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Estimation of biomass and carbon storage of moso bamboo (*Phyllostachys pubescens* Mazel ex Houz.) in southern China using a diameter–age bivariate distribution model

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Carbon storage estimation for fast-growing bamboos remains limited because of its wide distribution and spatial variation. This study estimates biomass production and carbon storage of a moso bamboo (*Phyllostachys pubescens* Mazel ex Houz.) forest in southern China. A diameter–age bivariate distribution model based on the Weibull distribution function and a single bamboo biomass estimation model based on diameter and age were used to predict the biomass and carbon storage. The parameters of the two models were obtained on the basis of the observation data. Results showed that moso bamboo biomass varied with age and diameter at breast height (DBH). The corresponding estimated biomass and carbon storage in the study area were 88.23 and 40.45 Mg ha^{-1}, respectively. One-sixth of older culms from the entire stand were removed by selective cutting, and the annual yields of biomass and carbon were 14.07 and 6.74 Mg ha^{-1}, respectively. The moso bamboo forest has higher carbon sequestration capacity than Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook.) forest, tropical mountain rain forest, loblolly pine (*Pinus taeda* L.) forest and oriental oak (*Quercus variabilis* Bl.). The present model could be used well to estimate accurately the biomass carbon of moso bamboo at regional scale in southern China.

Introduction

Bamboo forests are among the most important forest types in the world and are mostly distributed in the tropical and subtropical regions of Asia. In China, the bamboo forest area is $\sim 5.4 \times 10^6$ ha, accounting for ~3 per cent of the total forest area (Jia, 2009). Bamboo provides wood and food for human life, as well as economic and ecological benefits (Scurlock *et al*., 2000). The growth patterns of bamboos differ from those of timber, and unique characteristics include fast growth, high production and rapid maturation from shoot to culm (Fu, 2000; Scurlock *et al*., 2000). China has ~500 species in 39 genera of bamboos, among which moso bamboo (*Phyllostachys pubescens* Mazel ex Houz.) occurs extensively (3.37 M ha or 70 per cent of the total bamboo forest area) (Zhu *et al*., 1994; Chen *et al*., 2009; Wang *et al*., 2013). This species can reach a height of 20 m when mature and is harvested mainly for poles and edible shoots throughout Southeast Asia (Fu, 2000). The development of bamboo forests is facilitated by the rhizome and culms produced belowground annually. Thus, bamboo forests generally have an uneven age structure, with differently aged culms distributed throughout a stand (Scurlock *et al*., 2000; Yen and Lee, 2011).

The carbon cycle has recently become an important global issue, and plants have served a major function in carbon storage. However, most studies of woody species have focused on assessing the capability of trees to sequester carbon (Rotzer *et al*., 2010; Tian *et al*., 2011; Fayolle *et al*., 2013); however, few studies have examined bamboos. Rapidly growing moso bamboo has high carbon stock production and potential in carbon sequestration. Previous studies have observed significant variations in the estimation of moso bamboo carbon storage (Zhou and Jiang, 2004; Chen *et al*., 2009; Wang *et al*., 2013). Therefore, there is a need for a method of accurately estimating the biomass and carbon content of moso bamboo. The objectives of this study are: (1) to develop a method to estimate biomass and carbon storage of moso bamboo for southern China based on a diameter and age distribution model and (2) to determine the annual yield and potential of moso bamboo in terms of carbon fixation.

Materials and methods

Study areas

The study region (108°47′–122°00′ E and 23°30′–34°38′ N) is located in southern China and covers five provinces: Fujian, Jiangxi, Hunan, Zhejiang

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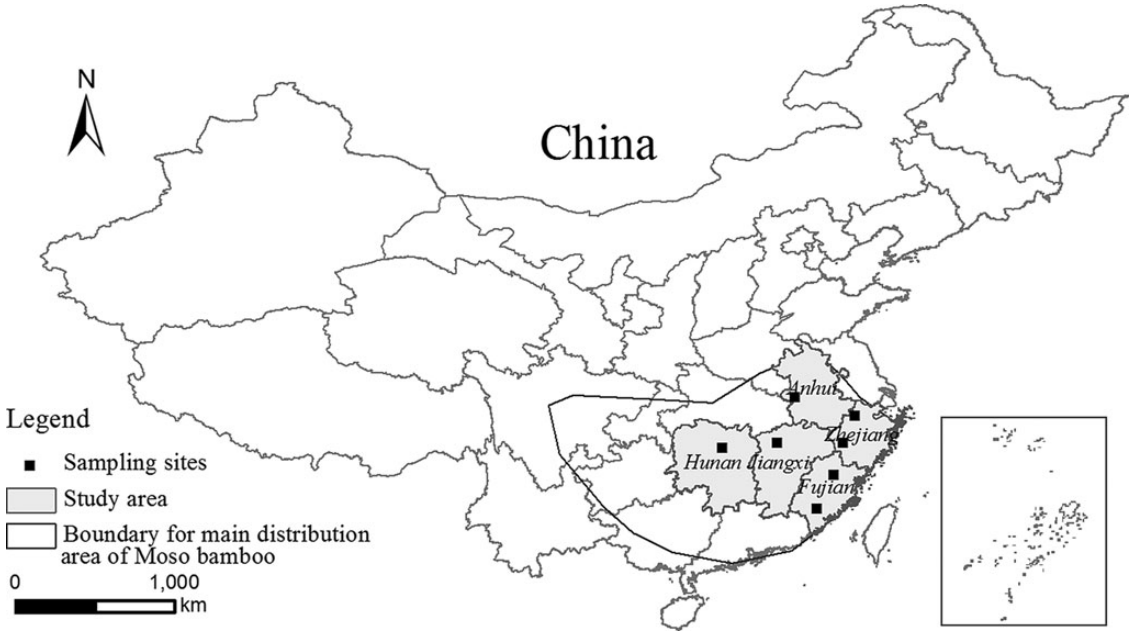

