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Compatible above-ground biomass equations and carbon stock estimation for small diameter Turkish pine (*Pinus brutia* Ten.)

Oytun Emre Sakici · Omer Kucuk · Muhammad Irfan Ashraf

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Abstract Small trees and saplings are important for forest management, carbon stock estimation, ecological modeling, and fire management planning. Turkish pine (*Pinus brutia* Ten.) is a common coniferous species and comprises 25.1% of total forest area of Turkey. Turkish pine is also important due to its flammable fuel characteristics. In this study, compatible above-ground biomass equations were developed to predict needle, branch, stem wood, and above-ground total biomass, and carbon stock assessment was also described for Turkish pine which is smaller than 8 cm diameter at breast height or shorter than breast height. Compatible biomass equations are useful for biomass prediction of small diameter individuals of Turkish pine. These equations will also be helpful in determining fire behavior characteristics and calculating their carbon stock. Overall, present study will be useful for developing ecological models, forest management plans, silvicultural plans, and fire management plans.

Keywords Biomass · Allometric equations · Small diameter trees · Model accuracy · Error-in-variable model · *Pinus brutia*

O. E. Sakici (✉) · O. Kucuk
Faculty of Forestry, Kastamonu University, Kastamonu, Turkey
e-mail: oesakici@kastamonu.edu.tr

M. I. Ashraf
Department of Forestry and Range Management, PMAS Arid Agriculture University, Rawalpindi, Pakistan

Introduction

Global climate is changing at a higher pace in recent years than in the past. The global average temperature in the glacial age was estimated to be 2–5 °C lower than the present. About 1 °C increase in average temperature had been recorded during the last century. This alarming increase calls attention to serious concerns in relation to global warming (Papadopol 2001). In order to lessen or prevent global warming, it is necessary to reduce the amount of greenhouse gases in the atmosphere and enhance the amount of CO_2 absorption by trees. The amount of CO_2 in the atmosphere could be reduced by three ways: (i) reduction of CO_2 emissions, (ii) the use of biofuels (biomass) instead of fossil fuels, and (iii) increasing the amount of CO_2 storage (Janzen 2004). Forests are considered as the most effective means of carbon storage because they consume more CO_2 than other terrestrial ecosystems and can keep the carbon for too long (Aydın 2010). Forests are the most important carbon sink of the earth, due to their biomass presence. Forest biomass contains 80% of the above-ground and 40% of the below-ground carbon in the earth (Dixon et al. 1994; Goodale et al. 2002; Saeed et al. 2016). In this respect, forests are considered as a main pool for atmospheric CO_2. The studies related to the measurement and monitoring of biomass and carbon stocks of forests are highly valued due to the contribution of forest ecosystems in the regulating global carbon cycle and climate change mitigation (Vogt 1991; Kurz et al. 1996; Peichl and Arain 2007).

The United Nations Framework Convention on Climate Change (UNFCCC) has an important status among the five outputs of the United Nations Conference on Environment and Development (UNCED) organized at Rio, Brazil, in 1992. The aim of the convention was to reduce greenhouse gas emissions and to provide funding sources. The Kyoto Protocol and the recent Paris Agreement are ambitious targets to combat climate change. Under these agreements, countries are committed to reduce greenhouse gas emissions or to increase their rights through carbon trading (UN 1992, 1998, 2015). Turkey is obliged to declare its forest resources and their contribution to the global carbon cycle under these international agreements. The studies related to biomass assessment and carbon storage quantities have scientific and economic importance.

The accurate information about carbon storage capacity of forests reflecting all layers of the ecosystem is required to develop national development plans for the forestry sector. This is required to prepare and to implement functional forest management plans, to arrange fire management strategies, and to conduct other ecological modeling studies. Therefore, the stand biomass capacity of all forest types from the seedling stage to the oldest forest system is inherently important for carbon storage estimations. In this situation, since the productive young forests comprise 38% of the total forests in Turkey (GDF 2012), biomass and carbon estimates are vital for the productive young forests as well as old forests.

