Environmental Engineering and Management Journal February 2021, Vol. 20, No. 2, 309-318
http://www.eemj.icpm.tuiasi.ro/; http://www.eemj.eu

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PREDICTING CANOPY FUEL CHARACTERISTICS IN *Pinus brutia* Ten., *Pinus nigra* Arnold AND *Pinus pinaster* Ait. FORESTS FROM STAND VARIABLES IN NORTH-WESTERN TURKEY

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Abstract

Canopy fuel characteristics play an important role in crown fire behaviour in conifer forests. In this study, the canopy fuel characteristics of Calabrian pine, Anatolian Black pine and Maritime pine stands in Turkey are estimated using forest stand parameters. Sets of equations are fitted to the measured data revealing correlations between canopy fuel characteristics and stand parameters by performing a stepwise multiple regression analysis. At the stand level, the resulting models explain a high percentage of the observed variability. The developed equations can be used by forest and fire managers to estimate canopy fuel characteristics, predict crown-fire behaviour and design fuel treatment projects in Turkey.

Key words: forest fires, fuel characteristics, regression models, stand variables

Received: January, 2020; Revised final: June, 2020; Accepted: September, 2020; Published in final edited form: February, 2021

1. Introduction

The estimation of plant biomass has significant implications for the management and functioning of forest ecosystems. Biomass is directly linked with the primary productivity of ecosystems, carbon emission and sequestration, energy pathways and nutrient cycles, wildlife habitats, and forest fire potential (Foody, 2003; Houghton et al., 2009; Roussopoulos and Loomis, 1979; Sah et al., 2004; Ter-Mikaelian and Korzukhin 1997).

Forest fires are an important ecological factor shaping the landscapes in many parts of the world including the Mediterranean basin. Recent statistics (from 1988 to 2016) reveal that at least 2114 forest fires affect an average of 10615 ha of forested area in Turkey every year (General Directorate of Forestry, 2016). Although surface fires account for most of the area burned in these areas, severe ecological impacts and difficulty of fire control are usually associated with crown fires (Bilgili, 1998).

Crown fire behaviour is highly dependent on canopy fuel characteristics. Canopy fuel characteristics such as canopy base height (*CBH*), canopy fuel load (*CFL*) and canopy bulk density (*CBD*) are commonly accepted as the main parameters controlling crown fire initiation, fire spread and effects (Alexander and Cruz, 2012). Therefore, quantitative estimates of canopy fuel characteristics are required for developing reliable crown fire behaviour prediction models (Fernández-Alonso et al., 2013; Scott and Reinhardt, 2001) and assessing crown

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fire hazard (Andreu et al., 2018; Küçük et al., 2007; Mitsopoulos and Dimitrakopoulos, 2014).

There are many studies discussing the crown fuel characterisation of different tree species. Stocks (1980) developed regression equations to estimate the weights of crown fuel components in Black spruce stands in north central Ontario. Johnson et al. (1989) developed regression equations to predict the crown fuel weights of Lodgepole pine and White spruce from the height and crown width in Alberta. Cruz et al. (2003) developed regression models using common stand parameters (e.g., stand density, basal area and stand height) as independent variables to predict canopy fuel characteristics (e.g., *CBH*, *CFL* and *CBD*) for Douglas-fir, Ponderosa pine, mixed conifer and Lodgepole pine stands in western United States and Canada. Mitsopoulos and Dimitrakopoulos (2007) developed allometric equations to estimate the crown fuel weight of Black pine trees in Southern Bulgaria. Küçük et al. (2008) developed several regression equations for the prediction of aboveground foliage and branch biomass of Calabrian pine and Anatolian black pine in the north and north-western regions of Turkey. Mitsopoulos and Dimitrakopoulos (2014) developed regression equations for the estimation of canopy fuels in Aleppo pine stands in Greece.

Calabrian pine (*Pinus brutia* Ten.) and Anatolian black pine (*Pinus nigra* J.F. Arnold) cover 26% and 19% of the forested areas in Turkey, respectively. In addition, Maritime pine (*Pinus pinaster* Ait.) is one of the most commonly used exotic tree species in afforestation activities. Together with other coniferous species, they constitute more than half of the forested areas in Turkey. Most of these areas are susceptible to forest fires. Crown fires are common in most pine forest types in Turkey. Various models have been developed for the prediction of fire behaviour and fuel moisture dynamics and fuel load (Baysal et al., 2019; Bilgili et al., 2019a; Bilgili et al., 2019b). Although some studies have been carried out on the characterization of crown fuel (Kucuk et al., 2007; Kucuk et al., 2008), the results of these studies were based on allometric relationships. No studies have involved stand canopy characteristics to estimate fuel properties in the forested areas in Turkey.

The main objective of the study was to predict *CFL*, *CBD* and *CBH* values for *Pinus brutia*, *Pinus nigra* and *Pinus pinaster* stands in Turkey based on the easily measured stand canopy characteristics. The results of the study will contribute to fire behaviour prediction, biomass estimation, carbon sequestration and emissions from wildfires in pine ecosystems.