Figure 1 Study area and distribution of sampling sites.

Table 1 The climatic, edaphic and orographic descriptors of sampling counties

Sampling county	Longitude (°)	Latitude (°)	Average elevation (m)	Mean annual temperature (?)	Annual precipitation (mm)	Soil type
Huoshan, Anhui	116.27 E	31.36 N	153	15.0	1391	Mountain brown earth
Linan, Zhejiang	119.74 E	30.95 N	165	16.4	1628	Mountain yellow soil
Longyou, Zhejiang	119.19 E	28.94 N	248	17.1	1602	Mountain red earth
Jianou, Fujian	118.34 E	27.01 N	250	19.3	1670	Mountain red earth
Huaan, Fujian	117.52 E	25.02 N	204	21.0	1618	Mountain yellow earth
Fengxin, Jiangxi	115.32 E	28.76 N	109	17.3	1612	Mountain yellow earth
Taojiang, Hunan	112.21 E	28.53 N	106	16.6	1569	Mountain yellow soil

Soil type was based on genetic soil classification of China.

and Anhui (Figure 1). These provinces are rich in bamboo resources, which serve important functions in local socio-economic development. According to the seventh national forest resource inventory, the bamboo forest area in each of these provinces is $>30\times10^4$ ha, and the total area of bamboo forests in all these provinces account for 88.6 per cent of the Chinese bamboo forest area (Jia, 2009). This region belongs to a subtropical monsoon climate zone with a mean temperature of 18.7°C, and annual rainfall ranges from 1000 to 1800 mm. The climatic, edaphic and orographic descriptors of the sampling counties are summarized in Table 1.

Methods

Diameter and age distribution model and single bamboo plant biomass model

The diameter and age distribution model provided by Hyink and Moser (1983) and Zhou *et al*. (2011b) was adapted to estimate moso bamboo biomass and carbon storage based on a probability density function. The model is described as follows:

$$Y = N\int_d^{\infty}\int_t^{\infty} g(D,T)f(D,T)\,\mathrm{d}D\,\mathrm{d}T. \quad (1)$$

To determine the $f(D,T)$, a survival function was introduced based on the bivariate Weibull function with diameter and age. The formula of the survival function is as follows (Tawn, 1988; Shi *et al*., 2003; Ge *et al*., 2008):

$$F(d,t) = P(D>d, T>t) = \exp\left\{-\left[\left(\frac{d-a_1}{b_1}\right)^{c_1} + \left(\frac{t}{b_2}\right)^{c_2}\right]\right\}, \quad (2)$$

where a_1, b_1, c_1, b_2 and c_2 are parameters of the survival function.

The survival function can be expressed by $f(D,T)$ as follows:

$$F(d,t) = P(D>d, T>t) = \int_d^{\infty}\int_t^{\infty} f(D,T)\,\mathrm{d}D\,\mathrm{d}T. \quad (3)$$

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Therefore, the survival function (2) can be expressed in the following distribution function:

$$F(d,t) = P(D \le d, T \le t) = 1 - \exp\left[-\left(\frac{d-a_1}{b_1}\right)^{c_1}\right] - \exp\left[\left(-\frac{t}{b_2}\right)^{c_2}\right] + \exp\left\{-\left[\left(\frac{d-a_1}{b_1}\right)^{c_1} + \left(\frac{t}{b_2}\right)^{c_2}\right]\right\}. \quad (4)$$

$S(D > d, T > t)$ can be presumed as the surviving moso culms, the survival function of which can be expressed as follows:

$$S(D > d, T > t) = N_{\text{total}} P(D > d, T > t) = N_{\text{total}} \exp\left\{-\left\{\left[\left(\frac{d-a_1}{b_1}\right)^{c_1}\right] + \left(\frac{t}{b_2}\right)^{c_2}\right\}\right\}. \quad (5)$$

The details on the derivation of the distribution function form of the survival function can found in the study by Ge *et al*. (2008). The bivariate Weibull distribution model is a probability model of strict properties.

