

Vertical Crown Fuel Distributions in Natural Calabrian Pine (*Pinus brutia* Ten.) Stands

Ismail Baysal

Abstract

Calabrian pine (*Pinus brutia* Ten.) is the most widely distributed coniferous species in Turkey. Forests mostly composed of Calabrian pine constitute the most flammable forests in fire sensitive regions of the country. Especially, regenerated and immature stands of this species have the most fire-prone fuel type. This study evaluates the results of vertical crown fuel distribution and develops some crown fuel models to explain canopy fuel characteristics in natural Calabrian pine stands. A total of 35 trees were cut down and crown fuels were determined vertically. The highest crown fuel load was generally situated in the middle part of tree crown. The percentage of needles in each crown section increased gradually from the beginning of lower parts to the upper parts of tree crowns for three stand types. Total crown fuel loads were determined as 5.66 kg for regenerated stands, 11.57 kg for immature stands and 17.44 kg for middle age stands, respectively. Correlation and regression analyses were performed to determine the relationship between needles, branches, available fuels, total crown fuels and tree properties. The results of crown fuel distribution and the allometric equations developed in this study can be used to predict vertical fuel load at any height from ground to the top of Calabrian pine stands. The results of this study will contribute to the verification and evaluation of fuel load prediction models in use, and enhance the understanding of crown fire behavior mechanism in forest fires.

Keywords: biomass, crown fuels, available fuel, *Pinus brutia*

1. Introduction

In forest ecosystems, fuels are the result of stand growth and development, and are an indispensable part and driver of fire behavior and essential components of fire management. Forest managers are mainly interested in the amount of volume increment, while forest fire researchers and fuel managers are mostly interested in the productive parts of trees as a flammable material. Fire managers and fire management activities generally focus on decreasing or modifying the amount and properties of fuel (Agee et al. 2000, Agee and Skinner 2005) for the mitigation of fire behavior (Roccaforte et al. 2008) and management of forest fires (Hornby 1936, Ager et al. 2010, Syphard et al. 2011). This is due to the fact that fuels are the only parameters that can be intervened and controlled by the foresters among the other fire behaviour parameters such as topography and weather. Also, the characteristics and the dynamics of crown fuel load are

essential information for effective fire behavior prediction modeling (Kucuk et al. 2015) and fuel management practises (Cruz et al. 2003, Yavuz et al. 2018). Properties of forest fuels and fuel continuity at stand (Bilgili 2003) and forest level (He et al. 2004) determine fire behavior and its management (Keane et al. 2001, Omi 2015) especially in crown fire prone conifer forests (Cruz and Alexander 2017).

In conifer forests, crown fuels are the primary sources of flammable materials of stand canopies (Cruz et al. 2003). It is necessary to gather some information about the main parameters of canopy fuels (e.g., crown base height, crown fuel load and canopy bulk densities) (Cruz and Alexander 2014) for elucidating (Van Wagner 1977) and exploring of crown fire phenomena (Keyser and Smith 2010, Alexander et al. 2013) with existing fire models (Andrews 1986, Scott 1999, Finney 1998). The crown base height is an important parameter for the initiation of crown fire along

with surface fire, while the density of the crown fuel load supports the fire intensity and the spread rate of active crown fire. Determining crown fuel load, assessing canopy fuel characteristic and modeling crown fuel components are needed for forest fire behavior researches (Kucuk and Bilgili 2008), fire management plans (Hornby 1936), assessment of crown fire hazard (Scott and Reindhart 2001) and fuel management priorities (Corona et al. 2015). Moreover, description and modeling crown fuel characteristics in different stand types have crucial importance in fire management and forest management planning initiatives. Recent advances in predicting crown fire behavior require repeatable and meaningful estimation of canopy fuels (Kucuk et al. 2007) and investigation of its vertical distributions (González-Ferreiro et al. 2017).

To date, most studies were conducted to investigate the amount of crown fuel loads in some coniferous species (Brown 1978, Stocks 1980, Johnson et al. 1990, Mitsopoulos and Dimitrakopoulos 2007a, Kucuk et al. 2007, Bilgili and Kucuk 2009, Moore 2010). However, crown fuel distribution by vertical distribution on tree crowns was rarely taken into account (Kellomaki et al. 1980, Mäkelä and Vanninen 2001, Mitsopoulos and Dimitrakopoulos 2007b, Kucuk et al. 2007, Gómez-Vázquez et al. 2013). Over the last decade, crown fuel load (Kucuk et al. 2008, Kucuk and Bilgili 2008, Bilgili and Kucuk 2009, Güngöroğlu et al. 2018) or biomass determination studies in Calabrian pine species have been gaining more interest in Turkey (Durkaya et al.

2009, Sönmez et al. 2016, Eker et al. 2017, Sakici et al. 2018) and sparsely distributed areas in Europe and elsewhere (Zianis et al. 2011, de Miguel et al. 2014).

In spite of the existence of some studies on this species, there are no studies dealing with the characterization of vertical crown fuel distribution in tree and stand level from natural Calabrian pine stands. Therefore, the main objective of this study was to investigate and characterize vertical distribution of crown fuel in natural Calabrian pine stands. The study also focuses on the development of crown fuel models to assess canopy fuel characteristics of Calabrian pine stands.

2. Materials and Methods

2.1 Study Area

The study area is located at $36^{\circ} 54' 36'' - 37^{\circ} 10' 58''$ N and $31^{\circ} 02' 00'' - 31^{\circ} 13' 52''$ W coordinates. Sampling plots were selected from Akbaş Forest Planning Unit under the responsibilities of Serik State Forest Enterprise in Antalya Regional Directorate of Forestry. Elevation ranges from 250 to 370 m. Soil characteristics in the area are shallow and loam and sandy loam of limestone origin. In the study area, Mediterranean climate prevails characterized by dry and hot summer season with mild and rainy winters (GDF 2011) (Fig. 1).

The study area covers 20 654.7 ha of land area with 10 158.2 ha of forests. Productive forest area comprises of 7907.0 ha, while the remaining 2251.2 ha is non-