2. Materials and methods

2.1. Study area

The study area is located in Istanbul, north-west of Turkey, (41°01'N, 28°97'E) (Fig. 1). Istanbul is in the Marmara region, and the mean altitude is approximately 40 m. The climate of the study area is a typical Marmara climate, which has long, hot summers (25 °C) and short, mild winters (5 °C). The mean annual rainfall on this site is 815 mm, and the mean annual temperature is 14.5 °C.

Pure stands of Calabrian pine, Anatolian black pine and Maritime pine are found throughout Istanbul. Stands with low canopy closure (<40%) are usually associated with a dense understory dominated by mainly broad-leaved evergreen shrubs (maquis).

2.2. Tree measurements and data collections

A total of 63 measurement plots were established in the study area, of which 22 were in *Pinus brutia*, 21 in *Pinus nigra* and 20 in *Pinus pinaster* stands (Fig.1). The number of the sample plots was determined based on the stand types that could be found over the study area. The measurements plots were determined in such a way as to stand development stage and canopy closure representative of the study area. In Turkey, stand types are identify, considering tree species composition, stand development stage and canopy closure. The stand development stages are classified using *DBH* which are “a” (0-7.9 cm) “b” (8-19.9 cm), “c” (20-35.9 cm), “d” (36-51.9 cm) and “e” (>52). Also canopy closure is classified as 1 (10-39%), 2 (40-69%) and 3 (70-100%) considering the proportion of the forest floor covered by the vertical projection of the tree crowns. Stands that have lower stand development stages (a,b,c) are more vulnerable to crown fires because of higher amounts of consumable fuels.(Kucuk et al., 2012). Therefore, for each canopy closure class, sample plots were selected based on “a”, “b” and “c” development stages.

Measurements were made in plots measuring 20 m × 25 m (500 m^2). Plots were located in stands at least 30 m away from any openings to minimize the edge effects. The location of each plot was determined using a GPS device.

The following measurements were made for every tree in each plot: diameter at breast height (*DBH,* cm), tree height, canopy base height (*CBH*, m) and crown closure (*CC*, %). *DBH* was measured at 1.3 m above ground. *CBH* is defined as the vertical distance from the ground surface to live crown base (Mitsopoulos and Dimitrakopoulos, 2014; Wagner, 1977) and is measured using an altimeter (Haga). *CC* was measured as the proportion of the area of the ground covered by the vertical projection of the crowns (in percent) using a spherical densitometer (Lemon, 1956). Stand density (trees ha^{-1}) was calculated based on the number of trees in each sample plot. Individual-tree- and plot-level canopy fuel characteristics were determined for every stand sampled. The basal area (*BA*) for each sample plot was calculated using the Eq. (1):

$$BA = \sum_{1}^{n} \pi \frac{(DBH)^2}{4} \quad (1)$$

From the data obtained, stand-level canopy fuel characteristics were also determined.