Equation (6) was formulated to predict biomass (aboveground + belowground) of single moso bamboo plant based on pairs of the age (class) and diameter at breast height (DBH) (class) (Zhou *et al*., 2011b):

$$G(D,T) = x_1 D^{x_2}\left[\frac{x_3 T}{(x_4 + T)}\right]^{x_5} + x_6, \quad (6)$$

where x_1, x_2, x_3, x_4, x_5 and x_6 are parameters.

Equations (2), (4) and (5) can be used for parameter estimation, but in this study, Equation (5) was selected for its simple operation and stability (Ge *et al*., 2008). The parameters of Equation (5) were estimated by using a nonlinear least square method. According to Ge *et al*. (2008), the variable N_{total} was also considered as a parameter. The initial values of N_{total}, a_1, b_1, c_1, b_2 and c_2 were set as 2381, 0.40, 8.0, 3.5, 1.4 and 1.3, respectively. The parameters of Equation (6) were estimated by using a nonlinear least square method, and the initial values of x_1, x_2, x_3, x_4, x_5 and x_6 were set as 747.79, 2.77, 0.15, 0.03, 5.56 and 3.77, respectively. Simulative effects between observed and modelled data were tested by the determination coefficients (R^2). The biomass production and carbon storage of the whole stand were then calculated by summing the values for all bamboos in different diameters and age classes.

Determination of culm DBHs and ages within stands

For the carbon estimation at regional scale, we chose the representative counties which had the large moso bamboo area ($>3.0 \times 10^4$ ha). Moreover, the latitude and longitude factors were considered in the estimation. In order to cover the whole region as much as possible, the seven representative counties were chosen as shown in Figure 1. In every representative county, we chose three towns. Then we randomly chose three plots in each town and thereby total 63 ($7 \times 3 \times 3$) plots were selected from the five provinces and set for the estimation of bamboo stand characteristics. Each plot had an area of 0.01 ha (10×10 m). The total culms (the term culm means the bamboo stem which is main part of the single bamboo plant; therefore, it is used extensively as the unit of bamboo number as well) of each plot were recorded and they were converted into density by the equation: density (culm ha^{-1}) = total culms (culms) divided by 0.01 ha. The DBH ($\geq$5 cm) was measured, and the age of each bamboo culm was recorded. Four age classes were distinguished for all culms: 1–2, 3–4, 5–6 and 7–8 years old. In China, the age of moso bamboo was recorded in "Du," which shows the growth habit in "on" and "off year" bamboo stands. One "Du" corresponds to 1–2 years, whereas 2–4 "Du" are 3–4, 5–6 and 7–8 years, respectively (Fu, 2000). Determining the age of bamboo within a stand is difficult. Experienced foresters visually examine the culm colour and count the twig scars to determine bamboo age. The age of moso bamboo upon visual examination is mainly based on the culm colour, eyelash on cycle of culm sheath, powder under cycle of culm sheath and sheath in culm base. Details of the method for determining bamboo age could be found in the article of Fu (2000). Moso bamboo samples were selected according to their specific age, which was determined based on their characteristics.

Selection of sample bamboos

Sixty-three bamboo samples were obtained from the stand based on DBH and age, and the analysis was based on DBH class and age class. For the aboveground sections, these bamboo samples were divided into 1 m intervals for biomass measurement. The fresh weight of culms, branches and foliage were determined separately. The three sections of bamboo were sampled at the upper, middle and lower portion of the culm and then weighed for analysis. In order to make it practical to collect the belowground sections of the bamboo, we made an assumption that the belowground sections (roots, bamboo rhizomes and bamboo stump) were evenly distributed under the ground. The quadrat area of single bamboo plant under ground was the plot area (0.01 ha) divided by the total number of bamboo in the plot (culms). Determining the single bamboo quadrat area, a circle was made around the sampling bamboo plant. Then the quadrat was excavated deep to the depth of ~60 cm, where the roots and bamboo rhizomes can reach. In each quadrat, the fresh weight of the roots, bamboo rhizomes and bamboo stump were recorded separately in the field. Two separate sub-samples were taken from each section of the moso bamboo: one for dry matter determination and the other for elementary analyses. The samples were oven-dried at 105 °C until they reached a stable weight. Biomass estimation was based on the ratio of absolute dry weight to fresh weight. Furthermore, samples of each section, including culms, branches and foliage, roots, bamboo stump, bamboo rhizomes were ground into a powder for the determination of carbon content through elemental analysis (ELEMENTAR, Vario-MAX-CN, Germany).

Variables, including DBH class, age class and total biomass, were obtained from bamboo samples to estimate the parameters in Equation (6) and the relationships among the variables (including DBH class, age class and biomass of sections of bamboo) were tested by correlation analysis.

Analysis of percent carbon content from bamboo samples

Analysis of variance by a general linear model (fixed model) was used to compare the percent carbon content (PCC) among bamboo of different ages and from different sections. The PCC of each sample was determined by elemental analysis. If the PCC was significantly different at $P = 0.05$ based on bamboo age and section, the least significant difference (LSD) method was used to compare the differences.

