Front. Earth Sci.
DOI 10.1007/s11707-016-0562-7

RESEARCH ARTICLE

Carbon concentrations of components of trees in 10-year-old *Populus davidiana* stands within the Desertification Combating Program of Northern China

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Abstract Most studies do not consider the potential variation in carbon concentration among the different tree components of the same species in regional scale. This study examined the carbon concentrations of the components (i.e., foliage, branch, stem, and root) in a 10-year-old poplar species (*Populus davidiana* Dode) from the Desertification Combating Program of Northern China. The highest and lowest carbon concentrations were found in the stem and foliage, respectively. There was a significant difference in carbon concentrations among the different tree components. All of the observed carbon concentrations of tree components were lower than those predicted using the conversion factor of 0.5 applied to component biomass. Stem carbon made up 59.7% of the total tree biomass carbon. The power equation estimating proportion of tree biomass carbon against the independent variable of diameter at breast height explained more than 90% of the variability in allocation of carbon among tree components. Tree height, as a second independent variable is also discussed. Our results suggest that the difference in organic carbon concentration among tree components should be incorporated into accurately develop forest carbon budget. Moreover, further investigations on how the diameter at breast height equation developed in the present study performs across broader scales are required.

Keywords biomass carbon equation, carbon content, destructive sampling, diameter at breast height, poplar

1 Introduction

Increased atmospheric carbon dioxide (CO_2) concentration induced by human activities and consequently global climate warming have led to growing interest in carbon (C) sink enhancement (Mao et al., 2010; Chen and Han, 2015). China, among the largest CO_2 emitters in the world, was considered responsible for two thirds of the 3.1% global increase in anthropogenic CO_2 emissions as of 2007 (Yan and Yang, 2010). Though the Chinese government has committed to cut CO_2 emissions per unit of gross domestic product (GDP), the total amount of CO_2 emissions from China is expected to increase further (Chen and Zhang, 2010). Tree plantations mitigate elevated atmospheric CO_2 concentrations by sequestering C in biomass and soils (Mao and Zeng, 2010; Li et al., 2011). In order to increase C storage in forest ecosystems, the Chinese government initiated new programs and consolidated existing forest industry ecological restoration programs in the early 2000s (Liu et al., 2010). After 10 years of national afforestation and reforestation programs, accurate estimates of C sequestered by Chinese tree planting programs are need.

A ratio of C concentration to tree biomass is used to calculate whole tree C stock (Lamlom and Savidge, 2003). Toromani et al. (2011) used the C concentration to biomass ratio value of 47.5% to estimate the C storage of different aged poplar stands in Albania. In India, Singh and Lodhiyal (2009) also estimated the tree biomass and C allocation in an 8-year-old poplar plantation based on the same value of 47.5%. Subsequent analyses showed that C concentration can vary between different components within the same tree species, resulting in C ratios ranging from above to below 50% (Zheng et al., 2008; Tolunay,

Received April 30, 2015; accepted September 13, 2015

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2009; He et al., 2013; Pasalodos-Tato et al., 2015). The accuracy of C content assessments has been improved with estimations of C concentration in each tree component (Li et al., 2011). However, most studies do not consider variations in C contents between the different tree components.

Poplar (*Populus* spp.) plantations account for about 14% of all tree plantations in China (Wilske et al., 2009). With the launch of the Desertification Combating Program around Beijing and Tianjin (DCBT), poplar plantations in Northern China were promoted to timber production, stop desertification, and increase C sequestration (Gong et al., 2012; Buras et al., 2013). Some studies on poplar biomass and C stocks in China have been conducted (Liang et al., 2006; Fang et al., 2007; Hu et al., 2008). However, information on the C concentration of tree components is still lacking for the Chinese afforestation program.

