Biomass carbon density in natural oak forests with different climate conditions and stand ages in northwest China

Jun-Wei Yue, Jin-Hong Guan, Mei-Jie Yan, Jian-Guo Zhang, Lei Deng, Guoqing Li & Sheng Du

To cite this article: Jun-Wei Yue, Jin-Hong Guan, Mei-Jie Yan, Jian-Guo Zhang, Lei Deng, Guoqing Li & Sheng Du (2018): Biomass carbon density in natural oak forests with different climate conditions and stand ages in northwest China, Journal of Forest Research, DOI: 10.1080/13416979.2018.1536313

To link to this article: https://doi.org/10.1080/13416979.2018.1536313

Published online: 24 Oct 2018.
Biomass carbon density in natural oak forests with different climate conditions and stand ages in northwest China

Jun-Wei Yue, Jin-Hong Guan, Mei-Jie Yan, Jian-Guo Zhang, Lei Deng, Guoqing Li and Sheng Du

ABSTRACT
Oak forests are major communities in warm temperate forests in northern China. The dependence of biomass carbon accumulation and allocation patterns in above- and belowground on climate and stand age remains unclear. To quantitatively investigate the influence of temperature, precipitation, and stand age on the biomass carbon density (BCD) of each component in the forest and on the above/belowground allocation, field surveys were conducted at 32 plots with dimensions of 20 m × 50 m representing different ages and environmental conditions of natural oak secondary forests. Tree biomass was estimated using allometric biomass equations based on tree height and diameter at breast height (DBH). Biomass of shrubs, herbs, and litter was estimated by harvesting all the components. Carbon concentrations of all the plant components and litter were measured. Biomass carbon densities of trees and total ecosystems increased with increases in precipitation and stand age, but did not differ significantly with changes in air temperature. The ratio of above/belowground BCD showed significant positive correlation with stand age. Understory layers (shrubs and herbs) BCD showed positive relationships with precipitation, but had no obvious relations with stand age and temperature. BCD in litter layer decreased with increasing precipitation and had no definite variation trend along temperature and stand age gradients. The influence of precipitation on plant growth is greater than that of temperature in the forests. These findings indicate that water availability is the dominant environmental factor across these sub-humid climate sites.

Introduction
The increase in atmospheric carbon dioxide (CO₂) is accelerating global warming with serious consequences worldwide, such as extreme weather events and rising sea levels (Steffen et al. 1998; Schrag 2007). The Global Carbon Project (GCP 2015) suggested that CO₂ emissions from fossil fuels and industry increased by 0.6% in 2014, with a total of 35.9 Gt emitted to the atmosphere, 60% higher than that of the 1990 emissions. Forests are considered to have a great carbon sequestration ability and can therefore reduce the rate of global warming (Schimel et al. 2001; Han et al. 2016; Matsumoto et al. 2016). It is thus of great interest to understand the status of carbon stocks and the factors influencing them in various forest ecosystems.

Carbon stock in the biomass of an ecosystem is commonly expressed as biomass carbon density (BCD), and it includes the biomass in trees, understory vegetation, litterfall on the forest floor, and even the fine roots in soil. According to IPCC (2003, 2007), BCD is formed by trees and understory vegetation that assimilate CO₂ from the atmosphere into organic carbon and store it in plant biomass. Climate and stand age have significant influences on the BCD of forests and their spatial patterns (Pregitzer and Euskirchen 2004; Stegen et al. 2011; Yu et al. 2014).

Stand age influences carbon accumulation in forest ecosystems because of the significant variation in growth and mortality rates with increasing stand age (Li et al. 2013). Furthermore, stand age is one of the critical factors affecting changes in carbon allocation among ecosystem components, such as forest floor and coarse woody debris (Pregitzer and Euskirchen 2004; Martin et al. 2005; Peichl and Arain 2007). Comparison of the biomass of different ecosystems without considering stand age may provide inconsistent conclusions (Liu et al. 2014). For example, according to IPCC (2006), aboveground BCD increases from boreal to temperate, followed by tropical forests. However, this was a result based on the fact that 64% of existing global forests had not reached the mature stage (FAO 2010).

