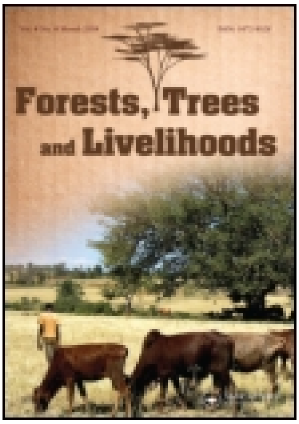

Forests, Trees and Livelihoods
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tftl20

Impacts of selective harvest on the carbon sequestration potential in Moso bamboo (Phyllostachys pubescens) plantations

Y. Kuehl [a] , Y. Li [a] & G. Henley [b]
[a] Environmental Sustainability Programme, International Network for Bamboo and Rattan (INBAR), 100102, Beijing, People's Republic of China
[b] Overseas Development Institute, London, UK
Version of record first published: 08 Mar 2013.

To cite this article: Y. Kuehl , Y. Li & G. Henley (2013): Impacts of selective harvest on the carbon sequestration potential in Moso bamboo (Phyllostachys pubescens) plantations, Forests, Trees and Livelihoods, 22:1, 1-18

To link to this article: http://dx.doi.org/10.1080/14728028.2013.773652

Forests, Trees and Livelihoods, 2013
Vol. 22, No. 1, 1–18, http://dx.doi.org/10.1080/14728028.2013.773652

Impacts of selective harvest on the carbon sequestration potential in Moso bamboo (*Phyllostachys pubescens*) plantations

Y. Kuehl[a]*, Y. Li[a] and G. Henley[b]

[a]*Environmental Sustainability Programme, International Network for Bamboo and Rattan (INBAR), 100102 Beijing, People's Republic of China;* [b]*Overseas Development Institute, London, UK*

Bamboos are among the fastest growing and most renewable forest resources, and are widely grown throughout the tropics and the subtropics. Properties related to their growth and utilization are beneficial for climate change mitigation and adaptation. However, these aspects are yet to be extensively researched. This paper studies the carbon sequestration potential of bamboos, using the example of Moso bamboo (*Phyllostachys pubescens*), and examining the impacts of selective harvest. By using time-series data and allometric equations, the paper develops an original model to survey the biomass accumulation of a Moso bamboo plantation. The carbon sequestration potential of bamboo is compared to a fast-growing species that grows in similar conditions – Chinese fir (*Cunninghamia lanceolata*). The modelled data indicate that carbon sequestration of Moso bamboo would only exceed that of Chinese fir when bamboo is selectively harvested – as this allows effective utilization of bamboo's characteristics of fast growth and high renewability; the simulation showed that a selectively harvested Moso bamboo plantation sequesters 305.77 t C/ha in 60 years. Although this study generated essential findings to determine the potential role of bamboo in climate change mitigation, it also demonstrated the need for further research to enable stakeholders to utilize bamboo effectively in these efforts.

Keywords: climate change mitigation; bamboo; sustainable forest management; carbon sequestration; biomass modelling; harvested wood products

Introduction

Bamboo is highly important as a basic livelihood crop and construction material for rural populations in Asia, Latin America and Africa, covering an area of about 31.5 million hectares globally (FAO 2010). China has a rapidly emerging bamboo sector worth US$ 11.8 billion annually (Buckingham et al. 2011). Bamboo is relied on heavily by some of the world's poorest people, and can be a significant pathway out of poverty (Belcher 1995), with high farmer returns and many options to support sustainable rural livelihoods (Marsh & Smith 2007). It is relatively easy to manage and is characterized by low investment costs for processing and inputs as well as flexible time requirements for seasonal work (INBAR 2004).

Although bamboo is a woody grass and not a tree, bamboo forests have unique but comparable features and functions to other types of forests within the carbon cycle (Lobovikov et al. 2011). Bamboo is one of the fastest growing and most renewable forest resources in the world. Bamboos have rapid growth rates, high annual re-growth after harvesting and high biomass production (Yen & Lee 2011). These characteristics render it of interest for climate change mitigation efforts. Bamboo can be integrated into all forest-based climate change mitigation activities, such as afforestation/reforestation, avoided

*Corresponding author. Email: ykuhl@inbar.int

deforestation and forest management (Kuehl et al. 2011; Lobovikov et al. 2011). However, questions have been raised on the importance of bamboo as a carbon sink (Dueking et al. 2011). Data, knowledge and methodologies for scientifically quantifying carbon sequestration of bamboo are currently limited and need to be further developed and researched. Generally, 'remarkably little is known about this entire sub-family of tall graminaceous plants, despite its everyday utilization, (. . .), by about 2.5 billion people' (Scurlock et al. 2000).

The impacts of climate change on people around the world are going to increase (IPCC 2011) and the largely negative impacts of climate change could be irreversible by 2017 if no further actions were taken (IEA 2011). Forests will have a central role in international action in combating climate change (Eliasch 2008). By converting land which currently stores relatively low levels of carbon into forested land, more atmospheric CO_2 can be removed from the atmosphere and stored in terrestrial ecosystems. This represents a relevant research area for bamboo, as a potential crop for afforestation and reforestation measures (Jiang et al. 2011). Moreover, bamboo can be processed into a wide range of products and as such can represent an effective tool in rural development (Ruiz-Perez et al. 1999). The successful use of bamboo in a wide range of different products demonstrates the high potential for bamboo as a sustainable 'potential key substitute for timber, cotton, construction material and edible products' (Buckingham 2009). New generations of bamboo products with longer lifespans have been developed recently (Benton et al. 2011). These innovative products offer prospects that sequestered carbon can be stored for a longer period. Further innovations should be encouraged to enhance the number of available durable bamboo products. In this context, bamboo can play an important role in reducing pressure on other forestry resources by indirectly reducing deforestation through the substitution of timber and plywood.

Using bamboo forests within a comprehensive approach to rehabilitate degraded hillsides, catchment areas and riverbanks has shown promising and quick results (Fu & Banik 1995). This represents a specific niche for bamboo: afforestation/reforestation with bamboo on lands on which other plants would not grow, or only grow with limited productivity. Bamboo is an effective tool to increase livelihood and landscape resilience, as well as to support local climate change adaptation measures (INBAR 2009; Lobovikov et al. 2011). Nevertheless, Buckingham et al. (2011) point out that bamboo is marginalized by international forestry policy that limits its global potential. For example, due to its botanical definition, some carbon accounting documents failed to include bamboo until recently. If bamboo were to be adequately recognized within international forestry policy, it could occupy an important position in climate change mitigation adaptation and sustainable development (Lobovikov et al. 2009).

Given the complexity of natural systems, and the fact that scientific research on the carbon cycle in bamboo has only started recently, questions have been raised about the performance of bamboo as a carbon sink. Magel et al. (2005) argue that growth of the new shoots in a bamboo forest occurs as a result of transfer of the energy accumulated in culms through photosynthesis in the previous year. As such, the growth of a bamboo culm is not driven by its own photosynthesis, but from energy from previous seasons which is stored in other parts of the bamboo system and, thus, the growth of new culms does not represent an indicator of sequestration rate. On the basis of this reasoning, the sequestration potential of bamboo is questioned. However, bamboo ecosystems survive for decades – therefore, it is not relevant if carbon sequestration occurs in the year before or at the same time as the growth of new shoots. Moreover, Zhou et al. (2009) argue that the bamboo system requires more inputs in the shooting season of young culms – indicating increased nutrient demand in the growing season.