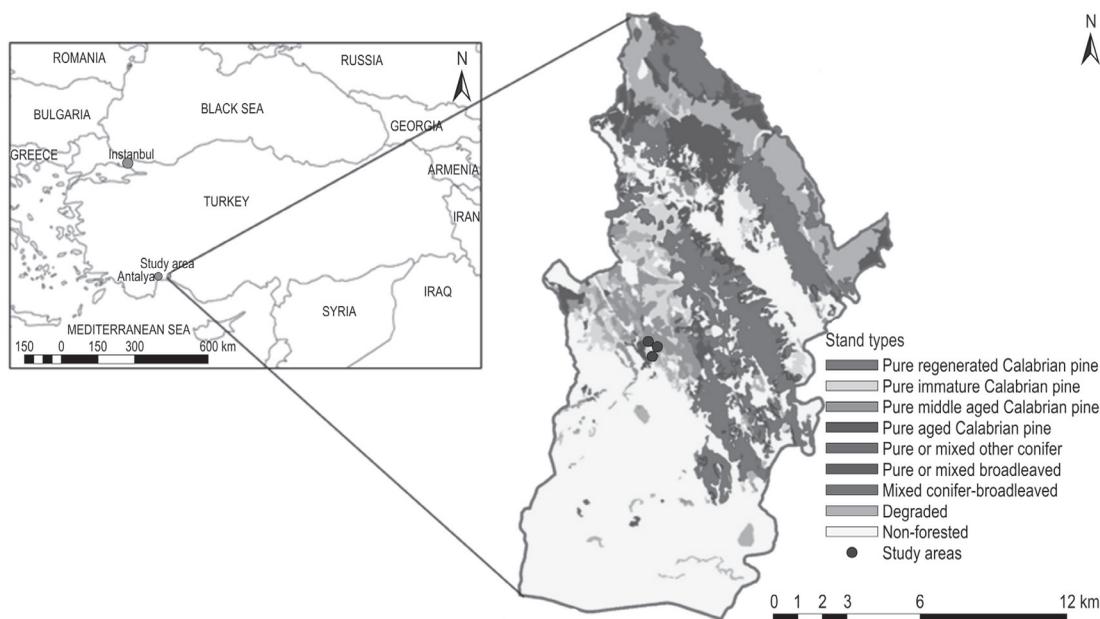


Fig. 1 Study area

productive. Forests of the study area are mainly composed of pure Calabrian pine stands (82%) (GDF 2011). This species has the largest distribution covering of nearly 5.8 million ha of forest lands in Turkey (GDF 2015). Calabrian pine is critically important in forest management studies because it is a fire prone species (Neyişi 1986) both in the case study area (Bilgili and Baysal 2013) and in the fire sensitive regions in Turkey (Bilgili and Kucuk 2009). The case study area was selected because of a few reasons. First of all, it is situated in a highly fire-sensitive region of the country and in the case study forests. Second, the forest is one of the most vulnerable forest areas to forest fires both in Turkey and Antalya Regional Directorate of Forestry. Lastly, the species composition of the area is mostly dominated by Calabrian pine prone to forest fires. Most of the forests in the case study area was burned by Antalya Serik-Taşagül forest fire in 2008 (Bilgili et al. 2010). As a result of frequent and large forest fires, nearly 65% of productive forests and nearly 50% of total forested areas in the case study area are composed of regenerated, immature or middle age Calabrian pine stands (Bilgili and Baysal 2013). These stands are very prone to intense crown fires because of their fuel characteristics (Bilgili et al. 2010). In this context, investigation of crown fuel characteristics of those stands is of great importance in fuel management and forest fire fighting activities in Calabrian pine dominated forests.

2.2 Measurement and Data Collection

First of all, some measurements and observations were conducted to obtain general characteristics of regenerated, immature and middle aged Calabrian pine stands. To do this, a total of 9 sampling plots was selected from pure and even-aged Calabrian pine stands with crown closure greater than 70%. All selected sampled plots had been treated at least once by commercial thinning before the study. The shape of the sampling plots was circular with radius ranging from 200 m² for regenerated stands to 400 m² for immature and middle aged stands. In calculating mean stand values for sampling plots, dead trees and trees with diameter at breast height (DBH) less than 8 cm were not taken into consideration. A total of nine sample plots, three for each stand type, were selected for this research. For the regenerated stands, three sample plots were taken and a total of 76 trees was measured. For immature stands, again three sample plots were selected and a total of 84 trees were measured. For middle aged stands, three sample plots were selected and a total of 79 trees were measured. In all sampling plots, a total of 239 trees were measured. Those three stand types are typical and representative of the case

study area. In each sample plot, the following tree characteristics were measured:

- ⇒ tree age – A, counted increment core in diameter at breast height
- ⇒ root collar diameter – RCD, cm
- ⇒ diameter at breast height – DBH, cm
- ⇒ tree height – H, m
- ⇒ crown base height – CBH, m
- ⇒ crown width – CW, m
- ⇒ crown length – CL, m
- ⇒ bark thickness of the tree trunk measured with bark gauge tool at 0.3 m above ground – BT, cm

A total of 35 trees were selected specifically to assess the amount of crown fuel and its vertical distribution on trees. The subject trees were selected taking into consideration the approximate expression for the average properties of the stands. All trees were selected from the dominant or codominant trees (Kraft 1884). Trees with defoliated branches on tree crowns or broken tops were disregarded (Brown 1978). The selected trees were cut at 0.3 m above forest floor and felled carefully by a professional forest worker supported by a few people to avoid any adverse effects such as loss of biomass. Tree height, live crown base height and crown length were measured for the verification of primer measurement data after felling the trees. Small trees were carefully handled as a whole and big trees were transported in two or three pieces to the nearest forest fire fighter team building. Trees were sectioned and marked in two meter long pieces from the cutting point up to the top of the tree. All living branches and needles for each 2 meter sections were removed from the trunk and carefully measured. Sectioning the trees and determining fuel materials for each section were conducted to obtain average values of fuel and its distribution both at tree crown and stand canopies of the sampled stands.

Needles were removed from the branches carefully and put into a tent cloth. The branches were then categorized into five classes such as:

- ⇒ very fine – VFB, 0–0.3 cm
- ⇒ fine – FB, 0.3–0.6 cm
- ⇒ medium – MB, 0.6–1 cm
- ⇒ thick – TB, 1–2.5 cm
- ⇒ very thick – VTB, >2.5 cm branch size (Kucuk et al. 2007).

Different classes of branches were separated into different buckets. The weights of all needles and branches for each 2 meter section were determined with precision scales (0.1 g sensitivity) in the field. For the determination of oven dried weights of the

measured fresh weight, sub-samples were taken, placed in wooded bags and transported to the laboratory. The sub-samples were placed in an oven and dried for 48 hours at 105 °C. Oven-dried fuel weights were measured at 0.01 sensitivity scale in the laboratory. Sub-samples were taken from nearly 5–10% of the total weight for needles and each branch class for each 2 m section. If the amount of needles and branches is quite low (i.e., if they have a volume that can fit in wooded bags), no sub-samples were taken. All materials were placed into wooded bags used to prevent deterioration (i.e., mold or rot) of the needles and branches and carry out fast drying of samples.

2.3 Statistical Analysis

All statistical analyses were performed using SPSS Statistics 21 for Windows. Descriptive statistics were used in order to obtain minimum, maximum, average, standard error of the estimate and standard deviation values of the sampled trees from the sampling plots taken from the sampled stands. Correlation and regression analysis were performed to determine tree properties and crown fuel components. Before the correlation and regression analyses, data were tested for normality. Parametric linear regression model was used to develop crown fuel and its components estimation. In linear regression, a stepwise procedure was followed. RCD (Root Collar Diameter), DBH (diameter at breast height), H (height), CBH (crown base height), CW (crown width), CL (crown length) were considered as independent variables. The needles (N), branches (VFB, FB, MB, TB, and VTB), available

amount of fuel load (AF) (generally composed of N, VFB and FB and usually consumed during crown fires Stocks et al. 2004), total fuel load (TFL) (N, VFB, FB, MB, TB, and VTB in each two meter section) and total crown fuel load (TCFL) (needle and branches) were considered as dependent variables. The evaluations were performed based on oven-dried fuel weight.

