Estimation of biomass and carbon storage of tree plantations in northern Iran

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ABSTRACT: To estimate the aboveground biomass and carbon storage in multi-species plantations we used species-specific equations method and three other generic methods. Astara county is located in northern Iran. It has a total area of 1,757 ha. Based on species-specific allometric equations, total aboveground biomass was calculated and varied between 81.13 and 98.21 $t \cdot ha^{-1}$ for *Acer velutinum,* 68.36 and 83.44 $t \cdot ha^{-1}$ for *Quercus castanifolia,* 71.88 and 119.22 $t \cdot ha^{-1}$ for *Tilia begonifolia,* 56.07 and 61.98 $t \cdot ha^{-1}$ for *Fraxinus excelsior* and from 37.92 to 51.34 $t \cdot ha^{-1}$ for *Prunus avium*. There was a significant difference between the mean values of total aboveground biomass estimation obtained by species-specific equations and the three generic methods for *Alnus subcordata, Pinus taeda* and *Pinus nigra*. Results indicated that using generalized methods produced more reliable and accurate estimations for native species than for exotic species for rapid biomass and carbon estimation in order to decide on plantation development in the area.

Keywords: aboveground biomass; generic methods; allometric equations; plantation development

Estimates made for Forest Resource Assessment (FRA) show that the world's forests store 289 Gt of carbon in their biomass alone. Sustainable management, planting, and rehabilitation of forests can conserve or increase forest carbon stocks, while deforestation, degradation, and poor forest management reduce them. For the world as a whole, carbon stocks in forest biomass decreased by an estimated 0.5 Gt annually during the period 2005–2010, mainly because of a reduction in the global forest area (FAO 2010). Among forest management options for carbon sequestration, afforestation (i.e. the establishment of trees on land not previously forested) has been recognized as a cost-effective and environmentally beneficial strategy for carbon sequestration (Niu, Duiker 2006).

Measuring the impacts and the long- and short-term storage capacity of forests to sequester CO_2 would allow for the development of informed policies aimed at reducing net CO_2 emissions. Terrestrial biotic carbon stocks and stock changes are difficult to assess (IPCC 2003), and most current estimates are subject to considerable uncertainty (Lowe et al. 2000; Jenkins et al. 2003).

There are different approaches for calculating the biomass and carbon stocks. One of them is a destructive way to directly estimate biomass. Fonseca et al. (2011) determined carbon directly in various components (leaves, branches, stems, structural roots and soil) in single-species plantations of two tropical native species and showed how site and species-specific data contribute to the overall goal of improving carbon estimates and providing a more reliable account of the mitigation potential of forestry activities on climate change. Another approach is a non-destructive method to develop an allometric equation that will allow us to estimate a tree mass from a few simple measurements, and then the application of this equation to the trees in a forest.

Allometry refers to the analysis of logarithmic-transformed bivariate size data by linear regression techniques that is integrated the $y = ax^{\alpha y,x}$

which is used subsequently. These equations address the relative change of one plant dimension, in relation to the relative change of a second plant dimension. The allometric scaling exponent $\alpha_{y,x}$ can be perceived as a distribution coefficient for the growth resources between organs y and x (Pretzsch, Dieler 2012).

West et al. (1997) reposted that allometric scaling relations, including the 3/4 power law for metabolic rates, are characteristic of all organisms and are here derived from a general model. West et al. (2009) indicated that whereas co-occurring plants usually compete for a common resource species in different taxonomic and functional groups, they exhibit similar scaling relations for structural dimensions and metabolic rates. So the theory should be very general and apply to diverse forests of coexisting tree species, irrespective of limiting resource, geographic location, and taxonomic or functional group. Furthermore, although derived for aboveground shoots, the model should also apply to belowground roots, which exhibit similar scaling relations. Moreover, in the second part of a quantitative theory for the structure and dynamics of forests they mentioned that the theory should apply to a wide range of forests despite large differences in abiotic environment, species diversity, and taxonomic and functional composition (Enquist et al. 2009).

Pretzsch and Dieler (2012) indicated that numerous empirical works show that variability of crown structure rather than constancy is essential for a tree's success in coping with crowding. We conclude that observed developments of plant structure seem to result from both general metabolic allometry and partitioning, which is inherent in all woody and herbaceous plant species, and speciesspecific structural allometry and variability in structure and space filling which reflects an adaptation and acclimation to selective pressure.