Depending on the species, most bamboo culms reach maturity after approximately 7–10 years, after which they deteriorate rapidly, releasing carbon from the above-ground (AG) biomass back into the atmosphere (Liese 2009). Below-ground (BG) biomass, the root and rhizome system, does not die when individual culms are harvested. For the bamboo system to be a continuous net sink, the carbon from the culms has to be stored before deterioration, so that the total accumulation of carbon in a solid state exceeds the carbon released into the atmosphere. Therefore, this present study compares managed bamboo forests (with regular selective harvest and carbon storage in harvested products) with unmanaged forests (without harvest). Bamboo has properties of fast growth and rejuvenation after cutting, which means that it can provide a harvestable yield every 1–2 years once maturity is reached. Its ability to rejuvenate itself from the BG rhizome system means that it does not require re-planting, as the bamboo's root and rhizome system does not die when sustainable and selective harvest methods are applied.

As a member of the grass family, several bamboo species are characterized by gregarious flowering. In some cases, all plants from the same species die simultaneously – resulting in the loss of carbon in the biomass. On the other hand, flowering usually results in the release of seeds, which can establish new bamboo ecosystems; germination rates of these fruits are typically low, but the grain quantity is 'considered sufficient' to establish the next generation (Shibata 2002). Although little is known about the flowering determinants, flowering cycles are known to be relatively constant for economically important species and global databases provide updated information about surveyed flowering cycles (INBAR 2011). Whether flowering represents a threat to the permanence of carbon sequestration in a given bamboo species is largely a question of risk assessment, the reliability of which depends on the state of information on the flowering cycle of the species. Where mechanisms are designed for the use of bamboo in carbon offsets, careful consideration of the flowering risk should be made. For Moso bamboo, gregarious and partial flowering – i.e. the flowering of individual clumps – are typical (Shibata 2002). However, Moso bamboo clumps have been observed to flower with intervals of at least 67 years (Watanabe et al. 1982; Shibata 2002) – thus, the risk of flowering to the permanence of issued carbon credits can be minimized. In addition, adequate risk management strategies – such as multi-species plantations – can further minimize risks.

This study, based on limited data, attempts to quantify bamboo's carbon sequestration potential in the case of Moso bamboo (*Phyllostachys pubescens* Mazel ex J. Houz.) – one of the most economically important bamboo species in China. Moso bamboo is a monopodial species which is widespread in East Asia. This paper surveys the impacts of management – in the form of regular harvest – on carbon storage of bamboo stands. In addition, the carbon sequestration potential of bamboo is compared to that of Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook.) – a widely spread, fast-growing tree species in subtropical China, growing in the same areas as Moso bamboo. The paper also surveys and compares the processes of biomass accumulation in bamboo by modelling the development of new plantations. On the basis of these findings, the potential of bamboo in global efforts to mitigate climate change can be defined more precisely. Where adequate, this study aims to develop policy recommendations. Finally, this study aims at identifying needs for further research to enable global stakeholders to realize the potential of bamboo for climate change mitigation.

Materials and methods

This section outlines the methodology and data sources for the analysis and model. The models deal with the accumulation of carbon in the bamboo plant (in the form of accumulated biomass) and do not describe the CO_2 fluxes.

With regard to the discussion on bamboo's performance as a carbon sink, this study follows a stock change approach. Carbon sequestration is determined by measuring the difference in standing carbon between year $(t + 1)$ and year (t), so details of the relocation of carbon between old and new culms are not relevant. This study focuses on carbon per unit area, rather than on carbon per culm, considering bamboo as an integrated culm–rhizome system.

This section is based on the extensive review of literature, focusing on methodologies for calculating biomass and carbon sequestration of the whole bamboo plant (AG and BG), and of fast-growing Chinese fir plantations. The longest period is 60 years, which covers two rotations of Chinese fir – which typically last for 30 years in China. Figure 1 illustrates the typical growth pattern and life cycle of Moso bamboo.

Figure 1 indicates the fast growth of Moso bamboo: within approximately two months after the emergence of a culm, the final height and diameter are almost reached. It also demonstrates that the peak of the compressive strength is reached during year 6; moreover, compressive strength also starts to decrease after year 6. Therefore, from an economic point of view, it is reasonable to harvest individual culms after year 6, when maturity is reached. Figure 1 also illustrates the beginning of deterioration of Moso bamboo towards year 10. For Moso bamboo, selective cutting takes place every 2 years, leaving a fixed amount of carbon stock standing. The harvested biomass is subsequently replaced by new culms that fill the voids left by the harvested culms within a year.

Chinese fir and Moso bamboo forests naturally grow at similar sites and require similar climatic conditions.[1] The age classifications of Chinese fir (Tian 2005) and Moso bamboo, however, are very different, as shown in Table 1. Chinese fir plantations are even-aged, whereas Moso bamboo stands are uneven-aged.

Bamboo biomass data were used to calculate the bamboo forest carbon stock increases, based on secondary data sources. From 1997 to 2003, Chen et al. (2004) recorded a time-series data of the diameter-at-breast height (DBH) of new culms in a Moso bamboo plantation in China[2] (Table 2).

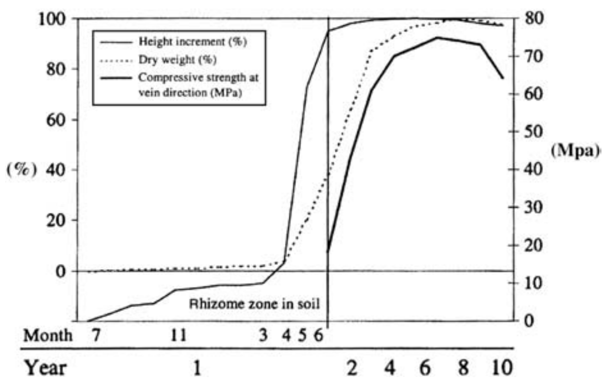

Figure 1. The growth curves of Moso Bamboo. Note: The months on the *x*-axis refer to the months within the first year (before emergence); years 1–10 refer to years after planting. *Source*: Fu (2001).

Table 1. Age classifications of Chinese fir and Moso bamboo plantations (without harvest).

	Age (years)				
	≤10	11–20	21–25	26–35	≥36
Chinese fir	Young stand	Medium age	Close to maturity	Matured	Old
Moso bamboo					
Stand	Young to mature	Matured	Matured	Matured	Matured
Individual culm	Matured	Dying			

Source: Lou et al. (2010) modified.