Accurate calculations of plantation ecosystem C budgets require measurements of the C contents of living plant materials. The objectives of this study were to: (i) measure the C concentrations of tree components in young even-aged poplar plantations of Northern China; (ii) calculate the weighted C content of individual trees; and (iii) develop regression equations for estimating the biomass C stock of tree components. To our knowledge, this is the first study investigating the C contents of tree components in poplar stands within the planting program of Northern China.

2 Materials and method

2.1 Site description

The study area of the DCBT (Fig. 1) is between 38°50′ N, 109°16′ E and 46°47′ N, 120°59′ E and at 400–1800 m above sea level. It is characterized as a semi-arid climate, and covers the Haihe River Plain, Taihang Mountain, Yanshan Mountain, and the Inner Mongolian Plateau. The study area was divided into three zones: the water resource protection zone in the Yanshan mountainous and hilly region, the desertificated land zone in the agro-pastural region, and the Otingdag sandy land zone, according to the distribution laws of bioclimatic zones and geomorphic types (Liu et al., 2013) (Fig. 1). Mean annual temperature of the study area is 5°C, and mean annual rainfall is 355 mm based on data from 1971 to 2000 recorded by the 21 meteorological stations in this region (China Meteorological Data Sharing Service System, http://cdc.cma.gov.cn, China Meteorological Administration). The rainy season starts in June and ends in September, with July rainfall accounting for 28% of the annual precipitation. According to the soil taxonomy (ST), the soils in the research area are Mollisols and Ultisols, with relatively low fertility (Gao et al., 2008). *Populus davidiana* Dode is the most dominant planted broad leaf species in this study area.

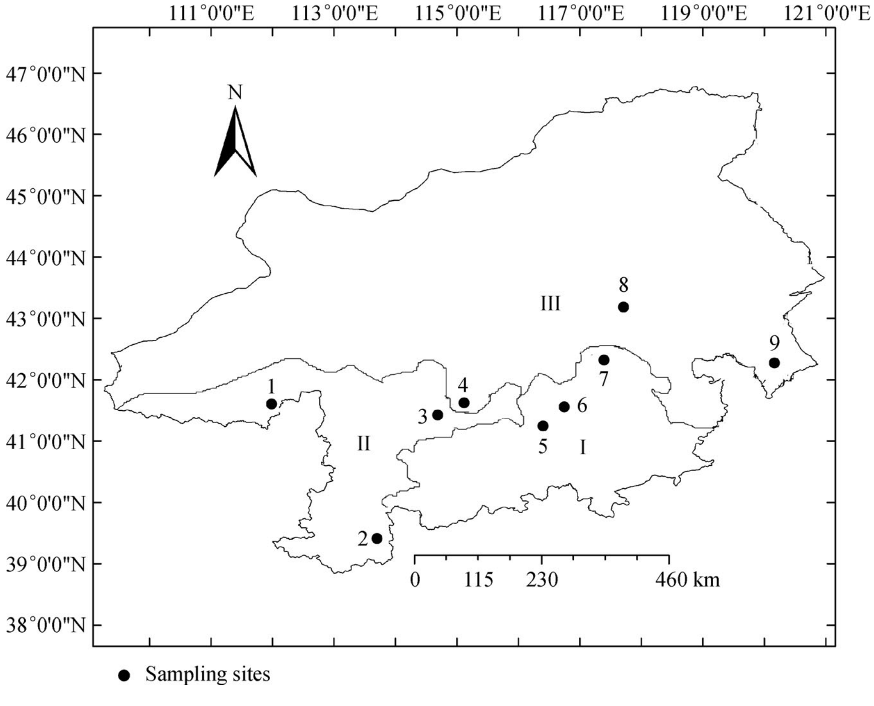

Fig. 1 Sampling plots of poplar trees in the DCBT region. I: water resources protection zone in Yanshan mountainous and hilly region; II: desertificated land zone in agro-pasture region; III: Otingdag sandy land zone.

