Carbon sequestration by Chinese bamboo forests and their ecological benefits: assessment of potential, problems, and future challenges

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Abstract: Bamboo is widely distributed in Southeast Asia, Africa, and Latin America. As a major non-wood forest product and wood substitute, bamboo is of increasing interest to ecologists owing to its rapid growth and correspondingly high potential for mitigating climate change. With a long history of production and utilization of bamboo, China is one of the countries with the richest bamboo resources and largest area of bamboo forest, and has paid unprecedented attention in recent decades to management of its bamboo forests. This review summarizes the versatility of bamboo in terms of its ecological benefits including carbon sequestration, water and soil conservation, its benefits for socioeconomic development, and its potential to mitigate climate change. Current problems, and the future potential of and challenges to rapidly expanding bamboo forests under both wider use of intensive management and the effects of global warming, are also discussed.

Key words: socioeconomic benefits, bamboo management, mitigate climate change, renewable resource, bamboo.

Résumé : Le bambou est largement distribué dans le sud-ouest de l'Asie, en Afrique et en Amérique latine. Comme produit forestier non-ligneux et substitut du bois, le bambou connaît un intérêt croissant auprès des écologistes à cause de sa croissance rapide et conséquemment de son grand potentiel pour mitiger le changement climatique. Avec sa longue histoire de production et d'utilisation des ressources en bambou, la Chine constitue un des pays possédant les plus grandes richesses en bambou et les plus grandes superficies en forêts de bambou; elle accorde une attention sans précédent au cours des récentes décades à l'aménagement de ses forêts de bambou. Cette revue fait état de la versatilité du bambou sous les termes de ses bénéfices écologiques incluant la séquestration du carbone, la conservation du sol et de l'eau, de ses bénéfices liés au développement socio-économique, et de son potentiel pour mitiger les changements climatiques. On discute des problèmes courants, le potentiel futur et les défis d'étendre les forêts de bambou tant au point d'une utilisation accrue de l'aménagement intensif, que des effets sur le changement global. bénéfices socio-économiques, aménagement du bambou, mitigation du changement climatique, ressource renouvelable, expansion du bambou.

Mots-clés : bénéfices socio-économiques, aménagement du bambou, mitigation du changement climatique, ressource renouvelable, bambou.

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Introduction

Bamboo (*Gramineae*), an ancient woody grass, is an important component of many forest ecosystems. The bamboo family includes more than 107 genera with more than 1300 species (Zhu 2001). Bamboo has unique features that distinguish it from most other woody plants. For example, culms that are connected by an extensive system of rhizomes, leading to rapid asexual reproduction of new culms (Janzen 1976; Isagi et al. 1997; Li et al. 1998). Bamboo adapts

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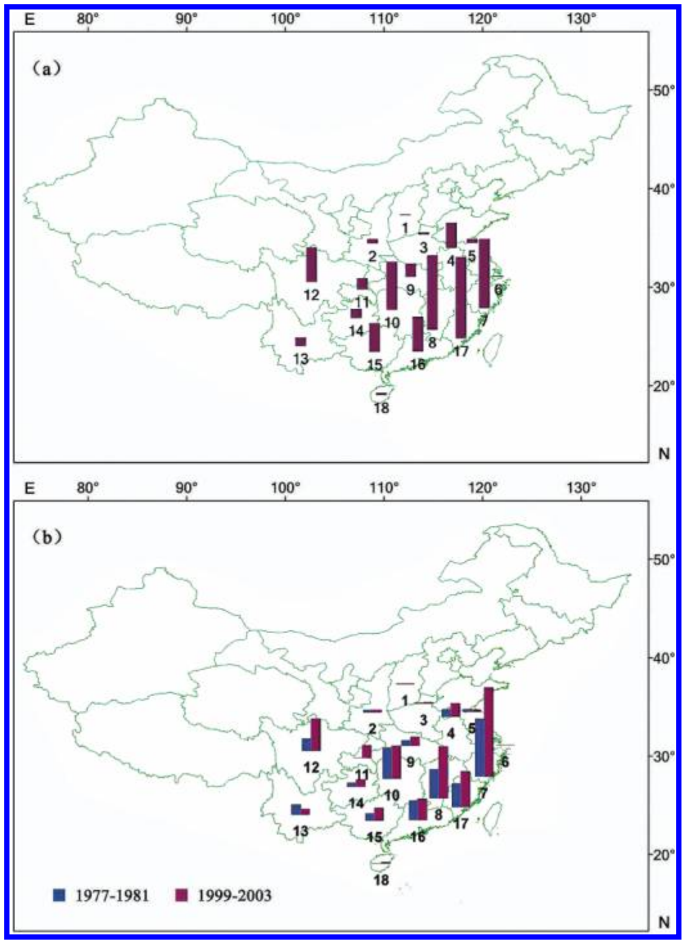
easily to a range of climatic and soil conditions, and is therefore widely distributed in the tropical and subtropical zones between approximately 46°N and 47°S latitude, covering a total area of about 31.5 million ha, and accounted for about 0.8% of the world's total forested area in 2010 (FAO 2010). Bamboo is common in Asia, Africa, and Latin America, but its origins lie in Southeast Asia. As a major non-wood forest product and wood substitute, bamboo has been widely used for numerous purposes. Compared with other types of forest, the bamboo forest generates different ecosystem services, such as carbon storage, and water and soil conservation because of its special root resprouting regeneration strategy and selective cutting utilization system (Lobovikov et al. 2007). Therefore, the bamboo forest is playing an increasingly important role in socioeconomic development and international trade.