One way for this study to have proceeded would have been to use the equations developed by other researchers for similar tree species. If these equations were used, there would be no need to develop new equations, which would have required that a few trees be sacrificed. The reliability of the current estimates of forest carbon stock and the understanding of ecosystem carbon dynamics can be improved by applying existing knowledge to the allometry of trees that is available in the form of biomass and volume equations (Jenkins et al. 2003; Lehtonen et al. 2004; Zianis et al. 2005; Miles, Smith 2009; Anderson et al. 2012). Bragg (2011) tested four different prediction systems to predict aboveground live biomass for the loblolly pine based on stem diameter at breast height (DBH). Estimates of carbon stock in forest plantations are generally based on allometric equations relating either carbon or biomass to diameter at DBH.

These equations are usually based on the measurement of the fresh mass of each tree with subsamples taken to determine moisture content to convert to dry weight. However, drying time and the number of sub-samples vary between studies.

The overall objective of this study is to estimate the aboveground biomass and carbon storage in multi-species plantations based on age, species type and altitude using different methods consisting of species-specific equations method as a basis (calculating stem volume, stem mass and use of allometric equations for other tree components) and Intergovernmental Panel on Climate Change (IPCC) Method (default values), Jenkins et al. (2003) Method (a set of compiled diameter-based allometric regression equations for estimating total aboveground biomass) and Chojnacky and Jenkins (2010) Method (modified meta-analysis of Jenkins et al. 2003 work) as three generic methods that are the most frequently used in biomass and carbon estimation in order to determine the predictive accuracy of the three methods in comparison with species-specific equations method for estimating rapid biomass and carbon to make plantation development decisions by suggesting eight species in the study area.

MATERIAL AND METHODS

Study area. The plantation hub of Iran is located in the northern part of this country. Astara county is located in Guilan province in the north and belongs to the "Hyrcanian forest" life zone (Fig. 1). It is a part that has the highest variety of successfully planted species. Annual temperature ranges from 6.2 to 26.1°C and average annual rainfall is about 1,500 mm. It has two watersheds with a total area of 43,791 ha. Annually planted tree species in pure small groups on a total area of 1,757 ha include *Acer velutinum, Fraxinus excelsior, Tilia begonifolia, Quercus castanifolia, Alnus subcordata*, *Prunus avium* (native species), *Pinus taeda* and *Pinus nigra* (exotic species) that are suggested for plantation in this region by the Forests, Rangelands, and Watershed Management Organization. Data are collected at the tree level and processed to obtain stand parameters.

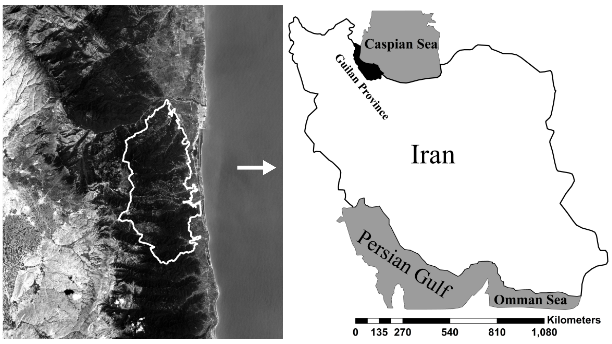

Fig.1. Location of the study area

Methods. Due to the lack of specific allometric equations for the selected tree species in Iran, we had to select allometric equations from other countries that are more generic based on similarity to the species type. We collected all allometric equations around Europe and America in terms of the geographical distribution of sampled trees, the number of sampled trees, the range of dimensions (d, h) of sampled trees, accounted dimensions and applied definitions. We found three more generic methods consisting of species-specific equations method, the IPCC method, the Jenkins et al. (2003) method and the Chojnacky and Jenkins (2010) method which have been used repeatedly in researches (Lowe et al. 2000; Zhang, Kondragunt 2006; Miles, Smith 2009; Bragg 2011; Sanquetta et al. 2011).

