POLISH JOURNAL OF NATURAL SCIENCES
Abbrev.: Pol. J. Natur. Sc., Vol 38(3): 197–214, Y. 2023

DOI: 10.31648/pjns.9009

BIOMASS, STEM VOLUME, AND CARBON SEQUESTRATION BASED ON ALLOMETRIC EQUATIONS FOR *POPULUS DELTOIDES* W. BARTRAM EX MARSHALL. PLANTATIONS (A STUDY OF GUILAN, IRAN)

***Tooba Abedi*[1], *Roya Abedi*[2]**

[1] ORCID: 0000-0001-9612-5374
[2] ORCID: 0000-0002-5650-0472
[1] Academic Center for Education, Culture and Research
Environmental Research Institute, Rasht, Iran
[2] Department of Forestry, Ahar Faculty of Agriculture and Natural Resources
University of Tabriz, Tabriz, Iran

Key words: allometric equation, correlation, annual increment, regression analysis.

Abstract

Populus deltoides W. Bartram ex Marshall is one of the most important economically (wood production), environmentally (biomass production and carbon sequestration), and fast-growing species in plantations. Therefore, this study aimed to investigate biomass, volume, and carbon sequestration models according to age by using the stem analysis method in poplar plantations in five regions of Guilan province. Measurement features included DBH and the total height of all trees in two plots with one hectare area in each region. 30 trees were randomly selected in different diameter classes and cut down and the discs were obtained in order to stem analysis. The annual rings of discs were counted, ages at different tree heights were obtained, and the diameter of the annual rings was measured to determine the annual diameter and volume increments. Carbon measurement, volume measurement of wood, and volume conversion to weight ratio were calculated. Finally, regression analysis was performed by the relationship between volume and biomass growth by age based on the highest coefficient of determination and minimum standard error. The results showed that the nonlinear models were able to show the highest coefficient of determination (R^2 = 0.93–0.99) and the least standard error of the relationship between these characteristics. These models can be applied for the annual growth assessment of poplar plantations in carbon sequestration and optimal management for achieving sustainable development of the various plantations.

Introduction

Tree allometry is the study of the relationships between tree's stem size, physiology, behavior in biology-associated, and differences in the

Address: Roya Abedi, University of Tabriz, Tabriz, Iran, e-mail: royaabedi@tabrizu.ac.ir

growth rates of the various parts of a tree stem. This allometry represented by equations in the form of regression models. Models could reflect the empirical relationship between biomass and easily measured dendrometrical variables of trees. Therefore, Efficient and accurate models for growth and yield are fundamental tools in forest sciences and play a key role in forest management, planning, and ecological studies. Forests compensate for the urgent need to reduce carbon dioxide at the atmosphere by increasing biomass storage. This solution achieved by increasing forest cover and plantation. Among the tree species, poplar has remarkable characteristics that make it suitable for plantation. Hence, It has become one of the most abundant species used in the world's forests for environmental and economic purposes (FANG et al. 2007). Among the fast-growing tree species, poplar becomes a good option for villagers, wood producers, and owners of the wood industries due to its fast growth, widespread distribution, ability to settle in different conditions, produce timber in the short harvest period, not produce large branches and leaves, rapid capital return investment, high biomass production mainly in stem, the possibility of hybridization, and ease of propagation, the feasibility of simultaneous cultivation with crops, abundant use and extensive in advanced woodworking industries as well as rural and traditional uses such as leaf edibility in animal husbandry (GUO and ZHANG 2010, MOUSAVI KOPAR et al. 2011, ESLAMDOUST and SOHRABI 2017).

The world's forest ecosystems influence carbon dioxide absorption and provide suitable carbon spin and storage conditions (NOBAKHT et al. 2011). Tree growth is important for storing atmospheric carbon in plants and producing biomass. Numerous biomass data and allometric equations have recently been collected to predict above-ground carbon in forest trees and the need to assess carbon stocks for national greenhouse gas balance estimating. It is consequential that accurate allometric equations are available to estimate carbon stocks from field inventory data (ARORA et al. 2014).

Growth means increasing the value of the characteristics (the diameter, height, biomass, and volume) of a living tree over a given period of time. It is one of the main biological components of plants, and the stem analysis method is a way to study the increment that can accurately evaluate the growth characteristics of trees. The principal purpose of this method is to calculate species growth in terms of forest management effects, competition, insect attack, and air pollution (ELAMDOUST et al. 2015). In this method, the tree is cut, split, dried, and weighed to calculate biomass accurately. Although it is a complex and high-cost process method in the operational phase, its integration into the allometric equations could lead to credible results. These equations are the functions that can compute dependent variables through the independent variables, thereby converting direct measurements of trees (diameter and height) into other variables such as biomass (PARSAPOUR et al. 2013). Regression-based approaches are used to construct allometric equations from the generated dataset (MALAKINI et al. 2020).

Many studies have been done on the growth behavior of woody species, especially poplar (PARSAPOUR et al. 2013, ESLAMDOUST and SOHRABI 2017, ESLAMDOUST 2022).

Using the regression analysis to find the relationships between biomass production and poplar characteristics to develop different allometric models between various parts of trees and their carbon sequestration ability showed significant correlations to predict biomass for the whole tree's organs (PARSAPOUR et al. 2013).

Predicting aboveground biomass (AGB) and carbon pools in Hyrcanian mixed-beech forests of Iran was measured by destructive sampling method (weighing 174 fallen trees and recording diameter at breast height (DBH), total height (H), and basic wood density (r) as explanatory variables). Developing allometric equations in ANN (Artificial Neural Network) models showed that the best-designed model for aboveground biomass predicted in the ANN method had higher accuracy than other allometric equations (VAHEDI 2016).

The potential of three fast-growing tree species' carbon storage in biomass, litter, and soil in south Caspian Sea plantations revealed that *P. deltoides* reached the highest biomass and carbon (81%) into the stem (ESLAMDOUST and SOHRABI 2017).

Allometric power equations were fitted based on the bark of *P. deltoides* in Iran and concluded that R^2 ranged from 0.89 to 0.90. These allometric equations provided the best fitted for relationships between total stem dry biomass, dry bark biomass, and DBH (ESLAMDOUST 2022).

An individual-tree diameter growth model was developed using the mixed effects regression method for managed uneven-aged stands of *Quercus* spp. and *Pinus echinata* Mill. in Highlands of Missouri. The model efficiency (R^2) was calculated from 0.26 to 0.57 (LHOTKA and LOEWENSTEIN 2011).

The potential of biomass production and carbon sequestration in the poplar plantations in China showed that biomass production did not differ significantly from seven to ten years, and trees had the highest biomass in the stem and lowest in the leaves. In addition, evaluating and comparing the percentage of diameter increment, basal area, height, and volume of poplar and swamp cypress by stem analysis method showed that the highest current diameter increment of poplar was obtained at four years (5.1 cm), the highest height growth at six years (3.1 m) and the greatest volume of poplar (0.094 m^3) was at the age of eight and concluded that this species to be suitable for economic and environmental plantations (FANG et al. 2007).

The diameter increment, biomass, volume, and carbon sequestration were reported by age in a poplar plantation in India. According to the allometric models, Carbon sequestration rates were calculated from 0.5 to 90.1 mg/ha at the age of 11 by the highest coefficient of determination. In consequence, the poplar was introduced as a suitable solution for sustainable carbon production and global carbon reduction (ARORA et al. 2014)

It was evaluated that the general or site-specific allometric equations, using diameter at breast height (as a predictor) are more accurate for estimating stem volume, stem biomass, branch biomass, aboveground woody biomass, and coarse root biomass in 14-year-old poplar plantations. Allometric model selection depended on the objective (yield evaluation, nutrient budget, carbon stocks), tree size, and plantation environmental condition (FORTIER et al. 2020)

According to reports, Iran ranks 10^{th} in the world in terms of the area under plantation (1 001 000 hectares (FAO 2020)). The northern Iran is a specific region due to its geographical location in terms of environmental and economic capabilities, and *P. deltoides* plantation has been popular in this region in recent decades (ESLAMDOUST 2022). But there is no specific model to estimate biomass and carbon in poplar plantations in Guilan province (one of the northern provinces of Iran). Consequently, the present study aims to investigate allometric equations of the biomass, volume, and carbon sequestration of *Populus deltoides* by stem analysis, to provide the best-fitted models for estimating these characteristics by age and supply information based on local condition of poplar plantations in Guilan province.

Materials and Methods

Study area

Five district plantations of *Populus deltoides* W. Bartram ex Marshall. located in Guilan Province, in the north of Iran are considered in this study (Figure 1). The characteristics of the plantations show in Table 1.

Table 1

Characteristics of study areas

District	Age	Site altitude [m.a.s.l]	Area [ha]
1	37	13	89
2	38	70	66
3	37	70	43
4	29	60	48
5	32	-20	38.9

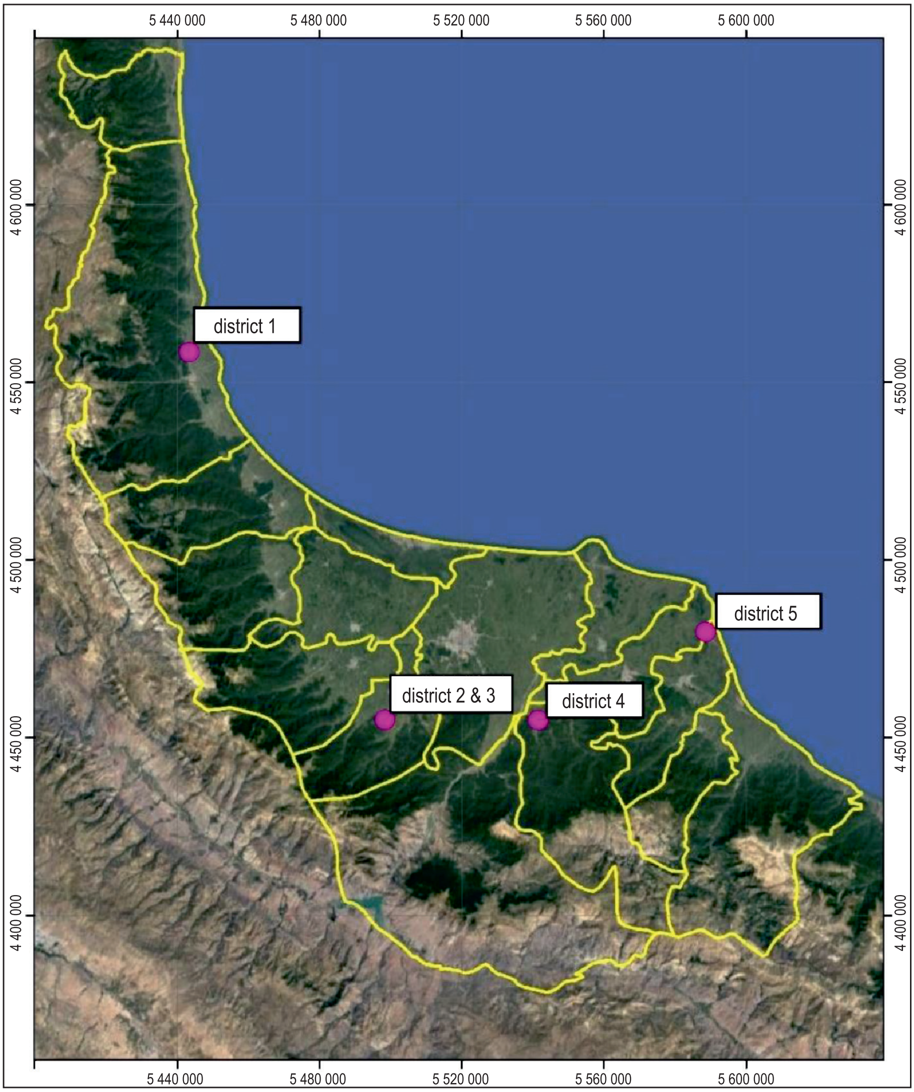

Fig. 1. Geographic location of study areas

Volume estimation

A single sample plot with one hectare area (100 m ×100 m) was sampled in each district of plantation (Arora et al. 2014, Mohammadi et al. 2017). The location of these plots was determined randomly inside the districts because the every district had homogenous stand condition (such as the same DBH classes, height, age and etc.). The diameter at breast height (DBH) and height of all trees were measured in each plot. The estimation of stem volume and compartment biomass at the plantation-scale often requires that trees of various sizes be felled, dissected into components, and weighed or measured. In total, 30 trees were destructively sampled, with regular distribution in diameter classes (Wang 2006, Segura et al. 2006). Data of stem analysis from these trees in different diameter classes across various site types and conditions were combined with plot sample data to calibrate the volume-age, volume increment- age and carbon storage- age equations in the whole stand model (Tian et al. 2020). The biomass and volume data obtained from these destructive sampling procedures are then used to develop allometric equations between a predictor variable that is easily measurable in the field, is usually diameter at breast height (DBH), and response variables, such as stem volume or the biomass of a given tree compartment. Then, these relationships are used to scale compartment biomass and volume at the plantation level using DBH values directly measured on each tree, or on a representative subset of trees of the plantation. Thus, the allometric equations selected have a direct effect on the volume or biomass estimated at the plantation level.

The cut-down trees were stratified into two biomass compartments: stem and branches (with DBH of greater than 10 cm) (Beets et al. 2012, Turner et al. 2012). In order to estimate the stem volume, discs are chosen from a different height of each tree's stems. Stems were cut at a height of 0.3 m from the ground. The trees were felled and cut into logs of acceptable merchantable lengths (2.3 m). At the end of each stem section, a disc with 8 cm thickness was cut and taken to the laboratory for stem analysis. The surface of each disc was sanded smoothly in order to reveal the growth rings. The rings were analyzed for annual increments (Metsaranta and Bhatti 2016). Annual diameter increment of tree-ring data is used to estimate the annual increment of a tree. Tree ring widths were measured by Digimizer graphical program and using dendrochronological methods analysis.

Tree volume is determined based on the tree's diameter and length. The stem is subdivided into sections of which length (L) and basal area (g) are measured; the basal area is either taken at the lower end (g_l) or the upper (g_u) end. Then, the following Smalian's formula is used for volume calculation (Zobeiry 1994):

$$V = \frac{g_1 + g_u}{2} \cdot L \quad (1)$$

where:
V – the volume of logs [m^3],
g_1 – the basal area at the lower end of trunk [m^2],
g_u – the basal area at the upper end of trunk [m^2],
L – trunk length [m].

Stand volume or stock is calculated by the multiplying volume of each age class by the number of trees per hectare.

The sampled discs were weighed and taken to the laboratory where square sub-samples of 4 cm × 4 cm × 4 cm were oven-dried at 100°C to constant biomass and the dry mass was determined with an electronic balance (Henry et al. 2010). The volume and the dry mass measurements were used to calculate the wood density as below:

$$D_C = \frac{W_0}{V_w} \quad (2)$$

where:
D_c – critical density [gr/cm^3],
W_0 – the dry mass of wood [gr],
V_w – the wet volume [cm^3].

The percentage of organic carbon in 30 stems and branches disc samples was determined by combustion in an electric oven (Arora et al. 2014). This study considered the carbon stored in live biomass as the stem. The amount of carbon sequestrated was obtained when the biomass increased by one unit per age. Finally, the conversion factor of volume to weight per ton of wood was obtained.

Carbon estimation

To measure carbon from 30 felled trees, some stem and branch discs were randomly selected in the diameter classes and transferred to the laboratory for carbon measurement and carbon stored in the tree biomass by combustion in the electric oven (Arora et al. 2014, Haidari et al. 2016). To measure the percentage of organic carbon, the wood was dried in the oven at 105°C for 24 hours (Forouzeh et al. 2008, Ghasemi Nejad Raeini and Sadeghi 2018, Naghdi et al. 2021). The discs that were completely dried were milled by an electric mill and after weighing the samples with digital scales, the samples were placed in the oven and burned for 4 hours at 600°C (Ghasemi Nejad Raeini and Sadeghi 2018). The burned samples were then weighed in the desiccator. By determining the ash weight, initial weight, and organic carbon/ organic matter ratios (eq. 3), the amount of organic carbon in each part was calculated separately (Ghasemi Nejad Raeini and Sadeghi 2018, Forouzeh et al. 2008).

$$OC\% = 0.56OM \tag{3}$$

where:
OC – organic carbon,
OM – organic material.

Results

The quantitative characteristics of the stands including the mean values of diameter, basal area, height, and volume are given in Table 2.