Climate has been identified as an important environmental factor that controls the carbon density of forests and their spatial patterns (Pregitzer and Euskirchen 2004; Stegen et al. 2011). Temperature is an important climatic variable. Aboveground BCD and air temperature showed a positive relationship in boreal and temperate forests (Keith et al. 2009), while it showed a negative relationship in humid tropical forests (Stegen et al. 2011). Precipitation is another critical climatic factor driving aboveground BCD. For instance, the BCD of Abies georgei forests showed a positive relationship with annual precipitation (Wang et al. 2014). Appropriate forest management practices based on climatic conditions may accelerate growth and consequently increase the carbon accumulation rate in the forests.

CONTACT Mei-Jie Yan yanmj@ms.iswc.ac.cn State Key Laboratory of Soil Erosion and Dryland Farming on Loess Plateau, Northwest A&F University, Yangling, Shaanxi, China

Supplemental data for this article can be accessed here.

© 2018 The Japanese Forest Society
The carbon allocation ratio of above- and belowground biomass is an important indicator to describe the carbon stocks in forest ecosystems. It is a key parameter for estimating terrestrial ecosystem carbon stocks, which is the result of plants adaptation to the ambient conditions (Leuschner et al. 2007; Luo et al. 2013). The carbon allocation ratios of above- and belowground biomass have been used to calibrate and estimate carbon storage in ecosystems from the more easily measurable aboveground biomass carbon. Previous studies showed that root–shoot biomass allocation ratios varied with stand age (Mokany et al. 2006; Wang et al. 2008) and forest types (Cairns et al. 1997). Focusing on the important indicators of special forest type would provide more accurate assessments of the carbon storage in the forest ecosystem in regional scale.

Oak forests are a major dominant community in temperate forests, and are widely distributed in northern China. The investigation of these ecosystems should contribute to the understanding of major forest types within the temperate vegetation zone. Studies on oak forests include the effects of environmental factors on carbon flux (Powell et al. 2006; Unger et al. 2009; Costa-e-Silva et al. 2015), carbon accumulation and allocation in different communities (Vallet et al. 2009; Karlik and Chojnacky 2014), and the impact of forest management approaches and different land-use histories on carbon balance (Fortin et al. 2012; Carter et al. 2015). Few studies have focused on the patterns and variation in BCD of these forests at a regional scale, i.e. covering precipitation and temperature gradients. Such approaches are crucial in predicting the responses of carbon balance to future climate change and improving management plans for the forests in this region.

To fill the knowledge gaps mentioned above, the present study examined natural oak communities varying in stand age, precipitation, and temperature conditions with the aims to: (1) estimate variability of the BCD of each component in the forests as a function of temperature, precipitation, and stand age; (2) determine the relationships between above/belowground ratio of BCD and stand age. The study can also provide important information on how the capacity of forest carbon sequestration will respond to future climate warming.

Materials and methods

Site description

The study was conducted in the forest zone of Longnan, Qingyang, and Tianshui cities/prefectures of Gansu Province (33°10′–36°3′N and 104°41′–108°36′E), the main region of oak forest distribution in northern China. This area covers a mean annual temperature (MAT) ranging from 7.8°C to 12.7°C and mean annual precipitation (MAP) ranging from 524 to 737 mm. Oak forests express some variations in composition with origin and distribution area. The oak forests in Longnan and Tianshui are dominated by *Quercus aliena var. acuteserrata* and *Q. variabilis*, whereas the forests in Qingyang, where the climate is slightly dryer, are dominated by *Q. liaotungensis*. Nevertheless, the three oak species share many genetic characters and belong to the very common dominant species of warm temperate deciduous forests in this region. *Q. aliena var. acuteserrata* and *Q. variabilis* often occur together in same locations, though *Q. liaotungensis* is mainly distributed slightly to the north. Common species with high abundance, besides oaks, include *Pinus tabulaeformis*, *P. armandii*, *Betula platyphylla*, and *Populus* spp. The study area is mountainous and the oak communities are distributed between 1309 and 2138 m a.s.l. *Ostryopsis davidiana*, *Lespedeza bicolor*, and *Lonicera japonica* are the main shrubs in the oak community, and *Cyperus iria* is the dominant species in the herbaceous layer. According to the manual by National Soil Survey Office (1998) in China, soil type in these zones includes Yellow-brown earths, Brown earths, Gray-cinnamon soils, and Sierozems, corresponding to the names by international classification of earths ferric luvisols, eutric cambisols, haplic luvisol, and calcric cambisols, respectively (FAO/UNESCO, cartographer 1988; Wu et al. 2003).