2.2 Measurements and data collection

The study was conducted in 10-year-old poplar stands from August to September 2011. Nine even-aged sites were selected in the DCBT area (Table 1), with three sites per regional scale zone (Fig. 1(b)). An experimental plot of 20 m × 20 m was established in each site, with tree densities within the plots ranging from 425 to 1025 trees·ha^{-1}. First, the height (*H*) and diameter at breast height (*DBH*) were measured for all trees in the sample plots. Mean *H* within sample plots varied between 5.6 m and 17.3 m, and mean *DBH* ranged from 5.4 cm to 16.5 cm (See details in Table 1). Then, the one tree within each plot that was closest to the mean *DBH* value of the plot was destructively sampled.

H and *DBH* of felled trees were measured with an accuracy of 0.1 cm. Each bole was then cut into several 2-m sections and each section was separated into stem, branch, and foliage. The fresh mass of each component was determined using an electronic balance with an accuracy of 0.001 kg. Roots from the stumps of the harvested trees were excavated to 100 cm depth. For each tree component, approximately 500−1000 g of fresh mass was randomly sampled and then dried at 65°C until reaching a constant weight. Using the dry weights obtained for these subsamples, stem, branch, foliage, and root mass were also determined for each destructively sampled tree. Descriptive information about the biomass of tree components is shown in Table 2. Samples were ground for C analysis. C content was measured following the potassium dichromate oxidation (external heat applied) method (Mao et al., 2010).

2.3 Biomass C functions

Power functions are often used in studies of biomass relationships (Pilli et al., 2006; Mendoza-Ponce and Galicia, 2010; Cao et al., 2012). In the present study, a power function was employed to describe the relationship between C stock of each component and *DBH*:

$$C_i = aDBH^b, \tag{1}$$

where C_i denotes the C stocks of tree component *i* (stem, branch, foliage, root, and total tree) (kg·tree^{-1}), and *a* and *b* are regression coefficients.

Furthermore, *H* might be another factor influencing C stock in each component. Thus, taking *H* into account improved the explained variation in C stocks of tree components among individual trees. When considering the integrated effects of *DBH* and *H*, Eq. (2) was used:

$$C_i = a(DBH^2H)^b. \tag{2}$$

The estimation of the relative difference (*ERD*) between the observed (*OC*) and the predicted C stocks (*PC*) (kg·tree^{-1}) was calculated using a tree level C conversion factor of 0.5, according to Eq. (3):

$$ERD = \frac{OC-PC}{OC} \times 100, \tag{3}$$

Table 1 Descriptive characteristics of the 9 sampling sites in the Desertification Combating Program (DCBT) of Northern China

Plot No.	Tree density/(trees·ha^{-1})	Mean height/m	Mean *DBH*/cm	Longitude (E)	Latitude (N)	Altitude/m
1	1025	9.6	15.9	111°47′45.05″	41°37′56.02″	1102
2	925	10.0	8.6	113°36′15.8″	39°43′41.5″	1115.2
3	825	6.0	5.4	114°46′30.9″	41°13′8.3″	1421.2
4	1025	10.2	11.6	114°58′18.36″	41°29′53.58″	1386
5	975	17.3	16.5	116°45′25.8″	41°9′43.4″	598.7
6	425	8.2	7.1	116°29′6.9″	41°22′4.2″	872.9
7	875	9.8	12.6	117°33′12.1″	42°10′31.6″	1097.5
8	950	5.6	9.6	117°25′51.62″	43°12′28.51″	1184.7
9	1000	14.5	14.8	120°45′45.91″	42°21′35.24″	408

Table 2 Biomass of tree components from sampled trees (*n* = 9)

	Biomass of dry weight/(kg·tree^{-1})				
	Foliage	Branch	Stem	Root	Total tree
Mean	3.36	5.02	21.18	6.77	36.32
SD	0.96	2.19	10.81	3.83	17.63
Min.	1.95	1.14	5.35	1.55	9.99
Max.	4.64	7.22	32.64	11.39	55.37

where *OC* and *PC* are calculated by multiplying dry mass by the corresponding C content and the C conversion factor of 0.5.

