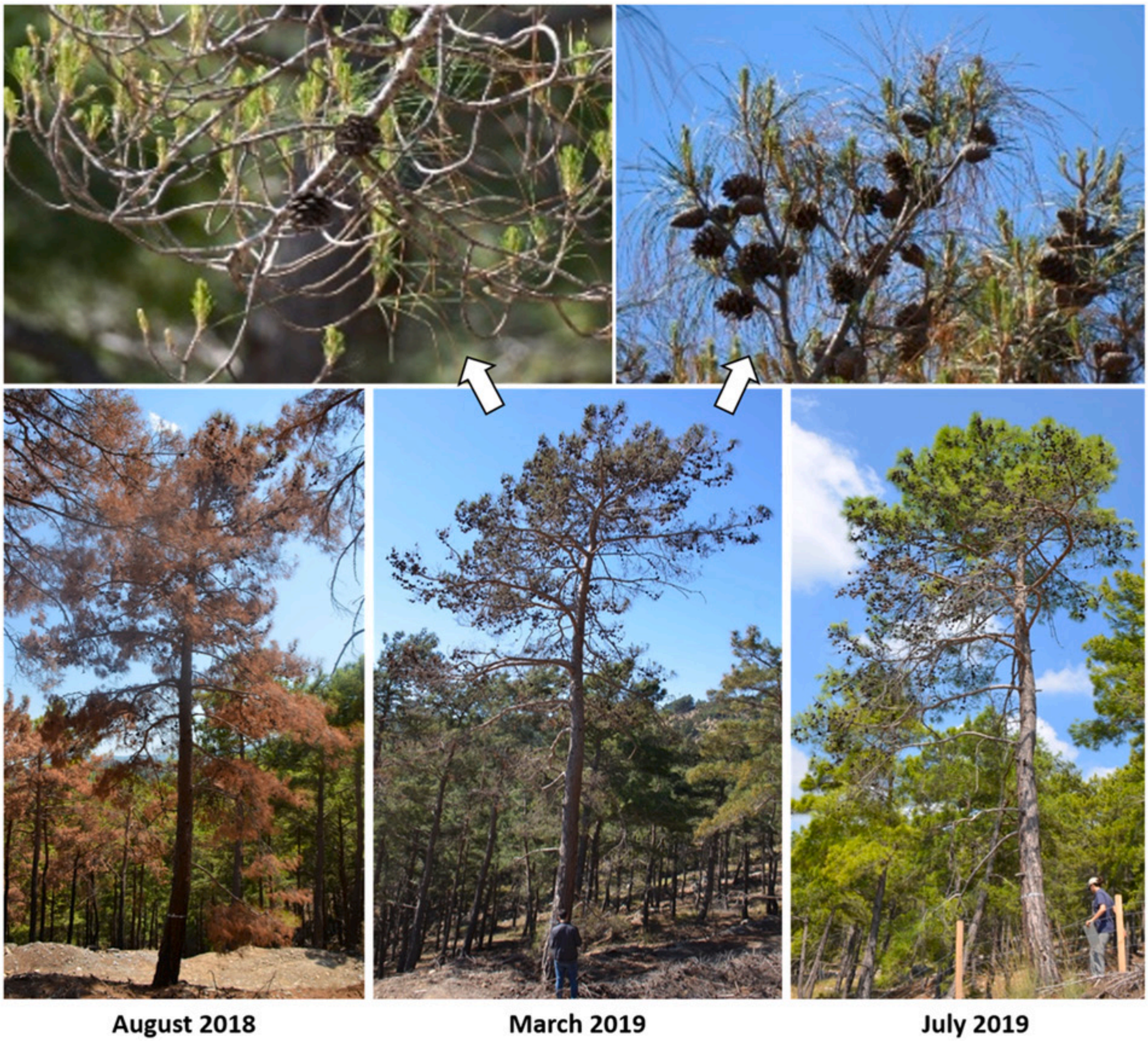

Fig. 6. Turkish pine tree at the Manavgat site. A tree with a CVS of 100 %, no cambium damage and a BCH_{mean} of 96 cm restored most of its crown during the first growing season after the fire due to high bud survival. Tree size characteristics were as follows: DBH= 44.7 cm, height= 14 m, bark thickness= 5.3 cm.

not consumed. Nonetheless, these trees still leafed out and formed a green crown with the beginning of the next growing season (see Fig. 6). This shows that Turkish pines with little to no cambium damage can survive and form a green crown at the beginning of the next post-fire vegetation period, even if their leaves are scorched, if the majority of the buds (i.e., meristems) are not killed. This fire resistance trait has been documented in other pine species with large buds, such as *P. ponderosa* Doug. ex Laws. and *P. jeffreyi* Balf., as well as for species that can resprout (Hood et al., 2018; Nolan et al., 2021). The bud length of Turkish pine measures between 1.5 and 2 cm (Gökmen, 1970; Gökşin, 2001) which is comparable to the bud sizes of *P. ponderosa* (2 cm) (USDA, 2024) and *P. jeffreyi* (2–3 cm) (conifers.org, 2024; Schütt Peter et al., 2008). Our results suggest that Turkish pine, similar to these two species, can tolerate fires of low or moderate intensity without damage to the buds.