Calculation of total aboveground biomass and carbon storage based on species-specific equations method

Based on the required accuracy, site conditions, tree species, and stand age, 65 rectangular plots of 500 m^2 area with the tree spacing of 3 × 3 m were chosen (Table 1). Stem volume and stem biomass were measured in terms of 65 rectangular plot measurements. The diameters (d) of all trees in each plot were measured, and height (h) was determined by sampling in all diameter classes.

First, the stem volume in terms of plot measurements was calculated using equation (1):

$$V = \mathrm{ba}_{1.3} \times h \times \mathrm{f}_{1.3} \quad (1)$$

where:
V – stem volume (l),
$\mathrm{ba}_{1.3}$ – basal area at DBH (m),
h – height (m),
$\mathrm{f}_{1.3}$ – form factor.

Stem biomass from wood volume to wood biomass was estimated using the following equation:

$$W = V \times R \quad (2)$$

where:
W – weight (kg),
V – stem volume (l),
R – basic wood density (kg dry matter·m^{-3} fresh volume).

To estimate other tree components (branches, foliage, or crown), biomass equations for selected tree species growing in Europe were used. All empirical relationships were included in the existing allometric equations, and the explanatory variables are always diameter at breast height (DBH), tree height (h), or a combination of the two (Appendix) (Zianis et al. 2005; Muukkonen, Mäkipää 2006). Furthermore, the carbon concentration of different tree parts is rarely measured directly, but generally assumed to be 50% of dry weight (Pretzsch 2009).

Estimation of total aboveground biomass and carbon storage based on IPCC Method

Good Practices Guidance for Land Use, Land-Use Change and Forestry was provided by IPCC for estimating, measuring, monitoring, and reporting carbon stock changes and greenhouse gas emissions. IPCC default values were used as a second method to estimate aboveground biomass (Table 2).

Table1. Site characteristics

Species	Area (ha)	Age (yr)	Elevation (m a.s.l.)	Number of plots
Acer velutinum	368.97	10–11–12	22–142	9
Alnus subcordata	544.67	10–11–12–13	16–128	8
Fraxinus excelsior	245.98	11–12	16–58	7
Quercus castanifolia	193.27	11–12	58–85	8
Tilia begonifolia	158.13	11– 12–13	22–143	8
Pinus taeda	105.42	12–13–14	123	9
Pinus nigra	87.85	10	837	8
Prunus avium	52.71	12	220	8

Table 2. Fractions of IPCC Method for estimating aboveground biomass (CF = 0.5)

Equation	BEF_2
$C = (V \times D \times BEF_2) \times CF$	pines 1.3 × (1.15–3.4) broadleaf 1.4 × (1.15–3.2)

C – total aboveground biomass, V – volume ($m^3 \cdot h^{-1}$), D – basic wood density (kg dry matter·m^{-3} fresh volume), BEF_2 – biomass expansion factor, CF – carbon fraction of dry matter

Estimation of total aboveground biomass and carbon storage based on the Jenkins et al. (2003) method

One of the most comprehensive works related to biomass estimation is a set of compiled diameter-based allometric regression equations for estimating total aboveground and component biomass defined in dry weight terms for trees in the United States. This method is an analysis that represents the first major effort to compile and analyze all available biomass literature to develop a set of generalized, consistent, national scale aboveground biomass regression equations. Equations for predicting the biomass of tree components were developed as proportions of total aboveground biomass for hardwood and softwood groups (Eq. 3).

$$Bm = Exp\ (\beta_0 + \beta_1 \ln DBH) \quad (3)$$

where:

bm – total aboveground biomass (kg dry weight),
Exp – exponential function,
β_0, β_1 – specific coefficients for a given species,
DBH – diameter at breast height (cm),
ln – log base e (2.718282).

Estimation of total aboveground biomass and carbon storage based on the Chojnacky and Jenkins (2010) method

This work updated the Jenkins et al. (2003) work with a modified meta-analysis with equations selected from about 2,500 available based on applicability for estimating biomass from only diameter measurements to estimate the biomass of individual trees and/or branch, bole, bark, or foliage components for North American tree species including several generalized conifer and hardwood equations.