Table 2
Quantitative characteristics of the study areas

District	DBH ±se [cm]	Basal area ±se [m^2/ha]	Height ±se [m]	Volume [m^3/ha]
1	35.04 ± 7.06	19.04 ± 0.04	26.74 ± 5.85	285.33
2	26.59 ± 6.84	19.29 ± 0.03	19.10 ± 4.10	212.29
3	35.67 ± 6.28	7.50 ± 4.9	23.22 ± 3.36	179.36
4	27.59 ± 4.67	13.27 ± 0.02	21.68 ± 1.98	155.58
5	30.68 ± 7.54	10.10 ± 0.04	22.93 ± 4.61	132.48

It was needed coefficients to convert volume to weight in carbon and biomass calculations in this study. The derived coefficients are shown in Table 3.

Table 3
Coefficients used in the analysis

Factor	Value
Wood density [g/cm^3] The conversion factor of volume and total carbon (*t* carbon/m^3)	0.32 $V = 0.1792C$ $R^2 = 0.99$

The diameter at the breast height relative to the age is shown in Figure 2. The relationship between age and diameter is an exponential relationship that is always increasing.

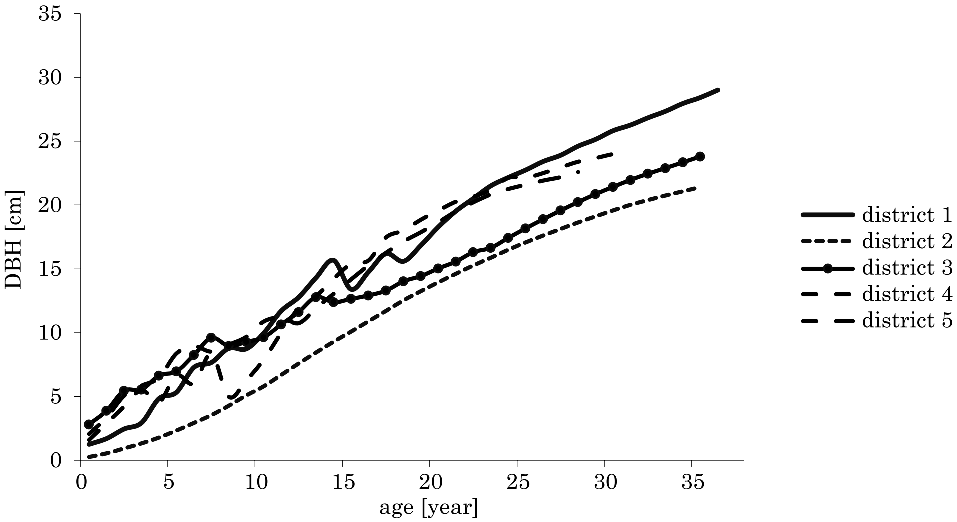

Fig 2. DBH relative to the age in plantations (district 1, district 2, district 3, district 4 and district 5)

The regression analysis of the DBH (*D*) and the stand age (*A*) of the *P. deltoides* plantations is shown in Table 4. This regression equations are very important because DBH is the most easily measurable parameter in the forest that can be obtained by determining its relation to other growth parameters. In these equations, after the formation of the points of DBH equal to age, the equations that have a higher determination coefficient of determination (R^2) and lower standard error (SE) are selected as the most appropriate equations because they show a better pattern of relationship between *D*-*A*. Therefore, according to the results, R^2 had high values with a range from 0.98 to 0.99, and SE was from 0.61 to 0.92. Therefore, the achieved models have sufficient high accuracy to show the relationship between DBH and Age in the studied stands.

Table 4

Dependence of DBH (*D*) and stand age (*A*) in *P. deltoides* plantations

District	Equation	R^2	SE	Kind of distribution
1	$D = 0.12 + \frac{76.05A^{1.13}}{56.43^{1.13} + A^{1.13}}$	0.99	0.67	Dr-Hill
2	$D = \frac{A}{(0.47 + 0.06A - 0.0007A^2)}$	0.99	0.38	resiprocal-quadratic-YD
3	$D = \frac{3.42 + 1.04A}{1 + 0.04A - 0.0003A^2}$	0.99	0.31	Hoerl
4	$D = \frac{2.98 + 0.71A - 1.74}{A^2}$	0.98	0.69	heat capacity
5	$D = \frac{24.24}{(1 + e^{4.07 - 0.23A})^{0.56}}$	0.98	0.92	Richards

Explanations: *D* – DBH [cm]; *A* – stand age [year]

Stand stock volume in plantations is shown in Figure 3. The volume relation to age showed that the highest volume per hectare is 272.7 m^3 per hectare in district 1 216.2 m^3 per hectare in district 2 247.3 m^3 per hectare in district 3 167.8 m^3 per hectare in district 4, and 91.2 m^3 per hectare in district 5. These volume values occurred at 31, 29, 29, 24 and 21 years, respectively. And according to the principle of diminishing marginal returns, it has been decreasing since these ages.