Table 2 shows that in newly established bamboo plantations, emerging bamboo culms gradually grow until maturity is reached (after year 10). Due to the lack of data for the years 8–60, small increases of DBH were assumed for years 8 and 9 after planting. In order to avoid overestimations, the final DBH for mature and maximum size culms was conservatively estimated to be 8.4 cm; other studies state larger mean DBH for bamboo (8.75 cm; Yen & Lee 2011). It should be considered that changing management or climatic conditions can impact bamboo sizes during the modelled 60 years.

Based on the DBH data set, Chen et al. (2004) derived an allometric equation for dried AG biomass per culm of Moso bamboo (see Equation (1)). The AG biomass includes bamboo culm, branches and foliage:

$$AG = -11.4970 + 3.0465 \times DBH + 0.1117 \times DBH^2 \quad (r^2 = 0.837) \tag{1}$$

Here, AG represents dried above-ground biomass of individual culms (in kg). Table 3 displays AG calculations (based on Equation (1) and the respective DBH from Table 2) and above-ground carbon (AGC), using the bamboo carbon ratio 0.5 – according to Equation (3).

Peng et al. (2002) determined the BG biomass of Moso bamboo in relation to the AG of the individual culm in the respective age. The BG biomass includes bamboo stump, rhizome and root system. Table 4 represents the ratio R of AG to BG, the so-called 'shoot/root ratio'.

Due to the lack of data, it was conservatively assumed that R remains constant after year 7, as individual culms are usually harvested in year 6 and – as mentioned earlier in

Table 2. Diameter-at-breast height (DBH) of new culms in a newly established Moso bamboo plantation.

Year after planting	DBH (cm)
1	3.8
2	4.5
3	5.2
4	5.8
5	6.5
6	7.1
7	7.5
8[a]	7.9
9[a]	8.2
10–60 (maturity)[a]	8.4

Source: Chen et al. (2004) and our own data.
[a]Based on estimations.

Table 3. Dried above-ground biomass, AG (kg/culm), and above-ground carbon, AGC (kg/culm), in a newly established Moso bamboo plantation.

Year after planting	AG (kg/culm)	AGC (kg/culm)
1	1.69	0.85
2	4.47	2.24
3	7.37	3.68
4	9.93	4.97
5	13.02	6.51
6	15.76	7.88
7	17.63	8.82
8	19.54	9.77
9	21.00	10.50
10–60 (maturity)	21.98	10.99

this paper – culms reach maturity after 7–10 years. The BG biomass share adopted here is a conservative estimate: 29.39% (culms aged 5 and 6 – see Table 4) at its highest, while other studies have estimated this share at 36.21% (Jiang et al. 2011). Based on *R*, the total dried biomass of each Moso culm *T* (in kg/culm) is calculated for each respective year:

$$T = \mathrm{AG} + (\mathrm{AG}/\mathrm{R}) \tag{2}$$

The carbon stock in bamboo biomass (Xu et al. 2007) is calculated according to Equation (3):

$$C = 0.5 \times T \tag{3}$$

where *C* is the carbon stock in biomass, 0.5 is the carbon fraction commonly used for trees and bamboo (Zhou & Jiang 2004; Xu et al. 2007, 2009; Qi et al. 2009) and *T* represents the total dried biomass of each Moso bamboo culm. Finally, in order to calculate the total biomass of a bamboo stand, the figures for individual Moso culms are dynamically added up, according to the respective growth pattern and culm density (see Tables 5 and 6), and the total biomass is converted into tons per hectare.

The following Equations (4) and (5) have been selected to calculate the total dried biomass of a newly established Chinese fir plantation (in t/ha) – using the common density

Table 4. Ratio *R* of dried above-ground biomass to below-ground biomass of Moso bamboo.

Age of culm	*R*	BG biomass of *T* (in %)
1	3.196	23.83
2	3.196	23.83
3	2.693	27.08
4	2.693	27.08
5	2.402	29.39
6	2.402	29.39
7	2.751	26.66
8[a]	2.751	26.66
9[a]	2.751	26.66
10[a]	2.751	26.66

Source: Peng et al. (2002) and our own data.
[a]Based on estimations.

of 2175 trees/ha (Tian 2005):

$$W_1 = 217.8639(1 - e^{-0.118053t})^{3.340} \quad (r^2 = 0.998) \tag{4}$$

$$W_2 = 168.91357(1 - e^{-0.13344t})^{3.4170} \quad (r^2 = 0.998) \tag{5}$$

Typically, Chinese fir is clear-cut harvested after 30 years (resulting in removal of carbon stocks). Therefore, W_1 and W_2 represent the total living biomass of Chinese fir in a plantation during the first and the second cycle, respectively; t represents the Chinese fir trees' age. Following the same approach for bamboo, the total biomass is converted into carbon stock using Equation (3).

One of the most relevant questions regarding bamboo carbon sequestration is to what extent the rapid canopy closure and early harvest influences the creation of biomass and carbon sequestration. Therefore, this section aims at analysing carbon sequestration patterns in newly established bamboo plantations, in two different scenarios: harvested (i.e. managed) and not harvested (i.e. not managed). Moreover, it compares the carbon sequestration of Moso bamboo with that of Chinese fir in both the scenarios.

A dynamic growth model has been developed (see Tables 5 and 6). The scenarios are a combination of reviewed data and our own assumptions supported by in-depth discussion with experts and relevant researchers. Mature culms are defined as culms with the maximum DBH of 8.4 cm.

The regular-harvest scenario comprises three periods and represents controlled growth with tending of emerging shoots as well as selective harvest. The growing period lasts from the planting of rhizome cuttings with a single young culm until shoots begin to emerge regularly. The transition period is characterized by a stand with regular emergence of shoots, selective harvest of an irregular number of culms for tending purposes (which contributes to the modelled carbon stock) and the coexistence of larger and smaller as well as mature and immature culms. The steady state is defined in this scenario by regular emergence and harvest – harvest taking place every 2 years – in a stand made up of equally sized culms. As can be seen in Table 5, the harvested biomass is fully replaced within 2 years. The steady state in the no-harvest scenario is defined by a stand that solely consists of equally sized culms. In both the scenarios, it is assumed that BG biomass remains constant once the steady state is reached.

In both the scenarios, initially 375 bamboos are planted per hectare. Out of these, 315 are allowed to grow in the first year in the harvest scenario (emergence rate of 84%). During the first years, more shoots emerge and grow in the no-harvest scenario, as shoots can emerge uncontrolled.

Results

This section presents the results of the simulations in both the scenarios. The calculations for Moso bamboo and Chinese fir are based on the methodology outlined in the previous section.

Comparison of carbon sequestration of Moso bamboo – regular-harvest scenario – and Chinese fir

In this scenario, harvested culms (i.e. AG biomass) are included in the calculation of annual sequestered carbon of the Moso bamboo plantation. Based on the dynamic growth pattern (see Table 5), Figure 2 compares the annual carbon increment of Moso bamboo

Table 5. Culm density based on a dynamic growth pattern of Moso bamboo – regular-harvest scenario.