Generalized equations were developed based on the allometric scaling theory (Chojnacky 2012); taxonomic groupings (genus or family) and wood specific gravity were used as surrogates for scaling parameters that could not be estimated. The update resulted in 35 biomass equations for taxa classification (Eq. 4).

$$B = C_i DBH^{2.67} + D_i DBH + C_{ij} DBH^{2.67} + D_{ik} DBH \quad (4)$$

where:

B – total aboveground biomass,
C_i, D_i – parameters for 21 given genera,
C_{ij}, D_{ik} – parameters for *j* or *k* defined indicator variables,
DBH – diameter at breast height.

Statistical analysis. Data were analyzed using one-way analysis of variance (ANOVA) with a confidence level of 0.05 to compare differences between mean values of species-specific equations and three generic methods. SPSS 16.0 (IBM, New York, USA) was applied for all statistical analyses.

RESULTS AND DISCUSSION

Estimation of total aboveground biomass using species-specific equations method

According to the species-specific allometric equations, total aboveground biomass was calculated as a product of tree components and was reported as stem biomass, crown biomass, and total aboveground biomass. The carbon content was also calculated for different species (Table 3).

According to the result of species-specific equations we found the highest biomass estimations as well as carbon storage contents for *Pinus taeda*, *Alnus subcordata, Acer velutinum, Quercus castanifolia, Tilia begonifolia, Fraxinus excelsior*, *Prunus avium* and *Pinus nigra*, respectively, which indicated that carbon storage in the biomass increased with plantation age, such as with *Pinus taeda*. Bragg (2011) found that depending on stem diameter at breast height (DBH), biomass varied considerably between different prediction systems for loblolly pine (*Pinus taeda*). The result of a research in northern Iran showed the best compatibility of *Pinus taeda* in comparison with other exotic conifer species (Hemmati et al. 2002; Mohammadnejad et al. 2003).

This amount was remarkably low in *Pinus nigra* due to the species age and short growth period at a higher altitude. Sanquetta et al. (2011) indicated that accounting for the variations in BEF and R and using regression equations to relate them to DBH, tree height and age are fundamental for *Pinus* spp. in obtaining reliable estimates of forest tree biomass, carbon sink, and CO_2 equivalent.

Table 3. Mean values of stem, crown and total biomass of different species (t·ha^{-1})

Species	Stem biomass	Crown biomass	Total aboveground biomass	Carbon content
Alnus subcordata	93.18	10.35	103.53	51.765
Acer velutinum	70.16	19.88	90.03	45.015
Quercus castanifolia	59.61	13.21	72.82	36.41
Tilia begonifolia	57.70	14.18	71.88	35.94
Fraxinus excelsior	44.28	11.79	56.07	28.035
Pinus taeda	121.02	20.74	141.76	70.88
Pinus nigra	15.73	4.31	20.05	10.025
Prunus avium	32.98	4.93	37.92	18.96

Estimation of total aboveground biomass using three other methods

Furthermore, the mean values of total aboveground biomass of different species were estimated by the three selected methods, and Table 4 shows the results for species-specific equations, IPCC, Jenkins et al. (2003) and Chojnacky and Jenkins (2010), respectively.

The results of this study showed that the biomass and carbon estimations differed due to the applied methods. Bragg (2011) used a test of a handful of different biomass prediction systems and found that the model choice definitely influences estimates of aboveground biomass. In addition, differences in equation forms and species groupings may cause small scale differences, depending on the tree size and forest species composition (Jenkins et al. 2003).

Comparison of applied models

To evaluate differences between the applied methods, first we graphed the means and standard errors and then we tested the equality of variance. Fig. 2 confirms that the variances in methods are equal for all species. Then we tested the method differences by plotting means which showed that the average biomass prediction is not equal across methods for *Pinus nigra, Pinus taeda,* and *Alnus subcordata* whereas for others there were no significant differences between methods.

Based on the statistical analysis we found that, on the one hand, there was no significant difference between the mean values of total aboveground biomass estimations obtained by species-specific equations and those of the three generic methods for *Acer velutinum, Quercus castanifolia, Tilia begonifolia, Fraxinus excelsior*, *Prunus avium.* They varied between 81.13 and 98.21 t·ha^{-1} for *Acer velutinum,* 68.36 and 83.44 t·ha^{-1} for *Quercus castanifolia,*71.88 and 119.22 t·ha^{-1} for *Tilia begonifolia,* 56.07 and 61.98 t·ha^{-1} for *Fraxinus excelsior* and from 37.92 to 51.34 t·ha^{-1} for *Prunus avium*. On the other hand, the mean values of total aboveground biomass estimations generated by species-specific equations in comparison with the three generic methods differed significantly for *Alnus subcordata, Pinus taeda,* and *Pinus nigra*. These generated results occurred for all native species except *Alnus subcordata,*

Table 4. Mean values of total aboveground biomass of different species estimated by different methods

Species	Total aboveground biomass (t·ha^{-1})				Mean	
	method 1	method 2	method 3	method 4	statistic	std. error
Alnus subcordata	103.53	130.45	102.56	94.4	107.7350	7.84
Acer velutinum	90.03	98.21	81.13	85.56	88.7325	3.64
Quercus castanifolia	72.82	83.44	78.5	68.36	75.7800	3.29
Tilia begonifolia	71.88	80.77	119.22	81.37	88.3100	10.52
Fraxinus excelsior	56.07	61.98	59.95	57.11	58.7775	1.34
Pinus taeda	141.76	157.31	106.16	115.04	130.0675	11.81
Pinus nigra	20.05	20.44	30.63	28.55	24.9175	2.73
Prunus avium	37.92	46.17	51.34	41.74	44.2925	2.89

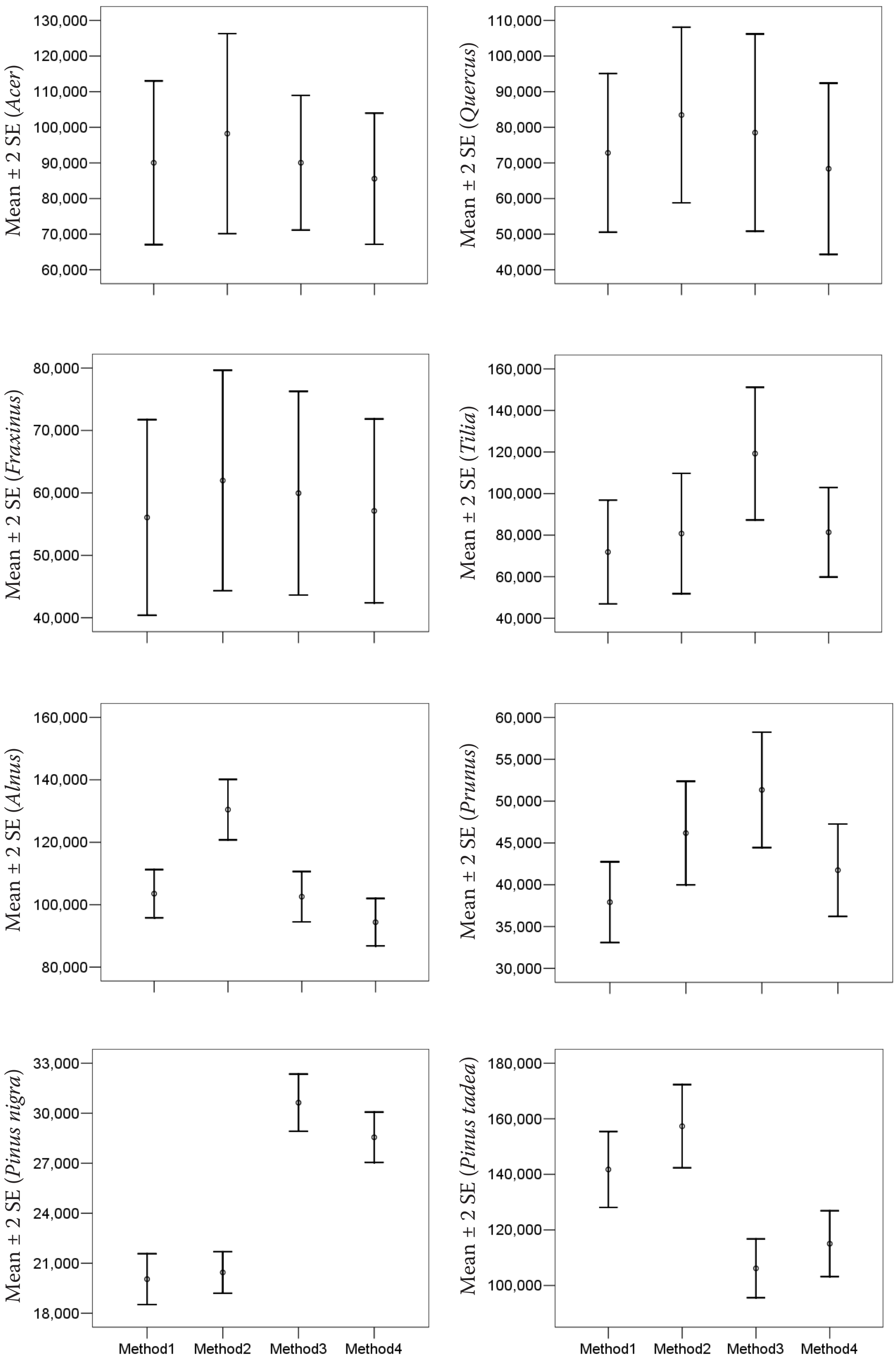

Fig.2. Equality results of variance across the applied methods

which indicated that using generalized methods may produce more reliable and accurate results for native species than for exotic species (Table 5).

Moreover, a method known as cell-wise multiple comparisons was used to specify exactly how the means differ and to test those specifications in order to compare the mean values of each method with the others. Cell-wise multiple comparisons test the difference between each pair of means, and yield a matrix where asterisks indicate significantly different group means at an alpha level of 0.05. Table 7 shows the details of the cell-wise multiple comparisons.

Results indicated that the biomass prediction produced by species-specific equations Method was significantly different from that of Jenkins et al. (2003) method and Chojnacky and Jenkins (2010) method for *Pinus taeda* and *Pinus nigra,*

Table 5. Visualization of group differences by means plotting (one-way ANOVA, df = 3)

Species	Sum of squares	Mean Square	*F*	Significance
Alnus subcordata	6E + 009	1,968,681,717.068	14.244	0.000
Pinus nigra	7E + 008	238,980,838.673	52.422	0.000
Pinus taeda	2E + 010	5,028,457,170.947	13.478	0.000
Prunus avium	8E + 008	267,681,954.725	3.829	0.020
Acer velutinum	8E + 008	250,222,821.793	0.221	0.881
Quercus castanifolia	1E + 009	346,839,306.196	0.283	0.837
Tilia beqonifolia	1E + 010	3,548,083,242.951	2.410	0.088
Fraxinus excelsior	2E + 008	50,837,069.018	0.112	0.952

