BIOMASS AND CARBON STOCK IN MOSO BAMBOO FORESTS IN SUBTROPICAL CHINA: CHARACTERISTICS AND IMPLICATIONS

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WANG B, WEI WJ, LIU CJ, YOU WZ, NIU X & MAN RZ. 2013. Biomass and carbon stock in moso bamboo forests in subtropical China: characteristics and implications. Bamboo forests are special forest resources in China with wide distribution, and important economic and ecological values. Of 500 bamboo species native to China, moso bamboo (*Phyllostachys pubescens*) is the most important in the terms of distribution, timber and other economic values. In this study, we examined the variations in biomass carbon stock of moso bamboo forests across subtropical China using national forest resources inventory data (1977–2008), along with stand biomass data compiled from literature. Our results showed that the biomass carbon of moso bamboo forests ranged from 219.56 to 299.31 Tg ha^{-1}, accounting for 4.7–5.9% of the total forest biomass carbon in China from 1977 till 2008. At stand level, mean biomass carbon was 70–85 Mg ha^{-1} in the northern and middle subtropical subregions, and 35–45 Mg ha^{-1} in the sout-west mountain and southern subtropical subregions. With high biomass carbon sequestration, along with the quick and low-cost regeneration, high growth rate, short rotation, high phytolith-occluded carbon content and high economic and ecological values, moso bamboo forest can play an important role in carbon sink forestry in subtropical regions of China.

Keywords: National forest resources inventory, carbon sink, forestry, carbon sequestration

WANG B, WEI WJ, LIU CJ, YOU WZ, NIU X & MAN RZ. 2013. Biojisim dan stok karbon hutan buluh moso di kawasan subtropika China: ciri-ciri dan implikasi. Hutan buluh merupakan sumber hutan yang istimewa di China dan mempunyai taburan yang luas serta nilai ekonomi dan ekologi yang penting. Daripada 500 spesies buluh asli di China, buluh moso (*Phyllostachys pubescens*) adalah yang terpenting dari segi taburan, hasil dan nilai ekonominya. Dalam kajian ini, kami menyelidik variasi stok karbon biojisim hutan buluh moso merentasi kawasan subtropika China dengan menggunakan data inventori sumber hutan negara (1977–2008) di samping data biojisim dirian yang dikumpul daripada kepustakaan. Keputusan kajian menunjukkan bahawa karbon biojisim hutan buluh moso berjulat antara 219.56 Tg ha^{-1} hingga 299.31 Tg ha^{-1}, iaitu 4.7%–5.9% daripada jumlah karbon biojisim hutan di China pada tahun 1977 hingga tahun 2008. Dari segi dirian, min karbon biojisim ialah 70–85 Mg ha^{-1} di subwilayah subtropika utara dan subwilayah subtropika tengah serta 35–45 Mg ha^{-1} di subwilayah subtropika gunung barat daya dan subwilayah subtropika selatan. Dengan pensekuesteran karbon biojisim yang tinggi, pertumbuhan semula yang pantas dan murah, kadar pertumbuhan yang tinggi, tempoh pusingan yang pendek, kandungan karbon fitolit terperangkap yang tinggi dan nilai ekonomi serta ekologi yang tinggi, hutan buluh moso dapat memainkan peranan penting dalam perhutanan takungan karbon di wilayah subtropika China.

INTRODUCTION

Carbon sequestration by growing forests is a cost-effective option for mitigation of CO_2 emissions caused by human activities (Pan et al. 2011). There is currently about 53 Mha of forest plantation in China with a volume stock of 1.5 billion m^3. Between 2005 and 2020, China has pledged to establish more than 40 million ha of plantations, referred to as carbon sink forest. As plantations have been recognised as the national strategy for

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mitigating atmospheric CO_2, it is essential to assess the potential of fast-growing and high yield plantations in carbon storage and sequestration at stand, regional and national scales.

China has 500 bamboo species belonging to 48 genera, compared with 1500 species and 87 genera of the world's total (Chen et al. 2009). The total area of bamboo forests in China is around 4.2 Mha, representing one fifth the world's total (22 Mha) and 3% of China's total forests (129.2 Mha). Currently, the total area of bamboo plantations in China increases by 3% a year and bamboo carbon stocks are projected to increase from 727.08 Tg C (1 teragram = 10^{12} gram) in 2010 to 1017.64 Tg C in 2050 (Chen et al. 2009).

Moso bamboo (*Phyllostachys pubescens*) is an indigenous bamboo species with distribution across the subtropical China. It covers about 70–80% of the total area of bamboo forests over the past three decades based on the national forest resources statistics in China (FRSC 1982–2009) (Figure 1). Compared with other bamboo species, moso bamboo has some superior attributes in terms of adaptation to environmental conditions, fast growth rate, multipurpose applications, and high ecological and economic values. Thus, it could play an important role in future carbon sink forestry in China. Some work has been done to estimate biomass carbon storage of moso bamboo forests at the regional level (Pan et al. 2004, Chen et al. 2009). However, the estimates may be too rough due to the use of relatively old inventory data, especially the use of single stand biomass across the entire subtropical region and parts of northern tropical region where climate and topography vary substantially (Figure 2).

In particular, bamboo species are well-known as proficient silica accumulators, producing phytolith-occluded carbon which is considered to be an important long-term (up to several thousands of years) terrestrial carbon fraction (Parr et al. 2010). Chemically, such a form of carbon is significantly important in storage and sequestration of carbon (Parr et al. 2010). In this study, we tried to assess the potential role of moso bamboo plantations in the strategy of developing China's carbon sink forestry by: (1) examining the spatial distribution of carbon storage and differentiation in carbon sequestration of moso bamboo plantations in different geographical subregions of subtropical China, (2) comparing moso bamboo carbon storage with major fast-growing tree species at stand and regional levels and (3) estimating the contribution of carbon storage by moso bamboo forests over the past 30 years to the national level using forest resource inventory data (till 2008) and stratified stand biomass data by different geographical subregions.

