Bamboo's fast growth is one of its many attributes which make it a useful resource for mankind. It is also commonly seen as an indication of a high ability to capture and sequester atmospheric carbon and consequently mitigate climate change, in a similar way that trees do. This report analyses the work carried out to date to explore different aspects of bamboo's growth, management and use which impact bamboo's carbon sequestration potential. Using modeling and comparison studies, the findings of this report suggest that bamboo's carbon sequestration rate can equal or surpasses that of fast-growth trees over short time periods in a new plantation, but only when bamboo is actively managed. A review of studies carried out in China indicates that bamboo is a relatively important carbon store at the ecosystem and national level. While the results of the report underline the gaps in knowledge in the field, they suggest that bamboo forest ecosystems can be leveraged to help mitigate climate change, whilst simultaneously providing other important services for human adaptation and development.

INBAR

Technical Report No. 32

Bamboo and Climate Change Mitigation

Lou Yiping, Li Yanxia,
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Giles Henley, