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Inventory-based estimation of forest biomass in Shitai County, China: A comparison of five methods

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Abstract. Several comparative studies have reported that there can be great discrepancies between different methods used to estimate forest biomass. With the development of carbon markets, an accurate estimation at the regional scale (i.e. county level) is becoming increasingly important for local government. In this study, we applied five methodologies [continuous biomass expansion factor (CBEF) approach, mean biomass density (MB) approach, mean biomass expansion factor (MBEF) approach, national continuous biomass expansion factors (NCBEF) proposed by Fang et al (2002), standard IPCC approach] to estimate the total biomass for Shitai County, China. The CBEF is generally considered to provide the most realistic estimates in term of regional biomass because CBEF reflects the change of BEF to stand density, stand age and site conditions. The forests of the whole county were divided into four forest types, namely Chinese fir plantations (CF), hardwood broadleaved forests (HB), softwood–broadleaved forests (SB) and mason pine forests (MP) according to the local forest management inventory of 2004. Generally, the MBEF approach overestimated forest biomass while the IPCC approach underestimated forest biomass for all forest types when CBEF derived biomass was used as a control. The MB approach provided the most similar biomass estimates for all forest types and could be an alternative approach when a CBEF equation is lacking in the study area. The total biomass derived from MBEF was highest at 1.44×10^7 t, followed by 1.32×10^7 t from CBEF, 1.31×10^7 t from NCBEF, 1.25×10^7 t from MB and 1.16×10^7 t from IPCC. Our results facilitate method selection for regional forest biomass estimation and provide statistical evidence for local government planning to enter the potential carbon market.

Keywords biomass expansion factors (BEFs), forest type, forest inventory, carbon market

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Introduction

Globally, about 80% of terrestrial biomass is stored in forests (Dixon et al. 1994), and forest biomass as well as methods for its estimation are of great interest due to the important role of forests with regards to mitigating global climate change (Guo et al. 2010, Seo et al. 2013). According to the United Nations Framework Convention on Climate Change (UNFCCC), signatory countries are obliged to report greenhouse gas emissions and removals (Bettelli et al. 1997).

Forest biomass acts as a continuous carbon sink of 1.9-2.6 Pg C a^{-1} [about 50% of biomass is carbon (IPCC, 2007)], accounting for 33% of carbon emissions from fossil fuel and land use changes (Houghton 2007, IPCC 2007, Pan et al. 2011), thus forests play an important role in mitigating and alleviating global climate change (Bonan 2008). However, different methods generate different biomass estimates (Guo et al. 2010, Yin et al. 2015). For example, based on the national forest inventory in 1999-2003, China's forest biomass carbon stock ranged from 5.7 Pg C (1 Pg C = 10^{15} g C) derived from the continuous biomass expansion factor (CBEF) approach to 7.7 Pg C derived from the mean biomass density (MB) approach (Guo et al. 2010), and it is even higher from MODIS-based estimation (8.6 Pg C, Yin et al. 2015). Thus, applying appropriate methods for regional forest biomass estimation are important for accurate estimation (Fang et al. 1998), which is itself essential when reporting data to the UNFCCC (IPCC 2006) and an essential step to enter into the carbon market.

Some early efforts in the 1970s were made to estimate the regional, national and global scale forest biomass using the MB approach (Whittaker et al. 1973, Woodwell 1978). This approach simply multiplies mean biomass observed from field measurement by forest area. However, direct field measurements with greater biomass than the mean biomass level in a region will lead an overestimation of forest biomass (Brown et al. 1984, Fang et al. 2005, Guo et al. 2010). With the increasing data availability of forest inventories, inventory data has been widely used to estimate the forest biomass at a large scale (Schroeder et al. 1997, Fang et al. 1998, Fang et al. 2005, Guo et al. 2010).