MATERIALS AND METHODS

Stand-level data compilation

In order to compare carbon storage in different areas, a data set was compiled by literature

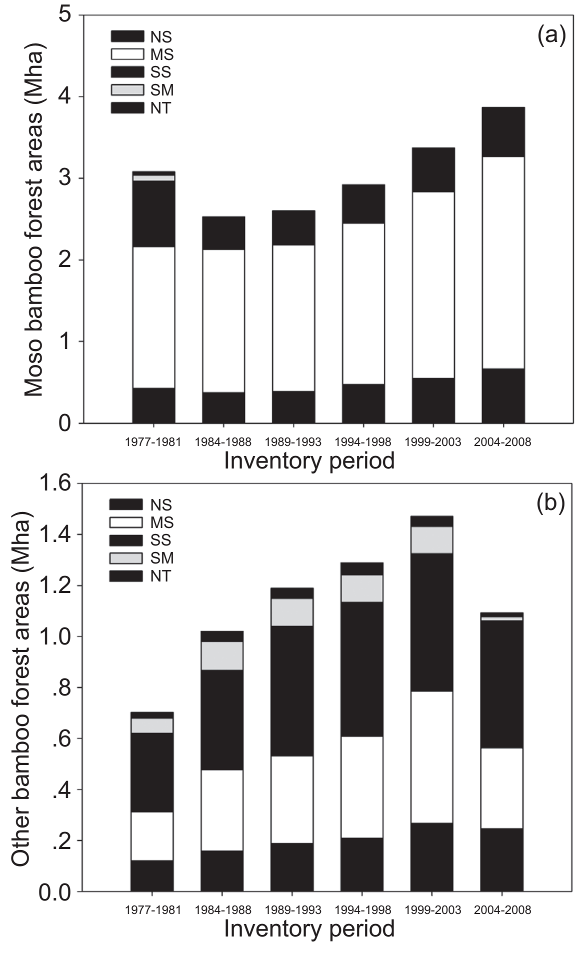

Figure 1 Changes of (a) moso bamboo and (b) other bamboo forest areas by subregions in China; NS = north subtropical, MS = middle subtropical, SS = south subtropical, SM = south-west mountain subtropical and NT = north tropical

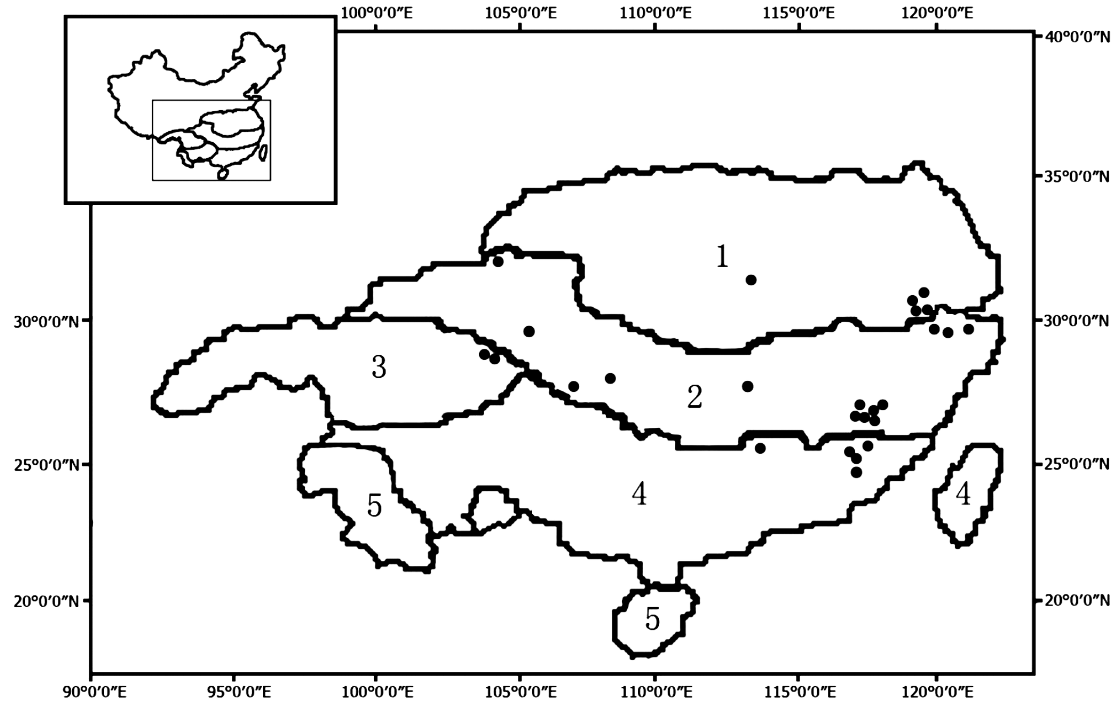

Figure 2 The distribution of moso bamboo forests in subtropical China and the locations of selected stands (black dots) in this study; the numbers stand for the subregions within distribution: 1 = north subtropical subregion (NS), 2 = middle subtropical subregion (MS), 3 = south-west mountain subtropical subregion (SM), 4 = south subtropical subregion (SS), and 5 = north tropical subregion (NT)

research from published and unpublished data sources. A total of 44 moso bamboo stands were identified together with information on geographical locations, biomass density and net primary productivity.

The distribution of moso bamboo forests in China could be divided into five subregions, namely, north subtropical (NS), middle subtropical (MS), south-west mountain subtropical (SM), south subtropical (SS) and north tropical (NT) subregions (Figure 2). However, the NT subregion only covered less than 1% of the total area of moso bamboo forests in China and was thus not included in this study. The selected stands included in this study were therefore divided into four subregion groups, NS, MS, SS and SM. Mean biomass density was calculated for each group (Table 1).

Regional-level biomass carbon

The areas of moso bamboo forest in the subregions in six inventory periods (1977–1981, 1984–1988, 1989–1993, 1994–1998, 1999–2003 and 2004–2008, Figure 1) and their mean biomass densities (Table 1) were used to estimate the total biomass and carbon stock of moso bamboo forests as illustrated by equation 1.

$$S = \sum_{i=1}^{4} \overline{B}_i \times A_i \times BF/10^6 \qquad (1)$$

where S is the total biomass carbon stock of moso bamboo forests in each period in China (Tg), i is the number of subregions (from 1 to 4 for NS, MS, SS and SM respectively), $\underline{B}_i$ is the biomass density of moso bamboo forests in each subregion (Mg ha^{-1}), A_i is the total area of moso bamboo forest in each subregion in each period (ha), and BF is conversion factor for biomass to carbon stock (BF = 0.5 in this study based on Zhou and Jiang (2004), Chen et al. (2009) and Yen and Lee (2011)).