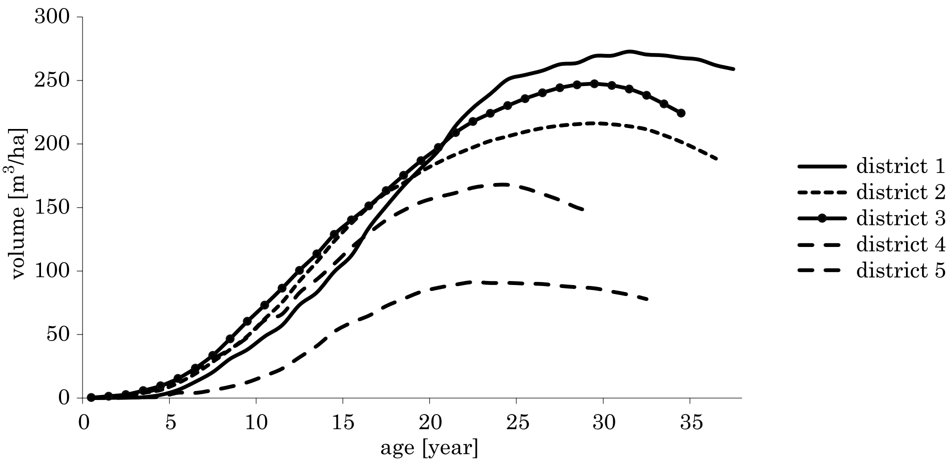

Fig 3. Stand stock volume in study areas (district 1, district 2, district 3, district 4 and district 5)

Volume (V) and age (A) regression analysis of *P. deltoides* plantations are shown in Table 5. Regression analysis of the relationship between volume and age based on the maximum coefficient of determination (R^2) and minimum standard error (SE) for plantations showed that R^2 was 0.99 in all districts and SE ranged from 1.83 (in district 5) to 4.06 (in district 3). Equations that have higher R^2 are more important because they show a better pattern of relationship between volume and age. However, all district's V-A aquations showed the same and high amount coefficient. The resulting regression models had sufficient accuracy and were able to fit the relationship between these two variables (V-A) with acceptable accuracy.

Table 5

Relationship between volume (V) and age (A) in *P. deltoides* plantations

District	Equation	R^2	SE	Kind of distribution
1	$V = 0.017(0.87)^A A^{3.96}$	0.99	3.49	Hoerl
2	$V = 0.13(0.89)^A A^{0.13}$	0.99	2.59	Hoerl
3	$V = \frac{-9.4 + 5.33A}{1 - 0.05A + 0.001A^2}$	0.99	4.06	rational model
4	$V = \frac{-6.39 + 3.57A}{1 - 0.07 + 0.002A^2}$	0.99	1.84	rational model
5	$V = e^{18.30 + \frac{-78.89}{A} - 3.30\ln(A)}$	0.99	1.83	vapor pressure model

Explanations: V – volume [m^3/ha]; A – stand age [year]

The volume increment curve shows the annual volume increment in the plantations in Figure 4. The volume increment was 3.04 m^3/ha/year at the age of 16 years in district 1. The volume increment was 3.9 m^3/ha/year at the age of 9 in district 2. The annual volume increment has the highest amount in this area. Volume increment was 3.07 m^3/ha/year at age 9 in district 3, and it was 2.43 m^3/ha/year at age 10 in district 4. volume has 2.4 m^3/ha/year at age 14 in district 5.

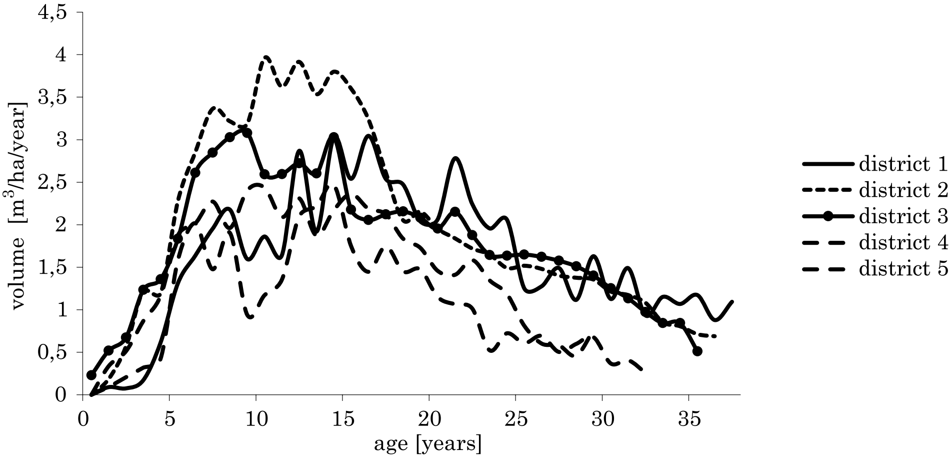

Fig 4. Above-ground volume increment [m^3/ha/year] of study areas (district 1, district 2, district 3, district 4, district 5)

Regression analysis between Annual Volume Increment (AVI) and age (*A*) of *P. deltoides* plantations are shown in Table 6. Equation's coefficient of determination (R^2) ranged from 0.86 to 0.94 in districts and Equation's standard error (SE) ranged from 0.19 to 0.34. The highest equation coefficient of determination was calculated for districts 1 and 2 ($R^2 = 0.94$; SE = 0.25) followed by district 3 ($R^2 = 0.93$; SE = 0.25), district 4 ($R^2 = 0.92$; SE = 0.19), and the lowest for district 5 ($R^2 = 0.86$; SE = 0.34). However, all districts had a high coefficient of determination and all the models in the regression between these two variables (AVI-*A*) were fitted with sufficient accuracy.