Due to its vast territory, complex terrain, and diverse climate, China has one of the richest bamboo resources in the world. China has the highest bamboo biodiversity, with 39 genera and 509 species, accounting for 36% and 39% (respectively) of the total bamboo genera and species in the world (Zhu 2001). Moreover, China's bamboo forests cover an area of 4.84 million ha in 2005, accounting for 2.8% of China's forested area and 15.4% of the world's area of bamboo (SFAPRC 2006; FAO 2010). The current area represents 1.5 times the estimated area in the 1950s, and has increased by about 0.1 million ha annually since that decade (Jiang 2010). Among the bamboo species, the Moso bamboo (*Phyllostachys pubescens*) forest covers the largest area, 3.37 million ha, accounting for 70% of China's bamboo forest area and 80% of the world's Moso bamboo area (SFAPRC 2006). Natural bamboo forest occurs in 18 of China's provinces, but more than half of the bamboo forest area is distributed in Fujian Province, Jiangxi Province, and Zhejiang Province (Fig. 1*a*). Because of its high ecological and socioeconomic versatility, and especially its great potential for carbon sequestration and its unique role in mitigating climate change (Fig. 2), bamboo has been receiving increasing attention in recent decades (Li et al. 2003; Zhou et al. 2006; FAO 2010).

Most previous studies of bamboo focused on its cultivation and management (Jiang et al. 2006; Chen et al. 2007; Mohamed et al. 2007; Li et al. 2010), its physiology (Li et al. 1998; Shi et al. 2005; Lin et al. 2008), its introduction into new regions (Xu and Qin 2003; Zhao et al. 2006), its hydrological effects (Xiao 2001; Wu et al. 2003; Onozawa et al. 2009; Shinohara et al. 2010), the processing and utilization of bamboo products (Zhang et al. 2008; Xu and Ren 2008), its productivity and carbon storage (Veblen et al. 1980; Tripathi and Singh 1994, 1996; Zhou and Jiang 2004; Xiao et al. 2007), and its policy and products (Ruiz Perez et al. 1996). However, there has been no comprehensive assessment of the ecological and socioeconomic benefits of bamboo forests in China. The objectives of the present paper are: (*i*) to review the literature on bamboo research and utilization in China; (*ii*) to evaluate the versatility of bamboo in terms of its ecological and socioeconomic benefits, and especially its potential role in the mitigation of climate change; (*iii*) to assess the potential of the bamboo forest, and the future problems and challenges related to the current rapid development of this resource.

Fig. 1. Distribution of Chinese bamboo forests in terms of their area (10 000 ha) and carbon storage (Tg). Vertical bars represent (*a*) the areas of bamboo forests in each province based on the 6th National Forestry Inventory (1999–2003) and (*b*) the carbon storage in each province based on the 2nd (1977–1981) and 6th (1999–2003) National Forestry Inventories. Sampling locations: 1, Shanxi; 2, Shaanxi; 3, Henan; 4, Anhui; 5. Jiangsu; 6, Shanghai; 7, Zhejiang; 8, Jiangxi; 9, Hubei; 10, Hunan; 11, Chongqing; 12, Sichuan; 13, Yunnan; 14, Guizhou; 15, Guangxi; 16, Guangdong; 17, Fujian; 18, Hainan.



Ecological benefits

Carbon sequestration

With its fast growth rate and high annual regrowth after harvesting, the bamboo forest has a high carbon storage potential (Table 1) (Zhou and Jiang 2004), especially when the harvested culms are transformed into durable products. The increased lifespan of durable bamboo products made possible by modern technology can ensure that the sequestered carbon will not return quickly to the atmosphere, thereby prolonging the carbon storage by bamboo.

Zhou and Jiang (2004) found that the total carbon storage capacity in a typical Moso bamboo ecosystem, including in the soil, was 106.36 t·ha^{-1}, of which the aboveground green vegetation stored 34.3 t·ha^{-1}, accounting for 32.3% of the total, and that the forest floor and soil (0 to 60 cm in depth) stored 72.2 t·ha^{-1}, accounting for 67.7% of the total (Ta-Table 2). This suggests that the soil carbon content is about twice the content in the aboveground vegetation. Similarly,

Fig. 2. Ecological and socioeconomic benefits provided by bamboo in China, and potential problems.