Biomass carbon density (D, Mg C ha^{-1}) of moso bamboo forests in each inventory period was calculated using biomass carbon stock (S, Mg C) and total area (A, ha^{-1}):

$$D = S / A \qquad (2)$$

RESULTS

Stand biomass in different subregions

Total stand biomass, aboveground biomass and belowground biomass were substantially higher in the NS and MS subregions than those in the SS and SM subregions (Table 1). The aboveground and belowground biomass ratio ranged from 2.06 in MS to 2.45 in NS, indicating that aboveground biomass was double that of the belowground. Within a subregion, there were large variations in total biomass stock. For instance, total stand biomass for selected stands in the MS ranged from 54.67 Mg ha^{-1} in Huitong, Hunan (Liu et al. 2010) to 572.29 Mg ha^{-1} in Fenghua, Zhejiang (Wen 1990).

Variations in biomass carbon stock in 30 years

From the 1970s till 1980s, there was a decline in moso bamboo forest area followed by a continuous increase till 2010s (Figure 1). The total biomass carbon stock of moso bamboo forests in China generally increased in the last 30 years from 219.56 Tg in 1977–1981 to 299.31 Tg in 2004–2008 (Figure 3). There was an exception, however, in 1984–1988 (195.93 Tg) where the total biomass carbon stock was substantially lower than the previous period (1977–1981, 219.56 Tg) due to a sharp decline in moso bamboo forests in the SS subregion including Guangdong, Guangxi and Yunnan provinces. Biomass carbon density of moso bamboo forests was also higher than other forest types in China, with an average value generally above 77 Mg ha^{-1} (Table 2).

Spatial variations of biomass carbon stock at the regional scale

The biomass carbon stock of moso bamboo forests in the NS and MS subregions increased in the last three decades (Figure 4). The increase in MS was 49.92%, i.e. from 149.97 Tg C in 1977–1981 to 224.82 Tg C in 2004–2008 whereas the change in NS was 76.67% (26.59 Tg C in 1984–1988 to 46.98 Tg C in 2004–2008). In the SS subregion, biomass carbon stock first decreased from 36.95 Tg C in 1977–1981 to 17.91 Tg C in 1984–1988 and then recovered to 26.99 Tg C in 2004–2008. In the SM subregion, biomass carbon stock appeared to decrease over time; it decreased as much as 90% from 1977–1981 till 1984–1988 (Figure 4).

Between the four subregions, MS had the highest biomass carbon stock, accounting for 75% of the total biomass carbon of moso bamboo forests in China in 2004–2008 followed by NS and SS with 16 and 9% respectively (Figure 4). The importance of biomass carbon stock in the MS subregion was negligible (Figure 4).

DISCUSSION

Contribution of moso bamboo forests to forest biomass carbon in China

Although the total biomass carbon of moso bamboo forests continuously increased in the

Table 1 Mean stand total biomass (TB), aboveground biomass (AB), belowground biomass (BB), aboveground/belowground ratio (AB:BB) and number of plots (n) in selected moso bamboo stands by subregions

Subregion	TB (Mg ha^{-1})		AB (Mg ha^{-1})		BB (Mg ha^{-1})		AB:BB		n
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	
NS	141.72	48.59	96.54	40.34	47.15	17.66	2.45	0.93	4
MS	172.76	32.86	105.76	21.58	67.00	15.16	2.06	0.32	18
SS	91.99	14.75	64.72	10.27	37.27	4.61	2.38	0.13	6
SM	66.07	14.56	44.78	9.68	21.29	4.88	2.11	0.03	2

NS = north subtropical, MS = middle subtropical, SS = south subtropical and SM = south-west mountain subtropical subregions

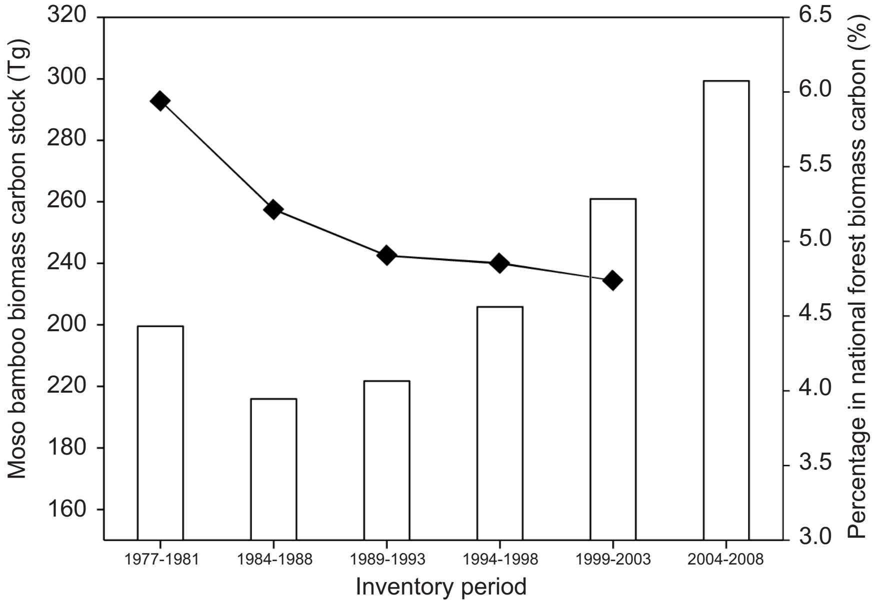

Figure 3 Changes in total biomass carbon stock (Tg) (open columns) of moso bamboo forests and the percentage (diamonds) of contribution to the total national forest biomass carbon stock in China over the last 30 years; the national forest biomass carbon data were adopted from Xu et al. (2007)

Table 2 Comparison of moso bamboo forests with other forest types in biomass carbon density in China at different inventory periods