Table 6

Relationship between annual volume increment (AVI) and stand age (*A*) in *P. deltoides* plantations

District	Equation	R^2	SE	Kind of distribution
1	$\mathrm{AVI} = 0.83(0.87)^A A^{2.01}$	0.94	0.25	Hoerl
2	$\mathrm{AVI} = \dfrac{0.21 + 0.16A}{1 - 0.13A + 0.008A^2}$	0.94	0.25	rational model
3	$\mathrm{AVI} = \dfrac{0.09 + 0.29A}{1 - 0.09A + 0.01A^2}$	0.93	0.25	rational model
4	$\mathrm{AVI} = 5.09 - 5.60(0.85)^A - 5.60A$	0.92	0.19	exponential plus linear
5	$\mathrm{AVI} = 0.08(0.82)^A A^{2.18}$	0.86	0.34	Hoerl

Explanations: AVI – annual volume increment [m^3/ha/year]; *A* – stand age [year]

The results of the carbon change values by age in the study areas are shown in Figure 5. The process of carbon change is dependent on volume. The amount of carbon increases with volume. Therefore, the pattern of carbon sequestration is similar to the stand volume.

Results showed that carbon values related to age had the highest value of 49.7 tons per hectare in district 1, followed by 46.9 tons per hectare in district 2 45.1 tons per hectare in district 3 30.6 tons per hectare in district 4 and 16.6 tons per hectare in district 5. These carbon values occurred at 31, 32, 29, 24, and 22 years, respectively. These ages were similar to the amounts of the stand volume in relation to age (Figure 3).

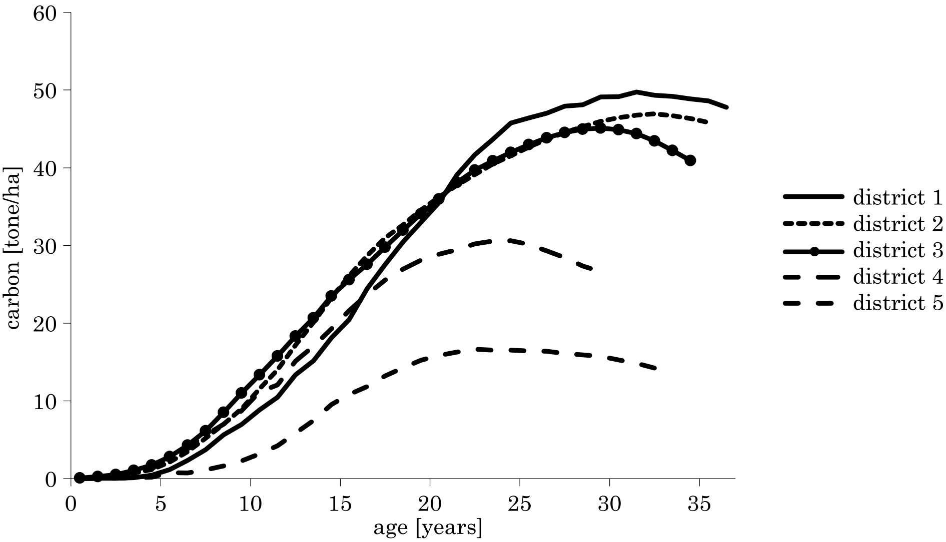

Fig 5. Carbon storage in stand stock in study areas (district 1, district 2, district 3, district 4, district 5)

The results of the regression analysis of carbon dependence (*C*) and the age (*A*) in the study areas are shown in Table 7. The equations show the nonlinear pattern between carbon storage and age in all districts. The best equations are the higher coefficients of determination (R^2) and lower standard errors (SE). All districts had a high coefficient of determination (R^2 = 0.99). Equation's standard error (SE) ranged from 0.33 (district 4 and 5 equations) to 0.63 (district 1 equation). Therefore, all the models in the regression between these two variables (*C*-*A*) were fitted with sufficient accuracy.

Table 7

Dependence of carbon [ton/ha] and stand age [year] in *P. deltoides* plantations

District	Equation	R^2	SE	Kind of distribution
1	$C = 0.003 \cdot 0.879^A \cdot A^{3.96}$	0.99	0.63	Hoerl
2	$C = 0.024 \cdot 0.891^A \cdot A^{3.17}$	0.99	0.46	Hoerl
3	$C = 0.37 \cdot (0.9)^A A^{2.97}$	0.99	0.54	Hoerl
4	$C = \frac{-1.16 + 0.65A}{1 - 0.07A + 0.002A^2}$	0.99	0.33	rational model
5	$C = e^{16.59 - \frac{78.89}{A} - 3.30\ln(A)}$	0.99	0.33	vapor pressure model

Explanations: C – carbon sequestration [ton/ha]; A – stand age [year]

Discussion and Conclusions

In the study of ESLAMODOUST et al. (2014), the highest volume increment was reported for poplar at the age of eight, while the highest volume increment was nine to ten years old in the present study (Figure 4). This can be attributed to site conditions, planting distance, density, and silvicultural operations on the plantation. In a study by FANG et al. (2007), biomass analysis showed that higher densities have more biomass.

Volume increment variations by age appear due to thinning over the past years, and data on the thinning rate of the study areas are not available. Therefore, the thinning operation effects were not considered in calculations of optimal operating age in the present study.

The allometric equations of biomass estimation for four poplar species demonstrated that the tree stems as a dependent variable produced more accurate models than other variables. Other features such as DBH, height, and bark thickness presented moderate to poor accuracy (PARSAPOUR et al. 2013). In the present study, stem biomass was computed by the stem analysis method. Consequently, highly accurate models have been obtained with a coefficient of determination greater than 0.99 (Tables 4 to 7). Fang et al. (2007) also reported the most accurate models in calculating carbon sequestration from stem biomass analysis.

According to Figure 2, the diameter growth based on age has a sine shape diagram. The diameter growth was fit using inventory data from the growth of 29–38 years in the study areas. Diameter growth was developed using stem analysis by a destructive method.