Calculation of bamboo biomass density and carbon storage density

Single bamboo biomass (kg) was determined using Equation (6) based on the diameter and age class, whereas biomass density (kg ha^{-1}) was calculated by summing up all bamboo biomass values in different diameters and age classes within the unit area (ha). The carbon storage density (kg C ha^{-1}) of moso bamboo was calculated based on the biomass, i.e. the carbon storage of all bamboos at different age classes (Σ biomass at certain age class $\times$ carbon content by its age class) within the unit area (ha) was summed to determine biomass carbon storage density. Parameter estimations were performed in Matlab 7.0 (MathWorks Inc., Natick, MA, USA) and statistical analyses were completed in SPSS 17.0 (SPSS Inc., Chicago, IL,

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USA). Figures were plotted in Sigma plot 10.0 (Systat Software Inc., Chicago, IL, USA) and Matlab.

Results

Diameter and age distribution

The mean moso bamboo density (culm per unit area) and the total culm number of the 63 investigated moso bamboo plots were 3968 ± 793 (mean $\pm$ SD) culm ha^{-1} and 2831 culms, respectively. The observed culm numbers of 63 plots at each diameter and age class, as well as the cumulated values, are summarized in Table 2. The density of different diameters and age classes exhibited large variability, ranging from 2 to 142 culms ha^{-1}. The distribution of density values for different diameter classes showed a similar pattern in different age classes, in which the shape of the diameter distribution approached a normal distribution. Most culms were cantered at diameters 8 and 12 cm and the corresponding percentages of culms are 77.8, 75.1, 70.4 and 84.3 per cent in age classes 1, 2, 3 and 4, respectively. Based on the data in Table 2 and Equation (5), parameter estimation was based on the diameter and age distribution of the 63 plots, yielding values of $N_{total} = 2384.30$, $a_1 = 3.10$, $b_1 = 7.10$, $c_1 = 3.40$, $b_2 = 1.90$ and $c_2 = 1.50$. The real and model values of survival individuals are summarized in Table 3. The determination coefficient (R^2) is 0.999, which indicates that Equation (5) is a good fit for the diameter and age distribution of moso bamboo. Therefore, the diameter and age distribution of moso bamboo in the study area is suggested to follow bivariate Weibull distribution. Figure 2 shows the bivariate Weibull probability distribution for the diameter and age of moso bamboo.

The estimated number of moso bamboo in 63 plots for different diameters and age classes is summarized in Table 2. The distribution of the estimated number of moso bamboo for different diameters and age classes showed a similar pattern as that observed. Moso bamboo was mainly distributed in age classes 1 and 2, accounting for 31.70 and 34.7 per cent, respectively. The number of moso bamboo in diameter classes 8 and 12 in age classes 1, 2, 3 and 4 accounted for 85.01, 85.01, 85.45 and 84.86 per cent, respectively.

Biomass of single moso bamboo plant

Table 4 shows the characteristics and biomass of moso bamboo samples, whereas Figure 3 shows the proportions of foliage, branches, culms, roots, bamboo rhizomes and bamboo stump to total biomass. We found that DBH and total biomass varied with age, but there was no significant trend observed (Table 4). The proportions of foliage, branches, culms, roots, bamboo rhizomes and bamboo stump to total biomass were 3.55–4.90, 7.90–9.71, 53.51–60.75, 5.68–12.96, 6.09–8.61 and 12.19–13.65 per cent, respectively (Figure 3). The relationships among these variables were tested by correlation analysis. The results showed that total biomass and DBH had a significantly positive correlation ($R = 0.87^{**}$), whereas no significant correlation ($R = 0.24$) was found between total biomass and age. However, a significantly positive correlation ($R = 0.26^{*}$) was observed between culms and age, whereas no significant correlation was observed among other sections and ages.

By using the observed data on DBH and age class from the sampled bamboo in the 63 plots, the parameter estimation in

Table 2 Observed number and estimated number of moso bamboo in 63 plots for different diameters and age classes

Diameter class (cm)	Age class (du)											
	1			2			3			4		
	Observed number	Cumulated value	Estimated number	Observed number	Cumulated value	Estimated number	Observed number	Cumulated value	Estimated number	Observed number	Cumulated value	Estimated number
5	19	2381	15	30	1632	16	20	817	8	2	300	7
6	31	2310	39	43	1580	43	31	795	25	5	298	16
7	54	2200	74	71	1501	80	56	759	47	24	293	31
8	106	1995	109	124	1350	121	81	679	70	52	269	46
9	142	1632	135	125	1093	147	85	546	86	68	217	57
10	133	1212	137	147	815	148	79	393	88	68	149	57
11	123	785	112	127	521	124	69	246	72	39	81	47
12	79	427	74	89	286	81	50	138	48	26	42	31
13	38	183	39	41	121	42	26	62	24	8	16	16
14	17	70	14	15	46	17	14	28	9	5	8	7
15	7	19	6	3	12	5	6	9	4	3	3	2

The unit for the observed number, cumulated value and estimated number is culms.