Forest	Biomass carbon density (Mg C ha^{-1})						Reference
	1977–1981	1984–1988	1989–1993	1994–1998	1999–2003	2004–2008	
Moso bamboo	71.29	77.55	77.51	77.31	77.39	77.38	This study
Other forests*	38.65	36.78	37.87	36.04	38.56		Xu et al. (2007)
Other forests*	45.75	43.53	42.58	44.91			Fang and Chen (2001)
Other forests*	43.10	39.70	38.70				Liu et al. (2000)
Other forests*		41.32					Zhao and Zhou (2004)
Other forests*		57.07					Zhou et al. (2000)

*In FRSC (1982–2009), forests are classified into 38 types (including Korea pine, oak, larch, poplar, broadleaved mixed forests, spruce, *Abies* spp., birch and hardwood but excluding bamboo forest, economic forest and shrubs) in 1977–1981, 37 types each in 1984–1988, 1989–1993, 1994–1998 and 1999–2003, and 46 types in 2004–2008

last three decades, its relative contribution to the national forest biomass carbon stock decreased from 5.94% in 1977–1981 to 4.74% in 1999–2003 (Figure 3). This decline resulted from the substantial increase of national forest biomass carbon stock with increasing use of other tree species in the massive afforestation and reforestation efforts in China (Xu et al. 2007). Nevertheless, moso bamboo forest is still one of the most important forest types for biomass carbon stock in China. Of the 38 forest types identified in biomass carbon storage estimation in 1984–1988, oak forest was the largest (835.94 Tg C) and *Metasequoia glyphostrobodes*, the lowest (0.08 Tg C) (Wang et al. 2001). Moso bamboo forests rank seventh (195.93 Tg C) after oak, larch, broadleaved mixed forests, spruce, fir and birch forests (Table 3) (Wang et al. 2001).

The higher stand biomass in NS and MS (141.72 and 172.76 Mg ha^{-1} respectively) than in SS and SM (91.99 and 66.07 Mg ha^{-1} respectively) observed in this study may be attributed to the more suitable climatic and

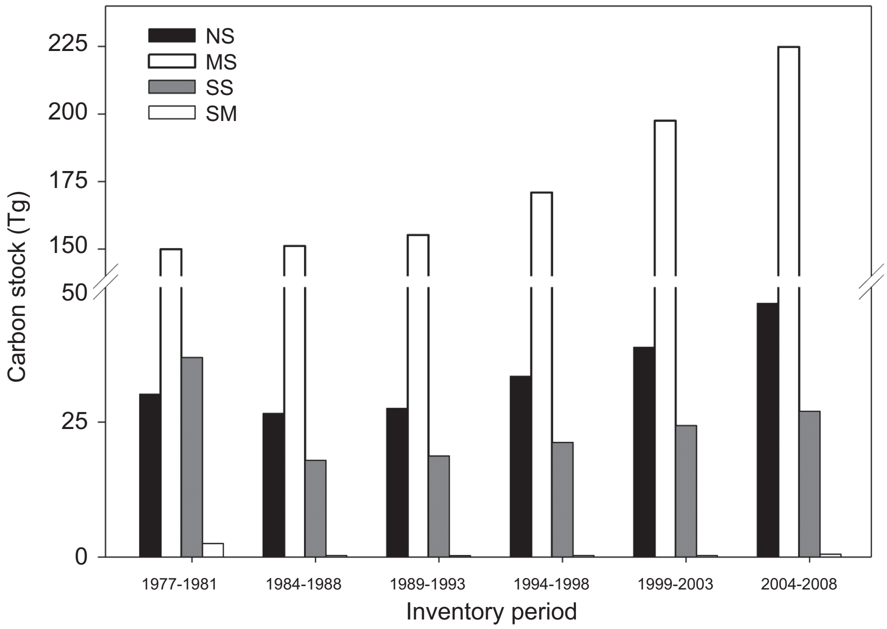

Figure 4 Changes of biomass carbon stock in moso bamboo forests by subregions over the last 30 years; NS = north subtropical, MS = middle subtropical, SS = south subtropical and SM = south-west mountain subtropical subregions

Table 3 Ranks of forest vegetation carbon sequestration in China from 1984–1988 (Wang et al. 2001)

Rank	Vegetation type	Carbon stock (Tg)	Rank	Vegetation type	Carbon stock (Tg)
1	Oak	835.94	20	*Cupressus* spp.	27.25
2	*Larix* spp.	450.18	21	*Tsuga tchekiangensis*	25.51
3	Broadleaved mixed forest	429.77	22	*Pinus kesiya* var *langbinanensis*	24.97
4	Spruce	330.17	23	*Tilia* spp.	21.52
5	*Abies* spp.	314.43	24	Chinese pine	20.41
6	Birch	233.92	25	*Fraxinus mandshurica, Juglans mandshurica, Phellodendron amurense*	18.08
7	Moso bamboo	195.93			
8	Hardwood forest	192.96	26	Mongolian Scots pine	15.5
9	*Pinus massoniana*	138.58	27	*Pinus armandii*	9.46
10	*Pinus yunnanensis*	110.73	28	*Keteleeria fortunei*	3.52
11	Poplar	100.96	29	*Phoebe bourmei*	2.89
12	Softwood forest	94.13	30	*Casuarina* clone	2.11
13	Mixed coniferous and broadleaved forest	76.69	31	*Eucalyptus* spp.	1.89
			32	*Cinnamomum camphora*	1.56
14	Chinese fir	63.69	33	*Davidia* spp.	0.65
15	*Pinus densata*	58.34	34	*Cryptomeria janponica*	0.33
16	Other forest	31.58	35	*Pinus thunbergii*	0.21
17	Coniferous mixed forest	29.83	36	*Pinus densiflora*	0.12
18	Korea pine	28.38	37	*Sassafras tsumu*	0.12
19	Tropical forest	28.04	38	*Metasequoia glyphostrobodes*	0.08

soil conditions of the former which are located in the center of moso bamboo distribution in China, in additional to more intensive management in these two subregions (Tables 1 and 4). The values obtained in this study were also lower than the 159.86 Mg ha^{-1} reported by Chen et al. (2009) for moso bamboo forests throughout the entire distribution. The lower

Table 4 Climatic condition, soil condition and management patterns in the representative distribution area of moso bamboo forests in each subregions