2.4 Data analysis

Data were analyzed by one-way analysis of variance. When the difference was significant, multiple comparisons were made with the Tukey's HSD test. R^2 values were calculated to evaluate regression equations. In all statistical analyses, the significance level was set at $\alpha = 0.05$. Data analyses were performed using SPSS Version 15.0 for Windows (SPSS Inc., Chicago, IL, USA) and Sigmaplot Version 12.5 for Windows (Systat Software Inc., San Jose, CA, USA).

3 Results

3.1 C contents of tree components

In this study, the C concentrations significantly differed among tree components ($F = 8.16$, $P < 0.001$). Among the tree components, the highest C concentration was in the stem ((44.70±1.30)%), whereas the lowest C concentration was in the foliage ((40.52±1.12)%) (Table 3). The results of *ERD* clearly showed that the *PC* for the tree components was generally higher than the *OC*, which indicated that the C content might be overestimated if using a C conversion factor of 0.5 (Table 3). The relative contribution to tree biomass C content was 59.7% in the stem, 18.3% in the root, 13.4% in the branch and 8.6% in the foliage (Fig. 2).

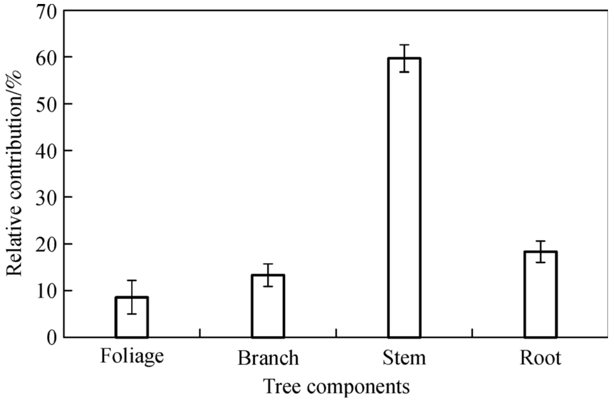

Fig. 2 Relative carbon contribution of the different components of 10-year-old poplar trees (Mean±SD).

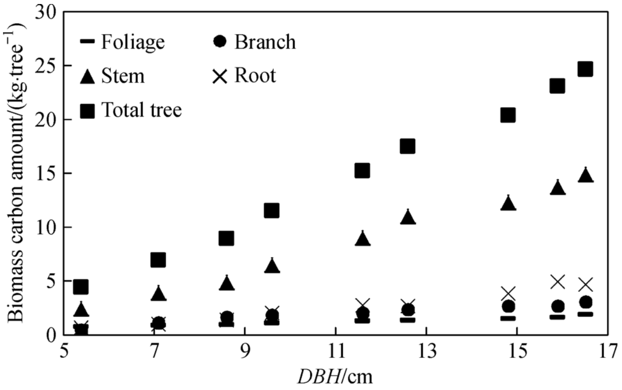

Fig. 3 Relationship between biomass carbon and diameter at breast height (*DBH*) (cm) of tree components for poplar species.

3.2 Biomass C functions

There was a high correlation between biomass C stock of tree components and the *DBH* (Fig. 3). The non-linear regression equations of biomass C against the independent variables of *DBH* and DBH^2H explained greater than 90% of the variability in foliage, branch, stem, and total tree C (Table 4). The regression of root biomass C against DBH^2H explained the least amount of the variation in C ($R^2 = 0.862$) of all C biomass components. All regressions, except for those including DBH^2H as an independent variable, had a significance level of $P < 0.0001$. The significance level of the regression of root biomass C against (DBH^2H) was $P < 0.05$. Furthermore, the regressions with *DBH* as the independent variable provided better fits than those with DBH^2H (Table 4). Of all component biomass C tested, the relationships between foliage and branch biomass C against *DBH* exhibited the most variation (Table 4).