Allometric relationships are often applied in tree biomass model fitting and described by power-high equations. In the present study, power functions provided a strong fit (R^2 values in the range of 0.93–0.99 and the low value of SE) for biomass estimation of P. deltoides. Moreover, the relationships between stem volume, volume increment, and carbon biomass were in specific age to each stand. Therefore, allometric equations that ignore stand age may lead to inaccurate estimations of tree biomass. Consistent with this finding, PEICHL and ARAIN (2007) found a relationship between allometric equations of aboveground biomass and stand age in other tree species.

Carbon sequestration in plantations is directly related to age (Figure 5). Furthermore, the influence of different factors such as types of species, stand age, and management activities may have made different results from the effect of plantation on carbon (KARAMI-KORDALIVAND et al. 2015). mortality caused a loss in the carbon of the standing budget (Figure 4) (METSARANTA and BHATTI 2016). The modeling of the annual carbon uptake by poplar seedlings explained that the linear logarithmic model in terms of seedling collar diameter had the highest accuracy (VAHEDI et al. 2015). It was in accordance with the results of the present research that all the factors including volume – age, volume increment – age, and carbon – age obtained the high coefficient of determination ($R^2 = 0.99$) and low standard error in the top models. It means that the presented models have a high accuracy and indicate a very high correlation between the parameters in the modeling process and the high accuracy of the computations. Therefore, it can conclude that these models can be used as allometric models and indicators to predict volume, volume increment, and especially carbon sequestration values to save time, cost, and non-destructive sampling in future studies. Even, the models can be applied for the annual assessment of carbon sequestration of poplar plantations for optimal management and achieving sustainable development of the plantations.

In this context, ALEMI et al. (1977) have emphasized that the assessment of forest stands over time depending on the accuracy and type of used models. Therefore, the presentation of highly accurate models would be validated. PARSAPOUR et al. (2013) and ALI et al. (2019) explicated that stem biomass provides a high accuracy for modeling this parameter. On the other hand, it seems that the incorporation of the stem analysis method and allometric equations will lead to the development of high-accuracy models that can be easily documented from their results. It can be used in annual management decisions such as thinning at different ages of plantations to reach the optimum rotation age. Although the stem analysis method is a time-consuming and costly destructive method, its results will be highly documented and reliable. Furthermore, this method is performed for a specific species or a site for one time, and its results can be usable many times. Comparison between destructive and non-destructive carbon sequestration measurement methods showed that the destructive methods had more acceptable accuracy for carbon sequestration evaluation than the non-destructive, and the outputs of all optimized destructive allometric equations have high reliability (VAHEDI et al. 2016). These results can be easily and accurately available for optimal management and operation of plantations.

Accepted for print 27.12.2023

References

ALI A., AHMAD A., AKHTAR K., TENG M., ZENG W., YAN Z., ZHOU Z. 2019. *Patterns of biomass, carbon, and soil properties in Masson pine* (*Pinus massoniana* Lamb) *plantations with different stand ages and management practices*. Forests, 10(645): 1–19.

ARORA G., CHATURVEDI S., KAUSHAL R., NAIN A., TEWARI S., ALAM N.M. 2014. *Growth, biomass, carbon stocks, and sequestration in age series of Populus deltoides plantations in Tarai region of central Himalaya*. Turkish Journal of Agriculture and Forestry, 38: 550–560.

BEETS P.N., KIMBERLEY M.O., OLIVER G.R., PEARCE S.H., GRAHAM J.D., BRANDON A. 2012. *Allometric equations for estimating carbon stocks in natural forest in New Zealand*. Forests, 3(3), 818–839.

ESLAMDOUST J., SOHRABI H., HOSSEINI S.M. 2015. *Evaluation of growth Feature of Populus deltoides and Taxodium distichum trees using stem analysis*. Journal of Natural Ecosystems of Iran, 5(3): 51–58 (in Persian).

ESLAMDOUST J., SOHRABI H. 2017. *Carbon storage in biomass, litter, and soil of different native and introduced fast-growing tree plantations in the South Caspian Sea*. Journal of Forestry Research, 29(2): 449–457.

ESLAMDOUST J. 2022. *Bark content variations and the production of Populus deltoides as a source of bioenergy under temperate climate conditions*. Journal of Forestry Research, 33(4): 1–9.

FAAL-KHAH I., RAMEZANI KAKROUDI E., ALIJANPOUR A., SHAFIEI AB. 2017. *The effect of spacing on quantitative and qualitative characteristics of black poplar* (*Populus nigra* L.). Journal of Forest Research and Development, 2(4): 337–351 (in Persian).

FANG S., XUE J., TANG L. 2007. *Biomass production and carbon sequestration potential in poplar plantations with different management patterns*. Journal of Environmental Management, 85: 672–679.

FOROUZEH M.R., HESHMATI A., GHANBARIYAN G.A., MESBAH SH. 2008. *Comparison potential carbon sequestration Helianthemum lippii (Pers.), Dendrostellera lessertii (Van Tigeh.) and Artemisia sieberi Besser in arid rangeland of Iran (case study: Garbayegan Fasa in Fars province).* Iranian Journal of Environment Science, 46(2): 65–72 (in Persian).

FORTIER H., TRUAX B., GAGNON D., LAMBERT F. 2020. *Allometric equations for estimating compartment biomass and stem volume in mature hybrid poplars: General or site-specific?* Forests, 8(309): 2–23.

GHASEMI NEJAD RAEINI M., SADEGHI H. 2018. *Evaluation of carbon sequestration in soil and plant organs of Zygophyllum atriplicoides and Gymnocarpus decander (Case study: Saleh-Abad, Hormozgan).* Iranian Journal of Range and Desert Research, 24(4): 699–707 (in Persian).

GUO X., ZHANG X. 2010. *Performance of 14 hybrid poplar clones grown in Beijing, China.* Biomass and Bioenergy, 34: 906–911.