Site	Latitude (N)	Latitude (E)	Mean annual temperature (°C)	Mean annual precipitation (mm)	Soil type	Soil bulk density (g cm^{-3})	Soil organic matter (%)	Management	Reference
NS									
Yixing, Jiangsu	31° 07' – 31° 37'	119° 31' – 120° 03'	14 – 19	1150 – 1490	Yellow brown soil			a + b + c + e	Zhang & Ding 1997
Anji, Zhejiang	30° 23' – 30° 53'	119° 14' – 119° 35'	12.2 – 15.6	1100 – 1900	Red soil			a + b + c + e	Pan et al. 2010
MS									
Linan, Zhejiang	30° 14'	119° 42'	15.9	1424				a + b + c + d + e	Zhou & Jiang 2004
Fuyang, Zhejiang	29° 44' – 30° 12'	119° 25' – 120° 09'	16.2	1300 – 1400	Yellow red soil	1.12	2.17	a + b + c + e	Gao 2004
Dagangshan, Jiangxi	27° 30' – 27° 50'	114° 30' – 114° 45'	15.8 – 17.7	1591				a + b + c + d + e	Wang et al. 2009
Huitong, Hunan	26° 50'	109° 45'	16.5	1200 – 1400	Yellow red soil	1.05	3.61	a + b + c + d + e	Xiao et al. 2010
Shunchang, Fujian	26° 39' – 27° 12'	117° 30' – 118° 14'	18.7	1568	Red soil	1.04	3.43	a + b + c + e	Zhang 2008
SM									
Changning, Sichuan	28° 28'	105° 00'	18.3	1104				a + b	He et al. 2008
Yiliang, Yunnan	27° 61'	104° 06'	19	900 – 1600	Purple soil			a + b	Zheng et al. 2008
SS									
Yongan, Fujian	25° 55' – 25° 58'	117° 31' – 117° 33'	23	2000	Red soil			a + b + c + e	Qi et al. 2009

Soil types in this table follow the Chinese classification or Haplic Calcisol according to the FAO classification; management methods included (a) digging bamboo shoots, (b) weeding, (c) fertilisation, (d) irrigation and (e) keep new bamboos; NS = north subtropical, MS = middle subtropical, SS = south subtropical and SM = south-west mountain subtropical subregions reading observed in this study could be due to the fact that we divided the forest into four subregions, used data from more than two time-plots and applied area-based method to calculate the means.

Characteristics of carbon stock and sequestration in moso bamboo forest ecosystems

Moso bamboo forests have some distinct aspects in carbon storage and sequestration compared with other forest types. Moso bamboo reached maximum biomass carbon stock at about 6 years with a major fraction (60%) of accumulated biomass occurring in the first year, much earlier than other fast-growing tree species in the subtropical areas (the mature age is usually about 20–30 years) (Figure 5). There are some popular fast-growing broadleaved and coniferous tree species in subtropical China (Table 5). Compared with tree forests, the biomass carbon stock of moso bamboo forests was generally higher especially if measured at the same age.

For moso bamboo stands, belowground biomass was about one third of total stand biomass in the four subregions (Table 1) compared with 20–30% in broadleaved and conifer trees in subtropical area. Therefore, much higher proportion of biomass carbon is stored in the soils of moso bamboo forests, with their roots remaining alive for vegetative reproduction after harvesting.

For most other fast-growing tree species, maximum net primary productivity occurred at > 10 years old and could continue for several years (Table 5, Figure 5). However, the net primary productivity of moso bamboo stands reached the peak in the first year, at 8 to 18 Mg C ha^{-1} year^{-1} and then quickly declined (He et al. 2008). Thus, moso bamboo stands had higher rates of carbon sequestration through a shorter period due to higher leaf area index (8.02) and could absorb 95% of the incident solar radiation (Zhou & Jiang 2004, Chen et al. 2009, Yen & Lee 2011). Furthermore, with green aerial parts (stem, branches and leaves), the photosynthetic area of the plant is maximised for high rate of carbohydrate production (Embaye 2003). Moreover, a fully developed rhizome-root system may lead to higher water-use and nutrient-use efficiencies, although the

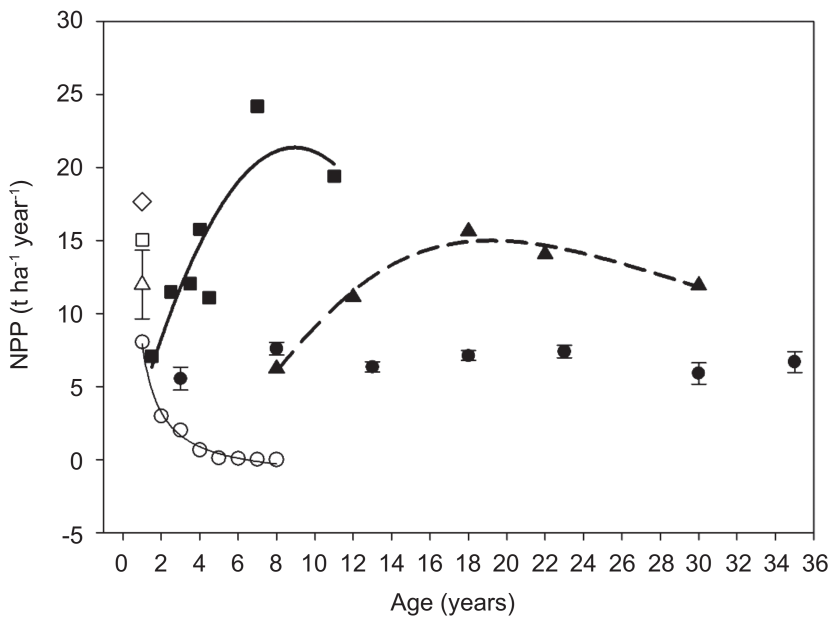

Figure 5 The relationship between net primary productivity (NPP) and stand age for moso bamboo and other forests in subtropical regions; open circles for south-west mountain subtropical subregion (SM) (He et al. 2008), open triangles, squares and diamonds for north (NS), middle (MS) and south (SS) subtropical subregions respectively (Wen 1990, Li et al. 1993, He et al. 2007), solid triangles for *Pinus massoniana* (Liu 1996, Ding & Wang 2001), solid squares for *Casuarina* clone (Ye et al. 2008), and solid circles for *Cunninghamia lanceolata* (Hou et al. 2009)