Majority of the studies on biomass estimations take into account only stand forms over some certain diameter at breast height values, the results of such studies cannot be used specifically for the individual small trees or saplings. Globally, there are few studies available on this topic, i.e., about young stands (e.g., Wagner and Ter-Mikaelian 1999; Claesson et al. 2001; Xiao and Ceulemans 2004; Pajtík et al. 2008; Chaturvedi and Raghubanshi 2013). Similarly, the relevant studies about small diameter trees in Turkey are also rare. Kucuk et al. (2008) developed needle, branch, and above-ground total biomass equations separately for small trees or saplings for Turkish pine (*Pinus brutia* Ten.) and Anatolian black pine (*Pinus nigra* J.F. Arnold subsp. *nigra* var. *caramanica* (Loudon) Rehder). In this study, stem base diameter ranges for small trees are 0.6–11.0 cm and 0.5–14.0 cm for Turkish pine and Anatolian black pine species, respectively, and diameter at breast height ranges for saplings is 9–19 cm and 6–26 cm, respectively. Bilgili and Kucuk (2009) have also developed needle, branch, and above-ground total biomass equations for Turkish pine trees and saplings. In this study, stem base diameter range of small trees is 3.4–11.0 cm and diameter at breast height range of saplings is 13–19 cm. Tolunay (2012) developed equations for predicting stem wood, bark, branch, needle, and above-ground total biomass for young Scots pine (*Pinus sylvestris* L.) stands with the help of data obtained from the sample trees with diameters at breast height ranging from 6.1–10.9 cm. The recent relevant studies were published by Eker and Ozcelik (2017) and Eker et al. (2017). In these studies, estimation models were developed for above-ground total biomass and component biomass of small diameter Turkish pine trees. However, both studies were for a small region of Turkey, and involved small trees taller than breast height only.

Various studies developed regression equations for young and old stands to be used in the calculation of biomass quantities for the Turkish pine, the coniferous tree species with the largest area in Turkey (5.6 million hectares) comprising one quarter of the total forests of Turkey according to GDF (2015) data. In the biomass equations developed for Turkish pine, diameter at breast height (D) and tree height (H) are used as independent variables to estimate biomass (Ünsal 2007; Yılmaz 2015; Sönmez et al. 2016). For equations to be used for young individuals whose heights were less than the breast height ($H < 1.3$ m) or whose diameters at breast height were below the commercial diameter limit according to Turkish standard ($D < 8$ cm), stem base diameter (D_0) and H are considered (Kucuk et al. 2008; Bilgili and Kucuk 2009). Zeng and Tang (2012) stated that in addition to diameter at breast height and tree height, tree volume (V) can be used as an independent variable in biomass equations and they have developed compatible equations estimating the volume and biomass simultaneously.

Kucuk et al. (2008) and Bilgili and Kucuk (2009) focused on the biomass of combustible materials of young Turkish pine trees and saplings, but estimates of stem volume and stem biomass were not included in their studies and no examination was made on the compatibility of biomass and volume equations. The aim of this study was to develop compatible regression equations that can be used in estimating biomass, volume and carbon stock for young Turkish pine trees, and saplings whose height has not reached breast height or whose diameters at breast height are below 8 cm.

Biomass equations were developed separately for above-ground total biomass and each biomass components (stem wood, branch, and needle).

Material and methods

Study area

Turkish pine has the largest area (5.6 million hectares) among coniferous species in Turkey, and this area comprises of 25.1% of the total forest area of the country (GDF 2015). Turkish pine is generally spreading in fire-prone areas such as Western Anatolia and Mediterranean regions as well as limited distribution in the northern and northeastern regions of the country. The data used in this study were obtained from field studies carried out in the entire distribution area of Turkish pine in Turkey. Figure 1 shows the distribution areas of Turkish pine in the country and the locations of samples taken.