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Table 3 Real and model values of culm survival

Item	Start age (du)	Start diameter (cm)										
		4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5
Real value	0	2381	2310	2200	1995	1632	1212	785	427	183	70	19
	1	1632	1580	1501	1350	1093	815	521	286	121	46	12
	2	817	795	759	679	546	393	246	138	62	28	9
	≥3	300	298	293	269	217	149	81	42	16	8	3
Model value	0	2376	2330	2207	1975	1629	1204	774	419	185	64	17
	1	1622	1591	1507	1349	1112	822	529	286	126	44	11
	2	798	783	742	664	548	405	260	141	62	22	6
	≥3	317	310	294	263	217	160	103	56	25	9	2

"0" represents the start of integral calculation for bamboo in age class 1 and "1" for bamboo in age class 2, and so on. The 4.5 in diameter represents the start of integral calculation for bamboo in diameter class 5 cm and 5.5 for bamboo in diameter class 6 cm, and so on. To do this is to treat the discrete variables (both diameter class and age class are discrete variable) as continuous variables. The unit for real and model values is culms.

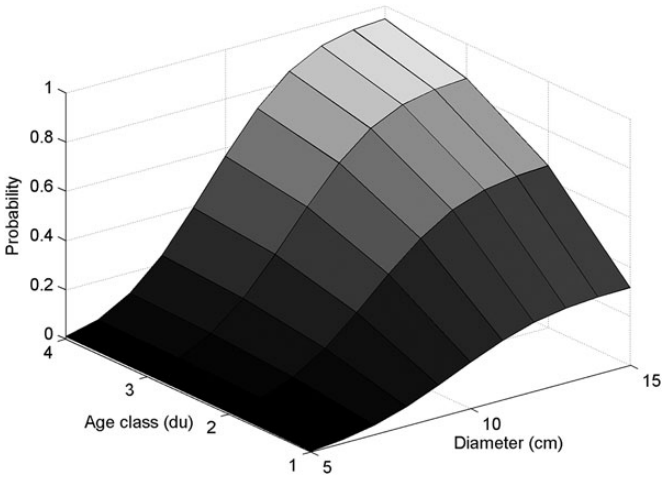

Figure 2 Bivariate Weibull probability distributions for diameter–age of moso bamboo.

Equation (6) was performed, yielding values of $x_1 = 105.20$, $x_2 = 3.31$, $x_3 = 0.11$, $x_4 = 0.02$, $x_5 = 4.53$ and $x_6 = 11.75$. Comparing the real and model values of the total biomass, the mean relative error was calculated as 0.128, and R^2 was 0.796, which suggests that Equation (6) was a good fit for calculating the biomass of a single moso bamboo plant based on diameter and age. The estimated biomass of a single moso bamboo for different diameters and age classes is shown in Figure 4.

PCC within sampled bamboos

The LSD method was used to compare the PCC values among ages and sections (Tables 5 and 6). The results showed that the PCC ranged from 41.67 to 51.58 for bamboo of various ages and sections. We found that the PCC was higher in culms than in other sections of the moso bamboo for all ages. Although PCC in different sections of bamboos for all ages showed different trends, the value remained higher in culms, bamboo rhizomes and branches than in bamboo stump, foliage and roots. Meanwhile, PCC insignificantly differed when age was varied in all sections of moso bamboo (Table 6). After the PCC of each section of bamboo was determined, carbon storage was calculated based on the mean PCC of a certain age and the biomass (aboveground + belowground) of a certain age.

Estimation and harvesting of biomass and carbon storage

Bamboo biomass density estimation was based on the observed bamboo density (3968 culm ha^{-1}) in the 63 investigated plots. The model of the bivariate Weibull distribution was combined with the result of Equation (6) (Figure 4) to predict the biomass and carbon storage. The distribution of biomass and carbon storage of moso bamboo within each diameter and age class is shown in Table 7. The patterns of biomass and carbon storage were very similar, and carbon storage in bamboo was nearly half of that for biomass. A moso bamboo forest has an uneven-aged stand, and selective cutting generally occurs every 2 years when most of the age classes of harvested moso bamboo were >3 du (Zhou and Jiang, 2004). The harvested biomass is subsequently replaced by new culms that fill the voids left by the harvested culms within a year. Therefore, from the time perspective, the moso bamboo forest was in dynamic equilibrium, and the harvested biomass of moso bamboo was appropriately one-third of the current amount at the time of cutting (one-sixth annually) (Zhou and Jiang, 2004). Therefore, the annual carbon fixation was one-sixth of the carbon storage of the current moso bamboo forest on average. As the distribution of yield of older culms was similar to that of current stand structures, the yield model can be expressed as

$$\frac{1}{6} \times N \int_{\mathrm{dLow}}^{\mathrm{dUp}} \int_{\mathrm{tLow}}^{\mathrm{tUp}} g(D, T) f(D, T) \mathrm{d}D\mathrm{d}T.$$

According to estimates, 88.23 Mg ha^{-1} of biomass and 40.45 Mg ha^{-1} of carbon storage were observed from moso bamboo stands. Meanwhile, the annual yields of biomass and carbon were 14.70 and 6.74 Mg ha^{-1}, respectively. Every 6 years,