Since most inventories record detailed information on stand volume by age class and tree species, it is possible and useful to calculate a biomass expansion factor (BEF) to convert stand volume to stand biomass, including the non-commercial biomass such as branches, leaves and roots (Fang et al. 2001, Guo et al. 2010). Sharp et al. (1975) estimated the regional forest biomass for Northern Carolina in the USA using a constant BEF of 2.0 Mg m^{-3}. However, more recent studies have indicated that the BEF is not a constant value and varies with forest age, site class and stand density (Fang and Wang 2001, Lehtonen et al. 2004, Teobaldelli et al. 2009, Correia et al. 2010, Yu et al. 2014). Thus, applying constant BEFs across all age classes and site conditions within a given forest type underestimates the forest biomass of younger or less productive stands and overestimates the forest biomass of older or more productive stands (Fang et al. 1998, Goodale et al. 2002). To reduce the bias of constant BEFs, BEF equations have been developed that include stand variables as predictors (Teobaldelli et al. 2009, Guo et al. 2010, González-García et al. 2013). Because it is difficult or inefficient to obtain BEFs for each age and site class at regional or national scales, Fang et al. (1998, 2001) and Fang and Wang (2001) derived a simple linear relationship between BEFs and stem volume using field inventory data across China. Since the stand volume could reflect the impacts of stand age, stand density and other factors on biomass, it can be used to calculate the forest biomass using forest area and volume derived from forest inventory data without information about age, site class, etc (Fang et al. 2002, Guo et al. 2010).

In order to establish an international standard estimation of forest biomass, IPCC (2003) proposed a similar approach using forest volume, wood density, BEF and the shoot/root ratio. Many reference values for wood density, BEF and shoot/root ratios for different forest types were also provided (IPCC, 2003). This simplifies the biomass estimation and comparison globally. Using the constant BEF proposed by IPCC (2003), the total forest biomass of five provinces in China reported by Li et al. (2012) was 1.79×10^9 t, but it was much lower than 2.42×10^9 t as derived using the continuous BEF. Therefore, the IPCC proposed approach may not necessarily be appropriate for some study areas.

This study was conducted in a mountainous county of Anhui Province with a forest cover of 80%. Timber and by-products from the forests are the main income for local residents. The increasingly important role of sequestrating CO_2 by forests has attracted considerable political and scientific attention from the local government that is aiming to enter the carbon market. The first step to enter the carbon market is to quantify the biomass on the county level. Thus, in this study, five well-known methods, namely the continuous biomass expansion factor (CBEF) approach, the mean biomass density (MB) approach, the mean biomass expansion factor (MBEF) approach, national continuous biomass expansion factors (NCBEF) proposed by Fang et al (2002), and the standard IPCC approach, were used to estimate the forest biomass of four forest types. The objectives were to: (1) build a continuous BEF equation relating stand volume for each forest type; and (2) to compare the biomass estimation derived from the five methods. These results could contribute to the improved understanding of method selection of regional biomass estimation.

Materials and methods

Study area

The study was conducted in Shitai County (29°59’-30°24’ N, 117°12’-117°59’ E, Figure.1), Anhui province, China. It has an area of about 900 km^2, about 80% of which is covered by forests. It is a mountainous area with an elevation range of 50 m to 1000 m and steep slopes with an average of 66%. The region has a mid-subtropical, humid, mountainous climate with distinct seasonality (Geng et al. 2011). The annual average temperature is 16^{o}C with an annual mean maximum of 40.9^{o}C and an annual mean minimum of -13.2^{o}C (Lu 2010). The mean annual precipitation is about 1668 mm with high inter-annual variability and about 70% of the precipitation occurs during flooding seasons (Geng and Wang 2011). The average annual sunshine duration is 1704 hours and the pan evaporation is 1256 mm (Lu 2010).

Plot design

This study is a part of the Lin^{4}Carbon project, in which three different scales of inventories are distinguished: (1) land use inventory and forest inventory (LUI/FI) that produce information over the whole extent of the sampling frame based on systematic grids 3 × 3 km; (2) Forest management inventory (FMI) for those stands with forest management information with a 500 × 500 m systematic grid, which is also part of a Sustainable Forest Management

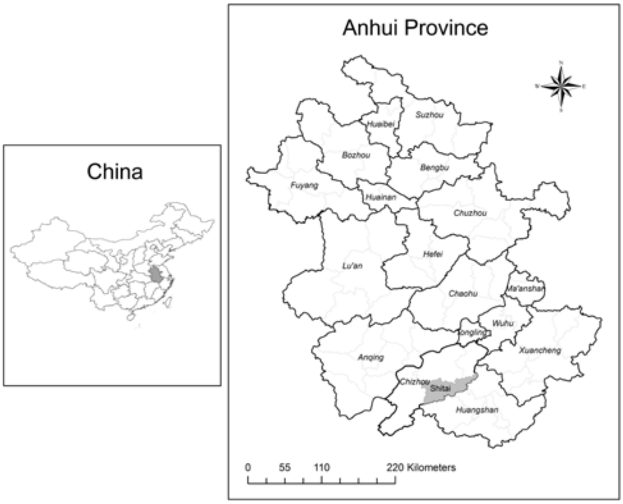

Figure 1 Location of Shitai County in the southern part of Anhui Province, South-Eastern China