3. Results and Discussion

3.1 Stand Characteristics

In sampling plots, a total of 239 trees were measured. Minimum age was measured in regenerated stands as 7 and maximum A was measured as 24 in immature stands with an average of 13.8 a year at DBH level. Minimum CBH was measured in regenerated stands as 0.4 m and maximum 12.5 m in immature stands with an average of 3.8 m. Minimum H was measured in regenerated stands as 3.8 m and maximum 22.5 m in middle aged stands with an average of 10.98 m. The number of trees per hectare ranges from 575 to 1550 with an average of 914 tree. Basal area ranges from 5.47 to 28.99 m² ha⁻¹ with an average of 16.9 m² ha⁻¹. Some descriptive statistics of the sample plots and measured trees properties for three stand types are given in Table 1.

3.2 Crown Fuel Load and Vertical Fuel Distribution

All sampled trees in the sampling plots were measured to investigate total crown fuel loading in tree

Table 1 Some average properties of measured trees in sampling plots

Stand type	Sampling plots	Statistics	A, year	DBH, cm	H, m	CBH, m	CW, m	CL, m	BT, cm	Trees, ha	BA, m ² ha ⁻¹
Regenerated	3 Measured 76 trees	Min.	7.00	8.00	3.80	0.40	1.10	2.25	1.10	1150.00	9.53
		Max.	14.00	16.00	12.75	5.25	4.40	9.85	4.00	1550.00	14.29
		Average	11.09	10.71	8.02	2.13	2.65	5.91	2.41	1266.67	11.85
		S.E.E.	0.78	0.26	0.22	0.12	0.08	0.18	0.06	120.19	1.37
		S.D.	2.58	2.26	1.89	1.03	0.71	1.57	0.52	208.17	2.38
Immature	3 Measured 84 trees	Min.	10.00	8.00	5.00	1.00	1.10	3.85	1.30	575.00	5.47
		Max.	19.00	24.00	14.50	6.00	7.90	12.70	5.00	900.00	20.51
		Average	14.36	14.08	10.87	3.26	3.39	7.60	3.13	700.00	11.82
		S.E.E.	0.83	0.45	0.29	0.13	0.13	0.22	0.09	101.07	4.50
		S.D.	2.77	4.13	2.62	1.22	1.23	2.03	0.83	175.00	7.79
Middle aged	3 Measured 79 trees	Min.	12.00	8.00	6.75	1.70	1.15	1.50	1.70	575.00	13.05
		Max.	24.00	37.00	22.50	12.50	6.65	13.00	6.00	775.00	28.99
		Average	15.83	18.89	14.06	5.88	3.57	8.18	3.59	658.33	20.43
		S.E.E.	1.23	0.70	0.44	0.34	0.15	0.29	0.10	60.09	4.64
		S.D.	4.26	6.26	3.90	3.04	1.32	2.53	0.90	104.08	8.04

*Min. – Minimum; Max. – Maximum; Av. – Average; S.E.E. – Standard Error of Estimate; S.D. – Standard Deviation; BA – Basal Area

crowns for each stand type. The properties of the destructively sampled trees are given in Table 2.

To characterize and illustrate the amount of crown fuel load and its components from the beginning of CBH to the top of tree, crown fuels were fully destructively determined without taking sub-samples

(Mitsopoulos and Dimitrakopoulos 2007a) for each 2 meter section (Tahvanainen and Forss 2008) for each sampled tree (Table 3).

Afterwards, the percentages of each crown fuel component was calculated in relation to total fuel load of each section of the tree. Additionally, the percentage

Table 2 Sampled tree properties and crown fuel characteristics

Stand type	Statistics	Sampled tree characteristics							
		A, year	RCD, cm	DBH, cm	H, m	CBH, m	CW, m	CL, m	BT, cm
Regenerated 12 trees among 76 sample trees	Min.	15.00	12.00	8.00	6.90	1.50	2.00	3.80	1.60
	Max.	33.00	17.50	11.40	9.30	5.50	3.10	7.10	2.80
	Av.	21.08	14.56	9.69	8.18	2.65	2.56	5.52	2.07
	S.E.E.	1.46	0.55	0.32	0.26	0.32	0.09	0.28	0.13
	S.D.	4.98	1.90	1.11	0.89	1.02	0.32	0.96	0.45
Immature 12 trees among 84 sample trees	Min.	25.00	15.20	12.40	8.95	2.80	2.50	4.57	1.30
	Max.	38.00	22.60	16.00	11.75	6.60	4.85	8.85	3.40
	Av.	29.41	19.46	14.01	10.54	3.69	3.62	6.84	2.38
	S.E.E.	1.46	0.75	0.34	0.28	0.33	0.20	0.33	0.17
	S.D.	5.07	2.59	1.19	0.97	1.15	0.70	1.15	0.60
Middle aged 11 trees among 79 sample trees	Min.	25.00	17.50	11.40	9.30	2.38	2.65	3.80	1.60
	Max.	41.00	28.30	20.00	15.90	8.90	4.70	10.12	4.00
	Av.	32.75	23.83	17.53	13.00	5.18	3.88	7.82	2.81
	S.E.E.	1.40	0.79	0.63	0.64	0.68	0.20	0.46	0.24
	S.D.	4.85	2.74	2.19	2.21	2.35	0.68	1.61	0.83

Table 3 Sampled tree crown fuel characteristics

Stand type	Statistics	Crown fuel characteristics							
		N, g	VFB, g	FB, g	MB, g	TB, g	VTB, g	AF, g	TCFL, g
Regenerated 12 trees	Min.	1393.39	226.55	619.63	351.60	990.36	0.00	2293.94	3635.90
	Max.	3358.91	872.45	1259.43	842.86	2475.28	241.20	4952.16	7523.35
	Av.	2272.00	485.16	857.66	563.97	1453.07	25.43	3614.83	5657.31
	S.E.E.	209.58	59.77	59.27	48.53	117.19	20.32	294.94	369.84
	S.D.	726.02	207.04	205.33	168.11	405.98	70.40	1021.69	1281.18
Immature 12 trees	Min.	2238.54	362.74	842.67	539.03	1319.65	0.00	3660.59	5941.29
	Max.	4571.07	1170.64	2247.60	1615.92	5377.15	4497.14	7487.41	18300.94
	Av.	3404.25	709.90	1562.43	1168.38	3813.80	907.96	5676.58	11566.72
	S.E.E.	214.88	73.59	133.05	93.61	334.06	375.15	387.57	1008.16
	S.D.	744.37	254.94	460.89	324.27	1157.21	1299.57	1342.56	3492.38
Middle aged 11 trees	Min.	3258.86	431.60	912.98	447.98	1216.26	64.05	4759.96	6488.24
	Max.	7852.77	2575.92	3246.05	2378.62	7626.60	5355.76	13 370.50	26 514.10
	Av.	5649.45	1097.39	2245.54	1562.93	4624.59	2262.48	8992.39	17442.39
	S.E.E.	438.89	166.58	176.54	155.08	512.08	511.57	723.06	1687.95
	S.D.	1520.36	577.04	611.55	538.77	1773.91	1772.12	2504.75	5847.22

of each crown fuel component was also calculated in relation to total crown fuel load of each tree. Hence, vertical distribution of crown fuels and its components were characterized at tree crown and stand canopy level (Mitsopoulos and Dimitrakopoulos 2007b). Distribution of crown fuel components for three stand types are given in Table 4.