Table 5 Stand biomass carbon density (BC) and annual net biomass carbon sequestration (ANC) of some important fast-growing forests in subtropical China

Forest type	Location	Geographic coordinate	MAT (°C)	MAP (mm)	Altitude (m)	Soil depth (cm)	Density (stem ha^{-1})	Age (year)	BC (Mg C ha^{-1})	ANC (Mg C ha^{-1} year^{-1})	Reference
MS subregion											
Cinnamomum camphora	Zhuzhou, Hunan	27° 50 N,112° 54 E	17.4	1430	50–200	-	-	18	45.5*	4.78*	Yao (2003)
Pinus massoniana	Qianyanzhou,Jiangxi	26° 44 N, 115° 04 E	17.9	1491	100	100	-	20	42.5*	3.16*	Shen (2006)
Pinus elliottii	Qianyanzhou, Jiangxi	26° 44 N, 115° 04 E	17.9	1491	100	100	-	20	55.0*	4.55*	Shen (2006)
Cunninghamia lanceolata	Huitong, Hunan	27° 03 N, 109° 53 E	16.5	1300	200–500	-	1530	15	52.8	7.36	Xiao et al. (2010)
Acacia melanoxylon	Nanning, Guangxi	22° 58 N, 108° 21 E	21.8	1350	200	80	1415	9	86.6*	9.6*	Liang et al. (2010)
A. cincinnata	Nanning, Guangxi	22° 58 N, 108° 21 E	21.8	1350	200	80	1398	8	56.3*	6.3*	Huang et al. (2010)
A. mangium	Nanning, Guangxi	22° 58 N, 108° 21 E	21.5	1350	250	70	775	11		9.7*	Qin et al. (2007)
SS subregion											
Castanopsis carlesii	Sanming, Fujian	26° 11 N, 117° 26 E	19.0	1586	350–400	-	367	10	37.2*		Liao et al. (1991)
Tsoongiodendron odorum	Sanming, Fujian	26° 11 N, 117° 26 E	19.4	1586	220	-	2100	13	28.5*	2.28*	Liu et al. (1993)
Phoebe bourmei	Youxi, Fujian	25° 50 N, 117° 48 E	19.2	1620	500–700	100	1985	8	23.1	1.97	Wei and Ma (2006)
P. massoniana	Shunchang, Fujian	26° 29 N, 117° 30 E	19.2	1620	500–700	100	1590	7	16.6	1.82	Wei and Ma (2007)
C. lanceolata	Fujian	26° 11 N, 117° 26 E	19.2	1620	500–700	100		7		2.07	Wei (2005)
Casuarina clone	Huian, Fujian	24° 55 N, 118° 55 E	19.8	1029		80–100		8	62.7		Ye et al. (2008)
A. cincinnata	Pinghe, Fujian	24° 20 N, 117° 26 E	22	1859	150–250	-	900	7	31.9	4.98	Pan et al. (2009)
A. melanoxylon	Pinghe, Fujian	24° 20 N, 117° 26 E	22	1859	150–250	-	1000	7	26.5	4.06	Pan et al. (2009)
A. mangium	Pinghe, Fujian	24° 20 N, 117° 26 E	22	1859	150–250	-	875	7	19.7	3.03	Pan et al. (2009)

*A factor 0.5 was used to convert the stand biomass density (Mg ha^{-1}) to BC Mg C ha^{-1} and change the net primary productivity (Mg ha^{-1} year^{-1}) to ANC (Mg C ha^{-1} year^{-1}); MAT = mean annual temperature; MAP = mean annual precipitation; MS = middle subtropical and SS = south subtropical subregions bamboo subfamily (Bambusoideae) lacks the C4 photosynthetic pathway and anatomy (Jones 1985). However, moso bamboo forests have been recognised as C4 plants (Yen & Lee 2011). This uncertainty in the photosynthetic pathway of moso bamboo forest needs further research.

In addition to the total carbon stock, in assessing the potential of sequestering carbon in a forest ecosystem, it is essential to determine stable parts of total carbon stock which represent an ability of fixing carbon at a long-term level. For bamboo forests, a median phytolith-occluded carbon yield was about 0.36 t equivalent CO_2 ha^{-1} $year^{-1}$, and the global potential for such a biosequestration via phytolith carbon (from bamboo and/or other similar grass crops) was 1.5 billion t equivalent CO_2 ha^{-1} $year^{-1}$, which was equivalent to 11% of the current increase in atmospheric CO_2 (Parr et al. 2010). These data indicate that for managing the vegetation such as bamboo forests, there is potential to produce considerable quantities of securely biosequestered carbon through production of phytolith-occluded carbon.

Use of moso bamboo as carbon sink forest tree species

One of the essential issues in managing carbon sink forest is to choose suitable trees by site conditions in order to maximise ecological and economic potentials. Carbon sink forest is dedicated to reducing greenhouse gas emissions and, at the same time, providing ecological and economical benefits. This multiple-benefit management strategy requires that the tree species used for carbon sink forest should meet the following criteria: (1) fast growing and high potential for carbon sequestration, (2) strong adaptation to nutrient-poor site conditions, and (3) good ecological and economic values. Moso bamboo is one of such tree species in subtropical China. Moso bamboo grows fast and provides economic benefit to local farmers (Zhang 2008, Chen et al. 2009) while protecting the environment (carbon sequestration, water conservation, soil conservation, nutrient accumulation, atmosphere environment purification, biodiversity conservation) (Wang 2007). The total export of moso bamboo products in 2005 reached USD1.05 billion, a huge income for local farmers.

In moso bamboo forests, woody biomass carbon accounted for 75 to 80% of the total carbon stock (Xiao et al. 2007, Wang et al. 2009), higher than other forest types. The residence time of carbon was about 80 years in woody biomass, less than 5 years in litter, 15.6 years in fine root biomass and 47.4 years in foliage biomass (Xu et al. 2006). The large woody biomass carbon in moso bamboo forests and considerable bamboo products will likely enhance the residence time of carbon for moso bamboo carbon pool. Additionally, higher phytolith concentration of moso bamboo also produced more stable soil organic carbon compared with other tree species (Parr et al. 2010), and so did the bamboo charcoal (Fu & Yin 2009). Thus, the carbon pool of moso bamboo forests should be more stable than other forest types.