Sample plots establishment and survey of trees

The sampling plan was implemented according to the method of scaling down: grid-site-plot, following the IPCC (2003). The special method of establishing sample plots followed the guidance of Observation and Investigation for Carbon Sequestration in Terrestrial Ecosystems (Technical Manual Writing Group of Ecosystem Carbon Sequestration Project 2015). The number and location of sample plots of major communities were determined according to the weight of area, volume, distribution range, age class, which were referred from previous national forest surveys. Meanwhile, the age classes including young, mid-aged, premature, mature, and over-mature forests should be incorporated in the sample plots, so that the sample plots have the greatest representative significance for the forest type. According to the principles mentioned above, totally 32 representative sampling plots with dimensions 20 m × 50 m (several plots were slightly smaller depending on topography limitation) were established for the forests dominated by *Q. aliena var. acuteserrata*, *Q. variabilis*, and *Q. liaotungensis* (the abundance of oaks was more than 60%). These plots cover a variety of stand age and site conditions and have not been subjected to human interventions. For each plot, diameter at breast height (DBH) and tree height (H) were measured for stems with DBH ≥2 cm, and latitude, longitude, slope position, gradient, and species name were recorded. Stand age for each plot was determined by coring 10% of the biggest dominant trees (oak) or the three biggest dominant trees inside the plot (Hudiburg et al. 2009; Liu et al. 2014). The average ring counts of the tree samples for the species with the oldest age were used as the forest age in each plot (Spies and Franklin 1991; Van Tuyl et al. 2005). The characteristics of sample plots can be found in the supplementary material.

Estimation of biomass for the tree layer

Biomass of each component (stem, branch, leaf, and root) was calculated through available allometric biomass equations of major species based on DBH and H (Cheng et al. 2007; Forest Carbon Sequestration Project Office 2014). Three to five sample trees were selected from different DBH classes (large, medium, and small) of each major tree species for determining carbon content of tree components. Three branches were randomly sampled from each canopy (upper, middle, and lower)
with lopper and a total of nine branches were sampled in each sample tree. Three tree cores were taken with an increment borer at breast height of each sample tree and a proper amount of root samples were excavated. Approximately 300 g mixed sample of each component (stem, branch, leaf, and root) was collected and brought back to the laboratory for determination of carbon concentration. Allometric equations of the major species can be found in the supplementary material.

Estimation of biomass for the shrub, herb, and litter layers

In each plot, three 2 m × 2 m quadrats (subplots) for shrubs (DBH <2 cm) were established with representative shrub distribution along a diagonal of the sampling plot, and the species names and coverage were recorded. Shrubs in each quadrant were completely harvested to determine their biomass. Branches, foliage, and roots of shrubs were weighed in situ and a mixed sample of approximately 300 g of each component was collected for estimating moisture and carbon content.

A subquadrat with a size of 1 m × 1 m for herbs and litter was also sampled within each shrub quadrant. The species name, coverage of herbs, and thickness of litter were recorded. Foliage and roots of herbs and litter were also harvested separately and weighed for each subquadrat. Samples of each component were collected and weighed in the field, and brought back to the laboratory for determination of moisture content and carbon concentration.

