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Fuel characterization and crown fuel load prediction in non-treated Calabrian pine (*Pinus brutia* Ten.) plantation areas

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Successful management of young, fire-prone Calabrian pine forests requires an accurate characterization of surface and canopy fuel loads at stand level. This study characterizes the surface and canopy fuel characteristics in unthinned Calabrian pine plantations in Turkey. Fifteen sample plots were measured to determine the surface and crown fuel characteristics of very young, young and middle aged Calabrian pine stands (10 to 28 years old). Thirty-six trees were destructively sampled to quantify the crown fuel loads and canopy fuel characteristics of the stands. Surface fuel load ranged from 11.38 t ha^{-1} in the young stands to 35.27 t ha^{-1} in the middle aged stands. Dead fuel load as ladder fuels on the trees ranged from 0.77 kg in very young stands to 13.56 kg in the young stands. Live fuel loads on the trees ranged from 0.77 kg to 23.29 kg in the young aged stands. Total active crown fuel load was 58.7%, 52.1% and 49.5% of total crown fuel load in very young, young and middle aged stands, respectively. Our results improve the current crown fuel model predictions and showed the importance of dead fuel load in fire management studies both for the determination of crown fuel loads and the calculation of carbon stocks.

Keywords: Surface Fuel, Dead Crown Fuel, Live Crown Fuel, Non-treated, *Pinus brutia*, Türkiye

Introduction

Wildfires are the main threat in Calabrian pine forests, which cover nearly 5.2 million ha of forest lands in Turkey (GDF 2020). The ability to control forest fires with a successful prediction of fire behavior is mostly associated with the characteristics of fuel load (Bilgili 2003). In this sense, conifer plantations have a particular importance for fire managers and researchers as they are generally associated with extreme fire behavior (Douglas 1964) and intense crown fires (Van Wagner 1968, Alexander 1992). In the early years of the establishment on a suitable site, conifer plantations produce plenty of dead flammable materials mainly due to the lack of light after the onset of crown closure (Forrest & Ovington 1970). Dead needles suspended on the dead fine twigs under living tree crown serve as ladder fuels from surface fuels to live crown fuels (Cruz et al. 2003, Menning & Stephens 2007). In particular, the amount of canopy fuels coupled with extra shrub in the understory and other kinds of ladder fuels is highly decisive in the onset and spreading of crown fires (Cruz et al. 2017). For managing and understanding crown fires, investigations on comprehensive crown fuel load and canopy fuel characteristics have crucial importance (Affleck et al. 2012). Surface and ladder fuels and their properties are determinant on the initiation of crown fires (Byram 1959, Van Wagner 1977). After the transmission of surface fire up to tree crowns, canopy fuels and their characteristics (Cruz et al. 2003) become the driving factors for the spread and continuity of crown fires (Cruz & Plucinski 2007). In this sense, the canopy base height (CBH) and the canopy bulk density (CBD) are the two key parameters for the determination and explanation of canopy fuel characteristics (Cruz et al. 2003).

Information on characteristics and the vertical distribution of crown fuels is essential in fire behavior and fuel management studies. Some investigations have already been carried out to determine crown fuels or biomass for coniferous natural forest (Stocks 1980, Ter-Mikaelian & Korzukhin 1997) and plantations (Forrest & Ovington 1970, Ritson & Sochacki 2003, Koukoulomatis & Mitsopoulos 2007, Baysal et al. 2019). However, dead fuels or ladder fuels on trees have been rarely investigated (Mitsopoulos & Dimitrakopoulos 2007, Ruiz-González & Alvarez-González 2011, Wang & Niu 2016) especially in planted and non-treated (unthinned) conifer stands (Williams 1976, Chen & Li 2010). Other studies assessed the amount and properties of crown fuels of the broadest fuel types composed of Calabrian pine (Küçük & Bilgili 2008, Küçük et al. 2008, Bilgili & Küçük 2009, Güngöroglu et al. 2018, Baysal et al. 2019, Baysal 2021) and Anatolian Black pine (*Pinus nigra* J.F. Arnold – Küçük et al. 2007a, 2008) in Turkey. However, none of these studies dealt with the amount and characteristics of the ladder fuels on trees, especially in non-treated plantation forests. Furthermore, the vertical configuration of crown fuel load in non-treated Calabrian pine stands at tree level and the determination of canopy fuel characteristics at stand level have not been investigated.