Bamboo plants are particularly advantageous over other timber tree species for carbon sink purpose. They can quickly regenerate after harvesting, fire or insect damage through fast asexual reproduction and recover their carbon pools lost to disturbances. The horizontal growth of root systems increases their asexual fecundity and absorption capacity of nutrients and water from the soil, thus, enhancing survival and growth (Isagi et al. 1997).

Furthermore, bamboo forests are characterised by a complex network of rhizome-root system, which makes them excel other forest types in effectively holding soil particles together, thereby preventing soil erosion and promoting water percolation. Their high leaf area index and stand density help reduce erosion by rainfall interception and by sheltering the soil from wind erosion and sun drying. These properties will enable the moso bamboo forests to perform ecological functions better than most other timber forest types (Embaye 2003).

CONCLUSIONS

Moso bamboo forest is an important forest type in China in terms of timber, landscape, culture as well as economic values. In 2008, the total area of moso plantation was 3.87 million ha

(3% of total national forests) and the total biomass carbon was 299.31 Tg (about 6% of the total forest biomass carbon). With its higher annual net biomass carbon sequestration rate (6–22 Mg C ha^{-1} $year^{-1}$), shorter rotation, higher phytolith concentration, and higher economic and ecological values, moso bamboo plantations will play an essential role in carbon sink forestry of subtropical areas in China.

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REFERENCES

Chen XG, Zhang XQ, Zhang YP, Booth T & He XH. 2009. Changes of carbon stocks in bamboo stands in China during 100 years. *Forest Ecology and Management* 258: 1489–1496.

Ding GJ & Wang PC. 2001. Study on change laws of biomass and productivity of masson pine forest plantations. II. Biomass and productivity of stand at different age. *Sciencia Silvae Sinicae* 15: 54–60. (In Chinese)

Embaye K. 2003. Ecological aspects and resource management of bamboo forests in Ethiopia. PhD thesis, Swedish University of Agricultural Sciences, Uppsala.

Fang JY & Chen AP. 2001. Dynamic forest biomass carbon pools in China and their significance. *Chinese Bulletin of Botany* 43: 967–973. (In Chinese)

FRSC (National Forest Resources Statistics in China). 1982–2009. Statistics of Forest Resources in China (1977–2008). Chinese Forestry Press, Beijing. (In Chinese)

Fu JH & Yin ST. 2009. Utilization of bamboo charcoal. *World Bamboo and Rattan* 7: 42–45. (In Chinese)

Gao ZQ. 2004. Study on the community characteristics and evaluating on ecological functions of *Phyllostachys pubescens* stands. PhD thesis, Chinese Academy of Forestry, Beijing. (In Chinese)

He YP, Fei SM, Jiang JM, Chen XM, Yu Y, Tang SQ & Zhu WS. 2007. The spatial distribution of organic carbon in *Phyllostachys pubescens* and *Pleioblastus amarusin* Changning County. *Journal of Sichuan Forest Science and Technology* 28: 10–14. (In Chinese)

He YP, Yang ZJ, Jiang JM, Fei SM, Chen XM, Yu Y & Tang SQ. 2008. The quantity features and biomass structure of *Phyllastachys heterocycla* cv *pubescens* population in Changning, Sichuan. *Journal of Sichuan Forest Science and Technology* 29: 14–19. (In Chinese)

Hou ZH, Zhang XQ, Xu DY & Yu PT. 2009. Study on biomass and productivity of Chinese fir plantations. *Chinese Agricultural Science Bulletin* 25: 97–103. (In Chinese)

Huang Y, Tan J, Li SC, Qin WM, Zhu XL & Duan WX. 2010. Research on growth law, biomass and productivity of *Acacia cincinnata* plantation. *Journal of Anhui Agricultural Science* 38: 12050–12053. (In Chinese)

Isagi Y, Kawahara T, Kamo K & Ito H. 1997. Net production and carbon cycling in a bamboo *Phyllostachys pubescens* stand. *Plant Ecology* 130: 41–52.

Jones CA. 1985. *C4 Grasses and Cereals: Growth, Development and Stress Response.* Wiley, New York.

Li ZJ, Lin P & Qiu XZ. 1993. Studies on the biomass and productivity of *Phyllostachys heterocycla* cv *pubescens* community in southern Fujian. *Journal of Xiamen University (Natural Science Edits)* 32: 762–767. (In Chinese)

Liang YX, Qin WM, Wei ZM, Huang XY, Duan WW & Lin DS. 2010. The growth regularity, biomasses and productivity of *Acacia melanoxylon* in the southwest of Guangxi. *Journal of Fujian Science and Technology* 37: 1–4, 14. (In Chinese)

Liao HZ, Zhang CN, Di DS & Chen ZZ. 1991. Studies on ecosystem productivity of *Castanopsis carlesii* plantation. *Journal of Fujian College Forestry* 11: 313–317. (In Chinese)

Liu CH, Zhang CN & Zhen YM. 1993. Study on biomass and productivity of the pure stand and mixtures of *Tsoongiodendron odorum. Journal of Fujian College Forestry* 13: 267–272. (In Chinese)

Liu Q. 1996. Studies of the biomass and productivity of different age-group *Pinus massoniana* plantations. *Journal of Central South Forestry University* 16: 47–51. (In Chinese)

Liu CH, Fu BJ & Fang JY. 2000. Carbon dynamic of Chinese Forests and its contribution to global balance. *Acta Ecologica Sinea* 20: 733–740. (In Chinese)

Liu YF, Huang CD & Chen QB. 2010. Carbon storage and allocation of *Phyllostachys edulisecosystem* stands in scenic spot within the southern Sichuan bamboo sea. *Journal of Sichuan Agricultural University* 28: 136–140. (In Chinese)

Pan CX, Li XT & LV YL. 2010. Resources and biomass of *Phyllostachys heterocycla* cv. *pubescens* in Anji. *Journal of Zhejiang Forest Science and Technology* 30: 82–84. (In Chinese)

Pan H, Huang SD, Hong W, Zhu HR, Zhang ZH & Lin J, 2009. The carbon storage and distribution in three *Acacia* plantations. *Journal of Fujian College Forestry* 29: 28–32. (In Chinese)

Pan YD, Luo TX, Birdsey R, Hom J & Melillo J. 2004. New estimates of carbon storage and sequestration in China's forests: effects of age-class and method on inventory-based carbon estimation. *Climatic Change* 67: 211–236.