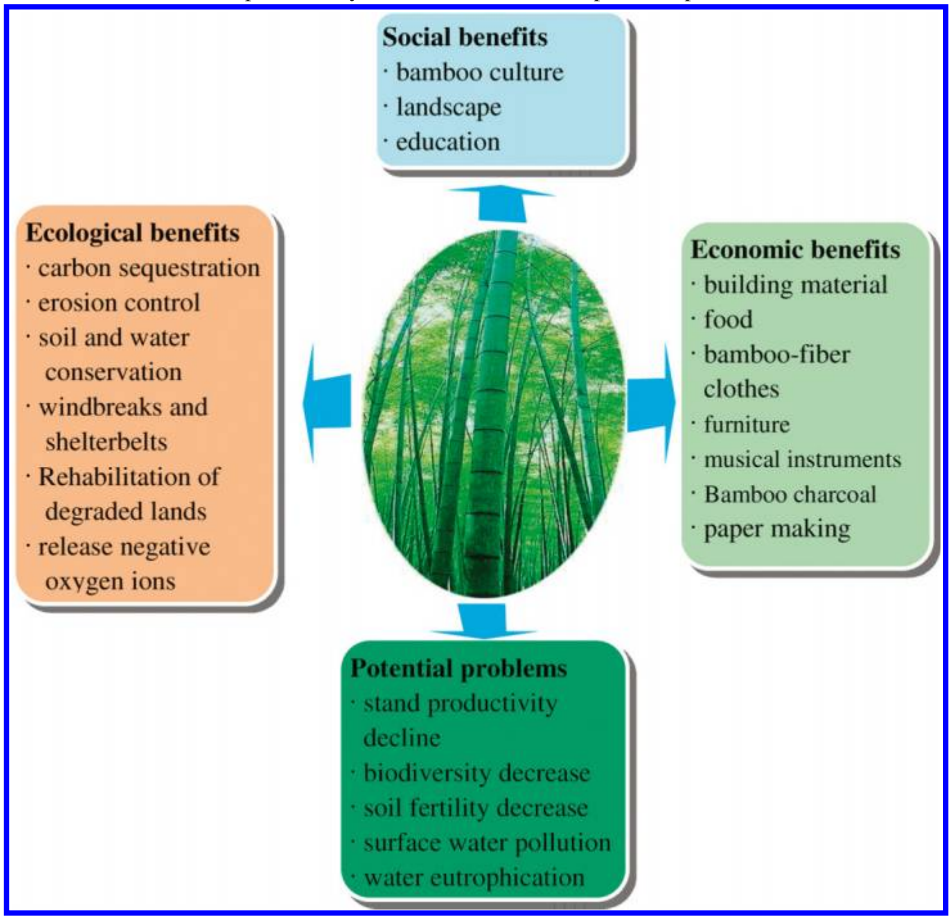


Table 1. Carbon storage by different organs of *Phyllostachys pubescens* (Zhou and Jiang 2004).

Organ	Carbon storage ($t{\cdot}ha^{-1}$)	Proportion (% of total)
Leaves	1.5±0.1	4.9
Branches	2.0±0.2	6.5
Culm	15.6±1.4	51.0
Underground trunk	1.7±0.2	5.6
Underground stem	3.7±0.3	12.2
Roots	6.1±0.5	19.8
Total	30.6±2.4	100

Note: Sample size: n = 7 for underground stem and n = 42 for the other organs.

Table 2. Carbon storage and spatial distribution in a typical *Phyllostachys pubescens* stand (Zhou and Jiang 2004).

Component	Carbon storage ($t{\cdot}ha^{-1}$)	Proportion (% of total)
Tree layer	30.6±2.4	28.8
Shrub layer	3.2±0.3	3.0
Herb layer	0.5±0.03	0.5
Subtotal (aboveground)	34.3	32.3
Litter layer	0.7±0.1	
0 to 20 cm in the soil	37.0±7.8	
20 to 40 cm in the soil	22.3±4.5	
40 to 60 cm in the soil	12.2±2.3	
Subtotal (soil)	72.2	67.7
Total	106.5	100

the total carbon storage in *Phyllostachys bambusoides* bamboo stands in Japan was 165.1 $t{\cdot}ha^{-1}$, of which 31.7% was aboveground and 68.3% was belowground (Isagi 1994). Tripathi and Singh (1996) also detected that the carbon stock in *Dendrocalamus strictus* bamboo stands in the Indian dry tropics was 75.4 $t{\cdot}ha^{-1}$, of which 23%–28% was distributed in vegetation, 2% in litter and 70%–75% in soil.

Because of bamboo's fast growth, the annual carbon fixation of the tree layer in a Moso bamboo forest was 5.10 $t{\cdot}ha^{-1}$, which was 1.33 times the value for a tropical mountain rain forest (Zhou and Jiang 2004), and 1.41 times the value for Chinese fir (*Cunninghamia lanceolata*) at 5 years old and 0.94 times at 12 years old in Huitong County, one distribution center of Chinese fir plantation (Zhao et al. 2009). This high annual rate of carbon accumulation means that the bamboo forest is one of the most efficient types of forest vegetation for carbon fixation.