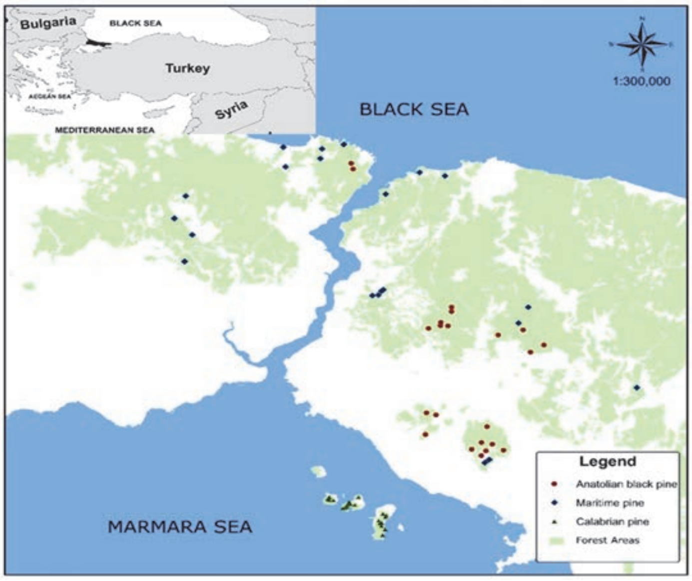

Fig. 1. Location of plot areas

These included: total canopy fuel load (CFL_t), available canopy fuel load (CFL_a), total canopy bulk density (CBD_t) and available canopy bulk density (CBD_a). Total canopy fuel load (CFL_t, kg m^{-2}) means the oven-dry mass of the canopy fuel (foliage and branches <0.3 cm, 0.3–0.6 cm, 0.6–1 cm and >1 cm in diameter) per unit ground area. However, only the fine fuels involving foliage and fine branches that are smaller than 0.6 cm in diameter are consumed in a crown fire (Jiménez et al., 2013). These fine crown fuels are termed as available *CFL* (CFL_a) (Fernández-Alonso et al., 2013; Cruz et al., 2003; Mitsopoulos and Dimitrakopoulos, 2014; Reinhardt et al., 2006; Scott and Reinhardt, 2002; Stocks et al., 2004). Total canopy bulk density (CBD_t, kg m^{-3}) refers to the oven-dry mass of the total canopy fuel mass per unit of canopy volume. Available *CBD* (CBD_a, kg m^{-3}) refers to the oven-dry mass of the available canopy fuel mass per unit of canopy volume. To estimate CFL_t, CFL_a, CBD_t and CBD_a , regression models developed by Kucuk et al. (2008) and Gómez-Vázquez et al. (2013) were used for Calabrian pine and Anatolian black pine and for Maritime pine, respectively. The data obtained were also used to determine important stand parameters. These included the number of trees per hectare (*N*, trees ha^{-1}), stand basal area (*BA*, m^2 ha^{-1}), dominant height (*H*, m), quadratic mean diameter (*QMD*, cm) and relative spacing index (*RSI*, %). *H* was defined as the average of the 10 tallest trees measured in each plot). The RSI refers to the average spacing divided by the dominant stand height and was calculated by the Eq. (2) (Hart, 1928):

$$RSI = \frac{10.000^{0.5}}{H \times N^{0.5}} \tag{2}$$

where *RSI* is a percentage (%) and *H* is measured in m.

A function of overall competition intensity was also calculated by the Reineke's Stand Density Index (*SDI*). *SDI* accounts for the decrease in the number of trees as the stand develops and the carrying capacity of the site is reached. *SDI* is based on the relationship between *QMD* and stand density (Eq. 3) (Reineke, 1933):

$$SDI = N\left(\frac{QDM}{25}\right)^{1.6} \tag{3}$$

where: *N* is measured per hectare (trees ha^{-1}) and *QMD* is measured in cm.

2.3. Statistical analysis

Multiple linear regression models were developed to estimate canopy fuel characteristics of the stands sampled. All the measured and estimated stand variables were considered as potential predictors during the process of the regression analysis. To select the variables for the regression models, stepwise selection method was used with the significance level for entering variables into the models and retaining them in the resulted equations (*p*-value) set at 0.05. The performance of the linear models were evaluated using the coefficient of determination (R^2) and the root mean square error (*RMSE*). Potential heteroscedasticity has been tested by the Breusch–Pagan test (Breusch and Pagan 1979), while the Variance Inflation Factor (*VIF*) was used for detecting potential multicollinearity (O'brien 2007). All statistical analyses were conducted using the statistical package SPSS (SPSS, 2013).

3. Results and discussion

Descriptive statistics for the stand parameters and canopy fuel characteristics in the three sampled pine species stands are presented in Table 1. For *Pinus brutia*, the stand characteristics ranged 9–31 cm for *DBH*, 4.5–12.7 m for *H*, 0.8–8.3 m for *CBH* and 20%–

90% for *CC*; for *Pinus nigra*, the stand characteristics ranged 4–31 cm for *DBH*, 2.4–14.0 m for *H*, 0.5–8.7 m for *CBH* and 25%–100% for *CC*; and for *Pinus pinaster*, the stand characteristics ranged 5–34 cm for *DBH*, 3.1–19.6 m for *H*, 0.4–12.8 m for *CBH* and 20%–85% for *CC*.

Linear regression models were developed to estimate canopy fuel characteristics, examining all stand parameters as potential predictors. Table 2 summarises the regression models developed. For all the studied pine species, a very good fit was observed for the canopy fuel characteristics based on the set of the measured stand parameters. The R^2 values were high in all regression models, whereas the *RMSE* values were insignificant. More specifically, for *Pinus brutia*, the stepwise linear regression analysis revealed *SDI* and *N* as the only statistically significant ($p<0.05$) variables for predicting *CFL*, explaining 99% of the variability in both CFL_a and CFL_t; *H* and *N* were the most significant predictors for *CBD*, explaining 91%, and 93% of the variation in CBD_a and CBD_t, respectively; and *H* and *QMD* explained 95% of the observed variation in *CBH*. No other stand variables were found to be significant in *Pinus brutia* plots. As for *Pinus nigra*, *N* and *SDI* were found to be the significant variables that explained 95% and 97% of the observed variation in CFL_a and CFL_t. *CC* and *N* were the most significant predictors of *CBD*, explaining 96% and 94% of the observed variability in CBD_a and CBD_t, respectively, whereas *H* and *QMD* explained 95% of the observed variation in *CBH*. Similar to *Pinus brutia* and *Pinus nigra,* the regression analysis for *Pinus pinaster* also provided a highly accurate models for predicting canopy fuel characteristics. *BA* and *RSI* were found to be the most significant predictors of *CFL*, explaining 99% of the variability in both CFL_a and CFL_t, whereas *H* and *QMD* were the significant variables that explained 96%, 97% and 90% of the variation in *CBH*, CBD_a and CBD_t, respectively. For all the models developed, independent variables were tested for potential multicollinearity and heteroscedasticity. However, *VIF* (0.9–2.4) and the Breusch–Pagan test (>0.05) indicated no significant multicollinearity or heteroscedasticity, respectively. Plots of the observed versus predicted values for all the equations that resulted from the statistical analysis are shown in Figs. 2-4.