Pan YD, Birdsey RA, Fang JY, Houghton R, Kauppi PE, Kurz WA, Phillips OL, Shvidenko A, Lewis SL, Canadell JG, Ciais P, Jackson RB, Pacala S, McGuire A D, Piao SL, Rautiainen A, Sitch S & Hayes D. 2011. A large and persistent carbon sink in the world's forests. *Science* 333: 988–993.

Parr JF, Sullivan LA, Chen B, Ye G & Zheng W. 2010. Carbon bio-sequestration within the phytoliths of economic bamboo species. *Global Change Biology* 16: 2661–2667.

Qi LH, Liu GL, Fan SH, Yue XH, Zhang H & Du MY. 2009. Effects of different tending measures on carbon density, storage and allocation pattern of *Phyllostachy edulis* forests in western Fujian Province. *Chinese Journal of Ecology* 28: 1482–1488. (In Chinese)

Qin WM, He B, Yu HG & Chen WJ. 2007. Biomass productivity of *Acacia mangium* plantations of different age classes. *Journal of Northeast Forestry University* 35: 22–24. (In Chinese)

Shen WQ. 2006. Carbon budgets of coniferous plantations in Qianyanzhou Experimental Station, Jiangxi China. PhD thesis, Beijing Forestry University, Beijing. (In Chinese)

Wang AH. 2007. Life cycle assessment of bamboo/wood products and its application. PhD thesis, Chinese Academy of Forestry, Beijing. (In Chinese)

Wang B, Wang Y, Guo H, Zhao GD & Bai XL. 2009. Carbon storage and spatial distribution in *Phyllostachys pubescens* forest in Dagangshan Mountain of Jiangxi Province. *Journal of Beijing Forestry University* 31: 39–42. (In Chinese)

Wang XK, Feng ZW & Ouyang ZY. 2001. Vegetation carbon storage and density of forest ecosystems in China. *Chinese Journal of Applied Ecology* 12: 13–16. (In Chinese)

Wei HD. 2005. Study on carbon storage and soil respiration of three forest ecosystems in mid-subtropical region, China. PhD thesis, Fujian Agricultural and Forestry University, Beijing. (In Chinese)

Wei HD & Ma XQ. 2006. Study on the carbon storage and distribution of *Phoebe bourmei* plantation ecosystem of different growing stages. *Journal of Yantai Normal University (Natural Science Edits)* 22: 130–133. (In Chinese)

Wei HD & Ma XQ. 2007. Study on the carbon storage and distribution of *Pinus massoniana* Lamb plantation ecosystems at different growing stage. *Journal of Northwest Agricultural Forestry University (Natural Science Edits)* 35: 171–174. (In Chinese)

Wen TH. 1990. An appraisal on the productivity factors of bamboo stands. *Journal of Bamboo Research* 9: 1–10. (In Chinese)

Xiao FM, Fan SH, Wang SL, Xiong CY, Zhang C, Liu SP & Zhang J. 2007. Carbon storage and spatial distribution in *Phyllostachy pubescens* and *Cunninghamia lanceolata* plantation ecosystems. *Acta Ecologica Sinica* 27: 2794–2801. (In Chinese)

Xiao FM, Fan SH, Wang SL, Guan FY, Yu XJ & Shen ZQ. 2010. Estimation of the carbon balance in moso bamboo and Chinese fir plantation ecosystem. *Scientia Silvae Sinicae* 46: 59–65. (In Chinese)

Xu T, White L, Hui D & Luo Y. 2006. Probabilistic inversion of a terrestrial ecosystem model: analysis of uncertainty in parameter estimation and model prediction. *Global Biogeochemistry Cycles* 20, GB2007, doi:10.1029/2005GB002468.

Xu XL, Ca MK & Li KR. 2007. Temporal-spatial dynamics of carbon storage of forest vegetation in China. *Progress of Geography* 26: 1–10.

Yao YJ. 2003. Biomass and nutrient accumulation of *Cinnamomum camphora* plantation. MSc thesis, Central South Forestry College, Beijing. (In Chinese)

Ye GF, Guo RH, Lu CY, Xiao SS & Wu HZ. 2008. Carbon storage of *Casuarina* forest ecosystem in different stages. *Channel of Science* 10: 3–7, 10. (In Chinese)

Yen TM & Lee JS. 2011. Comparing aboveground carbon sequestration between moso bamboo (*Phyllostachys heterocycla*) and China fir (*Cunninghamia lanceolata*) forests based on the allometric model. *Forest Ecology and Management* 261: 995–1002.

Zhang CS. 2008. Study on ecological function of different *Phyllostachy edulis* stands in northern Fujian province. PhD thesis, Chinese Forestry of Academy, Beijing. (In Chinese)

Zhang CX & Ding XC. 1997. Studies on yield of *Phyllostachys pubescens*. *Journal of Bamboo Research* 16: 31–36. (In Chinese)

Zhao M & Zhou GS. 2004. Carbon storage of forest vegetation and its relationship with climatic factors. *Scientia Geographica Sinica* 24: 50-54. (In Chinese)

Zheng JX, Dong WY, Chen C, Duan CX, Zhao JF & Lu ZH. 2008. Studies on the growth and rhythm of natural moso bamboo population in Haiziping. *Journal of Bamboo Research* 27: 32–37. (In Chinese)

Zhou GM & Jiang PK. 2004. Density, storage and spatial distribution of carbon in *Phyllostachy pubescens* forest. *Scientia Silvae Sinicae* 40: 20–24. (In Chinese)

Zhou YR, Yu ZL & Zhao SD. 2000. Carbon storage and budget of major Chinese forest types. *Acta Phytoecologica Sinica* 24: 518–522. (In Chinese)