Different calculation methods produce estimates of the total carbon storage in Chinese bamboo forests from 1999 to 2003 ranging from 605.5 to 1425 Tg C (Lou et al. 2010). During the past 5 decades, the increase in the area of bamboo stands has been accompanied by rapid increases in the carbon stocks of Chinese bamboo stands since the 1950s. Chen et al. (2009) estimated that total carbon storage has increased from 318.6 Tg C (1950 to 1962) to 631.6 Tg C (1999 to

2003) (Fig. 3). The carbon storage in bamboo forests differs among the regions of China; Zhejiang, Jiangxi, Fujian, Hunan, Guangdong, and Sichuan provinces had the major carbon pools (Fig. 1*b*), accounting for 80.0% to 83.1% of total carbon storage by bamboo forests from 1977 to 2003 (Wang et al. 2008).

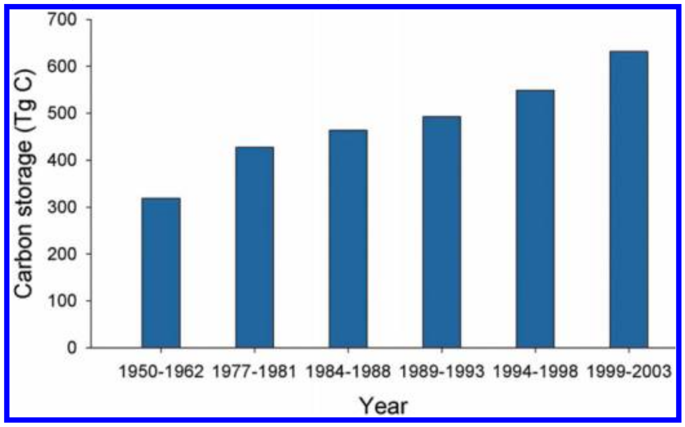
The carbon density for bamboo forests, which ranges from 168.7 to 259.1 t C·ha^{-1}, is generally much higher than China's average forest carbon density (38.7 t C·ha^{-1}), and is also higher than the global average forest carbon density of 86 t C·ha^{-1} (Lou et al. 2010). This indicates the huge potential for carbon sequestration in Chinese bamboo forests.

Erosion control and water conservation

Bamboo forests have an extensive rhizome system, a thick litter layer, highly elastic culms, and a dense canopy. These characteristics give bamboo forests a high capacity for erosion control, soil and water conservation, landslide prevention, protection of riverbanks, and windbreak and shelterbelt potential. In China, more than 90% of bamboo forests are found in the source regions of major rivers and lakes and along riverbanks, where they play an important role in regulating water flows, protecting water sources, and reducing water erosion (Xiao 2001).

Bamboo rhizomes are powerful stabilizers of the soil. A 5 year field experiment, located in Maojianshan Town, Yuexi County, Anhui Province (116°20′E, 30°40′N), showed an average surface soil runoff per month in bamboo forests of only 0.10 m^3·ha^{-1}, which is equivalent to only 77% of the rate for the Chinese fir forest and 35% of the rate for the *Pinus massoniana* forest (Wu et al. 2003); the resulting sediment delivery rate was 0.18 kg·ha^{-1}, amounting to only 42.8% of the rate for the Chinese fir forest and 23.6% for the *P. massoniana* forest. The anti-erodibility index (i.e., the ability of soil resisting water dispersing and suspension) in the top 40 cm of the soil in a bamboo forest was 1.05, which is higher than that of a *Robinia pseudoacacia* forest (0.98), a *Metasequoia glyptostroboides* forest (0.52), and a *Populus deltoides* forest (0.38 for the I-69 clone) (Xiao 2001). Cong et al. (2010) observed the anti-erodibility of four types of forest soil in the South Hilly Region of Jiangsu Province (118° 51′E, 31°38′N), and result showed that the order of anti-erodibility of different forest soil was: Moso bamboo (1.33) > Chinese fir (0.35) > *Quercus acutissima* (–0.75) > *P. massoniana* (–0.89). The ability of the Moso bamboo forest to stabilize soil (i.e., quantity of restrainting soil loss per unit area and per unit time) is 1.5 times that of the *P. massoniana* forest (Zheng and Hong 1998). In addition, the water conservation function (a comprehensive index, mainly including canopy interception, water holding of litter layer and Woodland soil infiltration of water storage reservoir) in Moso bamboo is about 30% to 45% more than that in the Chinese fir forest. Huang et al. (2010) comprehensively evaluated water conservation function of six stand types of ecological protection forest in Tonglu county, Zhejiang province (119°21′E, 29°49′N), and found that water conservation function in the Moso bamboo forest is about 46.7% and 57.4% stronger than that in the *P. massoniana* forest and the *Castaneam ollissima* forest, respectively, but is about 37.2% and 16.7% less than that in the *Cycloba lanopsisglauca* forest and the Chinese fir forest, respectively. Therefore, the bamboo forest is regarded as one of the forest types with stronger erosion control and water conservation potential

Fig. 3. Changes in carbon storage by bamboo forests in China since 1950 (data from Chen et al. 2009).