(SFM) Cooperation Project between the Shitai Forest Bureau and the German Development Bank (KfW); (3) Stand inventory of selected stands (SI) with a 100 × 100 m systematic grid. This resulted in the establishment of 158 plots. Among these plots, 74 plots were dominated by Chinese fir, 47 plots were dominated by hardwood broadleaved species, 28 plots were dominated by softwood broadleaved species and 9 plots were dominated by Mason pine (MP) forests (Table 1). The main broadleaved species include *Castanopsis sclerophylla*, *Cyclobalanopsis glauca*, *Castanopsis eyrei*, *Castanea mollissima*, *Cyclobalanopsis jenseniana*, etc. Other broadleaved species (with lower wood basic density) included *Liquidambar formosana*, *Rhus punjabensis*, *Rhus chinensis*, *Acer elegantulum*, *Cerasus pseudocerasus*, etc. The bamboo forests were not included in this study. In circular plots of 6 m radius, trees were measured for 10 cm < dbh < 20 cm, while in 10 m radius plots, trees with dbh > 20 cm were measured. Tree diameters were measured with a diameter tape to the nearest 0.1 cm and heights of one or two dominant trees, one co-dominant tree and one suppressed tree were measured in each plot. The crown of dominant trees extends above the general layer of the stand and intercepts direct sunlight across the top and upper branches. The diameters of dominant trees are usually amongst the largest in the stand. The crown of co-dominant trees lies within the main layer and their stem diameter lies in the middle of the range in the stand. The crown of suppressed trees lies entirely below the main canopy. The stem diameter of suppressed trees is amongst the smallest in the stand (Tang et al. 2015). If more than two plots were established in one stand, especially in well-managed stands, the average biomass was used to represent the stand because more plots in high production stands could overestimate the mean biomass of the whole county.

Definition of a biomass expansion factor (BEF)

In this study, a BEF is defined as the ratio of total stand biomass (including above-, below-ground and understorey biomass) divided by stand stem volume:

$$BEF = B/V \tag{1}$$

where B is the total stand biomass (Mg ha^{-1}), and V is total stem volume (m^3 ha^{-1}).

The allometric models for volume and biomass of the main species in the study area are shown in appendix Table 1 (Guisasola-Rodríguez 2014). Because we did not measure the belowground biomass, we used the ratios of below- and above-ground biomass for different species to estimate the belowground biomass (Fang et al. 1998, Wang et al. 2008).

Understorey biomass estimation

Understorey harvest was conducted in FMI and SI plots. In each plot, three systematic subplots of 40 × 40 cm were established that were distributed in directions of 0°, 120° and 240° from North and 3 metres away from the plot centre. All understorey vegetation, including grass and shrubs, were harvested by uprooting in each plot and washed in the lab. The understorey samples were dried at 70 °C to constant weight. A linear relationship between the aboveground biomass and understorey biomass was used to estimate the understorey biomass where the understorey was not collected.

Descriptions of biomass estimation approaches

In this study, five methods were used to estimate regional scale biomass as follows:

CBEF: $B_t = \sum_{i=1}^{4} A_i \cdot V_m \cdot BEF_i$ (2)

MB: $B_t = \sum_{i=1}^{4} A_i \cdot B_m$ (3)

MBEF: $B_t = \sum_{i=1}^{4} V_i \cdot BEF_m$ (4)

NCBEF: $B_t = \sum_{i=1}^{4} (a \cdot V_i + b)$ (5)

IPCC: $B_t = \sum_{i=1}^{4} V_i \cdot D \cdot BEF2 \cdot (1 + R)$ (6)

where B_t is the total forest biomass of Shitai County; i = 1, 2, 3 and 4, are the forest types; V_m is the mean volume per hectare; A_i is the total area, taken from the forest management inventory of Shitai County (Forest Bureau of Shitai County 2004); BEF_i is the biomass expansion factor; B_m is the mean biomass of forest type i; BEF_m is the mean biomass expansion factor; a and b are the coefficients for each forest type at the national level (Fang et al. 1998); D is the wood density proposed for these forests (IPCC 2003); $BEF2$ is the biomass expansion factor proposed by the IPCC (2003); R the shoot/root ratio (IPCC 2003).