The close relationship of Calabrian pine with fire ecology (Neyisçi 1986, Thanos et al. 1989) and fire behavior (Bilgili et al. 2010a) necessitates of extensive research to be carried out. Fires in the young and middle-aged Calabrian pine forests spread generally in the form of very severe surface fires and often crown fires (Bilgili et al. 2010b), especially in plantation areas (Bilgili et al. 2006). Therefore, the characterisation of fuel from tree to stand level (Keane et al. 2001, Cruz et al. 2003) in Calabrian pine forested areas (Baysal et al. 2015) are

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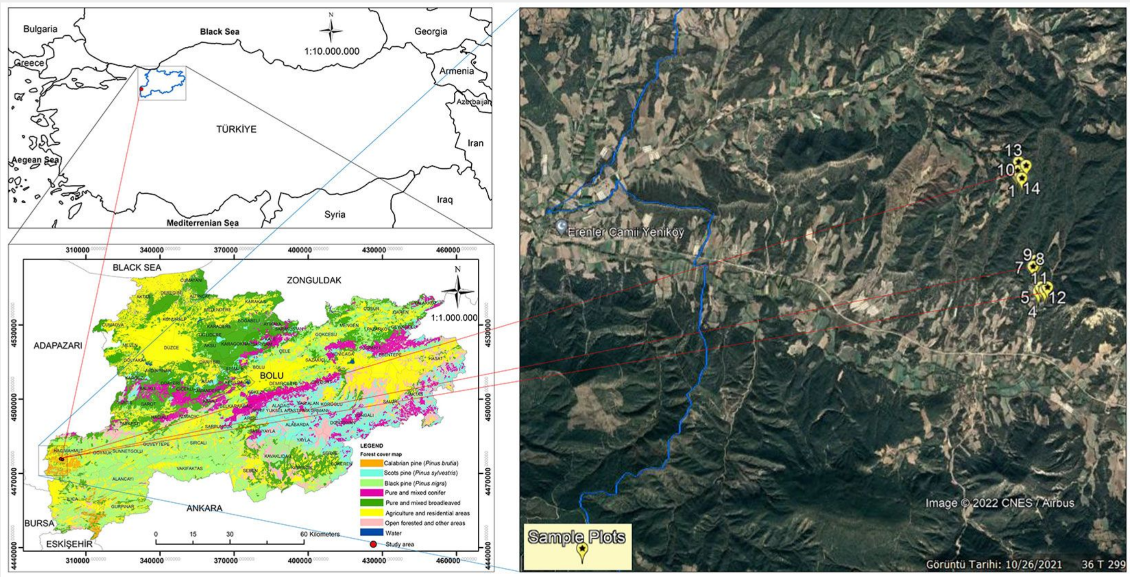


Fig. 1 - Location of the case study area in the Bolu Regional Directorate of Forestry, NW Turkey.

important for fire prevention and fire fighting activities (Küçük et al. 2007a).

The objectives of this study are to: (i) investigate the dead and live fuel loads on tree canopies and assess surface, ladder and canopy fuel properties; and (ii) develop models of ladder and crown fuel loads in non-treated Calabrian pine plantations. The results of this study will be useful in fire and fuel management studies in fire-prone forested areas.

Materials and methods

Study site

The study area is the Hacimahmut Forest Planning Unit (40° 22′ 17″ N, 40° 30′ 24″ E), located in Northwestern Turkey and managed by the Göynük State Forest Enterprise of the Bolu Regional Forestry Directorate (Fig. 1). The Hacimahmut Forest Planning Unit area is 20,949.9 ha, of which 71% is covered by forests (79.4% productive, 20.6% unproductive). Planted stands cover nearly 6% of total forests in the study area. Forests are mainly composed of Anatolian Black pine (43.9%), Calabrian pine (25.8), mixed conifers (15.1%), conifer-broadleaved mixed forests (5.6%), beech (7.5) and other tree species (2.1% – GDF 2018). Elevation ranges from 570 to 730 m a.s.l.