According to data, the highest fuel load was found in needle category (39.71%) for the regenerated stands, thick branch category (33.08%) for the immature stands, and needle category (32.54%) for the middle aged stands, respectively. The highest available crown fuel load (Stocks et al. 2004) of 63.28% was measured for the regenerated stands, 50.34% for the immature stands and 51.77% for the middle aged stands, respectively. The highest percentage in crown fuel load was located in the middle part of tree crown sections with 41.10% for regenerated, 37.46% for im-

mature and 24.36% for middle aged stands, respectively (Table 3). The percentages of needle values gradually increased from the beginning of lower parts to the upper parts of tree crown for three stand types. The branches did not perform the general trends as in needle fuel category. However, available fuels performed the same trend as in needle fuel category. The amount of needles, available fuels and total crown fuel loads for each vertical section of tree crowns are illustrated in Fig. 2.

For the same tree species in Turkey, no information has been reported for the vertical distribution of needles and branches percentage over the tree crowns for a pre-determined length in studies including crown fuel load (Kucuk et al. 2008, Bilgili and Kucuk 2009, Güngöroğlu et al. 2018) and biomass determination (Durkaya et al. 2009, Sönmez et al. 2016, Sakici et al. 2018, Eker et al. 2017). Similar information

Table 4 Average vertical fuel distribution percentages in stand canopies

Stand Type	VD, m	N ¹ %	N ² %	VFB ¹ %	VFB ² %	FB ¹ %	FB ² %	MB ¹ %	MB ² %	TB ¹ %	TB ² %	VTB ¹ %	VTB ² %	AF ¹ %	AF ² %	TCFL ¹ %	TCFL ² %
Regenerated	14.30–15.90	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	12.30–14.30	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	10.30–12.30	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	8.30–10.30	57.61	0.93	7.89	0.13	14.17	0.24	9.72	0.16	10.61	0.19	–	–	79.67	1.30	100	1.65
	6.30–8.30	48.23	12.63	7.04	1.70	14.09	3.56	10.66	2.73	18.17	4.73	1.81	0.51	69.36	17.89	100	25.86
	4.30–6.30	41.16	16.53	8.44	3.41	15.31	6.47	9.22	3.85	25.87	10.84	–	–	64.91	26.41	100	41.10
	2.30–4.30	32.97	8.88	9.41	2.63	15.50	4.48	10.12	2.85	32.00	9.62	–	–	57.88	15.99	100	28.46
	0.30–2.30	25.08	0.74	14.04	0.41	18.56	0.54	12.41	0.37	29.91	0.87	–	–	57.68	1.69	100	2.93
Immature	14.30–15.90	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	12.30–14.30	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	10.30–12.30	58.71	0.75	6.21	0.09	18.58	0.23	11.01	0.14	5.49	0.07	–	–	83.50	1.07	100	1.28
	8.30–10.30	42.68	7.20	6.03	1.02	14.18	2.39	14.30	2.53	21.93	3.61	0.88	0.11	62.89	10.61	100	16.86
	6.30–8.30	35.18	13.45	6.20	2.34	14.46	5.44	9.60	3.64	30.01	11.14	4.55	1.45	55.84	21.23	100	37.46
	4.30–6.30	22.77	7.89	6.11	2.05	12.55	4.28	9.08	3.11	35.89	12.17	13.60	3.76	41.43	14.22	100	33.26
	2.30–4.30	10.15	1.17	6.15	0.67	11.84	1.37	9.31	1.00	51.41	6.09	11.14	0.84	28.14	3.21	100	11.14
	0.30–2.30	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Middle aged	14.30–15.90	56.33	0.63	6.38	0.07	12.38	0.14	15.12	0.17	9.79	0.11	–	–	75.09	0.84	100	1.12
	12.30–14.30	50.31	3.68	5.31	0.37	13.02	0.92	8.40	0.60	22.96	1.63	–	–	68.64	4.97	100	7.20
	10.30–12.30	42.35	7.96	6.12	1.13	14.66	2.88	9.20	1.73	22.83	4.71	4.84	0.78	63.13	11.97	100	19.19
	8.30–10.30	34.19	8.18	5.83	1.40	13.11	3.28	9.25	2.32	26.62	6.61	11.00	2.57	53.13	12.86	100	24.36
	6.30–8.30	29.21	6.85	6.56	1.59	12.19	2.94	8.60	2.05	27.31	6.64	16.13	3.48	47.96	11.38	100	23.55
	4.30–6.30	23.16	4.10	6.15	1.06	11.83	2.10	9.08	1.61	27.16	4.78	22.62	4.17	41.14	7.26	100	17.82
	2.30–4.30	16.48	1.14	7.04	0.47	12.65	0.88	9.03	0.62	37.20	2.54	17.60	1.11	36.17	2.49	100	6.76
	0.30–2.30	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–

¹VD – vertical distance classes; ¹ – the percentage of each crown fuel component was calculated in relation to total fuel amount for each section of the tree; ² – the percentage of each crown fuel component was calculated in relation to total crown fuel load for each tree