	Year after planting																
Culm age	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15–59 (odd years)	16–60 (even years)
1	(375)[a]	315	299	276	565	720	160	215	550	550	550 (M)	550 (M)	550 (M)	550 (M)	550 (M)	550 (M)	550 (M)
2	0	0	315	299	276	565	720	160	215	550	550	550 (M)	550 (M)	550 (M)	550 (M)	550 (M)	550 (M)
3	0	0	0	315	299	276	565	720	160	215	550	550	550 (M)	550 (M)	550 (M)	550 (M)	550 (M)
4	0	0	0	0	315	299	276	565	720	160	215	550	550	550 (M)	550 (M)	550 (M)	550 (M)
5	0	0	0	0	0	315	299	276	565	720	160	215	550	550	550 (M)	550 (M)	550 (M)
6	0	0	0	0	0	0	315	299	276	565	720	160	215[b]	550[b]	550[b]	550 (M)	550 (M)[b]
7	0	0	0	0	0	0	0	315[b]	299[b]	276[b]	565[b]	720[b]	160[b]	0	0	0	550 (M)[b]
Total	0	315	614	890	1455	2175	2335	2550	2785	3036	3310	3295	3125	3300	3300	3300	3850
Phase								Growing						Transition[c]		Steady[c]	

Note: M, maximum size culms (with DBH of 8.4 cm).
Source: Chen et al. (2004) and our own data.
[a]Planted bamboo.
[b]Harvested (and contributing to carbon stock growth).
[c]Estimations.

Table 6. Culm density based on a dynamic growth pattern of Moso bamboo – no-harvest scenario.

Culm age	Year after planting																			
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19–30
1	(375)[a]	330	330	330	330	330	330	330	330	330	330 (M)	330 (M)	330 (M)	330 (M)	330 (M)	330 (M)	330 (M)	330 (M)	330 (M)	330 (M)
2	0	0	330	330	330	330	330	330	330	330	330	330 (M)	330 (M)	330 (M)	330 (M)	330 (M)	330 (M)	330 (M)	330 (M)	330 (M)
3	0	0	0	330	330	330	330	330	330	330	330	330	330 (M)	330 (M)	330 (M)	330 (M)	330 (M)	330 (M)	330 (M)	330 (M)
4	0	0	0	0	330	330	330	330	330	330	330	330	330	330 (M)	330 (M)	330 (M)	330 (M)	330 (M)	330 (M)	330 (M)
5	0	0	0	0	0	330	330	330	330	330	330	330	330	330	330 (M)	330 (M)	330 (M)	330 (M)	330 (M)	330 (M)
6	0	0	0	0	0	0	330	330	330	330	330	330	330	330	330	330 (M)	330 (M)	330 (M)	330 (M)	330 (M)
7	0	0	0	0	0	0	0	330	330	330	330	330	330	330	330	330	330 (M)	330 (M)	330 (M)	330 (M)
8	0	0	0	0	0	0	0	0	330	330	330	330	330	330	330	330	330	330 (M)	330 (M)	330 (M)
9	0	0	0	0	0	0	0	0	0	330	330	330	330	330	330	330	330	330	330 (M)	330 (M)
10	0	0	0	0	0	0	0	0	0	0	330[b]	330[b]	330[b]	330[b]	330[b]	330[b]	330[b]	330[b]	330[b]	330 (M)[b]
Total	0	330	660	990	1320	1650	1980	2310	2640	2970	3300	3300	3300	3300	3300	3300	3300	3300	3300	3300
Phase											Growing									Steady

Note: M, maximum size culms (with DBH of 8.4 cm).
[a]Planted bamboo.
[b]Dying/decomposing shoots.

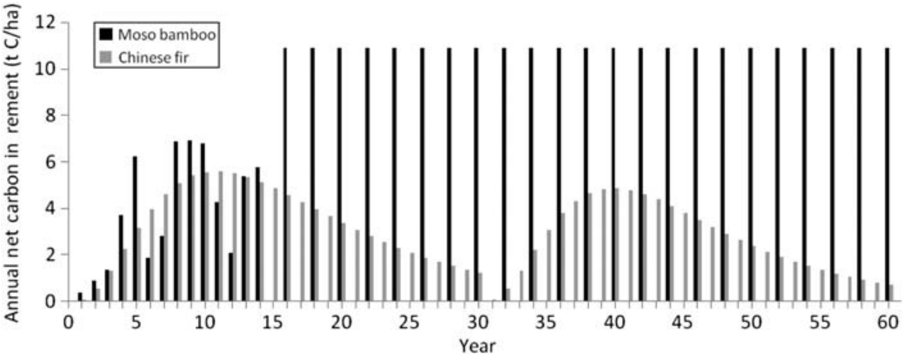

Figure 2. Comparison of modelled annual carbon stock increment of newly established Moso bamboo – regular-harvest scenario – and Chinese fir plantations.

and Chinese fir over two growing cycles of Chinese fir (after each growing cycle, Chinese fir is commonly clear-felled).

Figure 2 shows that Moso bamboo sequesters carbon regularly in the steady state: every 2 years. The annual carbon increment of Chinese fir peaks in the years 11 (first rotation) and 40 (second rotation), after which it steadily decreases until all trees are harvested in years 30 and 60. All harvested AG biomass of Moso bamboo and Chinese fir is assumed to be stored in durable products. Figure 2 also illustrates that Chinese fir sequesters carbon at a comparably lower rate during the second rotation, due to site degradation. Figure 3 compares total accumulated carbon of Moso bamboo and Chinese fir (during 60 years, i.e. two rotations).

The regular carbon increment of Moso bamboo plantations in the steady state is represented in a step-wise increase of total accumulated carbon. Figure 3 shows that during the first years, Moso bamboo sequesters carbon at a comparably quicker rate. In this scenario – starting in year 7 – bamboo carbon is also stored in harvested AG biomass, whereas for Chinese fir all sequestered carbon is part of the standing biomass in the plantation (which is then harvested in years 30 and 60). Once the steady state of the bamboo plantation is reached, only harvested AG biomass contributes biannually to the growth of total carbon stocks in this scenario, whereas BG biomass is assumed to remain constant (including all culms age 1–6 years).

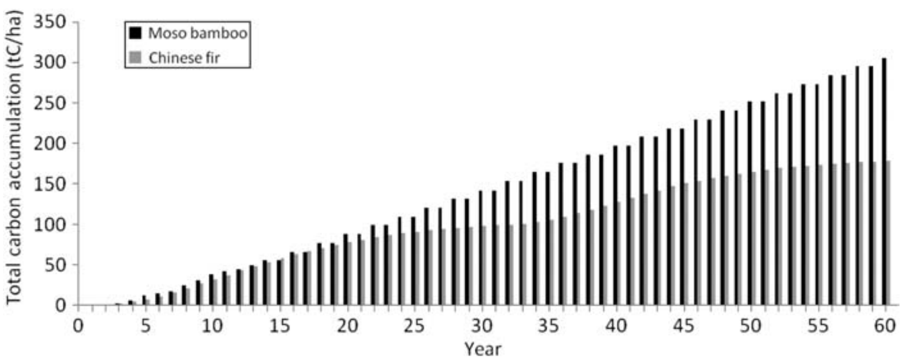

Figure 3. Patterns of modelled aggregated carbon accumulation of newly established Moso bamboo – regular-harvest scenario – and Chinese fir plantations within 60 years.