The study area is located in the transition zone between the Black Sea climate and the Central Anatolian climate. According to the meteorological data over the period 1991-2020, rainfall mostly occurs in the spring and winter months, with an average annual precipitation of 573.6 mm. The lowest precipitation occurs in September with an average 26.5 mm and the highest in June with an average 68.9 mm. In the summer season, the temperature is quite high with summer drought periods. The lowest average temperature is recorded in January with -2.4 °C and the highest in June with 28.7 °C. According to the last 93-year meteorological data, the lowest temperature occurred in January with -31.5 °C and the highest in August with 39.8 °C (GDM 2022).

Selection of the sample plots

The sample plots were selected from the compartments no. 161, 162, 181 and 183 in the Hacimahmut Forest Planning Unit. Field measurements were carried out during the summer and autumn seasons of 2018. In order to assess the stand characteristics and determine the amounts of fuel load, 15 sample plots were randomly selected according to their development stage and crown closure in pure non-treated (unthinned) Calabrian pine plantations (Fig. 2). Each sample plot was 200 m^2 and the shape was circular with a radius of 8 m.

Stands measurements

Several observations and measurements were carried out to determine the surface and aerial fuel properties in the sample

Fig. 2 - General view of very young (left) young (middle) and middle aged (right) stands.

plots. General descriptive information of the sample plots, including altitude, slope, aspect, crown closure and stand types were recorded. The spatial location of all sample plots, their altitude and aspect were measured with a global positioning system device. Pictures and video of the sample plots were taken in all directions within the sample plots for further evaluation. To characterise the main attributes of trees in the sample plots, diameter at breast height (DBH, cm), tree height (H, m), tree age (A, yrs), live crown base height (CBH, m), crown length (CL, m), crown width (CW, m) and bark thickness (BT, cm) in two perpendicular directions were measured. DBH was measured to the nearest 0.1 cm with a tree caliper in two direction. Tree height (H) was measured using a steel tape for short trees and an electronic height measurement device for tall trees. Crown width (CW) was measured as an average value according to the length of the widest living branch measurement in two orthogonal directions. Crown length (CL) was measured as a value calculated from the difference between tree height and CBH. The social status of each tree in the sample plots was assessed according to the classification system of Kraft (1884).

A total of 607 trees was measured in the 15 sample plots. Forty-eight trees were measured but discarded from average calculation because of undesired characteristics (*e.g.*, unhealthy or dead condition). The age (taken at 1.30 m above the ground) and bark thickness (measured at 0.30 cm above the forest floor) were also measured in a subset of 137 sampled trees.

Surface fuel measurements

Information on the litter and duff fuel materials is key in fire behavior studies and fire management plans (Küçük et al. 2007b, Keane 2013). For the determination of the surface fuel load and its characteristics, three subplots (30 × 30 cm in size) were established in each very young, young and middle aged sample stand, totaling 15 subplots. Each subplot was positioned to reflect the general surface fuel condition of the parent sample plot. Later, litter samples were carefully cut with hand pruning shears to the duff layer, collected and placed in plastic bags. Also, litter depth at each subplot was measured with a ruler at six different locations from the surface of duff layer to the upper part of litter layer. The surface fuel bed depth was calculated as the average depth at these six points. Duff samples were collected to the mineral soil and placed in a plastic bag labelled with plot and subplot numbers and the litter and duff samples were transported to the laboratory.

Ladder and crown fuel measurements

Overall, 36 trees were selected and felled from the 15 sample plots to assess the ladder and crown fuel load on trees. The selection was based on the average, minimum and maximum attributes of the measured trees to best reflect the characteristics of the parent sample plot. Trees heavily defoliated or with broken tops were not considered (Brown 1978). Each felled tree was divided into 1-meter sections starting from 0.30 cm above the ground. All dead or live fuel materials in each 1-m section were carefully cut, collected and weighted (Alexander et al. 2004) with no subsampling. Dead and live needles on the branches were carefully removed, separated and weighed in the field. Moreover, all dead and live branches in each section were classified according to their sizes and weighed in the field.