Data analysis

Statistical analyses were performed using R 3.0.2 (R Core Team 2014). Non-linear regression analysis was used to model the relationship between BEF and volume for each forest type. The relationships between BEF and volume were expressed as follows:

$$BEF = a + \frac{b}{V} \quad (7)$$

where a and b are coefficients.

Results

Stand characteristics of different forest types

The general characteristics of stand density,

Table 1 Descriptions of stand characteristics of different forest types

Stand	Mean BEF	Density (trees·ha^{-1})		BA (m^2·ha^{-1})		Volume (m^3·ha^{-1})		Biomass (Mg·ha^{-1})		Number of plots
		Mean (range)	CV (%)	Mean (range)	CV (%)	Mean (range)	CV (%)	Mean (range)	CV (%)	
CF	0.84	1025 (88-2416)	45.3	22.1 (1.0-58.1)	58.1	133.4 (4.2-356.9)	64.4	96.6 (3.6-256.2)	62.2	74
HB	1.18	826 (88-1920)	49.1	31.3 (0.7-85.3)	65.7	220.2 (2.4-816.8)	76.0	236.7 (4.1-1042.9)	84.9	47
SB	1.28	494 (88-1316)	69.4	13.3 (0.8-41.8)	97.6	91.4 (3.1-313.1)	108.3	94.1 (4.7-382.0)	107.3	28
MP	0.84	540 (177-1061)	67.7	17.8 (3.9-44.9)	81.6	110.8 (15.7-327.2)	92.2	89.1 (9.3-279.8)	97.6	9

Note. Abbreviations: BA - stand basal area, CV - coefficient of variation (%), CF - Chinese fir plantation, HB - hardwood broadleaved forests, SB - softwood broadleaved forests, MP - mason pine forests.

basal area, stand volume and biomass are displayed in Table 1. Stand density ranged from 88 to 2416 tree ha^{-1}. The lowest basal area was found in SB with 13.3 m^2 ha^{-1}, with the increase to 17.8 m^2 ha^{-1} for MP forests, 22.1 m^2 ha^{-1} for CF plantations and 31.3 m^2 ha^{-1} for HB forests. HB forests had the highest mean stand volume of 220.2 m^3 ha^{-1}, followed by CF plantations (133.4 m^3 ha^{-1}), MP forests (110.8 m^3 ha^{-1}) and SB had the lowest mean stand volume of 91.4 m^3 ha^{-1}. Mean stand biomass ranged from 89.1 Mg ha^{-1} in MP forests to 236.7 Mg ha^{-1} in HB forests. Among different forest types, SB forest had the highest coefficients of variance.

The relationship between BEF and stand volume

BEF ranged from 0.65 to 2.58 Mg m^{-3} for CF plantations, compared to the values from 0.87 to 3.03 Mg m^{-3} for HB, from 0.82 to 2.55 Mg m^{-3} for SB and from 0.73 to 0.94 Mg m^{-3} for MP forests (Figure 2). The average BEFs were 0.84 Mg m^{-3} for CF, 1.18 Mg m^{-3} for HB, 1.28 Mg m^{-3} for SB and 0.84 Mg m^{-3} for forests. BEF of different forest types showed a similar pattern such that the BEF decreases steeply at low volume values, typically below 50 m^3 ha^{-1}. Then, with the increase of stand volume, the BEF tended to level off and remained constant for the high stand volumes.

We also calculated a threshold of stand volume for the continuous BEF and constant BEF by assuming those continuous BEFs equalled the constant BEF. If the stand volume was lower than this threshold, the constant BEF