According to the applied model, in the regular-harvest scenario, Moso bamboo sequesters considerably more carbon than Chinese fir in the same time: 305.77 t C/ha compared to 178.05 t C/ha; which results in mean annual carbon increments of 5.10 t C/ha for Moso bamboo and 2.97 t C/ha for Chinese fir. Consequently, the modelled carbon stock of Moso bamboo in the regular-harvest scenario is 1.68 times higher than that of Chinese fir. It should be noted that it is assumed that all harvested AG biomass of Moso bamboo and Chinese fir are converted into durable products and are thus stored.[3] However, after 60 years, Chinese fir is clear-cut (no remaining standing AG biomass), whereas Moso bamboo has remaining standing AG and BG biomass.

Comparison of carbon sequestration of Moso bamboo – no-harvest scenario – and Chinese fir

It is important to compare and contrast the differences in carbon sequestration between managed (i.e. regularly harvested) and unmanaged bamboo (i.e. not harvested) stands. As Liese (2009) describes, an unmanaged, naturally regenerating bamboo forest contains culms of all ages, including dying and dead ones, the latter ones not being present in a managed bamboo forest.

In the no-harvest scenario, the emergence of shoots is not controlled; therefore, the forest grows comparably quicker in the first years in the no-harvest scenario than in the regular-harvest scenario. For simplicity, a gradual regular growing pattern has been assumed for this scenario. As demonstrated above, Moso bamboo culms start to deteriorate after 10 years. For the calculations, a complete instant biological deterioration of the dead biomass was assumed; it is assumed that the deteriorating culms are replaced by newly emerging shoots. The steady state of this scenario (after year 18) includes only maximum size culms. In order to facilitate a comparison, it is assumed that both scenarios have the same final culm density once the steady state is reached.

The no-harvest scenario is based on the dynamic growth pattern of Moso bamboo (see Table 6). Figure 4 compares the modelled annual carbon sequestration patterns of Moso bamboo in the no-harvest scenario and Chinese fir.

In the no-harvest scenario, the annual carbon increment of Moso bamboo is only comparably faster than that of Chinese fir in the first 3 years. The annual carbon increment of Moso bamboo begins to decrease after year 10 (when the first culms begin

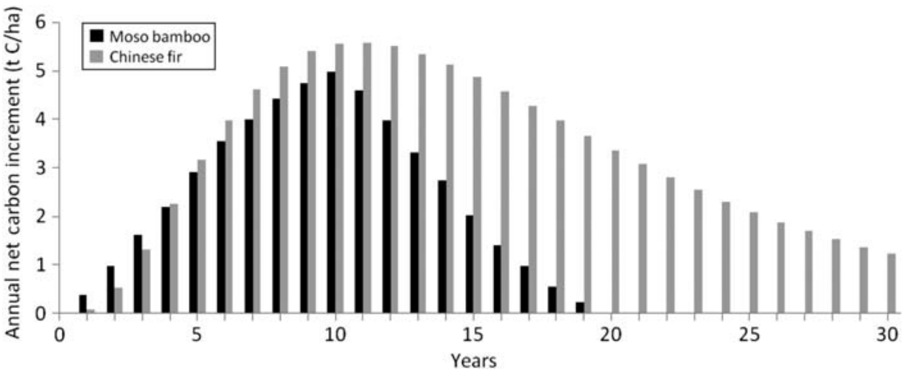

Figure 4. Comparison of modelled annual carbon sequestration patterns of newly established Moso bamboo – no-harvest scenario – and Chinese fir plantations.

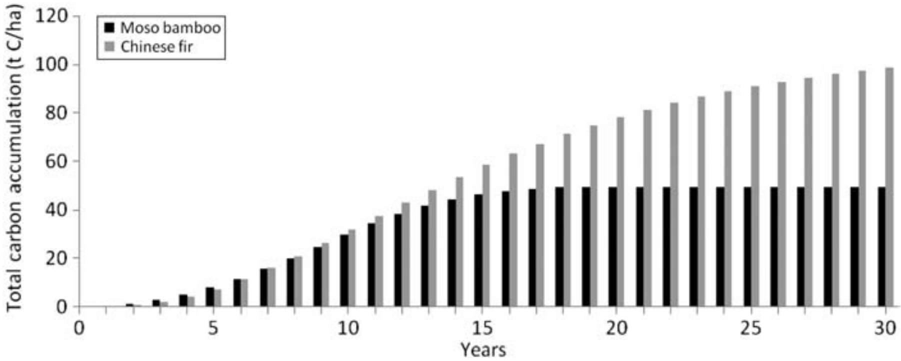

Figure 5. Patterns of modelled aggregated carbon accumulation of newly established Moso bamboo – no-harvest scenario – and Chinese fir plantations.

deterioration). After year 19, new biomass equals deteriorating biomass and there is no additional carbon increment. Figure 5 compares total aggregated carbon accumulation.

Without harvest, Chinese fir is modelled to accumulate considerably more carbon than Moso bamboo within the 30-year period of the Chinese fir rotation. Once the steady state is reached in the bamboo plantation, Moso bamboo's accumulated carbon remains constant, whereas Chinese fir's carbon stock keeps on increasing. Eventually, Chinese fir will also reach a comparable equilibrium in which newly emerging biomass is equalized by deteriorating biomass, but much later on than the Moso bamboo, and much later on than the 30 years of the rotation period. Due to the short lifespan of bamboo culms (and due to their lack of secondary growth), the Moso bamboo plantation reaches the equilibrium earlier and consequently sequesters less carbon in this scenario.

It should be noted that in this scenario, carbon sequestration of Moso bamboo continues after year 19. As demonstrated in Figure 6, Moso bamboo sequesters carbon throughout 30 years, in the form of new AG biomass. However, after year 19 – once all culms reached maturity – newly emerging AG biomass is equalized by deteriorating AG biomass.[4]

In this scenario, Moso bamboo sequesters around 49.51 t C/ha within 30 years without harvest, while Chinese fir sequesters around 98.75 t C/ha. The mean annual increment of Chinese fir is 3.29 t C/ha and of Moso bamboo, only 1.65 t C/ha. Consequently, the

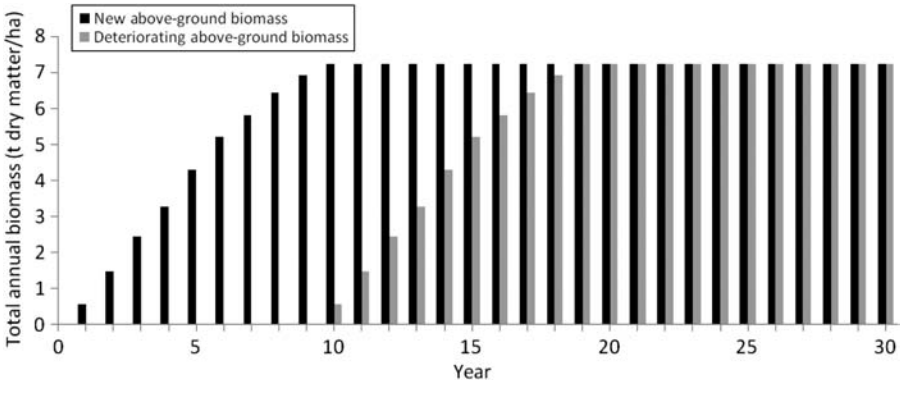

Figure 6. New above-ground biomass and deteriorating above-ground biomass of Moso bamboo – no-harvest scenario.

modelled carbon stock of Chinese fir is 1.99 times higher than that of Moso bamboo in the no-harvest scenario.