Table 1. Basic descriptive statistics

Species		***Pinus brutia***			
Variable	***n***	***Minimum***	***Maximum***	***Mean***	***Standard Devation eviation***
Basal Area (BA), m^2 ha^{-1}	22	0.855	34.774	13.070	9.452
Dominant Height (H), m	22	4.524	12.714	10.133	2.926
Stand density (N), trees ha^{-1}	22	112.000	1100.000	454.227	311.238
Canopy closure (CC), %	22	0.200	0.900	0.598	0.257
Quadratic Mean Diameter (QMD), cm	22	9.238	31.182	20.184	8.104
Relative Spacing Index (RSI), %	22	28.407	187.206	64.435	41.574
Stand Density Index (SDI)	22	25.838	667.471	281.836	179.417
Available Canopy Fuel Load (CFL_a), kg m^{-2}	22	0.081	0.706	0.308	0.201
Available Canopy Bulk Density (CBD_a), kg m^{-3}	22	0.017	0.215	0.071	0.051
Total Canopy Fuel Load (CFL_t), kg m^{-2}	22	0.110	0.991	0.425	0.277
Total Canopy Bulk Density (CBD_t), kg m^{-3}	22	0.024	0.286	0.097	0.070
Canopy Base Height (CBH), m	22	0.767	8.286	5.662	2.535
Species		***Pinus nigra***			
Variable	***n***	***Minimum***	***Maximum***	***Mean***	***Standard Devation eviation***
BA, m^2 ha^{-1}	21	2.007	33.462	10.060	8.663
Height (H), m	21	2.434	14.011	7.336	2.913
Stem density (N), trees ha^{-1}	21	112.000	2150.000	547.262	606.492
Canopy closure (CC), %	21	0.250	1.000	0.581	0.252
Quadratic Mean Diameter (QMD), cm	21	4.590	30.778	18.755	8.178
Relative Spacing Index (RSI), %	21	33.645	186.339	86.693	34.905
Stem Density Index	21	51.138	627.607	224.739	162.403
Available Canopy Fuel Load (CFL_a) kg m^{-2}	21	0.102	1.780	0.479	0.489
Available Canopy Bulk Density (CBD) kg m^{-3}	21	0.027	0.973	0.177	0.242
Total Canopy Fuel Load (CFL_t) kg m^{-2}	21	0.109	1.319	0.447	0.364
Total Canopy Bulk Density (CBD_t) kg m^{-3}	21	0.028	0.721	0.157	0.174
CBH m	21	0.538	8.672	4.023	2.371
Species		***Pinus pinaster***			
Variable	***n***	***Minimum***	***Maximum***	***Mean***	***Standard Devation eviation***
BA m^2 ha^{-1}	20	2.346	36.167	12.311	9.424
Height (H) m	20	3.074	19.607	10.414	3.740
Stem density (N) trees ha^{-1}	20	112.000	1700.000	460.900	385.009
Canopy closure (CC), %	20	0.200	0.850	0.548	0.234
Quadratic Mean Diameter (QMD), cm	20	5.029	34.586	19.510	6.816
Relative Spacing Index (RSI), %	20	25.608	113.389	61.601	28.989
Stem Density Index (SDI)	20	56.681	688.780	268.661	182.571
Available Canopy Fuel Load (CFL_a) kg m^{-2}	20	0.067	1.067	0.360	0.278
Available Canopy Bulk Density (CBD_a) kgm^{-3}	20	0.052	0.129	0.099	0.020
Total Canopy Fuel Load (CFL_t) kg m^{-2}	20	0.068	1.181	0.388	0.308
Total Canopy Bulk Density (CBD) kg m^{-3}	20	0.080	0.347	0.161	0.067
CBH m	20	0.359	12.786	5.964	2.983

Table 2. Statistics of the stepwise multiple regression

Variable	*Variables in equation*	*Equation*	*p-value*	*F*	R^2	*RMSE*
		Pinus brutia				
Available CFL	SDI, N	0.001+0.000078SDI+0.00063N	< 0.0001	15534.6	0.99	0.005
Available CBD	H, N	0.028-0.00265H+0.00015N	< 0.0001	99.5	0.91	0.016
Total CFL	SDI, N	0.00011+0.00012SDI+0.001N	< 0.0001	3563.5	0.99	0.015
Total CBD	H, N	0.033-0.00306H+0.00021N	< 0.0001	127.6	0.93	0.019
CBH	H, QMD	-2.694+0.6903H+0.0674QMD	< 0.0001	211.6	0.95	0.552
		Pinus nigra				
Available CFL	N, SDI	0.00627+0.000799N+0.0001562SDI	< 0.0001	4182.1	0.99	0.024
Available CBD	CC, N	0.0597-0.2348CC+0.000463N	<0.0001	223.6	0.96	0.050
Total CFL	N, SDI	0.0216+0.000556N+0.000537SDI	<0.0001	339.6	0.97	0.062
Total CBD	CC, N	0.031215-0.06590CC+0.00032N	<0.0001	156.5	0.94	0.043
CBH	H, QMD	-1.692+0.4324H+0.13562QMD	<0.0001	209.3	0.95	0.507
		Pinus pinaster				
Available CFL	BA, RSI	-0.01+0.0297BA+0.0000681RSI	< 0.0001	1494871.6	0.99	0.007
Available CBD	H, QMD	0.05286-0.005596H+0.005373QMD	< 0.0001	336.9	0.97	0.003
Total CFL	BA, RSI	-0.0377+0.0334BA+0.00025RSI	< 0.0001	136332.7	0.99	0.005
Total CBD	BA, RSI	-0.059+0.01030BA+0.02RSI	< 0.0001	77.9	0.90	0.022
CBH	H, QMD	-2.1015+0.8548H-0.04282QMD	< 0.0001	138.3	0.97	0.585