whereas no significant difference was observed between the biomass predictions produced by species-specific equations method and IPCC method. We continued with a comparison of different methods for biomass prediction for *Alnus subcordata*, and the results showed that biomass prediction produced by species-specific equations method was significantly different from that of IPCC method, whereas no significant difference was observed between the biomass predictions produced by Jenkins et al. (2003) method and Chojnacky and Jenkins (2010) method in comparison with species-specific equations method (Table 6).

A comparison of the mean values of total aboveground biomass estimated by species-specific equations method was significantly different from that of Jenkins et al. (2003) method and Chojnacky and Jenkins (2010) method for *Pinus taeda* and *Pinus nigra*. The results revealed that species-specific equations method produced different biomass and carbon estimations, as much as 18.84–25.11% higher than the averages of Jenkins et al. (2003) method and Chojnacky and Jenkins (2010) method for *Pinus taeda* and 42.39–52.76% lower than the averages of Jenkins et al. (2003) method and Chojnacky and Jenkins (2010) method for *Pinus nigra*.

Table 6. Cell-wise multiple comparison of different methods in terms of biomass prediction by Student-Newman-Keuls test

Species	Method	*n*	Subset (α = 0.05)	
			1	2
Alnus subcordata	4	8	94,402.52	
	3	8	102,562.1	
	1	8	103,529.4	
	2	8		130,451.8
	significance		0.283	1.000
Pinus taeda	3	9	106,167.4	
	4	9	115,040.1	
	1	9		141,755.1
	2	9		15,7316.6
	significance		0.337	0.097
Pinus nigra	1	8	20,046.64	
	2	8	20,449.00	
	4	8		28,556.95
	3	8		30,634.10
	significance		0.709	0.062

Furthermore, the mean values for *Alnus subcordata* indicated a significant difference between results of species-specific equations method and IPCC method when species-specific equations method produced biomass and carbon estimations as much as 26% lower than the average of IPCC method. This may show that large diameters due to wide age ranges caused different changes in the variance of different methods.