Tree size is considered an important factor in fire resistance, as crown height and bark thickness increase with tree height and diameter (Ryan et al., 1988) which aligns with our results. We found that as the diameter decreased, cambium damage increased, resulting in tree mortality. Trees with larger DBH were observed to have less cambium damage, even in the presence of bark char on the stem. This is because bark thickness increases with increasing diameter, providing better protection to the cambium against fire damage. Thick bark has been linked to reduced levels of tree injury for many species exposed to surface fire regimes (Brando et al., 2012; He et al., 2012; Keeley and Zedler, 1998; Van Nieuwstadt and Sheil, 2005). Thus, in surface fires, even those of low intensity, younger trees with thin bark face a higher risk of mortality due to the vulnerability of their cambium to damage, even if their crowns remain undamaged.

Direct measurement of cambium damage (CKR) is often difficult and time consuming (Ryan and Reinhardt, 1988; Thies et al., 2006). Thus, parameters that represent cambium damage but require less effort to measure, such as BCH_{mean} and BCI, can be useful surrogates. Even if bark charring reaches up the stem, there may be no damage to the cambium. If a fire spreads fast and has a short duration, the bark may blacken and char, but the temperature may not be sufficiently high to kill the cambium on thick-barked species, such as Turkish pine. For example, Hood et al. (2008) reported that cambium was rarely dead if the bark had light charring and was dead $<$40 % of the time if the bark had moderate charring on thick-barked conifers in the U.S.

In our study, 94 % of dead trees died after the first year. This suggests that for Turkish pine, it is mostly clear by the end of the first year whether trees will survive or not. Literature on post-fire mortality of Turkish pine is limited. Neyişçi et al. (2002) reported that only 114 out of a total of 8012 Turkish pine trees died one year after a prescribed fire, accounting for merely 1.4 % of all trees. Dying trees were of small diameter and short height. The results of our study support the findings of Neyişçi et al. (2002) that Turkish pine can survive low-intensity surface fires. The ability of pine species to recover from fire is threatened by increasing fire frequency and severity (Fernández-García et al., 2019). In this context, prescribed burning is a management tool to reduce understorey fuels and thus the intensity and severity of the fires that occur (Sagra et al., 2019). Prescribed burning is applied in many Mediterranean forests with pine species, such as *P. halepensis* Mill., *P. pinea* L. and *P. pinaster* Ait. (Battipaglia et al., 2016; Battipaglia et al., 2014; Botelho et al., 1996). These species are known to be resistant to low-intensity fire, with characteristics such as thick bark, large and sheltered buds, relatively thick needles, and a canopy architecture that offers increased protection of the crown to allow survival (Catry et al., 2006; González et al., 2007). Turkish pine is distributed at low and medium altitudes and has morphological characteristics similarly to the above-mentioned species. Taking into account our results, we therefore believe that prescribed burning could be used as a management tool in Turkish pine forests.

The second objective of this study was to examine the explanatory power of variables measured at different stem heights in order to assess which of these influenced post-fire mortality the most. Our results did not allow for a comparison of CKR measured at different stem heights. Only CKR_0 was included in the models. In previous studies on tree mortality, CKR has typically been measured at 0 cm stem height (Hood et al., 2008). Similarly, BCI is also usually measured at 0 cm, which also demonstrated the greatest explanatory power in our models. Conversely, diameter and BT, which are typically measured at 130 cm, showed the greatest explanatory power at that very same height.

Since this is the first post-fire mortality study of Turkish pine, it is important to further evaluate model accuracy in other fires and regions to create prediction tools for fire management practitioners. Additionally, stand-level estimates and assessment tables are required. Thus, it is necessary to conduct further research on this subject in the forthcoming years.

5. Conclusions

Forest managers need to be able to predict tree mortality in order to determine the number of trees to be removed from the site, the amount of timber production, and to plan reforestation efforts after a fire. This is only possible with mortality models based on a small number of variables that are easily measurable, and assessment tables constructed from these models. Based on our results, we recommend the mortality model that includes a crown damage variable (CVS) and DBH, a variable that is typically measured by forest managers following a fire. Both variables have high explanatory power and are easy to measure in the field. Our results show that Turkish pine can withstand high crown scorch levels and flush new foliage as long as cambium damage is low, indicating that Turkish pine buds can survive even when foliage is killed by fire. Therefore, we assume that Turkish pine buds may remain unaffected in low- to moderate-intensity fires allowing them to subsequently leaf out, but further research is needed to confirm our assumption. Our findings indicate that Turkish pine has the ability to withstand low-severity surface fires, thus making prescribed fires a viable option for managing this species.

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CRediT authorship contribution statement

Coşkun Okan Güney: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Aylin Güney:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Abdullah Sarı:** Writing – review & editing, Investigation. **Ali Kavgacı:** Writing – review & editing, Investigation. **Kevin C. Ryan:** Writing – review & editing, Methodology. **Sharon M. Hood:** Writing – review & editing, Visualization, Methodology, Formal analysis.

Declaration of Competing Interest

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.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2024.122265.

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