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Table 4 Biomass distribution between different culm components of moso bamboo samples

Age class	*N*	DBH (cm)	Biomass (kg)						
			Foliage	Branches	Culms	Roots	Bamboo rhizomes	Bamboo stump	Total
1	19	8.87 ± 1.87	0.99 ± 0.53	1.93 ± 1.08	10.82 ± 4.41	1.98 ± 1.02	1.74 ± 0.70	2.76 ± 1.26	20.22 ± 6.61
2	28	9.66 ± 1.64	1.00 ± 0.51	2.12 ± 0.99	11.88 ± 4.93	2.83 ± 1.18	1.33 ± 0.77	2.66 ± 1.51	21.83 ± 6.72
3	11	10.33 ± 1.76	0.94 ± 0.58	1.99 ± 1.36	14.21 ± 6.73	2.82 ± 0.85	1.82 ± 1.06	3.40 ± 1.76	25.18 ± 9.38
4	5	9.95 ± 1.94	0.88 ± 0.82	2.23 ± 1.64	15.06 ± 6.58	1.41 ± 0.34	1.90 ± 0.53	3.29 ± 1.28	24.79 ± 8.37

Data are represented as mean ± SD.

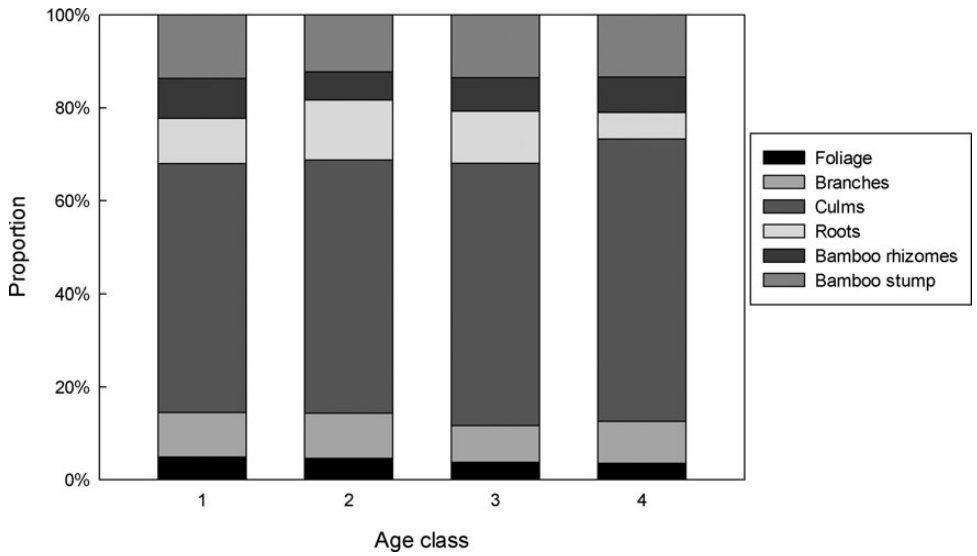

Figure 3 Proportion of foliage, branches, culms, roots, bamboo rhizomes and bamboo stump to total biomass for each age class.

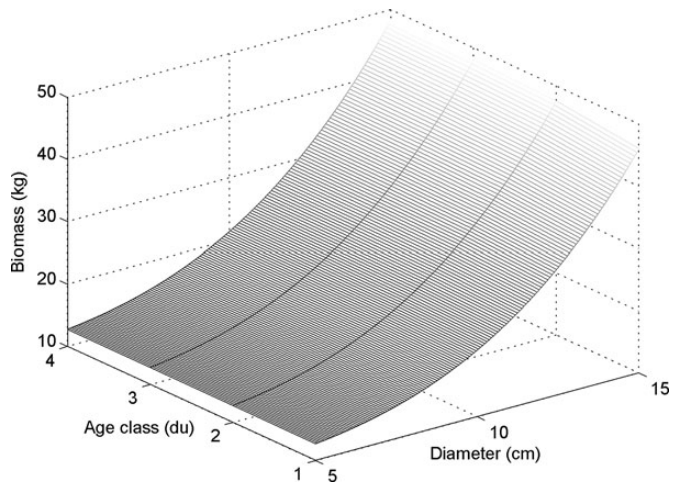

Figure 4 Biomass of a single moso bamboo for different diameters and age classes.

the yields of biomass and carbon were equal to the current status of stockings. Thus, the biomass or carbon storage of moso bamboo doubles the current status every 12 years.

Discussion

Increasing attention has recently been directed toward bamboo for its numerous advantages over other woody plants; these advantages include rapid growth, high production and versatility (Fu, 2001; Embaye *et al*., 2005; Chen *et al*., 2009). Most studies have emphasized the economic values of bamboo in providing wood and food for human life, whereas few have focused on its function in the global carbon cycle, including accumulation and storage of carbon, that combats the rising atmospheric CO_2 concentrations and future global warming (Yen and Lee, 2011; Song *et al*., 2013).