Analysis of carbon content and calculation of carbon density

The plant samples (excluding tree samples) were oven dried in the laboratory at 70°C until constant weight to estimate moisture content in order to calculate the net biomass of each component. Samples for analysis of organic carbon concentration were ground to a powder and determined using the traditional method of potassium dichromate oxidation-external heating. Forest biomass carbon densities were calculated as:

\[
BCDt = \sum_{i=1}^{4} \left( C_{i}T_{i}B_{Ti} \right) + \sum_{j=1}^{3} \left( C_{SJ}BS_{j} \right) + \sum_{k=1}^{2} \left( CHkBh_{k} + C_{k}B_{k} \right)
\]

where \( BCD_{t} \) is the biomass carbon density of a forest ecosystem over a specific area (t ha\(^{-1}\)), \( i \) is the tree component (i.e., stem, branch, leaf, and root), \( C_{Ti} \) is the carbon concentration of tree component, \( B_{Ti} \) is the biomass of the tree component (t ha\(^{-1}\)); \( j \) is the shrub tissue type (i.e., branch, leaf, and root), \( C_{SJ} \) is carbon concentration of the shrub tissue, \( B_{SJ} \) is the biomass of the shrub component (t ha\(^{-1}\)); \( k \) is the herb component (i.e., aboveground and belowground), \( C_{hk} \) is carbon concentration of the herb component, \( B_{hk} \) is the component biomass (t ha\(^{-1}\)); \( C_{k} \) and \( B_{k} \) are carbon concentration and biomass of the litter, respectively.

Belowground carbon density of an ecosystem (\( BCD_{b} \)) refers to total carbon density of the roots of tree, shrub, and herb layers, which was calculated from belowground components of trees, shrubs, and herbs as:

\[
BCDb = CTrBTr + CSrBSr + CHrBhr
\]

where \( C_{Tr} \), \( C_{Sr} \), and \( C_{Hr} \) are carbon concentrations in roots of the tree, shrub, and herb, respectively; \( B_{Tr} \), \( B_{Sr} \), and \( B_{Hr} \) are the biomass of the tree, shrub, and herb roots, respectively (t ha\(^{-1}\)).

Consequently, aboveground carbon density of an ecosystem (\( BCD_{a} \)) refers to total carbon density of aboveground components of the plant and litter layers, which was calculated from all aboveground components as:

\[
BCDa = BCDt - BCDb
\]

Climate data

In this study, MAP and MAT for each plot were extracted from baseline climatic layers based on latitude and longitude of the plot. Baseline climatic layers were downloaded from the WorldClim database at a spatial resolution of 10 arc-min, which were generated by using thin-plate smoothing splines with latitude, longitude, altitude, and monthly temperature and precipitation records from 1950 to 2000 from climate stations (Hijmans et al. 2005).

Statistical analysis

Means and standard errors of BCD were calculated from plot-scale data sets. Regression analyses were conducted to fit the relationship between BCD and forest age, MAP, and MAT. Multiple linear regressions were used to evaluate the combined effects of MAP, MAT, and stand age on carbon density in each layer and whole ecosystem. The coefficient of determination (\( R^2 \)), the level of probability (\( p \)), and akaike information criterion (AIC) were used to determine the goodness-of-fit of the curves. One-way ANOVA was used for evaluating the level of significance at \( p \leq 0.05 \) in the analysis of variance.

Results

Effects of precipitation on biomass and carbon stocks in oak forests

The biomass of investigated oak forests ranged from 73.67 to 438.53 t ha\(^{-1}\) and BCD\(_{t}\) varied from 32.75 to 213.66 t ha\(^{-1}\) within this region. According to \( R^2 \), \( p \), and AIC, linear model could well fit the variation trends of BCD in trees, shrubs, and herbs with precipitation gradient, while exponential decay model could well fit the pattern of BCD in litter layer along precipitation (Figure 1).