Table 3 C concentrations, observed (*OC*) and predicted C (*PC*) stocks of tree components, and the estimation of the relative difference (*ERD*) between *OC* and *PC*

Components	C concentration/%	*OC*	*PC*	*ERD*
Foliage	40.52±1.12^{a}	1.36±0.38	1.68±0.48	−23.45±3.50
Branch	42.63±2.32^{ab}	2.12±0.89	2.51±1.10	−17.61±6.80
Stem	44.70±1.30^{b}	9.43±4.79	10.59±5.41	−11.95±3.35
Root	42.99±1.32^{b}	2.90±1.66	3.39±1.92	−16.41±3.62
Total tree		15.81±7.64	18.16±8.82	−14.61±3.00

Note: Data are means±SD. Letters denote groups of significantly similar carbon concentration values, based on ANOVA ($P < 0.05$).

Table 4 Biomass carbon equations of tree components for 10-year-old poplar trees

Tree component	The model	*a*	*b*	R^2	Sig.
Foliage	$C_f = aDBH^b$	0.2037	0.7687	0.963	***
	$C_f = a(DBH^2H)^b$	0.2058	0.2595	0.925	***
Branch	$C_b = aDBH^b$	0.1250	1.1411	0.951	***
	$C_b = a(DBH^2H)^b$	0.1357	0.3762	0.904	***
Stem	$C_s = aDBH^b$	0.2029	1.5341	0.987	***
	$C_s = a(DBH^2H)^b$	0.2814	0.4775	0.910	***
Root	$C_r = aDBH^b$	0.0299	1.8187	0.982	***
	$C_r = a(DBH^2H)^b$	0.0577	0.5310	0.862	*
Total	$C_t = aDBH^b$	0.4149	1.4567	0.995	***
	$C_t = a(DBH^2H)^b$	0.5576	0.4553	0.916	***

Note: C_f = foliage biomass carbon (kg); C_b = branch biomass carbon (kg); C_s = stem biomass carbon (kg); C_r = root biomass carbon (kg); C_t = total tree biomass carbon (kg); *DBH* = diameter at breast height (cm); *H* = tree height (m); *a* and *b* = regression coefficient. Sig. = significance level: * significant at 0.05 level ($P \leqslant 0.05$); *** highly significant at 0.0001 level ($P \leqslant 0.0001$).

4 Discussion

4.1 C contents of tree components

In the present study, the C concentrations of tree components were ranked in descending order as stem > root > branch > foliage (Table 3). Fang et al. (2007) measured the C concentrations of foliage, branch, stem, and root of poplars as 42.9%, 47.9%, 50.1%, and 47.6%, respectively. They reported that the highest C concentration was found in the stem, which is in accordance with the present study. However, in a study carried out on aspen in northeastern China by Zhang et al. (2009), the highest C concentration was found in the foliage (47.1%) and the lowest in the stem (43.4%). The C concentration of tree components collected from the same species, but at different sampling sites, varied with analysis and sampling methods, stand age, pedoclimatic conditions, and origin (Bert and Danjon, 2006; Tolunay, 2009; de Aza et al., 2011). C concentration of tree components may also change depending on the sampling point of the crown. For example, Bert and Danjon (2006) reported a negative non-linear relationship between C concentration and branch diameter, with higher C concentration in branches located in the upper part of crown in *Pinus pinaster* Ait. This potential bias was avoided in the present study through randomized subsampling and selection of branch subsamples from various diameters.