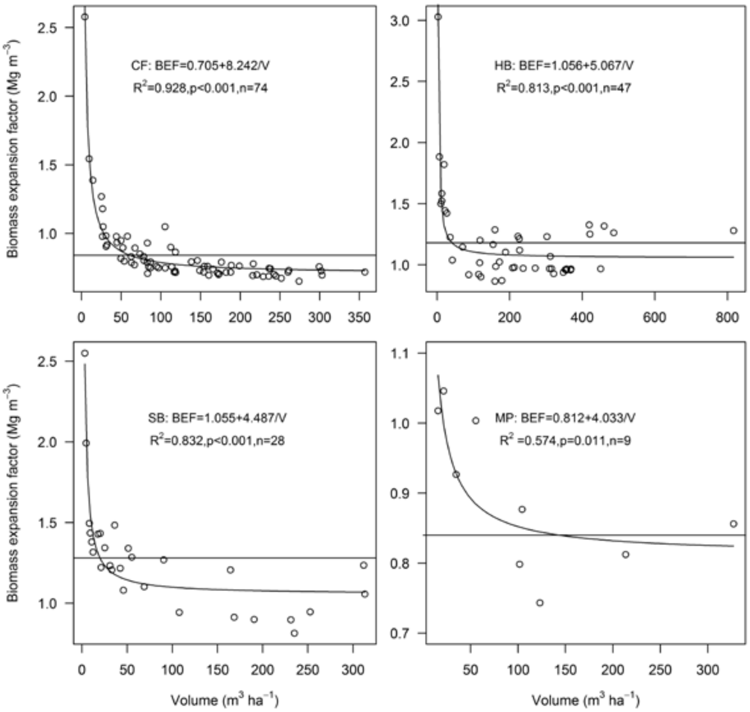

Figure 2 The relationship between biomass expansion factors and stand volume for different forest types. The horizontal lines mean mean biomass expansion factors, CF - Chinese fir, HB - hardwood broadleaf forest, SB - softwood broadleaf forest, MP - mason pine.

resulted in lower estimates of stand biomass compared to the continuous BEF method, and vice versa. The thresholds were 59, 39, 20 and 153 m^3 for CF, HB, SB and MP forests, respectively.

Biomass estimation of different forest types

Regardless of different approaches, biomass estimates were highest in HB forests, accounting for 83% of total biomass, followed by CF forests, MP forests and SB forests. Within the same forest type, biomass estimates differed greatly depending on the method used (Figure. 3). For example, total biomass of CF plantations ranged from 1.83×10^6 t calculated using the NCBEF approach and 2.52 ×10^6 t calculated using the MBEF approach (Figure 3). First, we compared the first three methods that were developed in our study. In comparison to the CBEF derived biomass, the MB approach produced lower estimates of biomass while the MBEF approach led to higher biomass estimates for different forest types. Secondly, we compared the biomass estimation method proposed by Fang et al. (1998) and the IPCC (2003) approach. The NCBEF approach produced higher biomass estimates for HB forests and lower biomass estimates for CF, SB and MP forests. The IPCC approach generated the lowest biomass estimates for all forest types. The MBEF derived total biomass (the sum of the four forest types) was highest at 1.87×10^7 t, followed by 1.79 ×10^7 t from NCBEF, 1.71 ×10^7 t from CBEF, 1.68 ×10^7 t from MB and 1.58 ×10^7 t from IPCC.

In order to further qualify the effects of using different methods on estimating the biomass of different forest types, we took the CBEF derived biomass estimation as a control and compared the ratios of biomass estimates from MB, MBEF, NCBEF and IPCC to that of CBEF (Figure 4). The MB approach generated relatively stable biomass estimates of different forest types (89%-98%), generating the most accurate estimation of total biomass compared to the other methods, while NCBEF had the greatest variability in biomass estimation, var-

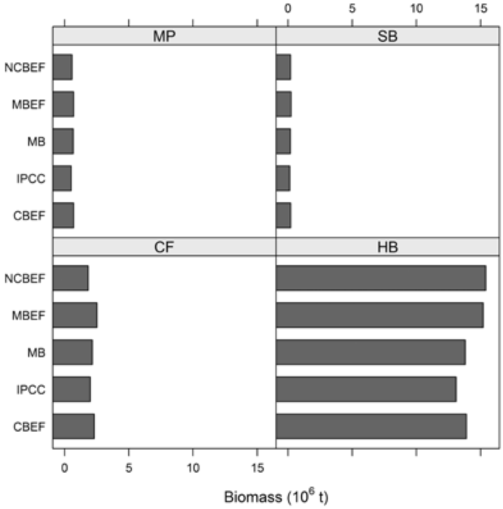

Figure 3 Biomass of different forest types and total biomass in Shitai County estimated by different methods (CF - Chinese fir, HB - hardwood broadleaf forest, SB - softwood broadleaf forest, MP - mason pine)