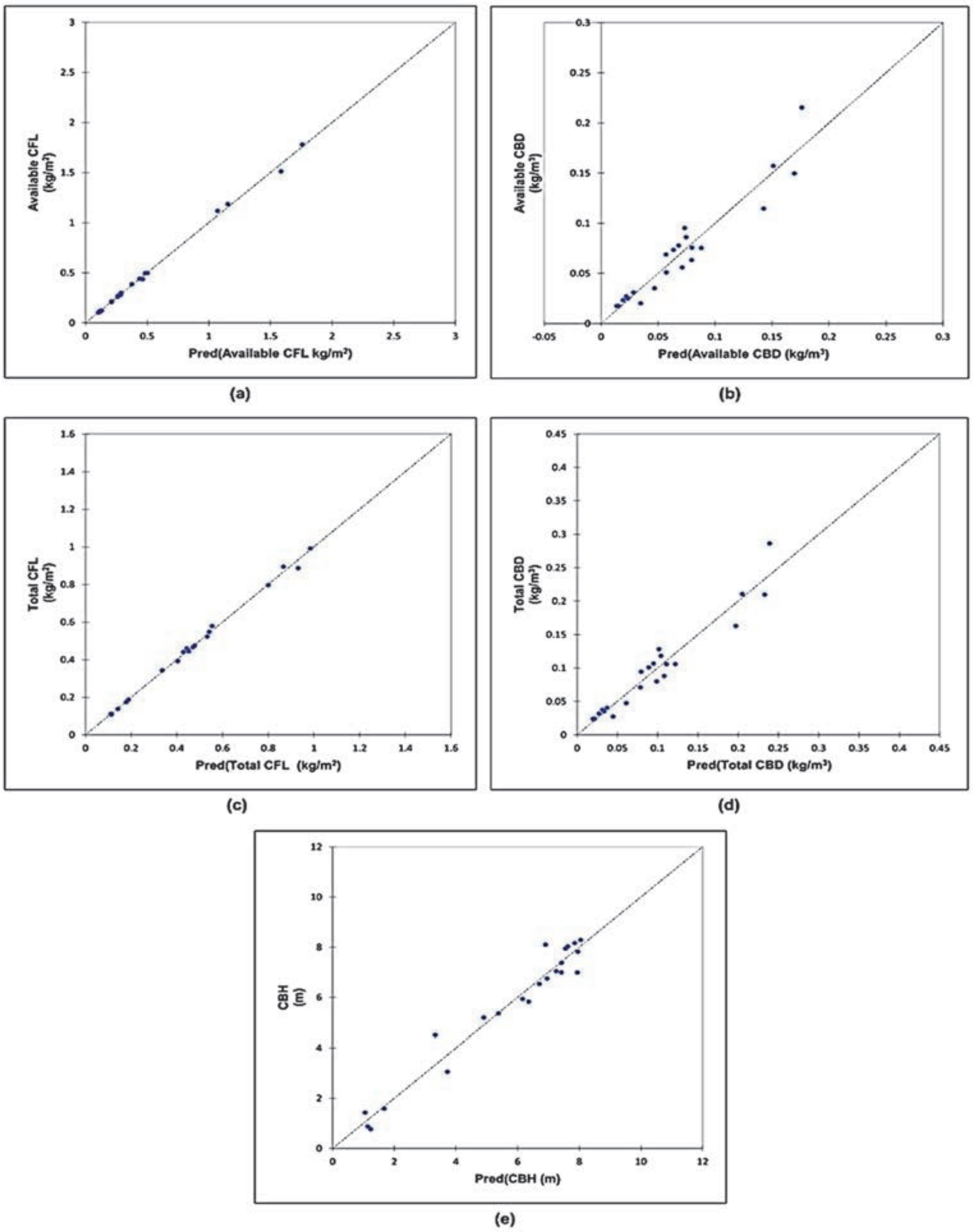

Fig. 2. Observed vs predicted values for Available CFL (a), Available CBD (b), otal CFL (c), Total CBD (d) and CBH (e) in *Pinus brutia*