Compared with other trees, bamboo, as a woody grass, has unique characteristics. In plantation bamboo, the culms sprout in horizontal rhizome systems with excellent productivity (Christanty *et al*., 1996; Fu, 2000; Yen *et al*., 2010). At the shoot stage, some plants yield sufficient food, whereas others are allowed to grow and become mature culms. After bamboo shoots emerge in early April, they typically reach a mature state with an average height of 15 m in <2 months (Song *et al*., 2013). Selective harvesting would be conducted every 2 years, and one-sixth of the bamboo would be cut per year on average. The rhizome systems would not die even after the aboveground biomass is removed, as the harvested biomass is subsequently replaced by new culms

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Table 5 Carbon content within various sections of moso bamboo in different age classes (%)

Age class	Foliage	Branches	Culms	Roots	Bamboo rhizomes	Bamboo stump
1	43.54 ± 1.34a	45.04 ± 0.75b	48.05 ± 1.00bc	44.45 ± 1.13bc	45.89 ± 1.15bc	44.76 ± 0.58c
2	44.65 ± 1.36a	46.56 ± 1.49ab	49.01 ± 0.73b	42.78 ± 1.16bc	46.78 ± 0.79bc	44.76 ± 1.96c
3	45.89 ± 1.40a	46.67 ± 0.51b	50.24 ± 0.87bc	44.56 ± 1.01bc	46.07 ± 0.69bc	45.45 ± 1.20c
4	45.01 ± 0.41a	46.43 ± 0.40b	50.30 ± 1.11bc	45.23 ± 0.73bc	46.25 ± 0.85bc	45.23 ± 0.69c

Mean ± SD and means marked with the same letter are not significantly different at $P = 0.05$ by the LSD method.

Table 6 Carbon content within various age classes of moso bamboo in different sections (%)

Sections	Age class 1	Age class 2	Age class 3	Age class 4
Foliage	43.54 ± 1.34a	44.65 ± 1.36a	45.89 ± 1.40a	45.01 ± 0.41a
Branches	45.04 ± 0.75a	46.56 ± 1.49a	46.67 ± 0.51a	46.43 ± 0.40a
Culms	48.05 ± 1.00a	49.01 ± 0.73a	50.24 ± 0.87a	50.30 ± 1.11a
Roots	44.45 ± 1.13a	42.78 ± 1.16a	44.56 ± 1.01a	45.23 ± 0.73a
Bamboo rhizomes	45.89 ± 1.15a	46.78 ± 0.79a	46.07 ± 0.69a	46.25 ± 0.85a
Bamboo stump	44.76 ± 0.58a	44.76 ± 1.96a	45.45 ± 1.20a	45.23 ± 0.69a

Mean ± SD and means marked with the same letter are not significantly different at $P = 0.05$ by the LSD method.

Table 7 Distribution of biomass and carbon storage of moso bamboo within each diameter and age class

Diameter class (cm)	Age class (du)							
	1		2		3		4	
	Biomass (kg)	Carbon storage (kg)	Biomass (kg)	Carbon storage (kg)	Biomass (kg)	Carbon storage (kg)	Biomass (kg)	Carbon storage (kg)
5	332.54	150.60	359.24	164.38	205.44	95.49	154.20	71.56
6	928.20	420.37	1015.28	464.56	590.82	274.61	398.75	185.05
7	1863.75	844.06	2042.72	934.68	1205.60	560.36	829.95	385.17
8	3098.76	1403.38	3370.00	1542.00	2012.29	935.31	1355.20	628.93
9	4294.00	1944.68	4685.04	2143.72	2769.91	1287.45	1903.16	883.22
10	4956.75	2244.83	5470.48	2503.11	3247.20	1509.30	2194.14	1018.26
11	4756.40	2154.09	5249.62	2402.05	3107.52	1444.38	2132.00	989.43
12	3667.20	1660.81	4095.06	1873.76	2394.00	1112.73	1644.76	763.31
13	2248.74	1018.42	2453.88	1122.81	1462.50	679.77	1016.82	471.89
14	991.07	448.84	1150.76	526.55	714.56	332.13	448.70	208.23
15	460.17	208.40	473.49	216.65	265.55	123.43	213.48	99.07

that fill the voids left by the harvested culms within a year. Therefore, for a mature bamboo plant, a similar age and diameter structure can be retained.

As shown in this study, the R^2 for the estimated and observed culm numbers for different ages and diameter classes was 0.999, which indicates that the diameter–age bivariate distribution model can accurately predict the culm number of moso bamboo in different diameters and age classes in the study region.