Further analysis suggested that the magnitude of changes in BCD along a precipitation gradient from 524 to 737 mm differed among different layers (Figure 1). BCD of the tree layer exhibited the largest response to precipitation, with approximately 3.16 t ha\(^{-1}\) per 10 mm of precipitation increase (\( R^2 = 0.2869; \ p < 0.01 \)); Total = 0.3164 MAP - 130.61). BCD in the herb layer showed the least response to the precipitation gradient,
with only 0.016 t ha\(^{-1}\) per 10 mm precipitation increase. BCD in litter layers decreased significantly with the increase in MAP, and MAP explained 57.47% of variation in BCD of the litter layer. As BCD for the tree layer accounted for 93.56 ± 0.74 percentage of BCD\(_t\), BCD\(_t\) showed a similar variation trend and exhibited significant positive correlation with increasing MAP (\(R^2 = 0.2663; p < 0.05\); BCD\(_t = 0.3039 MAP - 118.42\)).

In the tree layer, total BCD and BCD of stem, branch, and root increased by 147.99%, 234.28%, 87.79%, and 131.19%, while the BCD of leaves decreased by 16.69% with the changes of MAP from lower than 600 mm to higher than 700 mm (Figure 2). Total BCD in the shrub and herb layers increased with increasing precipitation; however, the BCD in the litter layer deceased along the precipitation gradient. BCD increased with increasing MAP by 1.24-fold, from 45.92 t ha\(^{-1}\) to 103.02 t ha\(^{-1}\) according to the results in Figure 2.

**Effects of temperature on the stocks of biomass and carbon in oak forests**

Regression analyses revealed no significant relationship between the BCD of each component in the tree, shrub, herb, and litter layers and MAT (\(R^2 < 0.0420, p > 0.05\)) except for the BCD of roots in the tree layer (\(R^2 = 0.164, p = 0.021\)).

Total BCD and BCD of stems, branches, and roots in the tree layer first decreased and then increased with increasing temperature (Figure 3), while the BCD of leaves in the tree layer changed slightly along a temperature gradient. The BCD of each component in the herb layer showed a similar change to that in the tree layer with increasing temperature. In the shrub layer, the BCD of each component fluctuated frequently and showed no significant tendency with increasing temperature (Figure 3). BCD in the litter layer increased first, and then decreased with increasing temperature (Figure 3). BCD\(_t\) changed irregularly with increasing temperature, with the lowest value (59.29 t ha\(^{-1}\)) occurring between 9°C and 10°C according to the results in Figure 3.

**Effect of stand age on the stocks of biomass and carbon in oak forests**

BCD of each component in the tree layer increased slowly for a stand age less than 100 years, and increased rapidly when stand age was over 100 years (Figure 4). The BCD in stems, branches, leaves, and roots in the tree layer increased by 131%, 177%, 91%, and 75% during the stand age of over 100 years compared to a stand age of 80–100 years. The BCD of each component in the shrub layer showed little change for stand age less than 100 years and increased sharply when stand age was over 100 years (Figure 4). However, the BCD of each component in the herb and litter layers changed irregularly under different stand age classes (Figure 4).

BCD in different layers along stand age exhibited different patterns (Figure 5). The positive relationship of BCD in
The BCD \textsubscript{a}/BCD \textsubscript{b} was regressed against stand age, which suggested that BCD \textsubscript{a}/BCD \textsubscript{b} had a significant positive relationship with stand age, and stand age explained 32.37% of the variation in BCD \textsubscript{a}/BCD \textsubscript{b} (Figure 6).

The integrative effects of precipitation, temperature, and stand age on forest ecosystem BCD

Multiple regression analyses were conducted to evaluate the comprehensive effects of MAP, MAT, and stand age on BCD for each component in different layers (Table 1). The combination of climatic conditions and stand age explained 54.21% of variations in BCD \textsubscript{t} and 55.38% (p < 0.01) of the variation in total BCD in the tree layer, suggesting climatic conditions and stand age played a vital role on carbon sequestration in oak forests.

Discussion

The response of BCD to climatic factors

Climate (precipitation, temperature, etc.) has important effects on the ecosystem succession, pattern, and production (Odum 1969; Stegen et al. 2011). Abundant rainfall is considered as a precondition for increased carbon sequestration.