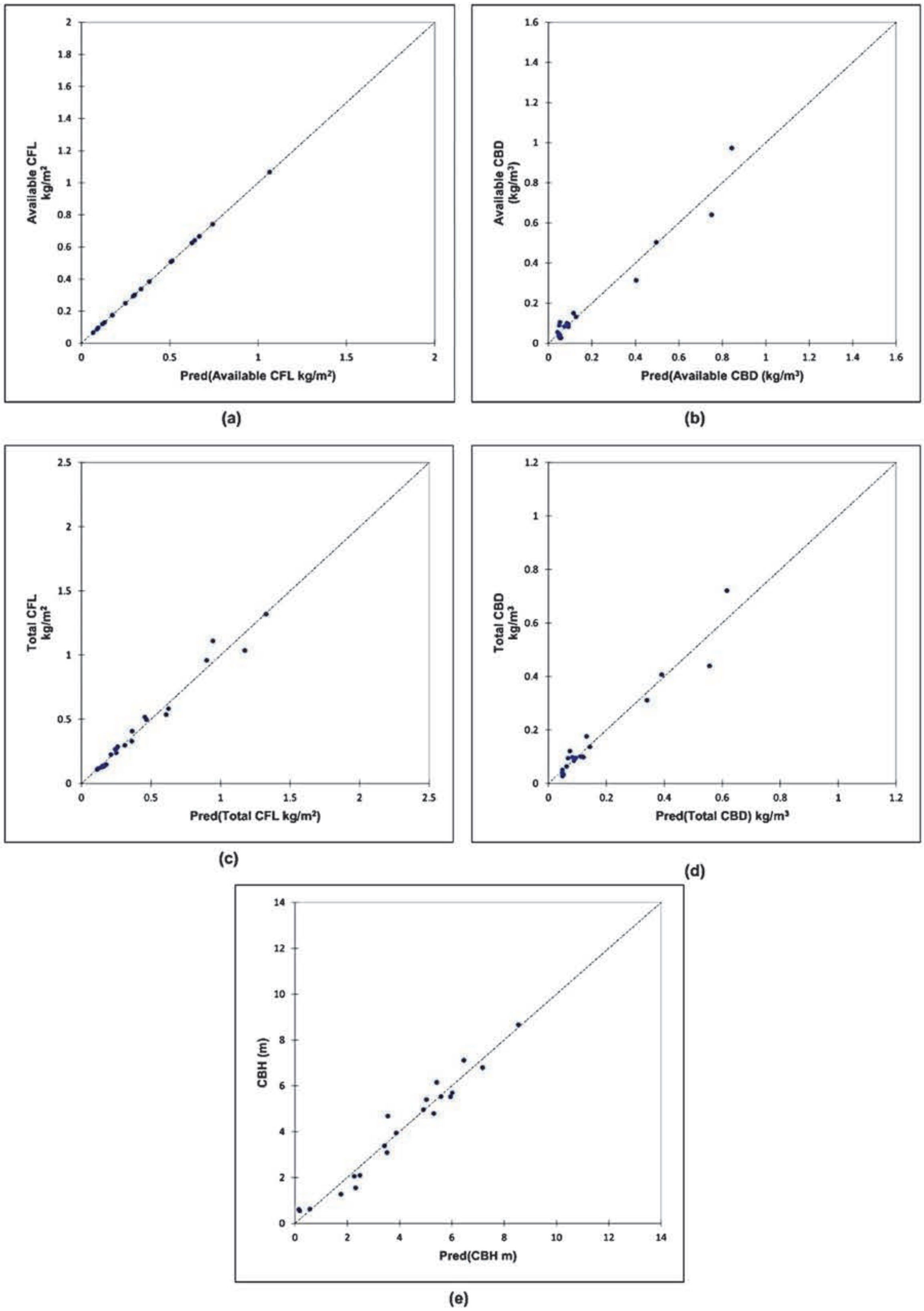

Fig. 3. Observed vs predicted values for Available CFL (a), Available CBD (b), Total CFL (c), Total CBD (d) and CBH (e)in *Pinus nigra*