Discussion

The modelled data indicate that sequestered carbon in Moso bamboo plantations would only exceed that of Chinese fir when it is managed, i.e. with regular selective harvest. Only in this way are bamboo's characteristics as a fast-growing and highly renewable plant utilized. This may explain why in the literature conflicting results have been reported. For example, Yen and Lee (2011) state that 'Moso bamboo is a superior species for carbon sequestration when compared with China fir', while Xiao et al. (2010) demonstrate that carbon pools of Moso bamboo are slightly lower than that of Chinese fir. Regular selective harvest of Moso bamboo plantations increases their carbon sequestration capacity, which implies that bamboo plantations can contribute to livelihoods of rural populations while combating climate change – which represents a significant difference between bamboos and most trees: bamboo plantations do not need to be 'locked up' to provide carbon sequestration services. Through selective harvest and storage of harvested biomass in durable harvested wood products (HWP), bamboo's fast growth and high renewability can be utilized for high carbon sequestration rates and can simultaneously allow rural communities to derive livelihood services. Considering the many ways in which bamboos can contribute to livelihoods – 1500 commercial applications have been recorded by Scurlock et al. (2000) – this represents a unique opportunity for policy makers.

Moreover, managed bamboo plantations can take pressure off other forest resources – which are not as quickly renewable as bamboo – if the harvested bamboo is stored in durable products which can act as substitutes.

This study also shows that the impacts of management and usage of products, in HWP, determine the role bamboo can play in climate change mitigation. In terms of durability, studies indicate that bamboo has comparable characteristics to other forest species for product development (Benton et al. 2011). However, more research into the durability of harvested bamboo products is necessary to be able to assess whether HWP from bamboo can represent a permanent carbon sink. It should be pointed out that in the simulation, Moso bamboo is harvested 31 times in the regular-harvest scenario, whereas Chinese fir is harvested only twice. Until harvest, the plantation is prone to external risks – which could potentially limit its sink function. On the other hand, harvested biomass can only be considered a permanent sink as long as it is processed into durable products – which also requires specific risk assessments.

The review of related literature shows that the standing carbon for Moso bamboo plantations varies strongly. The modelled data of this study are within the range described by the reviewed studies, indicating that the results of the model can be considered a realistic approximation (see Huang 1987; Huang et al. 1993; Li et al. 1993; Isagi et al. 1997; Chen et al. 1998; Peng et al. 2002; He et al. 2003, 2007; Zhou & Jiang 2004; Xiao et al. 2007; Qi et al. 2009; Hao et al. 2010; Yen & Lee 2011). Moreover, the reviewed studies support the conclusion that Moso bamboo can contribute to carbon sequestration in a similar way as Chinese fir – provided that the harvested resources are turned into durable HWP with long-term carbon storage. However, the results also illustrate that bamboo and trees have different sequestration patterns. Trials successfully demonstrated that bamboo can be applied for the rehabilitation of ecosystems on degraded lands (INBAR 2003). This indicates potentials for afforestation with bamboo on land which would otherwise not be suitable for other plants.

In both the scenarios, the calculated data are based on a maximum culm density of 3300 culms/ha. The culm density is obviously a relevant factor for the calculation of carbon sequestration per unit area. Reality shows that under intensive management practices in Moso bamboo forests in China, a density of 3500 culms/ha with DBH of 10 cm or higher can be reached (Chinese National Standard (GB/T 20391-2006) 2006). However, it can be expected that intensive management impacts bamboo's biomass accumulation. For example, Yen and Lee (2011) demonstrated that higher culm density leads to decreased DBH, i.e. lower biomass accumulation per culm. There may also be higher emissions resulting from intensive management practices. On the other hand, studies indicate that through management techniques, bamboo could sequester higher amounts of carbon. A Moso bamboo forest without harvest requires approximately 19 years to reach maturity, which is significantly faster than other timber species adapted to the same habitat. At the same time, regularly harvested bamboo stands require more frequent management practices compared to other forests, but can sequester higher amounts of carbon. Each development stage requires specific silvicultural interventions (Lobovikov et al. 2009). Therefore, the impacts of management practices on carbon sequestration capacity, the ecosystem and carbon distribution patterns of bamboo forest are key issues to be addressed and researched. At present, this issue has received little attention from researchers (Qi et al. 2009). Zhou et al. (2010) demonstrated that intensive management decreased total carbon storage in a Moso bamboo plantation. On the other hand, Yen and Lee (2011) emphasized that 'thinning is a necessary method to maintain vigor of bamboo forests'. These findings indicate that sustainable bamboo management is crucial for achieving continued carbon sequestration within bamboo plantations. Suitable management techniques should be developed and advocated for both bamboo plantations and natural bamboo forests to realize bamboo's full potential in carbon sequestration. Tenure and ownership of bamboo resources are globally diverse: the majority of Asian bamboo resources (73%) are publicly owned, whereas 63% of African bamboo resources are privately owned (FAO 2007). These access arrangements also need to be taken into consideration for the development of specific management measures and the assessment of bamboo's potential in climate change mitigation.

Naturally, bamboo often grows within mixed stands; therefore, the processes and interactions with other plants – also with regard to carbon sequestration – should also be researched, even more so when considering that it has been observed that 'the growth performance of bamboo in mixed stands exceeds the performance found in pure stands' (Fu 2001).

A study by Chen et al. (2009) estimated that the carbon stocks in Chinese bamboo plantations will increase from 727.08 Tg C in 2010 to 1017.54 Tg C in 2050 – which represents an increase of nearly 40%. Similar simulations are lacking for other countries and regions, but should be developed in order to be able to assess bamboo's global potential in climate change mitigation.

Due to the lack of appropriate data, the model and calculations used in this paper have several limitations. The model does not account for competition within the bamboo plantation. In addition, variations in the climatic conditions are not considered, and the data reflect only one bamboo species, Moso. The calculations presented in this study are based on current climate conditions. Climate change will impact the growth of Moso bamboo and Chinese fir as well, and may alter their resilience to increased precipitation, temperature variability, pests and diseases, as well as exposure to extreme weather events or fires. Species-specific vulnerability studies are needed to determine the resilience of bamboo resources to climate change. Another limitation of the studies presented is that they do not consider soil carbon. Isagi et al. (1997) demonstrated the significance of the soil carbon pool in Moso bamboo plantations – around 56% of total ecosystem *C* is stored in the soil system. Since this study only considered biomass (i.e. vegetative) growth for estimating carbon sequestration by Moso bamboo, it can be expected that total ecosystem carbon stocks are considerably larger. Moreover, it is likely that BG carbon stocks are actually dynamic, even after the stands reached the steady state. However, a quantification of these effects – based on the existing data – is not possible yet. These limitations emphasize the need for further research, especially on carbon fluxes and BG biomass generation within the bamboo ecosystem.