HAIDARI SAFARI KOUCHI A., IRANMANESH Y., ROSTAMI SHAHRAJI T. 2016. *Above-ground and soil carbon sequestration of white poplar (Populus alba* L.*) species in four different planting spaces* *in Chaharmahal and Bakhtiari province*. Iranian Journal of Forest and Poplar Research, 24(2): 200–213 (in Persian).

Henry M., Besnard A., Asante W.A., Eshun J., Adu-Bredu S., Valentini R., Bernoux M., Saint-André L. 2010. *Wood density, phytomass variations within and among trees, and allometric equations in a tropical rainforest of Africa*. Forest Ecology and Management, 260: 1375–1388.

Karami-Kordalivand P., Hosseini S.M., Rahmani A., Mokhtari J. 2015. *Effects of pure and mixed Caucasian alder (Alnus subcordata C. A. Mey.) and eastern cottonwood (Populus deltoides Marsh.) plantations on carbon sequestration and some physical and chemical soil properties*. Iranian Journal of Forest and Poplar Research, 23(3): 402–412.

Kazemi Najafi S., Ebrahimi G.H., Sadati S.E. 2012. *Effect of spacing and intercropping on stress wave velocity of planted poplar trees*. Journal of Forest and Wood Products (Iranian Journal of Natural Resources), 65(2): 187–197.

Lhotka J.M., Loewenstein E.F. 2011. *An individual-tree diameter growth model for managed uneven-aged oak-shortleaf pine stands in the Ozark Highlands of Missouri, USA*. Forest Ecology and Management, 261: 770–778.

Malakini M., Makungwa S., Mwase W., Maganga A.M. 2020. *Allometric models for estimating above – and below – ground tree carbon for community managed miombo woodlands: A case of Miyobe village forest area in northern Malawi*. Trees, Forests and People, 2: 10024.

Metsaranta J.M., Bhatti J.S. 2016. *Evaluation of whole tree growth increment derived from tree-ring series for use in assessments of changes in forest productivity across various spatial scales*. Forests, 7(303): 1–11.

Mohammadi Z., Mohammadi Limaei S., Lohmander P., Olsson L. 2017. *Estimating the aboveground carbon sequestration and its economic value (case study: Iranian Caspian forests)*. Journal of Forest Science, 63(11): 511–518.

Mousavi Kopar S.A., Modir-Rahmati A.R., Lashkar-Bolouki A., Kahneh E. 2011. *Adaptation of poplar clones in Safrabasteh, Guilan province*. Iranian Journal of Forest and Poplar Research, 19(2): 326–339 (in Persian).

Naghdi R., Mirzaei M., Aghajani A.H., Torkaman J. 2021. *Estimation stock and economic value of carbon storage of root and stump of Populus deltoides in poplar plantation of Guilan province*. Iranian Journal of Forest, 13(2): 197–208 (in Persian).

Nobakht A., Pourmajidian M., Hojjati S.M., Fallah A. 2011. *A comparison of soil carbon sequestration in hardwood and softwood monocultures (Case study: Dehmian forest management plan, Mazindaran)*. Iranian Journal of Forest, 3(1): 13–23 (in Persian).

Parsapour M.K., Sohrabi H., Soltani A., Iranmanesh Y. 2013. *Allometric equations for estimating biomass in four poplar species at Charmahal and Bakhtiari province*. Iranian Journal of Forest and Poplar, 21(3): 517–528 (in Persian).

Peichl M., Arain M.A. 2007. *Allometry and partitioning of above- and belowground tree biomass in an age-sequence of white pine forests*. Forest Ecology and Management, 253: 68–80.

Saeedi Z., Azadfar D. 2010. *Effect of spacing on growth characteristics of Paulownia fortunei (Case study: Dr. Bahram Nia forest management plan, Gorgan)*. Iranian Journal of Forest, 2(2): 151–163 (in Persian).

Tian X., Sun S., Mola-Yudego B., Tianjian C. 2020. *Predicting individual tree growth using stand-level simulation, diameter distribution, and Bayesian calibration*. Annals of Forest Science, 77: 57.

Turner E., Zainal Abidin Y., Barlow H., Fayle T., Hattah M., Jaafar H., Khen Ch., Larenus J., Nainar A., Reynolds G., Yusof Y., Khoo M., Ewers R. 2012. *The stability of altered forest ecosystems project: investigating the design of human-modified landscapes for productivity and conservation*. The Planter, (88): 453–468.

Vahedi A.A. 2016. *Artificial neural network application in comparison with modeling allometric equations for predicting above-ground biomass in the Hyrcanian mixed-beech forests of Iran*, Biomass and Bioenergy, 88: 66–76.

Vahedi A.A., Mattagi A.A., Akhavan R. 2015. *Modeling the annual uptake of atmospheric carbon by hybrid poplar seedlings (Populus euramericana 488) using growth equations*. Iranian Forest Ecology Journal, 4(13): 65–76 (in Persian).

Vahedi A.A., Salar K., Bijaninejad A.R. 2016. *Comparing the estimated accuracy of destructive and non-destructive methods of aboveground carbon sequestration of velvet maple (Acer velutinum Boiss.) in Hyrcanian forests*. Iranian Journal of Forest and Poplar Research, 24(1): 103–115 (in Persian).

Wang Ch. 2006. *Biomass allometric equations for 10 co-occurring tree species in Chinese temperate forests*. Forest Ecology and Management, 222: 9–16.

Zobeiry M. 1994. *Forest inventory (Measurement of tree and forest)*. Tehran University Press, 3: 401 (in Persian).