Moisture retention and rainfall interception

Bamboo forests have a strong capacity for rainfall interception and moisture retention. Zheng and Hong (1998) found that the rainfall interception ratio (vegetation canopy intercepting/rainfall) of the Moso bamboo forest is 1.3 times higher that of the Chinese fir forest. Similarly, Xue et al. (1996) observed that the canopy interception ratios for rainfall and stemflow are 6.1% and 6.3% higher in the Moso bamboo forest than that in the Chinese fir forest.

A single Moso bamboo can hold 5 kg of water and reinforce 4 m^2 of soil, and 1 ha of the Moso bamboo forest can store 3750 to 4200 t of water at the saturation point (Hui et al. 2003). The relative humidity in these forests is typically 5% to 10% higher than in adjacent open fields during the summer (Xiao 2001). In addition, because bamboo forests are an uneven-aged evergreen stand, annual selection cutting may favor many intact plants to protect the soil, and therefore does not weaken the forest's soil and water conservation functions or its ability to protect water sources (Xiao 2001).

Cleaning air, reducing noise, and maintaining wildlife biodiversity

Bamboo stands also are known as "natural oxygen bars". Tan et al. (2010) detected the concentration of negative oxygen ions in the air of a bamboo forest is 2 times that in an adjacent evergreen broad-leaved forest in ChaShanZhuHai National Forest Park in Chongqing city. The surface of a bamboo leaf is rough, and it can capture 4 to 8 g·m^{-2} of dust. A 40 m wide bamboo belt can also reduce noise levels by 10 to 15 dB (Li et al. 2003).

Bamboo also plays an important role in maintaining wildlife biodiversity. Bamboo provides food and habitat for numerous species of insects in the soil and tree layers, as well as for spiders, butterflies, birds, and other higher life forms (Lou and Henley 2010). The best-known of the animals that live in bamboo stands is the giant panda (*Ailuropoda melanoleuca*), which feeds almost exclusively on the tender culms and shoots of bamboo. Other animals, including elephants, wild oxen, brown bears, and wild boars, depend greatly on bamboo shoots and leaves in southern Yunnan Province. The fruit of some types of bamboo, including *Melocalamus com-*

pactiflorus and *Cephalostachyum pallidum*, contain high levels of starch and other nutrients, and are a preferred food for red deer, muntjac deer, wild boars, and other forest animals (Li et al. 2003). Bamboo forests also increase the number of bird species and quantity of birds. For example, in the *Phyllostachys glauca* forest and its surrounding areas in the Tai Mountains of Shandong Province, 7 orders, 16 families, and 63 species of birds are found, accounting for 43% of the total in these mountains (Li et al. 2003). Reid et al. (2004) also found that bird species richness was positively correlated with bamboo cover in Chilean temperate forests.

Bioenergy and other economic benefits

China's ever-growing population and improving standards of living are placing increasing pressure on the country's forest resources. As the most important non-wood forest product and wood substitute, bamboo is playing an increasingly important role in reducing timber demand pressure on China's forest resources. For example, since the nationwide prohibition on harvesting of natural forests was imposed in 1998, bamboo has rapidly become an excellent substitute for timber, and has entered many markets previously dominated by timber. In 2009, 1.36 billion bamboo culms were harvested, and the gross sales of bamboo amounted to more than US $10 billion in China, with exports to 177 countries reaching US$1.36 billion, ranking first in the world (Jiang 2010). Moreover, the bamboo forest is mostly cultivated as the collective forest in the hilly area in south China. The huge economic benefits derived from bamboo forest management have contributed much to rural development and poverty alleviation. Bamboo generates approximately 30% to 40% of a farmer's income (Xiao 1999). The bamboo industry has become the pillar of economy in mountainous area. The ongoing collective forest property right institution reform would further enhance the role of the bamboo industry in rural development. As a rising industry, the bamboo industry is booming in China.

Low-carbon and sustainable economics

Bamboo can support low-carbon and sustainable products. Bamboo has better physical (mechanical) properties than many other timber species, such as high tensile strength, high flexibility, and light weight; as a result, it can replace wood, steel, and concrete in many industrial applications and can be widely used as a building material. Unlike brick and cement structures, bamboo buildings are usually cheaper, lighter, and more earthquake-resistant. For instance, after the Sichuan earthquake of 2008 in China, semipermanent prefabricated bamboo shelters were used to accommodate hundreds of people (Henley and Lou 2009).

With a fiber content of 40% to 60% by weight and up to 2 times the annual fiber output per unit area compared with coniferous and broadleaved forests, bamboo is also a good source material for paper-making. Bamboo fiber fabrics, used in clothing and bed sheets, have high permeability to air and a high ability to absorb moisture, while also providing good absorption of ultraviolet rays and good anti-bacterial properties (Li et al. 2003). In addition, bamboo is a good material for the production of furniture, baskets, handicrafts, tools, mats, toys, fans, carvings, and musical instruments (Xie 1997).