Conclusions

This study underlines the similarities and differences in carbon sequestration between a monopodial bamboo and rapid-growing tree plantations. Under regular management practices in the form of biennial selective harvesting regimes, this study, through modelling and analysis of the carbon sequestration patterns, indicates that Moso bamboo plantations are likely to sequester carbon at a somewhat higher level than comparable fast-growing trees. Moso bamboo thus appears to be a viable option for carbon sequestration within forestry.

Sustainable management and selective harvesting practices are essential for bamboo stands to utilize and sustain their capacity for carbon sequestration. The quantity of sequestered carbon of an unmanaged Moso bamboo plantation was calculated to be around half of that of a Chinese fir plantation. When considering bamboo for afforestation, it should be realized that mixed stands might increase bamboo's productivity. This study also demonstrated that bamboo's characteristics of fast growth and high renewability imply potential for simultaneous carbon sequestration and livelihood utilization.

In a mature bamboo stand, the annual net carbon sequestration is constant due to the occurrence of full re-growth after regular selective harvesting. Moreover, after 60 years, the model demonstrated that bamboo has remaining standing biomass (with continuing carbon sequestration potential), whereas Chinese fir is clear-cut after 60 years and carbon sequestration processes are terminated.

Since harvested bamboo and plantation wood are counted as permanently stored carbon in the models used, the importance of HWP and their potential to contribute to carbon sequestration have been highlighted. In order to effectively capitalize on bamboo's advantages of fast growth and renewability, carbon accounting methodologies and mechanisms for HWP need to be developed. Moreover, policy makers should further support the usage of highly renewable bamboo as a substitute for timber, which can take the pressure off other forestry resources.

More research is needed to overcome the various limitations of this study, e.g. the share of carbon in the soil system has to be quantified in order to calculate ecosystem carbon stocks. Nevertheless, our results provide a strong indication that regularly harvested bamboo forests can contribute significantly to climate change mitigation. They also suggest that bamboo deserves more recognition from policy makers and researchers as a plant capable of providing solutions to climate change mitigation, adaptation and rural development.

Acknowledgements

The authors would like to thank Prof. Chen Shuanglin from the Research Institute of Subtropical Forestry of the Chinese Academy of Forestry and Prof. Zhang Peixin of the Anji Forestry Bureau for their constructive review and helpful insights. The authors also thank their colleagues at INBAR, Dr Lou Yiping and Dr Coosje Hoogendoorn, for their critical review and expertise.

Notes

1. Since the calculations for bamboo and Chinese fir are based on data from comparable but not identical locations in China, the differences and similarities in sequestration between bamboo and Chinese fir should be considered as an indication only, not as absolute and quantitative.
2. Coordinates of the research site: 28°31′–29°20′N, 118°41′–119°06′E.
3. BG biomass of Moso bamboo is assumed to remain constant.
4. In this scenario, it is assumed that BG biomass remains constant after year 19 – once all culms in the stand reach maturity and the maximum DBH of 8.4 cm.

References

Belcher B. 1995. Bamboo and rattan production to consumption systems: a framework for assessing development options. INBAR Working Paper No. 4. New Delhi: INBAR.

Benton A, Cronin T, Frith O, Jonkhart J, Wu J. 2011. Market potential of bamboo and rattan products. INBAR Working Paper 63. Beijing: INBAR.

Buckingham K. 2009. Deep roots in culture, shallow roots in nature: identifying sustainable bamboo management challenges for China and the implications for multidisciplinary research. Paper presented at: International Association of Agricultural Economists Conference; Beijing, China, Aug 16–22.

Buckingham K, Jepson P, Wu L, Rao I, Jiang S, Liese W, Lou Y, Fu M. 2011. The potential of bamboo is constrained by outmoded policy frames. Ambio. 40(5):544–548.

Chen H, Hong W, Lan B, Zheng Y, He D. 1998. Study on biomass and productivity of *Phyllostachys heterocycla* cv *pubescens* forest in the north of Fujian. Sci Silvae Sinicae. 1:60–64 (in Chinese with English summary).

Chen S, Wu B, Wu M, Zhang D, Cao Y, Yang Q. 2004. A study of the inter-annual succession rule and influential factors of young stands structures of *Phyllostachys pubescens*. J Zhejiang For Coll. 21(4):393–397 (in Chinese with English summary).

Chen X, Zhang X, Zhang Y, Booth T, He X. 2009. Changes of carbon stocks in bamboo stands in China during 100 years. For Ecol Manage. 258:1489–1496.

Chinese National Standard (GB/T 20391-2006) [Internet]. 2006. High yield management techniques for Moso bamboo stands; [cited 2012 Jun 15]. Available from: http://www.cn-standard.net/qtweb/debzfy/debzdetail/371/701C8D93.shtml

Dueking R, Gielis J, Liese W. 2011. Carbon flux and carbon stock in a bamboo stand and their relevance for mitigating climate change. J Am Bamboo Soc. 24(1):1–7.

Eliasch J. 2008. Climate change: financing global forests. The Eliasch review. London: Earthscan.

[FAO] Food and Agriculture Organisation of the United Nations. 2007. World bamboo resources. a thematic study prepared in the framework of the Global Forest Resources Assessment 2005. Rome: FAO.

FAO. 2010. FRA Global Forest Resource Assessment 2010 main report. FAO Forestry Paper 163. Rome: FAO.

Fu J. 2001. The competitive strength of Moso bamboo (*Phyllostachys pubescens* Mazel ex H. de Lehaie) in the natural mixed evergreen broad-leaved forests of the Fujian Province, China [PhD dissertation]. Göttingen: Georg-August Universität Göttingen.

Fu M, Banik R. 1995. Bamboo productions systems and their management. In: Rao I, Sastry B, editors. Bamboo, people and the environment. Proceedings of the Vth International Bamboo Workshop, Jun 19–22, Ubud. Beijing: INBAR.

Hao Y, Jiang H, Xiang C, Ma Y, Jin J, Yu S. 2010. Biomass structure of *Phyllostachys heterocycla* cv. *pubescens* population in the Tianmu Mountain. J Sichuan For Sci Tech. 31(4):29–33 (in Chinese with English abstract).

He D, Hong W, Wu C, Lan B, Huang H, Wu X. 2003. Study of biomass and energy distribution of natural *Phyllostachys heterocycla* cv. *Pubescens* in Wuyi Mountains and its comparison with high-yield forest. Acta Bot Boreal-Occident Sin. 23(2):291–296 (in Chinese with English abstract).