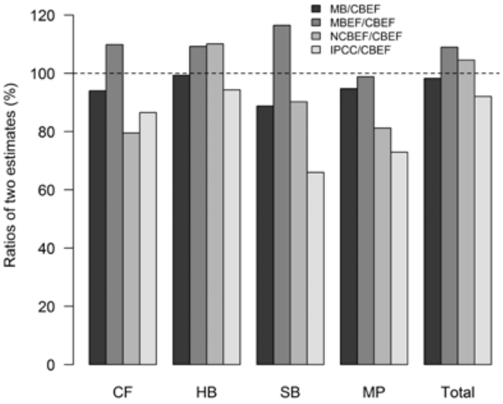

Figure 4 Comparison of biomass estimated using different methods, shown as the ratios of MB, MBEF, NCBEF and IPCC to CBEF. The black dash line represents a constant ratio of 100%. Abbreviations same as in Fig. 3, while Total - the total biomass of different forest types.

ying from 80% in CF to 110% in HB forests. The IPCC approach underestimated biomass by 35% for SB forests and 27% for MP forests. Compared with different forest types, different methods generated the most accurate biomass estimates for HB, varying from 94% for IPCC/CBEF and 110% for NCBEF/CBEF, and generated the least accurate estimates for SB forests, varying from 66% for IPCC/CBEF to 116% for MBEF/CBEF.

Table 2 BEFs of different forest types

Forest type	BEF	Sources
Chinese fir	0.75	(Fang et al. 2007)
	0.68	Calculated from Pan et al. (2004) using our data
	0.701-0.957	(Li et al. 2012)
	0.84	In this study
Conifer forest	1.30	(IPCC 2003)
Abies fabri	0.89	(Fang et al. 2007)
Deciduous oaks	1.47	(Fang et al. 2007)
Cypress	1.05	(Fang et al. 2007)
Betula	1.26	(Fang et al. 2007)
P. massoniana & P. yunnanensis	0.69	(Fang et al. 2007)
Cupressus	0.844-10.598	(Li et al. 2012)

Discussion

Comparison of BEFs

The mean BEFs were 0.84 Mg m^{-3} for CF and MP forests, 1.18 Mg m^{-3} for HB forests and 1.28 Mg m^{-3} for SB forests, which were generally comparable to the reported values of these or similar forest types (Fang et al. 2007, Li et al. 2012). For example, Li et al. (2012) found BEFs of CF plantations that ranged from 0.705 to 0.954 Mg m^{-3} in different provinces, while Fang et al. (2007) reported a BEF value of 0.89 Mg·m^{-3} for MP forests. However, the BEF of CF plantations was higher than the value calculated from Pan et al. (2004) and Fang et al. (2007) at the national level (Table 2). This deviation may have resulted from the stand volume distributions. For instance, Pan et al.'s (2004) calculation was based on a volume range of 10-707 m^3 ha^{-1} (n = 268), which has a wider spread of stand volume than our data set (4-357 m^3 ha^{-1}, n = 74), which does not include plots with high volumes.

In our study, BEF values varied with forest types, which has been illustrated by many other studies (Pan et al. 2004, Fang et al. 2007, Li et al. 2012). BEFs essentially represent specific weight in Mg m^{-3} and are influenced by the density of the tree canopy, stand wood volume, the wood density of the tree species and biomass allocation patterns (IPCC 2003, Pajtík et al. 2008, Correia et al. 2010). Thus previous studies have demonstrated that the higher BEFs are related to species morphology such as the lack of apical dominance with a polyarchic ramification resulting in a crown shape that is wider than it is deep (Mutke et al. 2005), which leads to higher biomass allocation to the crown compared to the stem (and wood volume) (Correia et al. 2010). The age of the tree could also lead the variations in BEFs because the allocation of biomass to different functional parts of a tree changes with age (Petersson et al. 2012). The average BEFs for larger areas can only reflect the mean age structure in the respective forest types, and they are not expected to be well adapted to local conditions and/or a specific stand age or diameter distribution. Thus, it should be noted that the BEFs developed in our study are applicable to the study area, and should be used with caution if applied to other forests.

The BEFs first declined with the increasing stand volume for low volume in all forest types (Figure 2), and then BEFs levelled off and remained stable for high volume values, which is highly consistent with previous studies (Fang et al. 1998, Teobaldelli et al. 2009, Correia et al. 2010, Guo et al. 2010). Therefore, using constant BEFs may underestimate or overestimate the forest biomass with different volume distributions. However, some researchers have determined a threshold for the use of a constant BEF based on a certain value of the predictor variables where the BEFs stabilize, and biomass estimation bias will be minimized (Brown et al. 1999). This could be a good way to simplify biomass calculation in mature when the stand volume estimates are available, but it should be applied cautiously to young stands or stands with a low productivity (González-García et al. 2013).