Data collection

In this study, the data obtained from measurements made on a total of 285 samples of small trees and saplings. Stem base diameters (D_0) and tree heights (H) were measured, and then the sample trees and saplings were cut from the soil level. The harvested trees were divided into three biomass components as stem wood, branches, and needles. The biomass components were separately labeled and transferred to the laboratory and the needle and branch samples were dried at 105 °C for 24 h. The samples extracted from the oven were cooled in a desiccator and their oven-dry weights were weighed with a sensitivity of 0.01 g. Conical form is a practical and reliable method to calculate stem volume of young small trees and saplings on biomass estimates (Rance et al. 2012). Stem volumes (V) were calculated assuming that stem forms are conical. The D_0 and H variables were used in these calculations. Oven-dry weights for the stem woods were obtained by multiplying the calculated stem volumes by 0.478 g cm^{-3}, which is wood density value for stem suggested by Tolunay (2013). Finally, the above-ground total biomass values of the samples were obtained by adding the biomass of stem wood, branch, and needle.

Compatible biomass equations

Regression analysis is the most common method used for the development both biomass and volume equations in forestry (e.g., Segura and Kanninen 2005; Brandeis et al. 2006; Guendehou et al. 2012; Kahriman et al. 2017). Studies for tree volume and biomass equations are usually carried out independently of each other. One of the most common forms of individual tree volume or biomass equations is described in Parresol (1999) and Zeng (2015) as in Eq. 1.

$$Y = \beta_0 X_1^{\beta_1} X_2^{\beta_2} \dots X_i^{\beta_i} + \varepsilon \tag{1}$$

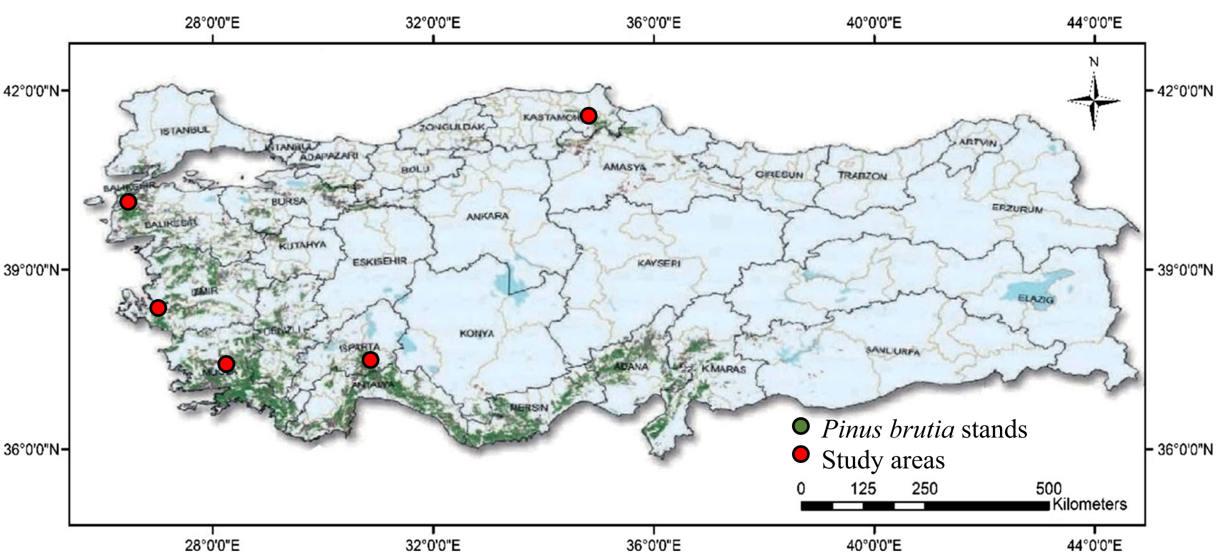

Fig. 1 Natural distribution of *Pinus brutia* in Turkey (GDF 2013) and study areas

where Y is volume or biomass, X_j are variables for tree dimensions, β_j are equation parameters, and ε is the error term. Since, above-ground total or component biomasses are strongly correlated with stem volume for an individual tree, there should be a compatibility between biomass and volume equations (Zeng and Tang 2012).