He Y, Fei S, Jiang J, Chen X, Yu Y, Tang S, Zhu W. 2007. The spatial distribution of organic carbon in *Phyllostachys pubescens* and *Pleioblastus amarus* in Changning County. J Sichuan For Sci Tech. 5:13–17 (in Chinese with English abstract).

Huang Q. 1987. Studies on the biomass of bamboo (*Phyllostachys pubescens*). J Subtrop For Sci Tech. 15(2):90–98 (in Chinese).

Huang Q, Yang D, Shen Y, Qiu G. 1993. Studies on the primary productivity of bamboo (*Phyllostachys pubescens*) grove. For Res. 6(5):536–540 (in Chinese with English abstract).

[IEA] International Energy Agency. 2011. World energy outlook 2011: executive summary. Paris: IEA.

[INBAR] The International Network for Bamboo and Rattan. 2003. Greening red earth: bamboo's role in the environmental and socio-economic rehabilitation of villages devastated by brick mining. Beijing: INBAR.

INBAR [Internet]. 2004. Bamboo – a brief introduction: a unique resource for livelihood development. INBAR Development Pages; [cited 2012 Jul 12]. Available from: http://www.inbar.int/livelihood/doc/Bamboo%20Introduction%20Devpage.pdf

INBAR. 2009. The climate change and bamboo: mitigation and adaptation. Beijing: INBAR.

INBAR [Internet]. 2011. Bamboo flowering database; [cited 2011 Jul 1]. Available from: http://www.inbar.int/flowering/search.asp

[IPCC] Intergovernmental Panel on Climate Change. 2011. Special report: managing the risks of extreme events and disasters to advance climate change adaptation – summary for policy makers. Geneva: IPCC.

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

Jiang P, Meng C, Zhou G, Xu Q. 2011. Comparative study of carbon storage in different forest stands in subtropical China. Bot Rev. 77(3):242–251.

Kuehl Y, Henley G, Lou Y. 2011. The climate change challenge and bamboo: mitigation and adaptation. Beijing: INBAR.

Li Z, Lin P, Qiu X. 1993. Studies on the biomass and productivity of *Phyllostachys pubescens* community in South Fujian. J Xiamen Univ (Nat Sci). 32(6):762–767 (in Chinese with English abstract).

Liese W. 2009. Bamboo as carbon-sink: fact or fiction? Paper presented at: 8th World Bamboo Congress; Bangkok, Thailand, Sept 16–19.

Lobovikov M, Lou Y, Schoene D, Widenoja R. 2009. The poor man's carbon sink: bamboo in climate change and poverty alleviation. FAO Non-Wood Forest Products Working Document No. 8. Rome: FAO.

Lobovikov M, Schoene D, Lou Y. 2011. Bamboo in climate change and rural livelihoods. Mitig Adapt Strat Global Change. 17(3):261–276.

Lou Y, Li Y, Buckingham K, Henley G, Zhou G. 2010. Bamboo and climate change mitigation. INBAR Technical Report 32. Beijing: INBAR.

Magel E, Kruse S, Luetje G, Liese W. 2005. Soluble carbohydrates and acid invertases involved in the rapid growth of the developing culms in *Sasa palmata* (Bean) Camus. Bamboo Sci Cult. 19:23–29.

Marsh J, Smith N. 2007. New bamboo industries and pro-poor impacts: lessons from China and potential for Mekong counties. In: Oberndorf R, Durst P, Mahanty S, Burslem K, Suzuki R, editors. A cut for the poor. Proceedings of the International Conference on Managing Forests for Poverty Reduction: Capturing Opportunities in Forest Harvesting and Wood Processing for the Benefit of the Poor; Ho Chi Minh City, Vietnam, 2006, Oct 3–6. Bangkok: FAO and RECOFTC (The Center for People and Forests).

Peng Z, Lin Y, Liu J, Zou X, Guo Z, Guo Q, Lin P. 2002. Biomass structure and energy distribution of *Phyllostachys heterocyla* cv. *pubescens* population. J Xiamen Univ (Nat Sci). 41(5):579–583 (in Chinese with English abstract).

Qi L, Liu G, Fan S, Yue X, Zhang H, Du M. 2009. Effects of different tending measures on carbon density, storage, and allocation pattern of *Phyllostachys edulis* forests in western Fujian province. Chinese J Ecol. 28(8):1482–1488 (in Chinese with English summary).

Ruiz-Perez M, Zhong M, Belcher B, Xie C, Fu M, Xie J. 1999. The role of bamboo plantations in rural development: the case of Anji County, Zhejiang, China. World Dev. 27(1):101–114.

Scurlock J, Dayton D, Hames B. 2000. Bamboo: an overlooked biomass resource? Biomass Bioenergy. 19:229–244.

Shibata S. 2002. Flowering of *Phyllostachys pubescens* and germination of caryopses. In: Kumar A, Tao I, Sastry C, editors. Bamboo for sustainable development. Proceedings of the Vth International Bamboo Congress and the VIth International Bamboo Workshop; San Jose, Costa Rica, 1998 Nov 2–6. INBAR Proceedings No. 7. INBAR, Beijing.

Tian DL. 2005. The function and process of Chinese Fir ecosystem. Beijing: Science Publishing House.

Watanabe M, Ueda K, Manabe I, Akai T. 1982. Flowering, seeding, germination and flowering periodicity of *Phyllostachys pubescens*. J Japanese For Soc. 64:107–111.

Xiao F, Fan S, Wang S, Guan F, Yu X, Shen Z. 2010. Estimation of the carbon balance in Moso bamboo and Chinese fir plantation ecosystem. Sci Silvae Sinicae. 46(11):59–65 (in Chinese).

Xiao F, Fan S, Wang S, Xiong C, Zhang C, Liu S, Zhang J. 2007. Carbon storage and spatial distribution in *Phyllostachys pubescens* and *Cunninghamia lanceolata* plantation ecosystem. Acta Ecol Sinica. 7:2794–2801 (in Chinese with English summary).

Xu X, Cao M, Li K. 2007. Temporal-spatial dynamics of carbon storage of forest vegetation in China. Prog Geogr. 26(6):1–10.

Xu X, Zhu X, Wang F, Mao H, Cheng Q, Wang L, Wang C, Zhu T. 2009. Carbon content rate of 11 reforestation tree species for carbon sink in Zhejiang. J Bamboo Res. 1:21–24 (in Chinese with English summary).

Yen T, Lee J. 2011. Comparing aboveground carbon sequestration between moso bamboo (*Phyllostachys heterocycla*) and China fir (*Cunninghamia lanceolata*) forests based on the allometric model. Forest Ecol Manag. 261:995–1002.

Zhou G, Jian R, Xu Q. 2010. Advance in study of carbon fixing and transition in the ecosystem of bamboo stands. Beijing: Science Press of China (in Chinese with English abstracts).

Zhou G, Jiang P. 2004. Density, storage and spatial distribution of carbon in *Phyllostachys pubescens* forest. Sci Silvae Sinica. 6:20–24 (in Chinese with English summary).

Zhou G, Jiang P, Mo L. 2009. Bamboo: a possible approach to the control of global warming. Int J Nonlinear Sci Numer Simul. 10(5):547–550.