Laboratory analyses

Litter and duff samples were transpoted to the lab and analyzed. The dead litter, bark flakes, cones and branches were classified in the litter samples. According to the classification of branches reported by Stocks (1980), very thin (BVF, 0.0-0.3 cm), thin (BF, 0.3-0.6 cm), medium (BM, 0.6-1.0 cm), thick (BTH, 1.0-2.5 cm) and very thick (BVT, >2.5 cm) branches were separated with a special steel ruler and prepared with a 0.05 mm sensitivity scale by a laser cutting device. Duff samples were accurately examined to avoid the presence of rock, stones or pebbles. Live crown fuel components of samples were preliminary dried at room temperature in the laboratory and then placed in an oven at 105 °C for 24 hours. Oven-dried fuel weight was measured using a 0.01 g sensitivity scale (Bilgili & Küçük 2009).

Statistical analysis

All statistical analyses were performed using the package SPSS Statistics® v. 21.0 (IBM, Armonk, NY, USA). Minimum, maximum and average values of tree measurements and stand properties were calculated. Correlation and regression analysis were carried out to determine the relationship between tree properties and crown fuel components. Data were tested for normality before correlation and regression analyses, and the relationships between independent and dependent variables were checked for linearity. A parametric linear regression based on the stepwise procedure was used to model crown fuel estimates. RCD (Root Collar Diameter), DBH, H, CBH, CW, CL were considered as predictors (independent variables). Needles (N), branches (BVF, BF, BM, BTH, BVT), dead and live active fuel (N+BVF+BF) and total crown fuels (all needles and branches) were considered as dependent variables.

Results and discussion

Stand characteristics

The stand age varied between 10 to 28 years, tree height from 2.7 to 16.6 m, tree diameter at breast height from 5.0 to 25.6 cm, crown base height between 0.7 and 9.5 m and crown closure from 70% to 95% (Tab. S1 in Supplementary material).

Any changes in the stands have an impact on fuel characteristics and thus on fire behavior (Bilgili 2003). It is well known that the silvicultural practices (*e.g.*, thinning) have an effect on the stand characteristics by re-locating the fuel position (Bilgili 1995). As Calabrian pine is a shade intolerant species (Boydak et al. 2006), silvicultural treatments play an important role in tree development and the regulation of fuel in Calabrian pine stands. In this context, this study provides new evidences on the fuel characteristics of non-treated, planted Calabrian pine stands in Turkey.

According to the social status (*i.e.*, the competitive status) of the measured trees based on the Kraft's classes (Fig. 3), about 80% of trees (276 dominants and 212 codominants) reach the upper canopy, while the remaining trees were suppressed (71) or unhealthy/dead trees (48). Such proportions support the evidence that thinning operations have not been carried out to date in the studied stands. The high share (35%) of codominant trees in the upper canopy and the high rate (20%) of suppressed trees resulted in a poor stand growth (Odabasi 1981). Overall, 55% of trees could be actually removed by silvicultural interventions, especially thinning from below.

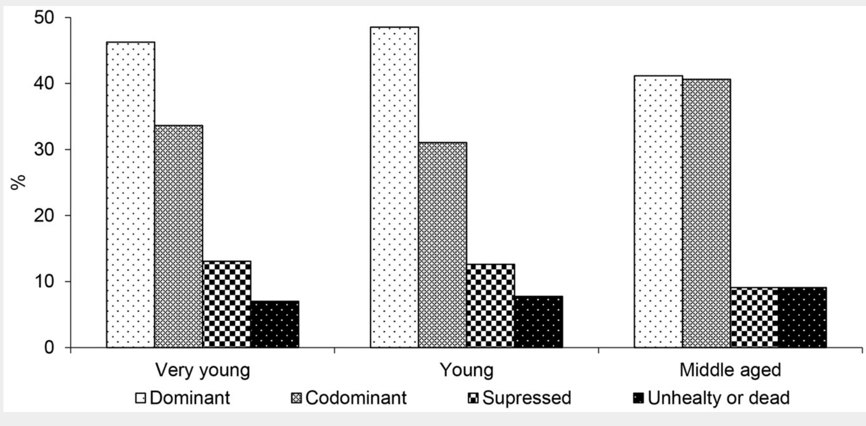


Fig. 3 - General tree status in three different stages of stand development.