Zeng and Tang (2012) stated that the predicted tree volume can be used as an independent variable in a biomass equation in their research on the compatibility of a double-entry biomass and volume equations based on D and H with same mathematical form. The mentioned volume (V) and biomass (M) equations are:

$$V = a_0 D^{a_1} H^{a_2} \quad (2)$$

$$M = b_0 D^{b_1} H^{b_2} \quad (3)$$

By means of the biomass conversion factor (BCF, Eq. 4) obtained by proportioning these two equations to one another, biomass values can be directly calculated for a tree of known volume. By simplifying Eq. 4, compatible biomass equation (Eq. 5) is achieved.

$$BCF = M/V = \left(b_0 D^{b_1} H^{b_2}\right) / \left(a_0 D^{a_1} H^{a_2}\right) \quad (4)$$

$$M = \left(c_0 D^{c_1} H^{c_2}\right) V \quad (5)$$

The c_i coefficients in Eq. 5 are related to the a_i and b_i coefficients as follows for the Eq. 2 and Eq. 3.

$$c_0 = b_0 / a_0$$

$$c_1 = b_1 - a_1$$

$$c_2 = b_2 - a_2$$

In the equation system proposed by Zeng and Tang (2012), V is tree volume, M is biomass, D is diameter at breast height, H is tree height, and a_i, b_i, and c_i are coefficients of the equations. In this study, M in the equations expresses the biomass quantities of biomass components, since it is intended to develop equations to estimate biomass of components and above-ground total biomass. D_0 was used instead of D in the equations because the stem base diameters were used as diameter values in the scope of the study. There is no compatibility between these double-entry volume, double-entry biomass, and compatible biomass-volume equations explained above, when the coefficients (a_i, b_i, c_i) are fitted independently from each other by using ordinary least squares (OLS) method. However, if the coefficients of all three equations are fitted simultaneously, compatible biomass-volume equations can be developed. Tang et al. (2001) suggested the error-in-variable modeling method to fit linear simultaneous equations in forest growth and yield modeling, and this method was adapted to solve

Table 1 Descriptive statistics

	D_0 (cm)	H (cm)	V (cm^3)	M_{st}		M_{br}		M_{nd}		M_{AG} (g)
				g	%	g	%	g	%	
Model development data (n=214)										
Minimum	0.6	35	5.5	2.6	2.9	17.4	6.6	4.9	8.8	30.5
Maximum	11.0	510	16147.5	7718.5	64.9	4948.7	80.1	1690.5	55.9	13799.0
Mean	2.9	120	745.7	356.4	23.5	408.8	51.9	180.1	24.6	945.3
Std. Deviation	2.05	79.3	1943.25	928.87	13.1	757.87	14.8	276.26	8.9	1915.25
Validation data (n=71)										
Minimum	0.6	33	7.4	3.5	5.6	10.8	14.0	5.3	8.9	27.1
Maximum	11.0	400	12664.7	6053.7	58.5	4856.2	83.8	1532.1	67.4	12442.0
Mean	2.9	119	769.1	367.6	23.7	455.4	51.5	179.5	24.8	1002.5
Std. Deviation	2.14	78.0	1968.68	941.03	11.8	893.55	14.5	274.62	10.1	2077.74

Percentage values of biomass components explain the ratio of each component in total aboveground biomass

D_0, stem base diameter; H, tree height; V, stem volume; M_{st}, stem biomass; M_{br}, branch biomass; M_{nd}, needle biomass; M_{AG}, above-ground total biomass

Table 2 Correlation matrix of the variables used in the analyses

	D_0	H	V	M_{st}	M_{br}	M_{nd}
H	0.893*					
V	0.874*	0.798*				
M_{st}	0.874*	0.798*	1.000*			
M_{br}	0.896*	0.781*	0.936*	0.936*		
M_{nd}	0.916*	0.820*	0.910*	0.910*	0.918*	
M_{AG}	0.909*	0.812*	0.984*	0.984*	0.981*	0.947*

*Correlation is significant at 1% significance level ($p < 0.01$)

compatibility problem when simultaneously fitting biomass and volume equations by Zeng and Tang (2012). Firstly, volume and biomass equations were fitted by OLS, and then compatible biomass equations, in which the estimated volume is also independent variable like D_0 and H, were developed in this adapted method.