BCD, as well as BCD of each component in the tree, shrub, and herb layers increased with increasing precipitation (Figure 2). Similar results were reported by Iglesias et al. (2012), who found that forests carbon stocks increased as the mean rainfall became more abundant. The high forest BCD recorded in the Changbai Mountains was strongly linked to the high precipitation in the area, an evidence that precipitation was probably the key driving force for the increase in forest BCD (Tan et al. 2007). However, BCD of different forests presents different variation trends. Stegen et al. (2011) found that BCD increased remarkably with MAP in dry tropical and

Table 1. Multiple regression analyses between forest stand age, MAP, MAT, and BCD in each layer.

<table>
<thead>
<tr>
<th>BCD</th>
<th>Regression equation</th>
<th>p</th>
<th>R\textsuperscript{2}</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCD\textsubscript{t}</td>
<td>Y = -143.3842 + 0.9790 Age + 3.6748 MAT + 0.2132 MAP</td>
<td>0.0001</td>
<td>0.5406</td>
<td>32</td>
</tr>
<tr>
<td>Tree</td>
<td>Y = -155.1026 + 0.9694 Age + 3.6092 MAT + 0.2268 MAP</td>
<td>0.0001</td>
<td>0.5538</td>
<td>32</td>
</tr>
<tr>
<td>Shrub</td>
<td>Y = -2.5179 + 0.0143 Age - 0.0567 MAT + 0.0050 MAP</td>
<td>0.0046</td>
<td>0.3667</td>
<td>32</td>
</tr>
<tr>
<td>Herb</td>
<td>Y = -0.8015 - 0.0010 Age + 0.0237 MAT + 0.0016 MAP</td>
<td>0.0701</td>
<td>0.2194</td>
<td>32</td>
</tr>
<tr>
<td>Litter</td>
<td>Y = 15.0378 - 0.0027 Age + 0.0987 MAT - 0.0202 MAP</td>
<td>0.0001</td>
<td>0.5782</td>
<td>32</td>
</tr>
</tbody>
</table>
temperate forests, and showed no trend with MAP in moist and wet tropical forests. Different precipitation amount also had effects on the variation tendency of forest BCD. Liu et al. (2014) analyzed a database of mature forests around the world (897 sites) and showed that aboveground BCD in the tree layer increased with increasing precipitation, until rainfall reached 2500 mm, then decreased gradually. Changes in BCD depending on different MAP could be attributed to variation in climate conditions in different regions. Due to the relatively dry climate (sub-humid and semi-arid) in the present study region, precipitation may have become the limiting factor to forest growth; therefore, forest BCD increased rapidly with an increase in precipitation.

Regression analyses showed that MAP explained nearly 30% of the variation in BCD in the tree layer in the area (Figure 1). BCD in shrub and herb layer increased with increasing precipitation (Figure 1). The result is in agreement with that of reported by Di (2015) and Sun et al. (2017), who found carbon storage in shrub and herb layers was positive with precipitation on the Loess Plateau. The results were ascribed to the moisture deficiency in arid and semi-arid areas, which seriously restricts the growth of vegetation, suggesting the key role of moisture for understory vegetation in oak forests. Zhao et al. (2014) revealed that the litter layer should be considered as an important component in BCD calculation. Maximum ratio of BCD in litter versus BCD was 14.47% among oak forest sample plots. However, BCD in litter decreased with increasing precipitation (Figures 1 and 2), which may be explained partly by the quicker decomposition rate under higher precipitation.