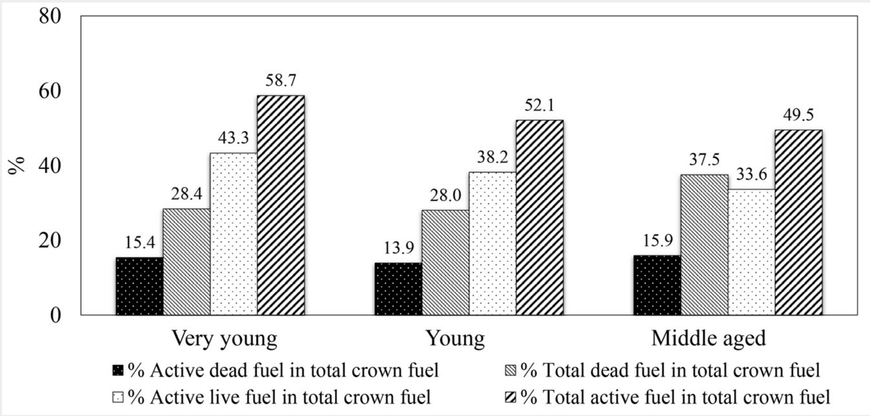
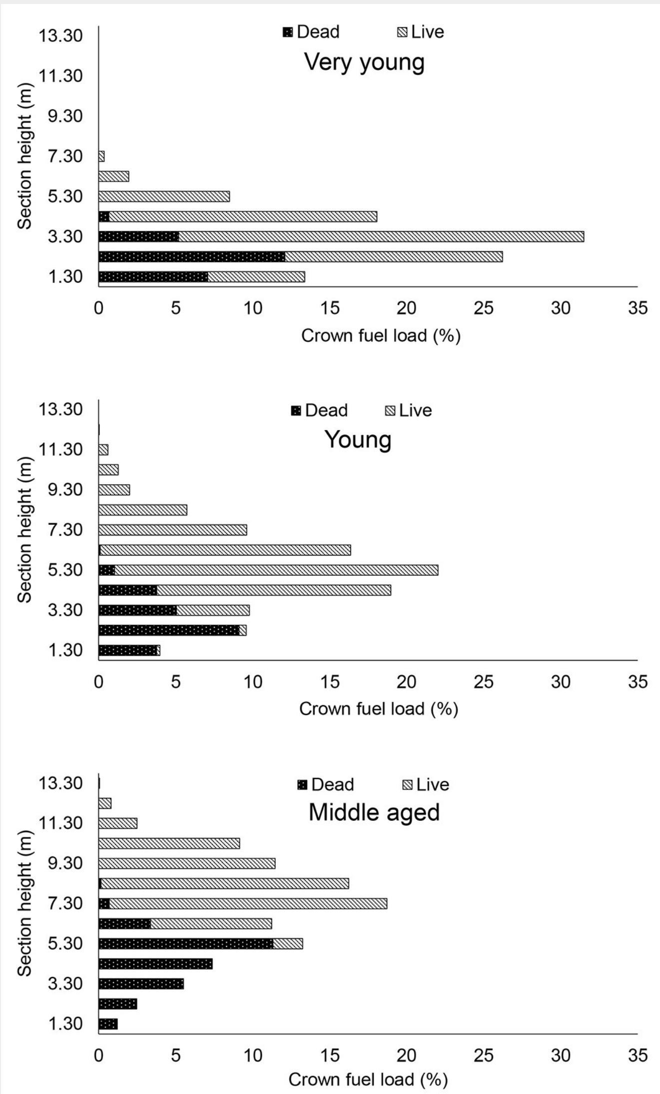


Fig. 4 - Active dead and live crown fuel percentage distributions of three different calabrian pine plantation stands.