Bamboo has been used in more than 1500 applications (Lobovikov et al. 2007). Morover, technological progress and innovative design will make bamboo more widely available in the future (Fig. 4). The production of bamboo products usually requires much less energy than comparable fossil-fuel based products, which means that a bamboo-based industry can indirectly reduce carbon dioxide emissions. Through modern engineering techniques, bamboo products may become more durable and therefore able to store carbon for longer periods. Thus, bamboo can contribute greatly to a future low-carbon society while also helping to conserve and restore forest resources.

Food

The extractives from bamboo shoots, leaves, and culms include a number of nutrients and other physiologically active compounds such as vitamins, amino acids, flavones, phenols, and organic acids (Xie 1997). These have important nutritive value or medicinal properties, and can be extracted and processed into drinks, medicines, foods, and food additives. Bamboo shoots are rich in saccharides, proteins, fats, mineral elements, and vitamins, and have therefore become a popular natural health food (Li et al. 2003). Bamboo shoots have always been a common ingredient in many Chinese delicacies. However, bamboo shoots are now processed into many kinds of food, including fresh shoots, dry shoots, and canned shoots, that are sold around the world (Xie 1997). Some new products, such as bamboo juice, beer, and vinegar are being developed (Li et al. 2003).

Bamboo for charcoal production

Bamboo charcoal is another important product, since it is a renewable biomass fuel that can replace wood charcoal or mineral coal. The calorific value of bamboo charcoal per unit weight is about half that of oil (Lobovikov et al. 2007). Bamboo charcoal is also acid- and alkali-resistant, can absorb water to decrease relative humidity (making the air more comfortable for humans), and can absorb many kinds of harmful gases (Li et al. 2003). Its absorption capacity is 6 times that of wood charcoal (Lobovikov et al. 2007). Thus, bamboo charcoal is an absorption material with a range of potential functions, and is increasingly widely used in human health care and in modern household environmental protection, where it replaces wood charcoal (Li et al. 2003).

Lehmann and Joseph (2009) found that bamboo biochar is an effective fertilizer that can enhance agricultural productivity in nutrient-poor soils, and that it has long-term benefits in terms of nutrient retention and availability and in terms of reducing leaching of nutrients such as nitrogen (Hua et al. 2009). In addition, it can improve water availability for plants and benefit soil microorganisms. Bamboo biochar was also found to be effective in absorbing ammonia in the soil. In addition, Van Zweiten et al. (2007) noted that bamboo biochar improved goat production when used as a feed additive.

Because of bamboo's faster growth and shorter rotation compared with most tree species, conversion of bamboo into biochar can increase the residence time of carbon in the soil and other products (to more than 1000 years) and can reduce emissions of other greenhouse-effect gases such as methane

Fig. 4. Examples of the utilization of bamboo for a wide range of products: (*a*) bamboo shoots; (*b*) bamboo-fiber fabric; (*c*) bamboo furniture; (*d*) a bamboo laptop; (*e*) bamboo handicrafts; (*f*) bamboo charcoal.

and nitrous oxide from the soil (Lehmann and Joseph 2009; Yanai et al. 2007). This means that bamboo biochar is a potential carbon sink and that creating bamboo biochar can effectively store large quantities of carbon.

Social benefits

China has more than 6000 years of history in cultivating and utilizing bamboo. Bamboo has been closely associated with clothing, food, shelter, and travel (Li et al. 2003). In ancient China, important documents were always written on strips of bamboo that were tied together until the first paper was invented from bamboo in China in the ninth century A. D. (Xie 1997). Bamboo pens, brushes, and musical instruments were invented ca. 3000 years ago. Because of its graceful and upright shape, bamboo was considered to have noble characteristics and was grown to encourage people to cultivate good character; as a result, it became an important subject in traditional Chinese paintings, literary works, and film and television works (Xie 1997). Many famous movies have been filmed in bamboo forests, such as *Crouching Tiger, Hidden Dragon*. A long history of bamboo handicrafts with exquisite workmanship, such as carvings and weavings, has made Chinese artisans famous around the world, and their work is loved by the Chinese people. Bamboo culture remains an essential part of Chinese daily life and civilization.

Bamboo forests are also a unique and important component of Chinese gardens and landscapes. For instance, *Bambusa multiplex*, *Phyllostachys aurea*, *P. bambusoides*, and other species are popular ornamental plants in gardens and have even been used as materials for Chinese bonsai (Xie 1997). The Bamboo-lined Path at Yunqi in Hangzhou, the Shunan Bamboo-Sea in Changning, and the bamboo forest along the Lijiang River in Guilin are popular tourist destinations.