Quantifying how the magnitude and distribution of forest BCD respond to increasing temperature is important for understanding the impacts of global warming on terrestrial carbon balance. The variations in BCD of each component in the different layers with MAT were complicated. BCD of most of the components showed no significant linear relationships with MAT. Selmants et al. (2014) pointed out that BCD of an ecosystem does not vary with MAT in Hawaiian tropical montane wet forests, which could partly support the findings of this study. Similar results were also reported by Stegen et al. (2011), who found a very weak relationship between forest biomass and MAT, the latter explaining only 2% of the variation in forest biomass. The weak relationship between BCD of each component in the different layers and MAT may be attributed to the biological characteristics of oak forests themselves. Temperature was not the limiting factor for the growth of oak forest in the area. In contrast to the above studies, Tan et al. (2007) suggested that climate warming was probably the key factor for forest BCD increase, which was consistent with the results of Raich et al. (2006), who noticed that forest biomass increased with MAT in moist tropical forests. Raich et al. (2006) also reported that BCD in litter increased first and then decreased with increasing temperature, which is different from the results of Gao et al. (2014) and Selmants et al. (2014), who reported that BCD in litter decreased with the increase in MAT. BCD, and BCD of each component in the tree layer are all less sensitive to MAT.

The interaction between precipitation and temperature is reported to be positively correlated with net ecosystem production (Luo et al. 2008). In this study, two-way analysis of variance showed that the interaction between precipitation and temperature was insignificant for biomass carbon accumulation in different layers (data not shown). This possible reason is that temperature has little effect on the accumulation of biomass carbon in this area.

The variation of BCD with stand ages

The magnitude of carbon storages and patterns of carbon sequestration in forests largely depend on stand age (Gough et al. 2008; Seedre et al. 2015). Previous studies on oak forest (Litton et al. 2004; Peichl and Arain 2006; Li et al. 2011) confirmed that stand age was an important variable for accurately estimating the forest biomass. Our research showed that stand age had a significant effect on BCD in forest and tree layer (Figure 5). The result is in line with the result reported by Zhao et al. (2014), who confirmed that the carbon storage of each component in the tree layer increased with increasing stand age, which partly supports the findings of the present study. With the increase in stand age, total BCD in the tree layer also increased, supporting the hypothesis that not only young forests but also old-growth forests have a great carbon sequestration potential (Zhou et al. 2006; Luysaert et al. 2008). The carbon sequestration of trees had not reached its stabilization stage (Figure 5) as the forest was still in a period of rapid growth and the stand ages for these plots were not old enough. BCD increased persistently with stand age, indicating a substantial potential of carbon accumulation.

Total BCD in the herb layer did not differ significantly with stand age, while the tendency of BCD in shrubs increased with stand age was uncertain (Figure 5). However, Taylor et al. (2007) found that total BCD in the understory (shrub and herb) initially increased and then decreased rapidly with increasing stand age. Forest management, stand-specific canopy, and soil conditions, all of which affect light, water, and nutrient availability for the growth of the understory, might explain this difference in results. The oldest stand had largest shrub BCD in this study. One possible explanation was the sparse canopy and the position (upper slope), which provided sufficient light for the growth of shrub, the other important cause was that shrubs having developed roots were flourishing under the forests, such as Fargesia qinlingensis, Actinidia polygama, and Cotonaster acuminnatus. The oldest stand with largest shrub BCD played an important role in determining the significant positive correlation between the BCD in shrub layer and stand age, but current data of BCD for shrub layer in old-growth forests are not sufficient to confirm this significant positive correlation (Figure 5). The results suggested that stand age had no significant effects on the carbon sequestration of herb layer, while the determination of positive correlation between stand age and BCD in shrub layer required more data on BCD of shrub layer in old forests. BCD in the forest floor is an important component that affects carbon transport from the tree to the forest soil carbon pool, although marginally (with an average of only 2.63 t ha−1). Therefore, the forest floor should be considered when evaluating forest carbon sequestration. Cheng et al. (2013), Zhao et al. (2014), and Li et al. (2013) reported that BCD in litter increased steadily with increasing stand age. In this study, the forest floor carbon showed no obvious trend along stand age.
_gradients (Figures 4 and 5). The result suggested that the carbon accumulation pattern in litter layer may be different from other layers during the process of succession in the forest.