Comparison of biomass estimates from different methods

In this study, the biomass was estimated using five well-known methods, and we found that different methods resulted in highly variable estimates of biomass for different forest types. CBEF uses stand volume as a function of BEF and accounts for the effects of forest age, stand density and site quality, allowing more realistic estimates of forest biomass than other methods (Fang et al. 2002, Teobaldelli et al. 2009). Therefore, the continuous BEF method is widely used to estimate forest biomass at regional or national scales (Fang et al. 2001, Guo et al. 2010, Li et al. 2012), because stand volume is usually one of the most reliably estimated variables from forest inventory (Petersson et al. 2012).

It is impossible to get a true value of regional biomass, therefore the CBEF derived biomass was taken as a control to compare the biomass estimation derived from the other methods (Fang et al., 2002, Guo et al., 2010). The ratio of MB/CBEF was 98% for total biomass, compared to 94% for CF, 99% for HB, 89% SB and 95% for MP, indicating that the MB approach did not result in a substantial difference in the biomass estimate (Figure 4). In contrast, the IPCC approach underestimated forest biomass of the different forest types and total biomass, suggesting that the IPCC approach is not suitable in our study area although it is a standard approach on a global level. A similar conclusion was found by Li et al. (2012) for regional biomass estimation using the IPCC approach. More interestingly, the NCBEF approach underestimated biomass of CF, SB and MP forests, but overestimated biomass of HB forests, subsequently leading to the most accurate estimation of total biomass compared to other methods. The result indicates that using the national approach proposed by NCBEF could generate bias in the biomass estimation of certain forest types, but not in total biomass. If total biomass estimates were required by the carbon market, rather than estimates specific to a certain forest type, the NCBEF approach would have been a good choice when BEFs are lacking. However, if biomass estimates for a specific forest type, such as CF, were required for the carbon market, the NCBEF approach would have underestimated the forest biomass by 20%.

Early approaches to simplify biomass estimation at the regional level applied the constant BEFs because only volume data was required (Sharp et al. 1975, Turner et al. 1995). However, more recent evidence shows that these constant BEFs are always the average values for a specific tree species, which are sometimes inaccurate given that stand age, stand density and site quality can change the BEFs (Lehtonen et al. 2004, Teobaldelli et al. 2009, Correia et al. 2010). Thus, applying constant BEFs values across all age classes and site conditions within a forest type underestimates the forest biomass of younger or less productive stands or overestimates the forest biomass of older and more productive stands (Fang et al. 1998, Goodale et al. 2002, Yu et al. 2014). In this study, the threshold stand volume where

BEFs equal the constant BEF were 59, 39, 20 and 153 m^3 for CF, HB, SB and MP forests, respectively. As expected, the constant BEFs overestimated the biomass of CF, HB and SB forests because the average volume (Table 1) was higher than these thresholds. As a result, MBEF overestimated the total biomass by 9% (Figure 4).

However, the data requirement of continuous BEFs, which can be determined using existing biomass and volume data, is stricter than other methods. When there is sufficient forest inventory data, including stand volume, forest area and a continuous BEF equation, the continuous BEFs method is a good choice to estimate regional forest biomass (Guo et al. 2010). Therefore, the continuous BEF equation proposed in this study could be directly used to estimate regional forest biomass in the study area.

Conclusions

Five methods were applied to estimate the forest biomass of Shitai County, China. The highest biomass estimate (1.87×10^7 t) was generated using the MBEF approach while the lowest biomass estimate (1.58×10^7 t) was generated using the IPCC approach. The CBEF was considered the most realistic estimate because it estimated biomass as a function of stand volume, which incorporated the effects of forest age, stand density and site quality. The data requirement of CBEF is stricter than the other methods because it is requires forest inventory data including the forest area and the continuous function of BEF. If there is not enough forest inventory data, the MB approach is another option in our study area because the MB derived biomass estimate had the lowest deviation from the CBEF approach for different forest types. The BEF equations developed in our study can be directly applied to estimate forest biomass for the study area if the stand volume is given without destructively sampling. Our results have further significance for method selection of biomass estimation for regional carbon accounting.

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