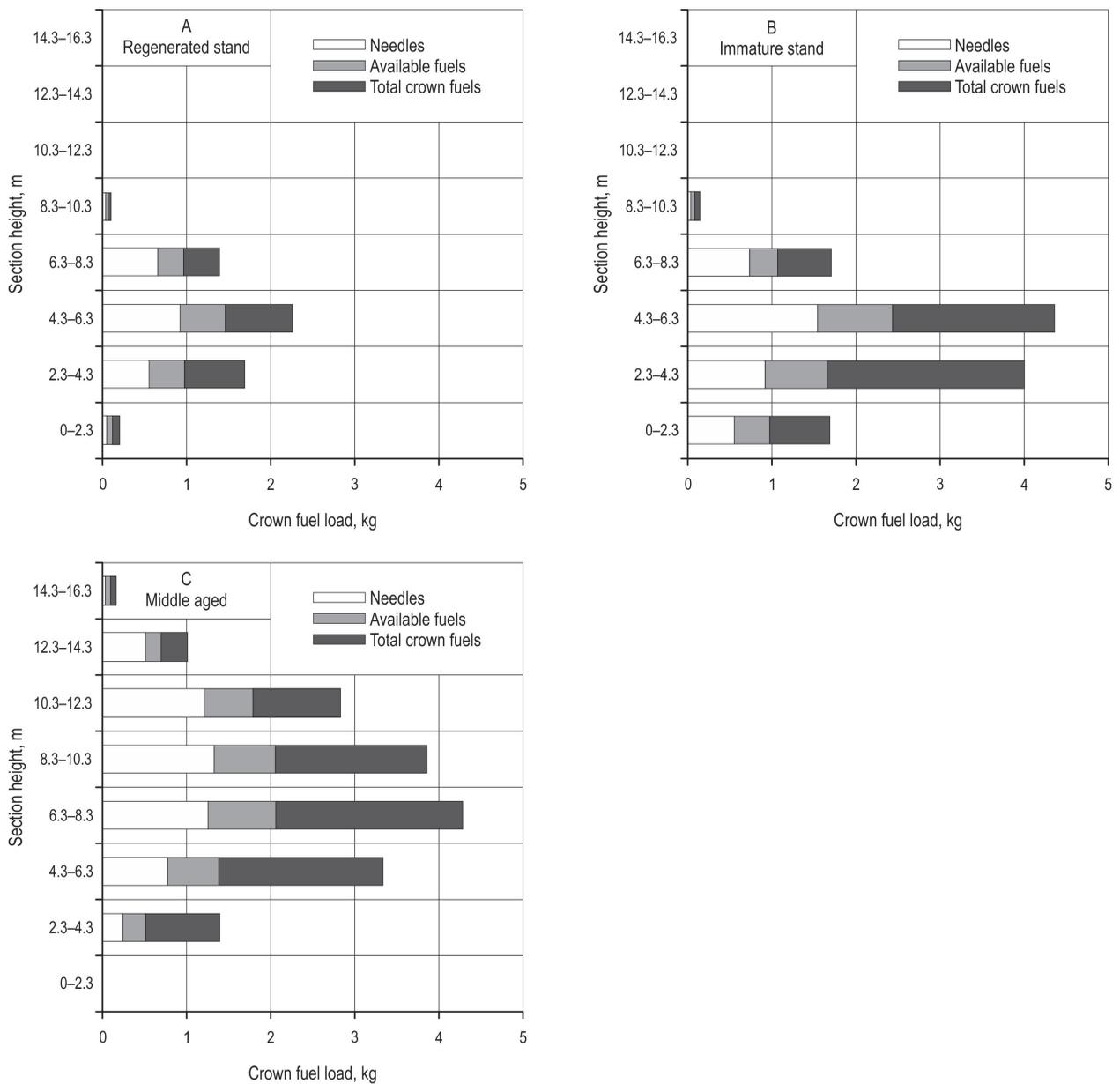


Fig. 2 Distribution of average needles, available fuels and total crown fuel on sampled trees for regenerated (a), immature (b) and middle aged (c) Calabrian pine stands

of vertical distribution of fuel or biomass on Calabrian pine trees from other countries has not been reported either (Zianis et al. 2011, de-Miguel et al. 2014). However, a work conducted in young Black pine *Pinus nigra* Arnold trees in Turkey (Kucuk et al. 2007) provided some information to explain the vertical fuel distribution. According to Kucuk et al. (2007), the highest fuel load was observed in the mid-portion of the crowns, the lowest fuel load was observed in the upper part of the crowns and moderate fuel weight was found in the lower part of the crowns. Our study

results are consistent with the results of Kucuk et al. (2007) in the middle, lower and upper parts of tree crown fuel load.

The percentage of needle weight within the live crown weight in regenerated Calabrian pine stands (39.71%) is close to Black pine needle weight (41%) (Kucuk et al. 2007) and Red pine (*Pinus resinosa* Ait.) needle weight (43%) (Brown 1965). These percentages for immature (30.46%) and middle aged stands (32.54%) are close to Calabrian pine needle weight percentage value (29.97%) found in the study conducted

for the same region by Güngöroğlu et al. (2018). However, Kucuk and Bilgili (2008) found this percentage very low (19.1%) for the same tree species in the North-western part of Turkey; Mitsopoulos and Dimitrakopoulos (2007) also found a very low percentage (17.24%) for Aleppo pine (*Pinus halepensis* Mill.) in the northern part of the island of Evia in central Greece. Brown (1965) also presented low needle percentage (21%) in crown weight of Jack pine (*Pinus banksiana* Lamb.) in his study. Our results indicated high fuel percentages in regenerated (63.28%), immature (50.34%) and middle aged stands (51.77%), compared to the studies conducted by Kucuk and Bilgili (2008) (34.4%) and Bilgili and Kucuk (2009) (37%) for the same tree species. Mitsopoulos and Dimitrakopoulos (2007) found the lowest percentage value of available fuel (30.36%) for Aleppo pine. However, Kucuk et al. (2007) indicated much higher available fuel percentage (74%) in their study for Black pine species than those found in all stands in our case study. In addition, our results are in close agreement with the results (56.60%) presented by Güngöroğlu et al. (2018). Site conditions, silvicultural interventions, studying of the same and different species and the sampling methods used in collecting data may be the causes of these differences. The differences in the study results generally stem from the differences of site conditions, silvicultural interventions, studying of different species or different sampling methods (Poudel et al. 2015).

3.3 Some Crown Fuel Components and Total Crown Fuel Load Prediction Models

Correlation and regression analyses were undertaken to investigate the relationships between the properties of sampled trees and oven dry fuel weight of tree crown components. According to correlation analysis results, needle fuel weight was closely related to A, RCD, DBH, H, CL, and CW ($p < 0.01$). Very fine, fine, medium and thick branches fuel weight were closely correlated with RCD, DBH, H, CL, and CW ($p < 0.01$). Similarly, total crown fuel load was closely related to RCD, DBH, H, CL, and CW ($p < 0.01$). FB and TCFL were correlated well with A ($p < 0.05$). Correlation analysis results are given in Table 5.

Some regression equations were developed to predict crown fuel components regarding the Calabrian pine tree properties. According to the equations developed, DBH alone accounted for 74% of the observed variation in total needle amount for all trees ($p < 0.05$), 77% of the observed variation in available fuels ($p < 0.05$) and 76% of the observed variation in total biomass of branches ($p < 0.05$). DBH and CL together accounted for 80% of the observed variation in available fuels ($p < 0.05$). DBH and CBH together accounted for 88% of the observed variation in total branches weight ($p < 0.05$). For the estimation of total crown fuel load, DBH alone accounted for 80% of the observed variation in total crown fuel load of sampled trees ($p < 0.05$). DBH and CBH together

Table 5 Correlation matrix

	A	RCD	DBH	H	CBH	CW	CL	N	VFB	FB	MB	TB	VTB	AF	TCFL
A	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–
RCD	.431**	1	–	–	–	–	–	–	–	–	–	–	–	–	–
DBH	.554**	.953**	1	–	–	–	–	–	–	–	–	–	–	–	–
H	.740**	.753**	.844**	1	–	–	–	–	–	–	–	–	–	–	–
CBH	.740**	.351*	.473**	.787**	1	–	–	–	–	–	–	–	–	–	–
CW	.259	.774**	.767**	.621**	.005	1	–	–	–	–	–	–	–	–	–
CL	.202	.829**	.790**	.483**	.030	.744**	1	–	–	–	–	–	–	–	–
N	.452**	.844**	.851**	.713**	.300	.775**	.706**	1	–	–	–	–	–	–	–
VFB	.212	.708**	.667**	.439**	-.012	.728**	.584**	.797**	1	–	–	–	–	–	–
FB	.406*	.890**	.886**	.693**	.228	.833**	.788**	.887**	.808**	1	–	–	–	–	–
MB	.452**	.847**	.863**	.691**	.253	.798**	.767**	.830**	.704**	.934**	1	–	–	–	–
TB	.226	.864**	.841**	.511**	.020	.802**	.893**	.723**	.683**	.881**	.842**	1	–	–	–
VTB	-.006	.602**	.675**	.245	-.118	.547**	.711**	.683**	.562**	.691**	.731**	.719**	1	–	–
AF	.422**	.873**	.870**	.697**	.245	.818**	.740**	.984**	.869**	.944**	.875**	.791**	.700**	1	–
TCFL	.354*	.895**	.896**	.639**	.159	.833**	.852**	.915**	.809**	.956**	.924**	.917**	.875**	.950**	1

*Correlation significant at the 0.05 level (2-tailed)

**Correlation significant at the 0.01 level (2-tailed)

accounted for 88% of the observed variation in total crown fuel load ($p < 0.05$) (Table 6).