Surface fuel loads (litter and duff)

The amount and characteristics of surface fuel were characterized by classifying the fuel materials of subplots in the sample stands (Tab. S2 in Supplementary material). The total surface fuel load ranged from 11.38 t ha⁻¹ in young stands to 35.27 t ha⁻¹ in middle aged stands. Forest floor depth ranged from 1.7 cm in very young stands to 5.1 cm in middle aged stands. According to a similar study conducted in the southern part of the same Calabrian pine forest, Cepel & Tekerek (1980) found surface fuel load between 7.2 to 43.4 t ha⁻¹. Further, for the same tree species, Baysal et al. (2015) found surface fuel load between 0.3 to 34.3 t ha⁻¹. In both the above studies, the largest amount of surface fuel load was recorded in the middle aged stands, close to the upper level of surface fuel load. Comparing our results to other conifer species, Williams (1976) reported an average surface fuel load of 22.7 t ha⁻¹ in a 12-year-old unthinned plantation of *Pinus radiata*, while Burrows et al. (1988) reported an average litter fuel load of about 10.5 t ha⁻¹ in a 17-year-old unthinned maritime pine plantation, and Botelho et al. (1994) assessed the litter fuel loads ranging from 1.2 to 6.3 t ha⁻¹ in 10-18-year-old stands of the same species.

Fig. 5 – Vertical distribution of live and dead crown fuel load in very young (upper panel), young (middel panel) and middle aged (lower panel) Calabrian pine stands.



Crown fuels

Thirty-six trees were felled for destructive sampling (Tab. S3 in supplementary material). The DBH of the felled trees ranged from 5.0 to 19.6 cm with an average of 11.3 cm, while their height ranged from 3.9 to 12.6 m, with an average of 8.2 m. According to the crown fuel load of the sampled trees for three different stand types (Tab. S4 in supplementary material), the lowest live crown fuel load was recorded in trees from very young stands (average: 4.59 kg), while the highest live crown fuel load was found in trees from the young stands (average: 13.89 kg). Similarly, the lowest dead crown fuel load was observed in the very young stands (average: 1.63 kg) and the highest in the young stands (average: 4.13 kg). Total dead and live crown fuel load of trees was found the lowest in very young stands, with 6.22 kg on average, while the highest was found in young stands with an average 18.02 kg. For middle aged stands, crown fuel load was about 34.5% less than in young stands. This result could be due to the higher basal area and crown closure of middle aged stands compared to young stands.

The percentage of dead, live, and dead and live crown fuel components for each stand was obtained by taking all dead crown fuels and live crown fuels on the felled trees (Fig. 4). When dead and live crown fuel load on trees were compared to the total crown fuel load in each stand type, live crown fuel percentages gradually decreased from very young to middle aged stands. In contrast, dead crown fuel load percentage gradually increased from very young to middle aged stands. Live fuel percentage was found to be the highest in the very young stand, based on the comparison of dead, live or dead and live active fuel on the tree to the total crown fuel load (dead and live crown fuels with stem and bark without cones). Also, the lowest active dead fuel load was found in the young stands, and the highest was found in the middle aged stands, with very similar percentage in the very young stands. Active live fuel is gradually decreasing from the very young stands to the middle aged stands (Fig. 4).

The vertical distribution of dead and live crown fuel percentage for each 1-m sectional height from the ground to the tree top is displayed in Fig. 5.

Tab. 1 - Regression models using tree characteristics (DBH, H, Age, CBH, BT) as predictors of the different types of fuel loads observed on the selected trees.