Based on the compatible equation form proposed by Zeng and Tang (2012), we have developed compatible biomass-volume equations for (i) stem wood biomass, (ii) branch biomass, (iii) needle biomass, and (iv) above-ground total biomass. The dataset was divided into two parts as model development data (75% of total data, 214 samples) and validation data (25% of total data, 71 samples) for developed equations. Initially, correlation analysis was performed in order to determine the relationships between the D_0, H, and V and biomass of components (stem wood, branch and needle) and the above-ground total biomass. Then, the equations considered D_0 and H variables as independent variables and the biomass quantities related to the biomass components (stem wood, branch, and needle) and the above-ground total biomass as dependent variables were developed with error-in-variable modeling method described above using model development data. The validities of the developed equations were controlled with the paired t test using validation data. Statistical analyses were performed using IBM SPSS Statistics 23 software.

Calculation of above-ground carbon stock

In the absence of empirical equations, carbon stock can be predicted by two methods called Good Practice Guidance for Land Use, Land-use Change, and Forestry (LULUCF) and Agriculture, Forestry, and Other Land Use (AFOLU) prepared by the Intergovernmental Panel on Climate Change (IPCC 2003, 2006). According to the LULUCF method, the stem biomass is obtained by multiplying the stem volume by the basic wood density, and then the calculated stem biomass value is multiplied by the biomass expansion factor (*BEF*) to predict the above-ground biomass. In the AFOLU method, the above-ground biomass is directly calculated from the stem volume by utilizing the biomass conversion and expansion factors (*BCEF*) (IPCC 2006). After calculating above-ground biomass by using one of these

Table 3 Coefficients of regression equations for predicting stem volume and stem, branch, needle, and total above-ground biomass

	Coefficients									R^2	SEE[a]
	a_0	a_1	a_2	b_0	b_1	b_2	c_0	c_1	c_2		
Stem volume	0.224	1.978	1.035							0.998	15,8
Biomass equations											
Stem				0.107	1.978	1.035				0.998	97.5
Branch				9.377	1.911	0.259				0.907	231.8
Needle				3.127	1.365	0.484				0.878	7.5
Above-ground total				3.009	1.816	0.655				0.979	276.8
Compatible biomass equations											
Stem							0.478	0.000	0.000	0.998	97.5
Branch							41.862	−0.067	−0.776	0.907	231.8
Needle							13.959	−0.613	−0.551	0.878	7.5
Above-ground total							13.431	−0.162	−0.380	0.979	276.8

[a] Standard error of estimate

Table 4 Paired *t* test results for regression equations

	Mean	SD[a]	SEE[b]	*t*	*p*
Stem volume (cm^3)	764.8	1965.9	233.30	0.560	0.577
Biomass equations					
Stem (g)	365.3	939.0	111.44	0.627	0.533
Branch (g)	414.0	754.5	89.54	1.413	0.162
Needle (g)	182.6	266.8	31.66	− 0.323	0.748
Above-ground total (g)	944.7	1960.2	232.63	1.683	0.097
Compatible biomass equations					
Stem (g)	365.6	939.7	111.52	0.560	0.577
Branch (g)	414.0	754.5	89.54	1.413	0.162
Needle (g)	182.6	266.8	31.66	− 0.322	0.748
Above-ground total (g)	944.6	1959.9	232.59	1.686	0.096

[a] Standard deviation

[b] Standard error of estimate

methods, the above-ground carbon stock is determined by multiplying the above-ground biomass with the carbon fraction (*CF*) given in IPCC (2003) and IPCC (2006).