Potential problems and future challenges

Impacts of bamboo management on biodiversity and ecological functions

Although bamboo forests provide considerable ecological and socioeconomic benefits, there are potential problems associated with their cultivation, including a decline in biodiversity, soil and water loss, decreased soil fertility, and water pollution due to intensive management using inorganic fertilizers and pesticides (Fig. 5). Intensive management of the Moso bamboo forest can simplify the structure of the forest and decrease the species richness and biological diversity of the tree, shrub, and herb layers, and can decrease soil microbial activity and biodiversity (Xu et al. 2008; Guo et al. 2009). Moreover, under intensive management, the natural soil fertility and site quality have gradually declined in some Moso bamboo forests (Lou et al. 1997; Chen et al. 2004), accompanied by damage to the soil's physical structure and consequently to a decrease in its water-retention capacity (Chen et al. 2004).

Yu et al. (2003) also found that intensive management led to a large decline in the health of a Lei bamboo (*Phyllostachys praecox*) forest ecosystem, with species richness and a Shannon–Wiener's diversity index decreasing by 54.5% and 32.0%, respectively. At the same time, the flowering rate and susceptibility to insects and disease increased, nutrient (N, P, and K) levels became unbalanced, soil enzyme activity decreased, and soil and water erosion increased with an overall decline in ecosystem functions. The biodiversity decrease undermines the quality and productivity of bamboo forests and would reduce their resistance to pests, diseases, and extreme weather events. For instance, bamboo forests were much more damaged than other forests, leading to a greater economic loss, by the snow disaster that struck southern China in 2008. In the long-term, this would threaten the ecological functions and sustainable development of bamboo forests (Lou and Henley 2010).

It is worthwhile to note that some farmers have begun returning farmland to bamboo forest in the pursuit of higher profits (Fig. 6), which may constitute a potential threat to China's food security and therefore merits concern. Perhaps more importantly, in mountainous areas, some other types of forest have been clearcut to plant bamboo for current economic benefit without considering the site condition and future market changes. Moreover, most bamboo forests are located in the source regions of China's main rivers and water systems, where inappropriate forest types change and management often leads not only to biodiversity loss, but also to heavy soil erosion and subsequently excess transport of N and P into surface waters via surface runoff, thereby exacerbating surface water pollution and eutrophication of downstream water (Gong et al. 2007). Also, some local small bamboo processing factories, producing various bamboo products mentioned previously, have inevitably caused pollution to the soil and water systems. However, because of its small scale and scattered distribution, it has not yet aroused much attention. To resolve these problems, it will be necessary to implement classified management of bamboo forests (i.e., management based on a careful consideration of the properties and carrying capacity of each site), to improve the managing level of the bamboo forest using advanced science and technology, to strengthen the enforcement of environmental protection law, and to orient cultivation towards the most appropriate ecological and socioeconomic functions to meet China's development needs and the need for ecological security.

The major environmental factors that control bamboo growth and distribution are temperature (the suitable mean annual temperature ranges from 15 to 20 °C), precipitation (the suitable mean annual precipitation ranges from 1000 to 2000 mm), and soil pH (suitable pH ranges from 4.5 to 7.0) (Zhou 1991; Xu and Qin 2003; Gu et al. 2010). Under the current global climate change scenarios, continuous global warming and enhanced nitrogen deposition would facilitate the spread of bamboo forest. In fact, the distribution of Moso bamboo has been expanding rapidly into other types of forest and gradually replacing previous pioneer tree species at higher altitudes and latitudes in recent decades. For example, in the Tianmu Mountain National Nature Reserve, the area of the Moso bamboo forest, without interference from human activities, has increased at an annual rate of 4.5 ha during the past 18 years, which represents an increase to 34 times the original area (Ding et al. 2006). Our last investigation in this reserve also showed that the Moso bamboo forest naturally expanded upward about 6 m in altitude during the last decade and this expansion was significantly correlated with an increase in mean annual air temperature ($p < 0.001$) (Song et al. submitted). A similar expansion has also occurred in Japan (Torii 1998). This expansion of Moso bamboo has greatly decreased the biodiversity and threatened the existence of other species in some areas, especially for some rare and endangered species, and this is an increasing concern (Yang et al. 2008).

Mitigating the impact of climate change by enhancing carbon sequestration in China

Due to its fast growth, bamboo is widely regarded as an ideal plant to sequester carbon, and is expected to play a bigger role in mitigating the impact of future climate change. Although bamboo forests already sequester huge amounts of carbon, they have enormous potential to increase China's capacity for carbon sequestration.

With a vast land area and low forest cover (only 20.4%; SFAPRC 2010), there is much barren land that may be suitable for bamboo cultivation in China. Because of its outstanding ecological and socioeconomic benefits, the bamboo forest is receiving greater attention from the government and the public and is regarded as an important forest type in future development plans for artificial forest in southern China. Based on the planned increase in the area of the bamboo forest because of afforestation programmes that are included in government strategy documents, the total carbon storage of the bamboo forest is expected to increase greatly in the future (Lou et al. 2010). The estimated carbon stocks in bamboo stands in 2050 will be 1017.64 Tg C (Chen et al. 2009). In addition, the bamboo forest is included in the list of eligible afforestation and reforestation projects under the Clean Development Mechanism (CDM; Lobovikov 2010), and this will also stimulate the expansion of the bamboo forest. For example, the world's first carbon sink project based on a Moso bamboo forest was launched in Lin'an city, Zhejiang

Fig. 5. Bamboo forest growing under (*a*) natural conditions and (*b*) intensive management.