To examine the temporal trends of carbon stock, the method of space-for-time substitution was frequently employed thanks to its convenience in application. It is noticed that uncertainty exists due to multiple biotic and abiotic variables other than stand age. There is a potential risk in using this method because it integrates across much environmental variance, and neglects much spatial heterogeneity within sites, which may limit the validity of the patterns for inferring mechanism or generating hypotheses about mechanism (Pickett 1989). Therefore, we should be aware of these issues and try to reduce these uncertainties when assessing the BCD in different forests.

Responses of above–belowground carbon allocation to stand age

Root biomass contributes a significant amount to ecosystem biomass and is imperative to the precise estimation of forest carbon pools (Peichl and Arain 2006). In this study, the highest ratio of BCD in root to BCD accounts for up to approximately 30%, the mean ratio of BCD\textsubscript{a}/BCD\textsubscript{a} was approximately 0.21. The result in this study falls near those of Jackson et al. (1996) and Cairns et al. (1997), which suggested the ratio of below- to aboveground biomass approximates 0.23 in temperate deciduous forest and ranges from 0.23 to 0.26 for major biomes around the world, respectively. Meanwhile, the ratio summarized by Huang et al. (2006) was 0.17–0.36 for Chinese forests. The ratio of BCD\textsubscript{a}/BCD\textsubscript{a} increased from 2.369 to 8.275 with increasing stand age (Figure 6), suggesting that aboveground of living plants grew quicker than roots with increasing stand age in forest ecosystems. The finding further verified previous studies conducted by Mokany et al. (2006), Peichl and Arain (2007), and Wang et al. (2008). They also reported that the ratio of above- to belowground biomass carbon in trees was positively related to forest stand age. It is assumed that trees allocate more resources to root biomass in the early stage in order to maximize water and nutrient assimilation that support survival and fast foliage growth (Helmsaari et al. 2002; Mund et al. 2002). With the increase in forest age, productivity and the relative amount of tree foliage biomass decreases, and the demand for nutrient and water supply from roots decreases consequently (Kurz et al. 1996; Vanninen et al. 1996; Claus and George 2005). However, as accurately assessing forest rooting patterns requires spatial integration and temporal integration (Jackson et al. 1996), adequate survey samples with a large forest age range are required to thoroughly confirm the relationship between BCD\textsubscript{a}/BCD\textsubscript{a} and stand age.

Conclusions

We found that BCD\textsubscript{a} and BCD in the tree layer increased with increasing precipitation and stand age. However, BCD\textsubscript{a} and BCD in the tree layer did not vary significantly with the changes in temperature. The ratio of BCD\textsubscript{a}/BCD\textsubscript{a} had a significant positive correlation with stand age, suggesting that more carbon is allocated to aboveground with increasing age. BCD in the understory (shrub and herb) increased with the increase in precipitation as a whole and had no obvious tendency under forest age and temperature. BCD in litter layer decreased with increasing precipitation and had no definite trend along temperature and stand age gradients. The influence of precipitation on plant growth is greater than that of temperature in oak forests. However, a profound understanding of the response of carbon storage in the different layers to climate conditions and stand ages requires careful annual monitoring of forest ecosystems in representative forests.

Geolocation information

The study was conducted in the forest zone of Longnan, Qingyang, and Tianshui cities/prefectures (33°10′–36°3′N and 104°41′–108°36′E) of Gansu Province in northern China.

Acknowledgments

The study was supported by the Strategic Priority Research Project of the Chinese Academy of Sciences (XDA0505022): Current stocks, sequestration rate and potential of forest carbon in the temperate western China. We gratefully acknowledge many other members (graduate and undergraduate students) from Northwest A&F University contributing to the field investigation.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by a grant from Chinese Academy of Sciences [Grant number XDA0505022].

ORCID

Sheng Du http://orcid.org/0000-0002-5580-399X

References

Fortin M, Ningre F, Robert N, Mothe F. 2012. Quantifying the impact of forest management on the carbon balance of the forest-wood product chain: a case study applied to even-aged oak stands in France. For Ecol Manage. 279-176–188.