Fuel type	Model no	Model	Constant a	Coefficient b	Coefficient c	Adjusted R^2	SEE
Live crown fuel	1a	ln *needle*= a+b×(ln *DBH*)	-3.534	1.812	-	0.840	0.323
	1b	ln *needle*= a+b×(ln *DBH*)+c×(ln *AGE*)	-1.693	2.249	-0.936	0.912	0.239
	1c	ln *branches*= a+b×(ln *DBH*)	-3.728	2.216	-	0.873	0.345
	1d	ln *branches*= a+b×(ln *DBH*)+c×(ln *CBH*)	-3.850	2.540	-0.595	0.949	0.220
	1e	ln *active*= a+b×(ln *DBH*)	-2.919	1.794	-	0.856	0.300
	1f	ln *active*= a+b×(ln *DBH*)+c×(ln *CBH*)	-3.023	2.069	-0.506	0.937	0.198
	1g	ln *crownfuel*= a+b×(ln *DBH*)	-3.012	2.079	-	0.874	0.323
	1h	ln *crownfuel*= a+b×(ln *DBH*)+c×(ln *CBH*)	-3.126	2.379	-0.553	0.947	0.208
Dead crown fuel	2a	ln *needle*= a+b×(ln *AGE*)	-11.938	3.007	-	0.602	0.722
	2b	ln *needle*= a+b×(ln *AGE*)+c×(ln *BT*)	-12.234	3.699	-1.718	0.704	0.623
	2c	ln *branches*= a+b×(ln *H*)	-2.107	1.491	-	0.654	0.386
	2d	ln *branches*= a+b×(ln *H*)+c×(ln *BT*)	-2.214	1.083	0.883	0.726	0.344
	2e	ln *active*= a+b×(ln *H*)	-2.274	1.227	-	0.602	0.355
	2f	ln *active*= a+b×(ln *H*)+c×(ln *BT*)	-2.365	0.882	0.745	0.669	0.323
	2g	ln *crownfuel*= a+b×(ln *H*)	-2.170	1.542	-	0.685	0.373
	2h	ln *crownfuel*= a+b×(ln *H*)+c×(ln *BT*)	-2.265	1.178	0.788	0.739	0.339
All crown fuel	3a	ln *needle*= a+b×(ln *DBH*)	-3.449	1.802	-	0.882	0.270
	3b	ln *needle*= a+b×(ln *DBH*)+c×(ln *DBH*)	-3.520	1.991	-0.347	0.919	0.233
	3c	ln *branches*= a+b×(ln *DBH*)	-2.379	1.855	-	0.946	0.181
	3d	ln *branches*= a+b×(ln *DBH*)+c×(ln *CBH*)	-2.420	1.963	-0.199	0.958	0.159
	3e	ln *active*= a+b×(ln *DBH*)	-2.078	1.573	-	0.906	0.207
	3f	ln *active*= a+b×(ln *DBH*)+c×(ln *AGE*)	-1.111	1.803	-0.491	0.934	0.174
	3g	ln *crownfuel*= a+b×(ln *DBH*)	-2.073	1.839	-	0.943	0.185
	3h	ln *crownfuel*= a+b×(ln *DBH*)+c×(ln *CBH*)	-2.121	1.964	-0.230	0.960	0.155

Crown fuel load models

No significant correlation was found between the live needles and live branches and CBH. However, CBH and dead crown fuel components were positively correlated ($p<0.01$), except for the dead very thick branches. Live and crown fuel loads on the trees were closely related to DBH, H and CW ($p<0.01$), but not CBH. In addition, the total amount of live and dead fuel loads of the felled trees were also found closely related to DBH, H, CW and CL ($p<0.01$). As for CBH, no significant correlation was found between the total amount of live and total amount of dead fuel loads on the selected trees.

Dead, live, and total dead and live fuel loads on trees were modeled by linear regression analysis (Tab. 1) taking tree characteristics as predictors (independent variables) of the fuel loads (dependent variables). The results of regression analysis showed that DBH was the main (Durkaya et al. 2009, Sönmez et al. 2016, Baysal 2021) and strongest predictors (Affleck et al. 2012) of live and total crown fuel loads (Tab. 1).

Crown fuel load data obtained from the sampled trees were then used to predict the stand canopy characteristics (Cruz et al. 2003) in terms of crown base height (CBH), crown fuel load (CFL), and canopy bulk density (CBD). Models 3b and 3e developed in this study (Tab. 1) were used to obtain the CBH, CFL and CBD estimates at the stand level for trees with DBH between 5-20 cm, while for trees with DBH>20 cm we applied the models 4j and 4k (see Tab. S5 in Supplementary material) developed by Güngöroğlu et al. (2018). The stand level characteristics of the canopy for the three different stand types are given in Tab. 2.