Since compatible biomass equations were developed for the components (stem wood, branch, and needle) and the above-ground total biomass in this study, carbon fraction was used to calculate carbon stock of each biomass component and above-ground total biomass. According to the AFOLU method, *CF* is 0.51 for conifers of temperate zone forests (IPCC 2006). This carbon fraction value can be used to calculate componential or above-ground total carbon stock of the above-ground biomass for Turkish pine forests in Turkey. After calculating the biomass values by using developed compatible biomass equations, the carbon stocks can be determined by multiplying the obtained biomass values with the mentioned *CF* of 0.51.

Results

The ranges of D_0, H, and V variables were 0.6–11 cm, 33–510 cm, and 5.5–16,147.5 cm^3, and biomass of stem

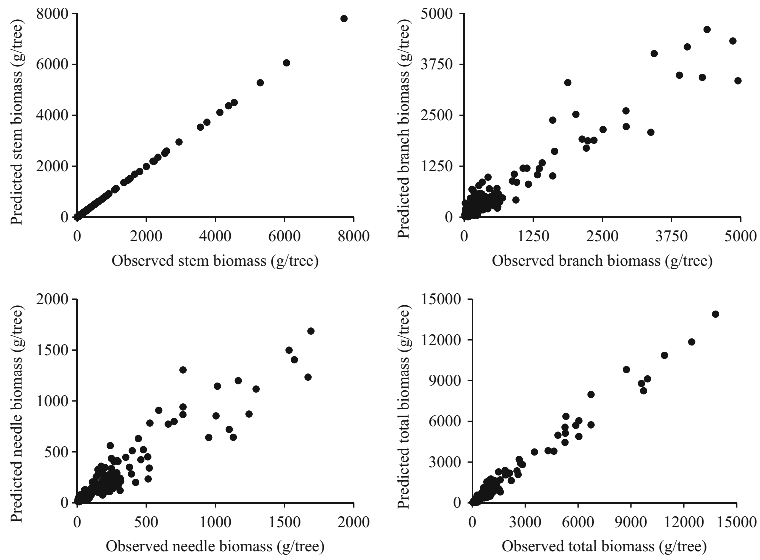

Fig. 2 Relationships between observed and predicted biomasses

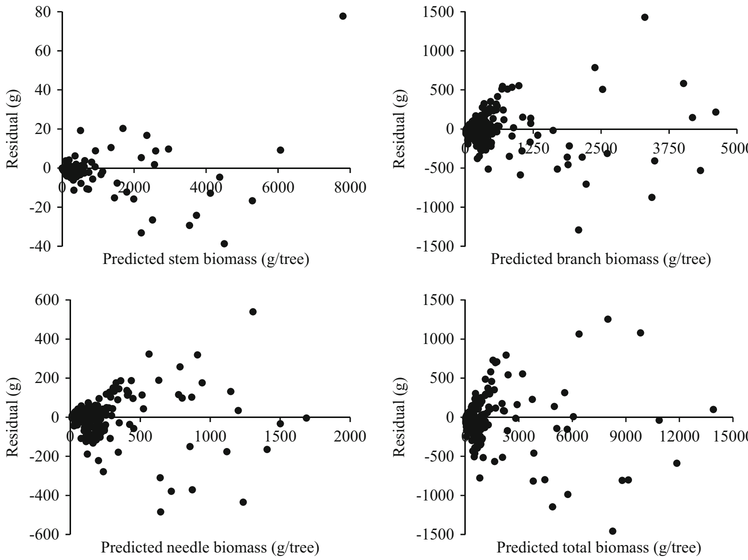

Fig. 3 Residual distributions of compatible biomass equations

wood, branch, needle, and above-ground total range 2.6–7718.5 g tree^{-1}, 10.8–4948.7 g tree^{-1}, 4.9–1690.5 g tree^{-1}, and 27.1–13,799.0 g tree^{-1}, respectively. When the ratios of biomass components to the above-ground total biomass were examined, it was understood that more than half of the above-ground total biomass (51.9% on average) is composed of branch biomass and the other half is shared approximately equal of stem wood and needle biomass (23.5 and 24.6% on average, respectively). Some descriptive statistics used in this study are given in Table 1, separately for the two data groups. The correlation analysis results to demonstrate the relationships between D_0, H, V, and componential M values for the samples are presented in Table 2.