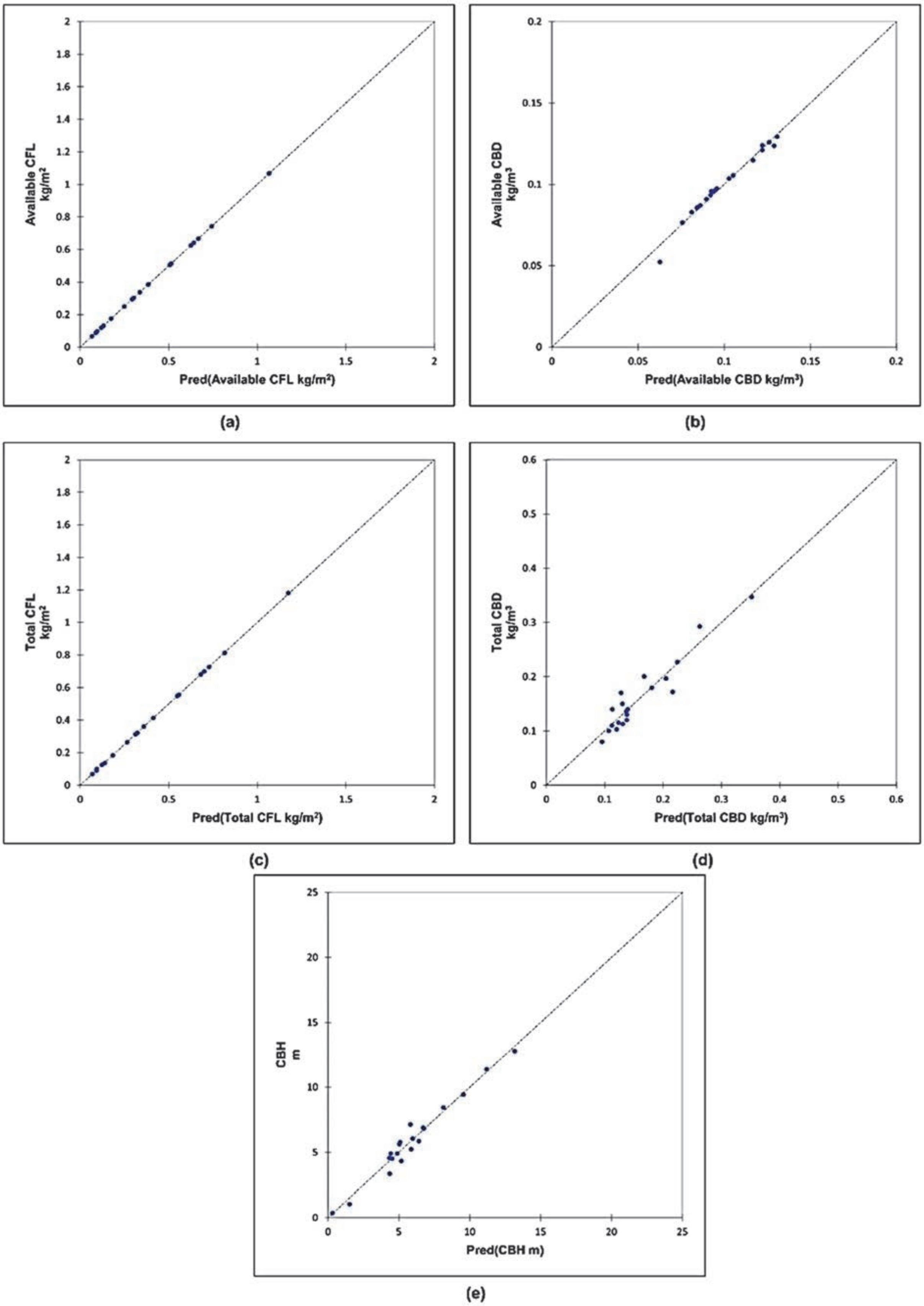

Fig. 4. Observed vs predicted values for Available CFL (a), Available CBD (b), Total CFL (c), Total CBD (d) and CBH (e) in *Pinus pinaster*

Few studies have dealt with the estimation of canopy fuel characteristics in the eastern Mediterranean pine forests (Kucuk et al., 2008; Mitsopoulos and Dimitrakopoulos, 2007; Mitsopoulos and Dimitrakopoulos, 2017). The results of this study indicated that mean canopy fuel characteristics (i.e., *CFL*, *CBD* and *CBH*) for Black pine, Calabrian pine and Maritime pine stands were comparable to and within the range reported by other studies in the Mediterranean Basin such as Spain (Fernández-Alonso et al., 2013; Gómez-Vázquez et al., 2013) and Greece (Mitsopoulos and Xanthopoulos, 2016) and in other parts of the world such as North America (Alexander et al., 2004; Cruz et al., 2003; Reinhardt et al., 2006; Scott and Reinhardt, 2001). However, most of the North American studies did not use allometric relationships developed from the same stands of the study sites; therefore, the results should be interpreted with care due to the possible effect of the regional variability (Stocks, 1980) and approaches and methodologies adopted and definitions used to describe fuel characteristics in different studies. In the current study, canopy fuel characteristics were estimated based on the implementation of species-specific crown fuel allometric models; hence, it is expected to provide more robust estimates of the *CFL*, *CBD* and *CBH* values of the studied species.