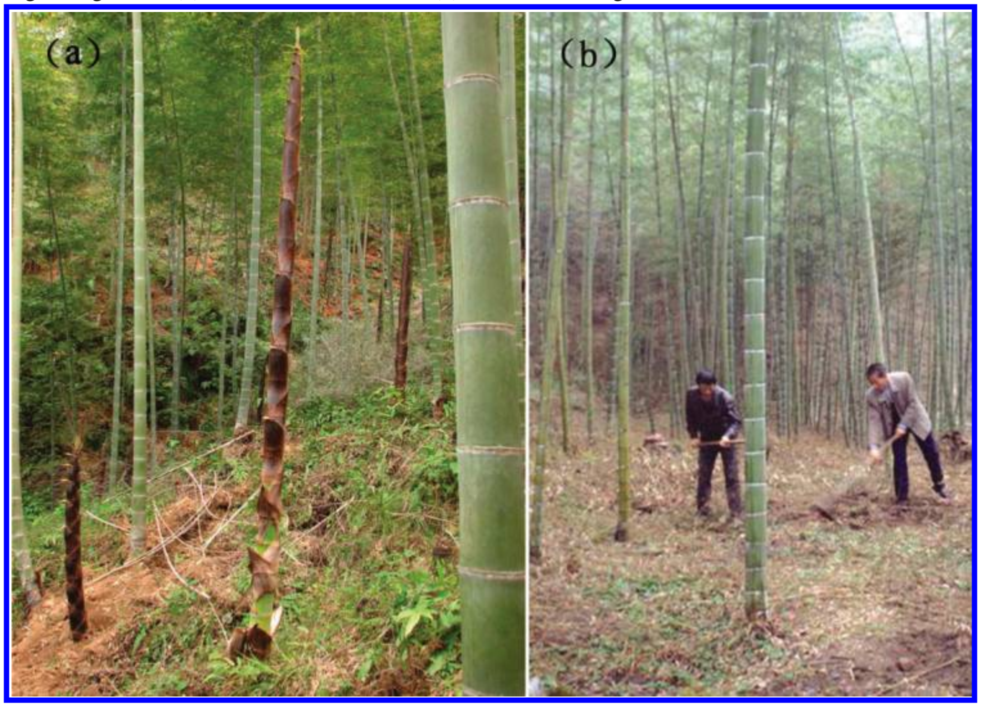


Fig. 6. Paddy field (*a, b*) and vegetable field (*c, d*) were partly supplanted by Lei bamboo (*Phyllostachys praecox*) forest for higher economic profits in Zhejiang Province.

province, in April 2008, funded by China's Green Carbon Fund.

Intensive management of the bamboo forest offers higher productivity than extensive management of the bamboo forest or naturally growing bamboo (Henley and Lou 2009; Qi et al. 2009; Zhou et al. 2006). Thus, increasing numbers of bamboo forests are being turned from natural conditions or extensive management towards intensive management (Xiao 1999). The ability to perform annual harvesting without affecting the forest's regrowth capacity is an outstanding characteristic of bamboo forests. Adjusting the stand's age structure and its density by means of annual thinning can increase productivity and thereby sequester more carbon (Xiao 2001). However, as noted earlier in this paper, it will be necessary to define sustainable management intensity for bamboo stands that will avoid the potential problems described earlier in this paper. This will increase the ecological and socioeconomic benefits provided by these forests, while enhancing the capacity of bamboo to mitigate climate change.

The carbon sequestration potential of the bamboo forest also depends on the lifespan of bamboo products. The carbon stored in these products will be released into the atmosphere when these products are either biologically degraded or burned. Thus, producing more durable bamboo products will be a good way to prolong carbon storage. With increasing consciousness of the need for environmental protection and the need to change unsustainable consumption habits, bamboo products with long lifecycles are becoming increasingly popular, which brings hope of more carbon sequestration. In addition, converting bamboo into charcoal as a substitute for fossil fuels could also provide additional opportunities to mitigate climate change.

Conclusions

Bamboo offers potentially huge ecological and socioeconomic benefits. Especially as a sustainable carbon sink, it has begun to receive increasing attention. China's long history of bamboo cultivation and use and its vast bamboo forest area give the country a unique opportunity to develop the bamboo forest and a bamboo industry. With China's government and the public paying more attention to bamboo forests, improving bamboo's already high productivity and developing more sustainable management practices and products will allow bamboo to play an increasingly important role in mitigating climate change. Furthermore, the rapid development of bamboo forests in China will set a good example for other developing countries, which will stimulate an increase in the area of the bamboo forest and subsequent carbon storage in Southeast Asia, Africa, and Latin America.

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