According to the results of the analysis, there were strong correlations between the biomass of components and of total above-ground and D_0, H, and V ($p < 0.01$). In the results of nonlinear regression analysis, the variables D_0 and H explained the whole of the variance (99%) in stem volume and stem wood biomass ($p < 0.05$) for the equations developed for stem volume (Eq. 1) and stem wood biomass, branch biomass, needle biomass, and above-ground total biomass (Eq. 2). The reason for this high explained variance percentage values (R^2) for both dependent variables is that the stem form is considered conical in the stem volume calculations and the stem wood biomass is calculated by the wood density (0.478 g cm^{-3}). The explained percentages of the variance of branch biomass, needle biomass, and above-ground total biomass of the D_0 and H variables were also very high, 91, 88, and 99%, respectively ($p < 0.05$). The explained variance percentage values of compatible biomass equations proposed by Zeng and Tang (2012) and adapted for stem wood biomass,

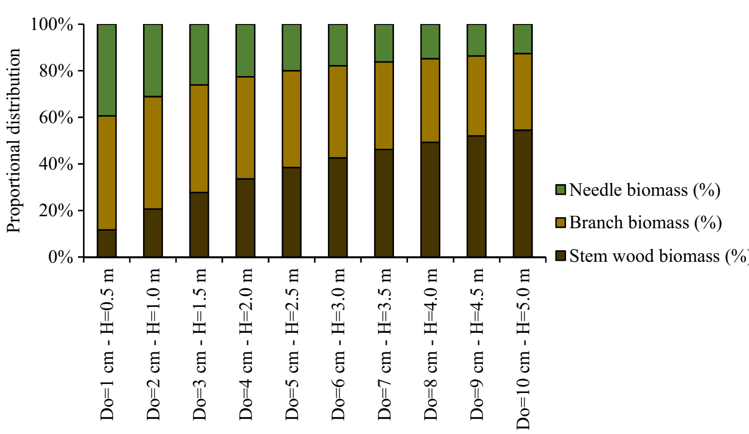

Fig. 4 Proportional distributions of biomass components in above-ground total biomass

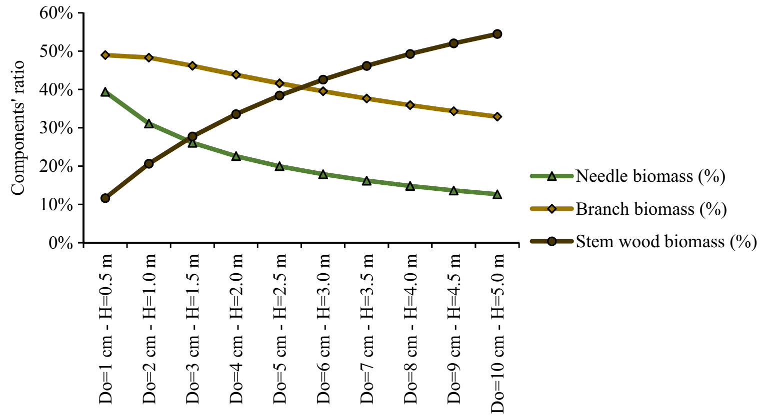

Fig. 5 Changes in biomass components' ratios in above-ground total biomass

branch biomass, needle biomass, and above-ground total biomass were also quite high in this study ($p < 0.05$).