According to the developed allometric equations for the estimation of different fuel components of tree crown, predicted and observed available fuel load (for model 2b), predicted and observed total crown fuel load (for model 4b) are given in Fig. 3. According to the results of crown fuel load determination studies conducted for the same tree species in fire sensitive region of Turkey, CW and H ($R^2 = 0.944$; $p < 0.01$) (Kucuk et al. 2008), CL and CW ($R^2 = 0.937$; $p < 0.01$) (Bilgili and Kucuk 2009), CL and DBH ($R^2 = 0.858$; $p < 0.01$) (Güngöroğlu et al. 2018) were used to estimate total crown fuel load in the developed regression models. In crown fuel load determination study for young Black pine trees in Turkey, Kucuk et al. (2007) used DBH to estimate total crown fuel load ($R^2 = 0.941$;

$p < 0.01$). Durkaya et al. (2009) used DBH and H ($R^2 = 0.841$; $p < 0.01$) to estimate total crown biomass on Calabrian pine species from the eastern part of Mediterranean region in Turkey (Fig. 3).

4. Conclusions

The characteristics and vertical distributions of crown fuels in natural Calabrian pine stands from the very fire sensitive Mediterranean region of the country were investigated in this study. With this study, unlike the other studies on this species, all live crown fuels weight of sampled Calabrian pine trees were determined with destructively labor-insensitive studies in the field. Models were developed to estimate total crown fuel load of foliage, available fuels and all components that could be developed using DBH parameter with

Table 6 Regression models developed for estimation of needles, available fuel, branches and total crown fuel load

Model No.	Models	F	R^2_{Adj}	SEE	Sig.
1a	$TCFL_{needle} = -2094.97 + (426.182 \times DBH)$	99.294	74.3	± 903.385	< 0.001
2a	$TCFL_{available} = -3409.773 + (691.057 \times DBH)$	113.255	76.8	± 1371.587	< 0.001
2b	$TCFL_{available} = -4762.276 + (515.752 \times DBH) + (553.675 \times CL)$	68.041	79.8	± 1279.439	< 0.001
3a	$TCFL_{branches} = -7678.458 + (1128.916 \times DBH)$	106.281	75.6	± 2312.982	< 0.001
3b	$TCFL_{branches} = -7578.854 + (1394.867 \times DBH) + (-994.575 \times CBH)$	123.880	87.8	± 1632.022	< 0.001
4a	$TCFL_{all} = -9773.432 + (1555.098 \times DBH)$	138.920	80.2	± 2786.858	< 0.001
4b	$TCFL_{all} = -9664.563 + (1845.786 \times DBH) + (-1087.087 \times CBH)$	129.129	88.3	± 2144.798	< 0.001

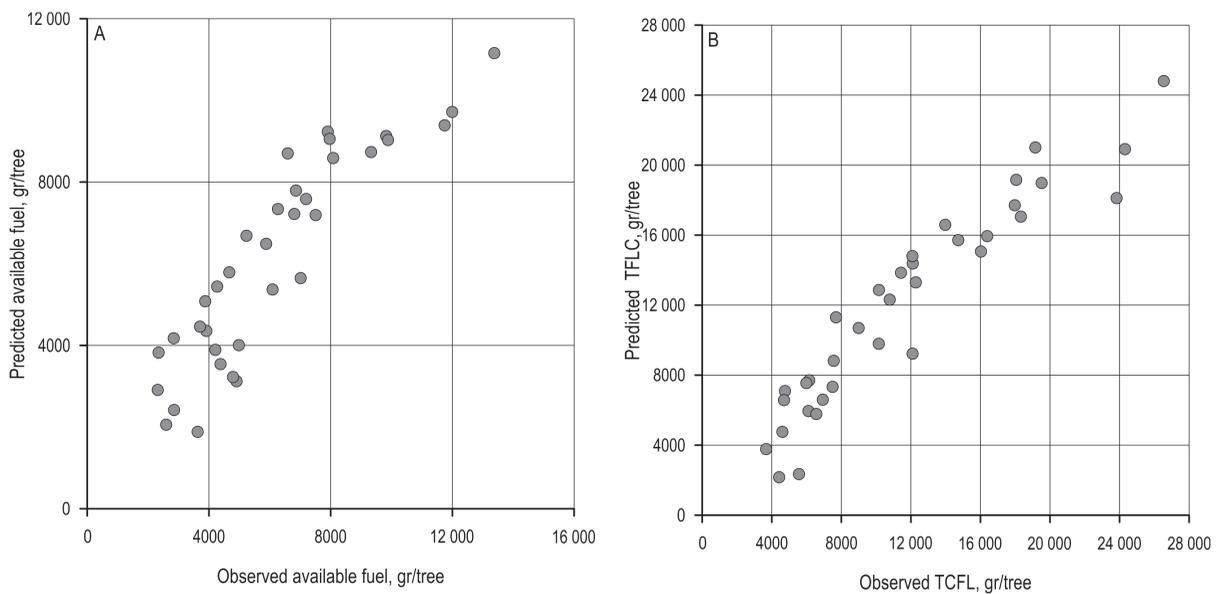


Fig. 3 Relationship between predicted and observed available fuel (a) and total crown fuel load (b)

high accuracy. In fact, DBH is a convenient parameter as it is usually measured during the field survey or estimated from remotely sensed data for forest inventory process and readily available for model development. In addition to DBH parameter, interpreting remote sensing data for obtaining some crown parameters (i.e. CBH, CL, and CW) also enhances the capabilities of representing fuel characteristics. The models developed in this study predicted weight of crown fuel components at any height from ground to top of tree using crown fuel components percentage. The model enables to predict the vertical distribution of crown fuels components and their weights for any height in stand canopies.

The results can help in assessing the critical pruning height and time for most flammable Calabrian pine stands for preventing crown fires. In fact, the forest practitioners need to carry out forest thinning operations (i.e., pre-commercial thinning) at the right time with the appropriate rate, particularly for fast growing natural trees of Calabrian pine in order to reduce the flammable loads of trees. The study indicates that timely treatment of young stands with appropriate rate is highly crucial as the fire frequency and sensitivity in young Calabrian pine stands are high according to the history of forest fires. The results may also be valuable for explaining and exploring crown fire initiation and spread mechanism both in forest fire fighting and forest fire research studies.

To enhance the functionality of the models, further research is necessary to investigate dead fuel materials in both natural or artificial Calabrian pine and other pine stands. The results here are mainly based on the data obtained from the range of tree properties and stands located in fire sensitive regions of Turkey. The regression models developed in this study works well for the same local conditions and for the range of measured tree properties. It was recommended that future similar studies using remote sensing methods be conducted for the representation of other Calabrian pine stands and widely distributed geographical forested areas for making accurate and improved predictions.

Acknowledgments

The author greatly acknowledges the support of General Directorate of Forestry and its institutions for their valuable contributions. Also, the author greatly acknowledges the support of Serik District Forest Ranger and forest fire fighters. Special thanks go to Cafer MEYDAN, Merih GÖLTAŞ, Uğur KARAKOÇ, Ferhat BOLAT and Kadir Alperen COŞKUNER for their great help in field work.