The lowest canopy fuel load (CFL) was predicted in the very young stands and the highest in middle aged stands, with an average of 0.72 kg m^{-2} for needles only and 1.265 kg m^{-2} for the active fuel (N, BVF and BF). Canopy bulk densities (CBD) ranged from 0.046 kg m^{-3} in very young stands to 0.230 kg m^{-3} in middle aged stands. Küçük & Bilgili (2008) reported an average CFL of 1.51 kg m^{-2} and a mean CBD of 0.212 kg m^{-3} for Calabrian pine stands in Turkey. Ruiz-González & Alvarez-González (2011) found

Tab. 2 - Descriptive statistics of the sampled trees for the determination of crown fuel load. CFL_{LN} and CBD_{LN} obtained from live needles. CFL_{AF} and CBD_{AF} obtained from live active fuels. (SD): standard deviation.

Stand types	Very young				Young				Middle aged			
	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD
CBH (m)	1.33	3.25	2.09	0.73	2.58	3.42	3.10	0.34	3.09	7.17	5.90	1.67
CFL_{LN} (kg m^{-2})	0.193	0.498	0.335	0.117	0.469	0.604	0.522	0.060	0.546	0.854	0.720	0.137
CBD_{LN} (kg m^{-3})	0.046	0.120	0.087	0.028	0.086	0.110	0.099	0.010	0.086	0.154	0.128	0.027
CFL_{AF} (kg m^{-2})	0.343	0.883	0.595	0.208	0.083	1.064	0.921	0.104	0.959	1.501	1.265	0.240
CBD_{AF} (kg m^{-3})	0.083	0.213	0.155	0.049	0.152	0.194	0.176	0.017	0.151	0.271	0.230	0.048

a mean CBD value of 0.21 kg m-3 in radiata pine plantations. Both the above findings are fully consistent with the mean CBD value observed in middle-aged stands in this study (0.23 kg m-3). Nonetheless, the mean CBD we recorded in the very young and young stands was lower than that reported in other studies (Küçük et al. 2007a, Küçük & Bilgili 2008, Ruiz-González & Alvarez-González 2011).

Moreover, Küçük et al. (2007a) reported average values of 2.20 kg m-2 and 0.148 kg m-3 for CFL and CBD, respectively, in a 13-year old Anatolian black pine plantation in the Northwestern Turkey.

In most of the carbon determination studies, dead fuel on trees was generally not taken into consideration. The result of this study highlight the importance of including the dead fuel load in investigations aimed to forest carbon assessment.

Conclusion

The changes of dead and living fuel in 10- to 28-year-old non-treated Calabrian pine plantations in Turkey were investigated. Dead fuel load in very young, young and middle aged stands was approximately 26.2%, 22.9% and 32.1% of the total crown fuel load, respectively.

Fuel loads were assessed from the mineral soil to the upper canopy for stands at three different stage of development. Our results may contribute to classify and mapping fuels with new technological methods, to enhance the fuel model predictions in Calabrian pine plantations in Turkey, and to determine post-fire fuel consumption.

List of abbreviations

The following abbreviations have been used throughout the paper: (A): Tree age; (AF): Active fuel; (BF): Thin branches; (BM): Medium branches; (BT): Bark thickness; (BTH): Thick branches; (BVF): Very thin branches; (BVT): Very thick branches; (CBD): Canopy bulk density; (CBH): Crown base height; (CFL): Crown fuel load; (CL): Crown length; (CW): Crown width; (DBH): Diameter at breast height; (GDF): General Directorate of Forestry; (H): Tree height; (N): Needle; (RCD): Root collar diameter; (TCFL): Total crown fuel load; (TDCFL): Total dead crown fuel load; (TLCFL): Total live crown fuel load.

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Author contributions

MY: field measurements, sample collection, lab analysis, data entry, statistical analysis, helped in writing the manuscript draft; IB: conceived the study and methodology, helped in field measurements, lab analyses, data processing, validation and statistical analysis, supervision, editing and revision of the manuscript; ÖK: conceived the study and methodology, statistical analysis, supervision, editing and revision of the manuscript.

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Supplementary Material

Tab. S1 - Descriptive statistics of the sample plots.

Tab. S2 - Surface fuel characteristics for the studied stands (t ha^{-1}).

Tab. S3 - Descriptive statistics of sampled trees for the determination of crown fuel load.

Tab. S4 - Quantitative descriptive data of crown fuel components in sampled trees.

Tab. S5 - Parameters of the models used for the calculation of live tree crown fuels in trees with DBH >20 cm.

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