Fuel complex characteristics commonly accepted as controlling crown fire spread are *CFL* and *CBD*. Because canopy fuel properties (quantification of live needle foliage, fine live and dead twigs etc.) of each tree species are different, *CFL* and *CBD* are different. Cruz et al. (2003) gave *CFL* values for the mixed conifer fuel type (mean: 1.4 kg kg m^{-2}), followed by *Pinus contorta* (1.0 kg m^{-2}), *Pseudotsuga menziesii* (1.0 kg kg m^{-2}) and *Pinus ponderosa* (0.61 kg kg m^{-2}). Scott and Reinhardt (2001) reported *CFL* values for *Pinus contorta* (1.22 kg kg m^{-2}) and *Pinus ponderosa*, (2.25 kg kg m^{-2}). We found *CFL* values for *Pinus brutia* (0.43 kg kg m^{-2}), *Pinus nigra* (0.45 kg kg m^{-2}) and *Pinus pinaster* (0.39 kg kg m^{-2}). Cruz et al. (2003) found similar *CBD* for *Pinus ponderosa* and *Pseudotsuga menziesii* (mean: 0.18 kg m^{-3}). They give *CBD* values for the mixed conifer fuel type (mean: 0.32 kg m^{-3}) and *Pinus contorta*, (0.28 kg m^{-3}). Scott and Reinhardt (2001) measured *CBD* for *Pinus ponderosa* (0.33 kg m^{-3}). We found *CBD* values for *Pinus brutia* (0.10 kg m^{-3}), *Pinus nigra* (0.16 kg m^{-3}) and Pinus pinaster (0.16 kg m^{-3}).

Analyses showed significant relationships between stand density indices (e.g., *N*, *SDI*, *RSI*), stand variables (e.g., *H*, *CC*) and canopy fuel characteristics. The results showed that there was a proportional increase of the *CFL* and *CBD* as the size and/or the stem density of the trees in a stand increased. This finding supports most of the previous studies that the stand-density variables are the most important variables affecting the canopy fuel characteristics (Cruz et al., 2003; Fernández-Alonso et al., 2013; Gómez-Vázquez et al., 2013; Mitsopoulos and Dimitrakopoulos, 2014; Reinhardt et al., 2006; Ruiz-González and Álvarez-González, 2011).

The results also showed that stand variables were important descriptors to explain the canopy fuel characteristics variation for the three species in the region. For example: for *Pinus brutia,* when the diameter is between 20 and 30 cm and stand density is 500-600 tress ha^{-1}, Total *CFL* and *CBD* varies between 0.11-0.99 kg m^{-2}, 0.04-0.29 kg m^{-3} respectively. When the diameter is between 31 and 40 cm and stand density is 250-300 tress ha^{-1}, Total *CFL* and *CBD* varies between 0.14-0.56 kg m^{-2}, 0.02-0.12 kg m^{-3} respectively. For *Pinus nigra,* when the diameter is between 5 and 15 cm and stand density is 900-1000 tress ha^{-1}, total *CFL* and *CBD* varies between 0.12-1.32 kg m^{-2}, 0.09-0.72 kg m^{-3} respectively. When the diameter is between 15 and 30 cm and stand density is 250-300 tress ha^{-1}, total *CFL* and *CBD* varies between 0.10-0.58 kg m^{-2}, 0.03-0.18 kg m^{-3} respectively.

For *Pinus pinaster* when the diameter is between 5 and 15 cm and stand density is 500-600 tress ha^{-1}, total *CFL* and *CBD* varies between 0.09-0.55 kg m^{-2}, 0.08-0.20 kg m^{-3} respectively. When the diameter is between 15 and 30 cm and stand density is 300-400 tress ha^{-1}, Total CFL and CBD varies between 0.14-1.18 kg m^{-2}, 0.14-0.35 kg m^{-3} respectively.

Variables such as *H* and *CC* were found to significantly affect the estimation of *CFL*, *CBD* and *CBH*. It should also be noted, however, that other factors, such as physiographic and soil conditions and climate regime as well as site index (Fernandes and Rego, 1998) might affect canopy fuel characteristics, and that past forest management practices (e.g., thinning, clearings etc.) could also potentially affect the canopy fuel biomass distribution in pine stands (Gracia et al., 2007; Gilliam et al., 1995). The incorporation of these variables in future predictive models may further improve the predictive power of the existing models, enabling fuel mapping at larger scales across the forested landscape.

4. Conclusions

The relationships between forest stand variables and canopy fuel characteristics was studied for Calabrian, Black and Maritime pines in north-western Turkey. The results revealed that canopy fuel characteristics (*CLF*, *CBD* and *CBH*) are strongly related to forest stand variables: primarily *N*, *SDI*, *CC*, *BA* and *H*, in all the examined species. The linear regression models developed for predicting canopy fuel characteristics explained a very high percentage of the observed variability.

It should be noted here that variability explained by the models is the variability of the residuals predicted by the allometric relationships obtained from the literature, not the actual variability of the original data. The results merely indicate that relationships developed using forest stand variables are as good as the allometric relationships developed from tree variables.

The estimation of canopy fuel characteristics based on forest stand measurements can be of great help for forest and fire managers to evaluate silvicultural interventions and fuel treatments, assess fire hazard, and predict fire behaviour and effects at the stand level. As known, some of the forest stand variables such as *N*, *BA* and *H* are already available in all forest inventories.

They can be estimated by high resolution remote sensing techniques, and variables such as *SDI* and *RSI* can easily be predicted. Therefore, predictions of the fuel complex characteristics from the developed models could easily be incorporated into the existing and under development forest management inventory systems. Future validation of the regression models with independent sampled data would be required as the regression models can only be valid within the range of the data used to develop the relationships.

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