5. References

- Agee, J.K., Bahro, B., Finney, M.A., Omi, P.N., Sapsis, D.B., Skinner, C.N., Van Wagtenonk J.W., Weatherspoon, C.P., 2000: The use of shaded fuel breaks in landscape fire management. *Forest Ecology and Management* 127(1–3): 55–66. [https://doi.org/10.1016/S0378-1127\(99\)00116-4](https://doi.org/10.1016/S0378-1127(99)00116-4)
- Agee, J.K., Skinner, C.N., 2005: Basic principles of forest fuel reduction treatments. *Forest Ecology and Management* 211(1–2): 83–96. <https://doi.org/10.1016/j.foreco.2005.01.034>
- Ager, A.A., Vaillant, N.M., Finney, M.A., 2010: A comparison of landscape fuel treatment strategies to mitigate wildland fire risk in the urban interface and preserve old forest structure. *Forest Ecology and Management* 259(8): 1556–1570. <https://doi.org/10.1016/J.FORECO.2010.01.032>
- Alexander, M.E., Cruz, M.G., Vaillant, N.M., Peterson, D.L., 2013: Crown fire behavior characteristics and prediction in conifer forests: a state-of-knowledge synthesis. Final report to the Joint Fire Science Program, project 09-S-03-1.
- Andrews, P.L., 1986: BEHAVE: Fire behavior prediction and fuel modeling system—burn subsystem, Part 1. USDA Forest Service INT-GTR194. 130 p. <https://doi.org/10.2737/INT-GTR-194>
- Bilgili, E., 2003: Stand development and fire behavior. *Forest Ecology and Management* 179(1–3): 333–339. [https://doi.org/10.1016/S0378-1127\(02\)00550-9](https://doi.org/10.1016/S0378-1127(02)00550-9)
- Bilgili, E., Kucuk, O., 2009: Estimating above-ground fuel biomass in young Calabrian pine (*Pinus brutia* Ten.) in Turkey. *Energy & Fuels* 23(4): 1797–1800. <https://doi.org/10.1021/ef800346s>
- Bilgili, E., Baysal, İ., Dinç Durmaz, B., Sağlam, B., Küçük, Ö., 2010: Evaluating big forest fire break out in Turkey 2008. In: *Proceeding of the III. National Black Sea Forestry Congress; Artvin, Turkey* 1270–1279 p.
- Bilgili, E., Baysal, İ., 2013: The effects of forest fires on forest management plans: A case study of Akbaş forest sub-district. In: *Proceedings of for the 50th Anniversary of the Forestry Sector Planning in Turkey (In memory of Prof. Dr. İsmail ERASLAN)*; Antalya, Turkey, 224–233 p.
- Brown, J.K., 1978: Weight and density of crowns of Rocky Mountains conifers. USDA Forest Service, Intermountain Forest and Range Experiment Station, Research Paper INT-197, (Ogden, UT).
- Corona, P., Ascoli, D., Barbati, A., Bovio, G., Colangelo, G., Elia, M., Garfi, V., Iovino, F., Laforteza, R., Leone, V., Lovreglio, R., Marchetti, M., Marchi, E., Menguzzato, G., Nocentini, S., Picchio, R., Portoghesi, L., Puletti, N., Sanesi, G., Chianucciet, F., 2015: Integrated forest management to prevent wildfires under Mediterranean environments. *Annals of Silvicultural Research* 39(1): 1–22. <https://doi.org/10.12899/ASR-946>
- Cruz, M.G., Alexander, M.E., Wakimoto, R.H., 2003: Assessing canopy fuel stratum characteristics in crown fire prone fuel types of western North America. *International Journal*

- of Wildland Fire 12(1): 39–50. <https://doi.org/10.1071/WF02024>
- Cruz, M.G., Alexander, M.E., 2014: Canopy fuel characteristics of conifer forests. *Fire Management Today* 73(4): 12–16.
- Cruz, M.G., Alexander, M.E., 2017: Modelling the rate of fire spread and uncertainty associated with the onset and propagation of crown fires in conifer forest stands. *International Journal of Wildland Fire* 26(5): 413–426. <https://doi.org/10.1071/WF16218>
- De-Miguel, S., Pukkala, T., Assaf, N., Shater, Z., 2014: Intra-specific differences in allometric equations for aboveground biomass of eastern Mediterranean *Pinus brutia*. *Annals of Forest Science* 71(1): 101–112. <https://doi.org/10.1007/s13595-013-0334-4>
- Durkaya, A., Durkaya, B., Ünsal, A., 2009: Predicting the aboveground biomass of calabrian pine (*Pinus brutia* Ten.) stands in Turkey. *African Journal of Biotechnology* 8(11): 2483–2488.
- Eker, M., Spinelli, R., Gürlevik, N., 2017: Determining the quantity and quality of biomass obtained from the thinning of Turkish red pine stands. *Biofuels, Bioproducts and Biorefining* 12(1): 12–21. <https://doi.org/10.1002/bbb.1836>
- Finney, M.A., 1998: FARSITE: Fire area simulator-model development and evaluation. USDA Forest Service Research Paper RMRS-RP-4. 47 p. <https://doi.org/10.2737/RMRS-RP-4>
- GDF, 2011: Akbaş forest management plan. General Directorate of Forestry, Ankara, Turkey. 285 p. (in Turkish).
- GDF, 2015: Forest of Turkey. Republic of Turkey Ministry of Agriculture and Forestry, General Directorate of Forestry Publications, Ankara, Turkey, 32 p. (in Turkish).
- Gómez-Vázquez, I., Crecente-Campo, F., Diéguez-Aranda, U., Castedo-Dorado, F., 2013: Modelling canopy fuel variables in *Pinus pinaster* Ait. and *Pinus radiata* D. Don stands in Northwestern Spain. *Annals of Forest Science* 70(2): 161–172. <https://doi.org/10.1007/s13595-012-0245-9>
- González-Ferreiro, E., Arellano-Pérez, S., Castedo-Dorado, F., Hevia, A., Vega, J.A., Vega-Nieva, D., Álvarez-González, J.G., Ruiz-González, A.D., 2017: Modelling the vertical distribution of canopy fuel load using national forest inventory and low-density airborne laser scanning data. *PLoS One* 12(4): e0176114. <https://doi.org/10.1371/journal.pone.0176114>
- Güngöroğlu, C., Güney, Ç.O., Sarı, A., Serttaş, A., 2018: Predicting crown fuel biomass of Turkish red pine (*Pinus brutia* Ten.) for the Mediterranean regions of Turkey. *Şumarski List* 142(11–12): 601–610. <https://doi.org/10.31298/sl.142.11-12.4>
- He, H.S., Shang, B.Z., Crow, T.R., Gustafson, E.J., Shifley, S.R., 2004: Simulating forest fuel and fire risk dynamics across landscapes-LANDIS fuel module design. *Ecological Modelling* 180(1): 135–151. <https://doi.org/10.1016/j.ecolmodel.2004.07.003>
- Hornby, L.G., 1936: Fire control planning in the Northern Rocky Mountain region. Progress Report 1. USDA Forest Service Ogden UT, 179 p.
- Johnson, A., Woodard, P., Titus, S., 1990: Lodgepole pine and white spruce crown fuel weights predicted from diameter at breast height. *Forestry Chronicle* 66(6): 596–599. <https://doi.org/10.5558/tfc66596-6>
- Keane, R.E., Burgan, R.E., Wagtendonk, J.V., 2001: Mapping wildland fuels for fire management across multiple scales: integrating remote sensing, GIS, and biophysical modeling. *International Journal of Wildland Fire* 10(4): 301–319. <https://doi.org/10.1071/WF01028>
- Kellomäki, S., Hari, P., Kanninen, M., Ilonen, P., 1980: Eco-physiological studies on young Scots pine stands. II. Distribution of needle biomass and its application in approximating light conditions inside the canopy. *Silva Fennica* 14(3): 243–257. <https://doi.org/10.14214/sf.a15033>
- Keyser, T.L., Smith, F.W., 2010: Influence of crown biomass estimators and distribution on canopy fuel characteristics in ponderosa pine stands of the Black Hills. *Forest Science* 56(2): 156–165. <https://doi.org/10.1093/forestscience/56.2.156>
- Kucuk, O., Bilgili, E., 2008: Crown fuel characteristics and fuel load estimates in young calabrian pine (*Pinus brutia* Ten.) stands in northwestern of Turkey. *Fresenius Environmental Bulletin* 17(12b): 2226–2231.
- Kucuk, O., Bilgili, E., Fernandes, P., 2015: Fuel modelling and potential fire behavior in Turkey. *Şumarski list* 139(11–12): 553–560.
- Kucuk, O., Saglam, B., Bilgili, E., 2007: Canopy fuel characteristics and fuel load in young black pine trees. *Biotechnology and Biotechnological Equipment* 21(2): 235–240. <https://doi.org/10.1080/13102818.2007.10817452>
- Kucuk, O., Bilgili, E., Saglam, B., 2008: Estimating Crown Fuel Loading for Calabrian Pine and Anatolian Black Pine. *International Journal of Wildland Fire* 17(1): 147–154. <https://doi.org/10.1071/WF06092>
- Kraft, G., 1884: Beiträge zur Lehre von den Durchforstungen, Schlagstellungen und Lichtungshieben. Hannover, Germany: Klindworth's. <https://doi.org/10.3931/e-rara-71417>
- Mäkelä, A., Vanninen, P., 2001: Vertical structure of Scots pine crowns in different age and size classes. *Trees* 15(7): 385–392. <https://doi.org/10.1007/s004680100118>
- Mitsopoulos, I.D., Dimitrakopoulos, A.P., 2007a: Allometric equations for crown fuel biomass of Aleppo pine (*Pinus halepensis* Mill.) in Greece. *International Journal of Wildland Fire* 16(5): 642–647. <https://doi.org/10.1071/WF06038>
- Mitsopoulos, I.D., Dimitrakopoulos, A.P., 2007b: Canopy fuel characteristics and potential crown fire behavior in Aleppo pine (*Pinus halepensis* Mill.) forests. *Annals of Forest Science* 64(3): 287–299. <https://doi.org/10.1051/forest:2007006>
- Moore, J.R., 2010: Allometric equations to predict the total above-ground biomass of radiata pine trees. *Annals of Forest Science* 67(8): 806. <https://doi.org/10.1051/forest/2010042>
- Neyişçi, T., 1986: The historical role of fires on (*Pinus brutia* Ten.) forests of Antalya-Doyran region. *Forestry Research Institute Publication* 29: 67–91. (In Turkish)