In the present study, stem wood contained the highest proportion of the tree biomass C. The C distribution among tree components may depend on tree species (Zheng et al., 2008; Wang et al., 2009; Zhang et al., 2009), stand density (Fang et al., 2007; Hu et al., 2008), stand age (Fang et al., 2007; Li et al., 2011; Fonseca et al., 2012), and site conditions (Mendoza-Ponce and Galicia, 2010). As a tree grows older, the proportion of C within the branch and foliage decreases and stem percentage increases. In a study performed in Korea, the proportion of biomass C allocated in the stem for 8-, 19-, 30-, and 51-year-old Korean Pine stands was 29.3%, 37.3%, 46.6%, and 57.6%, respectively (Li et al., 2011). Fang et al. (2007) found that stored C in the stem made up 64.9%–72.9% of tree biomass C within 10-year-old poplar plantations of various stand densities in China. All these results support the view that stem wood is the dominant sink for atmospheric CO_2 within regrowth forests (Schlesinger and Lichter, 2001).

Accurate estimation of forest C stock and flux is a prerequisite for assessing the contribution of forest ecosystems to global C budgets. Vegetation component C levels are usually calculated as dry biomass multiplied by a C concentration conversion factor (Zhang et al., 2009). Currently, a mass-based C concentration conversion factor of 50% is widely accepted (Liang et al., 2006). According to this theory, Gower et al. (2001) used the C concentration conversion factor to summarize net primary production and C allocation patterns in boreal forests. Petersson and Melin (2010) also used this coefficient to estimate the C stock in stump systems at a national scale in Sweden. In this study, the C concentration of all tree components was less than 50%. If a C concentration of 50% had been assumed, the total C stored in the poplar plantation ecosystem would have been overestimated. For determination of a reliable C inventory, C concentration among tree components within the most commonly planted tree species must be determined. Furthermore, the relationship between C concentration of different tree components and tree age, stand density, and site conditions must be investigated (Tolunay, 2009).

4.2 Biomass C functions

Calculations of tree or stand level C stock generally involve estimations of biomass, which are then converted into a C stock value. Therefore numerous regression equations have been developed to calculate biomasses for various tree species (Muukkonen, 2007; Clifford et al., 2013). However, there is no universally accepted regression equation for biomass C prediction in poplar species. In this study, biomass C equations of tree components were developed using the independent variables of *DBH* and *DBH*^{2}*H*. *DBH* alone explained 95.1%–99.5% of the variability within tree components (Table 4). Compared to *DBH*-only equations, R^2 values for *DBH-H* equations decreased for various tree components (Table 4). In contrast, Wang (2006) suggested that adding *H* as the second independent variable statistically significantly improved equations for biomass estimation. However, some studies have suggested that *H* is rarely used in practice because it is less accurate and much more difficult and time-consuming to measure than is *DBH* (Gower et al., 1999; Dorado et al., 2006). Considering these short fallings and the decrease in R^2s of regressions including *H*, as well as *DBH*, as an independent variable (Table 4), we suggested that only the independent variable of *DBH* be included in regression equations estimating the biomass C of poplar plantation ecosystems. However, generalization of the relationship between *DBH* and biomass C must be evaluated across broader scales than the present experiment.

5 Conclusions

The C concentrations of tree components ranged from 40.52% to 44.70%, which is lower than commonly reported values of 47.5% or 50% used to convert biomass measurements into C storage estimates. The *DBH*-only equation proved to be the most simple and accurate method to estimate the biomass C of tree components. This is crucial information about poplar species in the tree planting program of Northern China. Our results suggest that the differences in organic carbon concentration among tree components should be utilized to accurately develop forest carbon budgets. For a more reliable calculation of the C storage in plantation forests, similar studies need to be performed for other tree species.

Acknowledgements We thank Xinqiang Zhang, Xinhua Zeng, and Xin Zhao for their assistance in the field survey and laboratory analysis. This work was funded jointly by the Strategic Priority Research Program of the Chinese Academy of Sciences (No. XDA05060600), the Natural Science Foundation of Hebei Province (No. C2015503008), and the Doctoral Initial Fund Project of Hebei Academy of Sciences (No. 20150503LR62-1). We would also like to thank Christine Verhille at the University of British Columbia for her assistance with the English language and grammatical editing of the manuscript.

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