The allometric model based on DBH and height is generally used to predict tree biomass. However, the difficulty in measuring the height of moso bamboo in the field survey caused us to use the age variable as a substitute for the height variable for ease of measurement (Zhou and Jiang, 2004). The analysis of biomass revealed that dry matter production was highly correlated to DBH but did not correlate with age. However, many studies have emphasized that the biomass accumulation of bamboo increases with age (e.g. Shanmughavel and Francis, 1996; Scurlock *et al.*, 2000). In our study, a relationship between aboveground biomass and age was not prevalent, which was consistent with the study by Yen *et al.* (2010) who reported that the lack of a relationship between age and biomass accumulation was not attributed to the same sample being measured at different times, but was rather attributed

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to the sampling of the same bamboo forest with different plants of different ages. With respect to one culm, the height and biomass increase with age, particularly in the early stage of bamboo growth (Zhou *et al*., 2006). The relation analysis revealed that the culms, which account for the major part of bamboo biomass, had a high correlation with age. Therefore, age should be considered as a dependent variable for the prediction of biomass from the model.

Generally, one approach to estimate carbon storage in trees is to calculate biomass based on timber volume equation and then select the appropriate carbon transfer coefficient (PCC) (Zhou *et al*., 2011a; Alvarez *et al*., 2012; Fayolle *et al*., 2013). In most studies, the carbon transfer coefficient was set as 0.5 when the PCC was not actually determined for certain species (Yen *et al*., 2010). However, the PCC varies with tree species and sections (foliage, branches and stems), and even the same tree type has different PCC values in different climate zones (Zhou and Jiang, 2004; Xiao *et al*., 2007; Yen and Lee, 2011). Therefore, an accurate estimation for carbon storage of trees or forests requires detailed PCC measurements. We found that the PCC of moso bamboo was lower in the bamboo stump, foliage and roots, but higher in the culms, bamboo rhizomes and branches. This phenomenon is contrary to results from such trees as the Taiwan red cypress (*Chamaecyparis formosensis* Matsum.), Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook.) and Japanese cedar (*Cryptomeria japonica* (L. f.) D. Don). However, the foliage of these species had higher PCC values than the other sections (Yen and Huang, 2006). The results of in this study show no obvious changing trend between age and the carbon content in different sections of moso bamboo, which differs from the findings of other forest studies. Fang *et al*. (2002) showed that the PCC in the perennial branch and leaf was higher than that in younger trees. Ruan *et al*. (1997) demonstrated that the PCC in the branches and leaves of Oriental oak increased with age. The difference in the change rule of PCC between moso bamboo and other trees may be attributed to the biological characteristics, growth rhythm and rotation cycle of bamboo. According to estimates, the carbon storage from moso bamboo stands (aboveground + belowground) was 40.45 Mg ha^{-1}, which is less than that of numerous trees, such as Chinese fir (65.33 Mg ha^{-1}), oriental oak (*Quercus variabilis* Bl.) (100.03 Mg ha^{-1}) and loblolly pine (*Pinus taeda* L.) (105.36) (Ruan *et al*., 1997). However, according to the growth characteristic of bamboo and the management habit of bamboo farmers, selective harvesting would be conducted every 2 years, and one-sixth of the older culms of the entire stand was cut yearly on average (Zhou and Jiang, 2004). This practice yields 14.70 Mg ha^{-1} of biomass and 6.74 Mg ha^{-1} of carbon. These findings are astonishing and indicate that the total amount of bamboo removed every 6 years was equal to the current standing of bamboo (88.23 and 40.45 Mg ha for biomass and carbon storage, respectively). This result also revealed that moso bamboo had higher carbon sequestration capacity than other trees, including Chinese fir (3.49 Mg ha^{-1} yr^{-1}) (Fang *et al*., 2002), tropical mountain rain forest (3.83 Mg ha^{-1} yr^{-1}), loblolly pine (5.79 Mg ha^{-1} yr^{-1}) (Ruan *et al*., 1997) and oriental oak (2.46 Mg ha^{-1} yr^{-1}) (Ruan *et al*., 1997). According to the total culms of moso bamboo in China (9.157 billion culm) (Jia, 2009), carbon storage of this species in China was estimated to be 203.61 Tg, and every 6 years, the yield of carbon was equal to the current status of stockings.

The biomass of moso bamboo in other studies ranged from 23.7 to 572.3 Mg ha^{-1}, equal to carbon storage with 11.8–286.2 Mg ha^{-1} as summarized (Chen *et al*., 2009). The carbon storage of moso bamboo in our study was relatively close to that of the recent studies which showed 34.3 (Zhou and Jiang, 2004), 55.9 (Qi *et al*., 2009) and 40.6 Mg ha^{-1} (Yen and Lee, 2011), respectively. However, there was no correlationship between the site position and biomass carbon.

Overall, the advantage of the method used in this study lies in the convenience of estimating the bamboo biomass and carbon storage when the total culm number of the bamboo is known. Based on the total culm, the number of moso bamboos for different diameters and age classes can be estimated through the Weibull distribution. With the biomass equation, the biomass of one culm of bamboo can be calculated based on its diameter and age class. Accordingly, the total bamboo biomass can be determined by summing all the biomass values of bamboo in different diameters and age classes. Therefore, the proposed method is suitable for biomass or carbon storage estimation at the regional scale because the scale transformation factor, which is required for other methods, need not be considered in the proposed approach.

Conflict of interest statement

None declared.

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