- Omi, P.N., 2015: Theory and practice of wildland fuels management. *Current Forestry Reports* 1(2): 100–117. <https://doi.org/10.1007/s40725-015-0013-9>
- Poudel, K.P., Temesgen, H., Gray, A.N., 2015: Evaluation of sampling strategies to estimate crown biomass. *Forest Ecosystems* 2(1): 1–11. <https://doi.org/10.1186/s40663-014-0025-0>
- Roccaforte, J.P., Fule, P.Z., Covington, W.W., 2008: Landscape-scale changes in canopy fuels and potential fire behaviour following ponderosa pine restorations treatments. *International Journal of Wildland Fire* 17(2): 293–303. <https://doi.org/10.1071/WF06120>
- Sakici, O.E., Kucuk, O., Ashraf, M.I., 2018: Compatible above-ground biomass equations and carbon stock estimation for small diameter Turkish pine (*Pinus brutia* Ten.). *Environmental Monitoring and Assessment* 190(5): 285. <https://doi.org/10.1007/s10661-018-6656-9>
- Scott, J.H., 1999: NEXUS: A system for assessing crown fire hazard. *Fire Management Notes* 59(2): 20–24.
- Scott, J.H., Reinhardt, E.D., 2001: Assessing crown fire potential by linking models of surface and crown fire behavior. Res. Pap. RMRS-RP-29. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 59 p. <https://doi.org/10.2737/RMRS-RP-29>
- Sonmez, T., Kahriman, A., Şahin, A., Yavuz, M., 2016: Biomass equations for Calabrian pine in the Mediterranean region of Turkey. *Şumarski List* 140(11–12): 567–576. <https://doi.org/10.31298/sl.140.11-12.4>
- Stocks, B.J., 1980: Black spruce fuel weights in northern Ontario. *Canadian Journal of Forest Research* 10(4): 498–501. <https://doi.org/10.1139/x80-081>
- Stocks, B.J., Alexander, M.E., Wotton, B.M., Steffner, C.N., Flannigan, M.D., Taylor, S.W., Lavoie, N., Mason, J.A., Hartley, G.R., Maffey, M.E., Dalrymple, G.N., Blake, T.W., Cruz, M.G., Lanoville, R.A., 2004: Crown fire behavior in a northern jack pine-black spruce forest. *Canadian Journal of Forest Research* 34(8): 1548–1560. <https://doi.org/10.1139/X06-185>
- Syphard, A.D., Keeley, J.E., Brennan, T.J., 2011: Comparing the role of fuel breaks across southern California national forests. *Forest Ecology and Management* 261(11): 2038–2048. <https://doi.org/10.1016/j.FORECO.2011.02.030>
- Tahvanainen, T., Forss, E., 2008: Individual tree models for the crown biomass distribution of Scots pine, Norway spruce and birch in Finland. *Forest Ecology and Management* 255(3–4): 455–467. <https://doi.org/10.1016/j.foreco.2007.09.035>
- Van Wagner, C.E., 1977: Conditions for the start and spread of crown fire. *Canadian Journal of Forest Research* 7(1): 23–24. <https://doi.org/10.1139/x77-004>
- Yavuz, M., Sağlam, B., Küçük, Ö., Tüfekçioğlu, A., 2018: Assessing forest fire behavior simulation using FlamMap software and remote sensing techniques in Western Black Sea Region, Turkey. *Kastamonu University Journal of Forestry Faculty* 18(2): 171–188. <https://doi.org/10.17475/kastorman.459698>
- Zianis, D., Xanthopoulos, G., Kalabokidis, K., Kazakis, G., Ghosn, D., Roussou, O., 2011: Allometric equations for aboveground biomass estimation by size class for *Pinus brutia* Ten. trees growing in North and South Aegean Islands, Greece. *European Journal of Forest Research* 130(2): 145–160. <https://doi.org/10.1007/s10342-010-0417-9>



© 2021 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).

Authors' address:

İsmail Baysal, PhD *
 e-mail: ismailbaysal@duzce.edu.tr
 Düzce University
 Faculty of Forestry
 Department of Forest Engineering
 81620, Düzce
 TURKEY

* Corresponding author

Received: December 14, 2019
 Accepted: May 17, 2020