The expected relationships described above between the c_i coefficients of compatible biomass equations and the a_i and b_i coefficients of volume and biomass equations were also provided. Results related to regression equations developed for stem volume, stem wood biomass, branch biomass, needle biomass, and above-ground total biomass estimation are given in Table 3. All coefficients of regression equations given in Table 3 were statistically significant ($p < 0.05$). The results of the paired t test performed with the validation data to test the validity of regression equations developed are given in Table 4. For all the equations, there were no significant differences between observed and predicted values ($p > 0.05$) and it was decided that the equations were statistically usable. The relationships between observed and predicted biomasses with compatible biomass equations are shown in Fig. 2 and the residual distributions of the compatible biomass equations are also shown in Fig. 3. When the residual distributions are examined, it can be seen that all biomass equations have very small residuals in low biomass values, but the residuals are partially increased with the increase in biomass quantities. When looking at the directions of residuals, the residuals were distributed randomly in all compatible biomass equations and the mean residual values were close to zero. Mean residual values for stem wood, branch, needle, and above-ground total biomass estimates were − 1.0, − 18.3, 0.3, and − 35.6 g, and mean absolute residual values were 2.6, 122.8, 51.2, and 153.2 g, respectively.

When the proportional distributions of stem wood, branch, and needle biomass in above-ground total biomass are examined from thin and short individuals towards thick and long individuals, the stem wood biomass ratio increased gradually while the ratios of branch and needle biomass decreased (Fig. 4). For example, from an individual with $D_0 = 1$ cm and $H = 50$ cm to an individual with $D_0 = 10$ cm and $H = 500$ cm, stem wood biomass ratio increased from 12 to 54%, while branch and needle biomass ratios decreased from 49 to 33% and from 39 to 13%, respectively (Fig. 5).

If young Turkish pine individuals are thought to be between 1 and 10 cm in stem base diameter and 50 and 500 cm in tree height, according to the developed compatible equations, above-ground total, stem wood, branch, and needle biomasses are ranged between 39–11,539 g, 6–6326 g, 26–3820 g, and 21–1467 g, respectively. Assuming that the number of young individuals per hectare is 10,000, above-ground total, stem wood, branch, and needle biomasses vary between 0.4–115.4, 0.06–63.3, 0.3–38.2, and 0.2–14.7 tons per hectare, respectively. When these values were multiplied by the *CF* (0.51) according to the same assumption, carbon storages in the above-ground total, stem wood, branch, and needle biomasses of young Turkish pine stands in Turkey will be in the range of 0.2–58.9, 0.03–32.3, 0.15–19.5, and 0.1–7.5 tons per hectare, respectively.

Discussion and conclusions

It is very important to know the volume and biomass of young stands as well as the mature ones. This information is needed to determine growing stock and biomass, to predict carbon stock, to estimate the amount of combustible material, etc. This information is also very important for Turkish pine which has a very wide distribution area in Turkey.

The results show that stem wood biomass, branch biomass, needle biomass, and above-ground total biomass can be reliably estimated with D_0 and H values. Because these values explained nearly the total variability of stem wood biomass and above-ground total biomass variability, and 91 and 88% of the branch and needle biomass variability, respectively.

Direct measurement of biomass values requires cutting of individual tree for precise information, as well as laborious, time consuming, and costly task. For this reason, estimations by using the variables that are easier to measure are suggested instead of direct measurements (Alemdag and Horton 1981). Although Kucuk et al. (2008) and Bilgili and Kucuk (2009) have developed equations for branch, needle, and above-ground total biomass estimates separately for young trees and saplings of Turkish pine, they have not studied on stem volume and stem wood biomass estimates and compatibility of biomass equations with the volume equation. Prediction successes of branch, needle, and above-ground total biomass equations developed in this study are similar to the results of Kucuk et al. (2008) and partly higher than the results of Bilgili and Kucuk (2009).

The biomass equations developed in this study can estimate biomass amounts of biomass components and above-ground total biomass of small trees and saplings in Turkish pine stands. The total biomass values of young Turkish pine forests can be estimated with the help of biomass values related to the individuals in stands. In addition, based on the biomass estimates obtained, carbon stocks for young Turkish pine forests can also be predicted using the carbon fraction value of 0.51.

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