A research was carried out in Australia to test the reliability of a range of allometric equations. It showed that uncertainties resulting from the application of allometric equations to estimate aboveground biomass are very low (generally < 10% difference between measured and estimated biomass) when using site-based allometrics, or moderate (generally < 16% difference between measured and estimated biomass) when generalized non-site allometrics is used. This report contains a comprehensive set of new allometric equations that can be used to estimate the biomass of mixed species (CSIRO 2013).

CONCLUSION

One of the main plantation purposes in the area is producing more biomass and carbon stock as the forest area per capita in Iran is 0.2 ha as compared with the global standard of 0.8 ha, so development of forest plantations is a vital need in the face of forest conversion and increasing population pressure on the land (Shamekhi, Mirmohamadi 2012). To continue for plantation development in the area, knowing about species with high biomass and carbon production per ha is essential.

This research estimated aboveground biomass and carbon storage in terms of per hectare multi-species plantation of six native and two exotic species based on species-specific equations using plot-based data as diameter and height combined with published equations to compare with three more generic prediction methods (IPCC method, Jenkins et al. 2003 method, Chojnacky, Jenkins 2010 method). Considering that the development of local biomass equations is a resource expensive operation, the models that allow per hectare quantification of biomass and carbon use simple field estimation variables, such as basal area, which represents an important advantage toward the precise and reliable quantification of carbon accumulation in plantations (Fonseca et al. 2011).

According to the results, in the same site conditions, Jenkins et al. (2003) Model, and Chojnacky and Jenkins (2010) Model are more reliable for native species as well as IPCC model for exotic species in the region. However, these methods are not completely ideal for calculating total aboveground tree biomass and carbon storage, but they can be more reliable for native species than for non-native species for the rapid estimation of biomass and carbon in decision making and species selecting for plantation development.

We suggest other researches on more native species as well as exotic species in Iran to increase the reliability and efficiency of biomass and carbon estimations as important environmental issues.

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Appendix. Existing biomass equations for different tree components (Zianis et al. 2005; Muukkonen P., Mäkipää R. 2006)

Species	Tree components	Unit			Equation	*a*	*b*	*c*	*d*
		BIOM	D	H					
Alnus subcordata	BR	kg	mm	–	$a \times D^b$	0.000003	2.880598		
Alnus subcordata	FL	kg	mm	–	$a \times D^b$	0.000003	2.547045		
Acer velutinum	ln biomass (CR)	kg	cm	–	$a + b \times dia + c \times (\ln(dia^d))$	−2.8534	0	2.1505	1
Q. castanifolia	BR	kg	cm	–	$a \times D^b$	0.0021	3.3064		
Q. castanifolia	FL	kg	cm	–	$a \times D^b$	0.0024	2.6081		
Tilia begonifolia	ln biomass (BR)	g	cm	–	$a + b \times dia + c \times (\ln(dia^d))$	0.945	0	2.939	1
Tilia begonifolia	ln biomass (FL)	g	cm	–	$a + b \times dia + c \times (\ln(dia^d))$	−1.559	0	2.868	1
Fraxinus exelsior	$\log_{10}$biomass	g	cm	–	$a + b \times (\log10(dia^c))$	1.06339	2.53542	1	
Fraxinus exelsior	$\log_{10}$biomass	g	cm	–	$a + b \times (\log10(dia^c))$	1.41578	1.69383	1	
Prunus avium	ln (BR)	kg	cm	–	$a+b\cdot\ln(D)+c\cdot(\ln(D))^2$	2.7241	1.4068	0.4646	
Prunus avium	ln (FL)	kg	cm	–	$a+b\cdot\ln(D)+c\cdot(\ln(D))^2$	2.2305	0.607	0.7941	
Pinus taeda	$\log_{10}$biomass	lb	in	–	$a + b \times (\log10(dia^c))$	−0.573	2.538	1	
Pinus nigra	CR	kg	cm	m	$a+b\cdot D^2\cdot H+c\cdot D^2$	−8.7135	6.7203×10^{-4}	0.11893	

BR – branches, FL – foliage, CR – crown, D or dia – diameter at breast height, H – height; *a*–*d* – coefficients

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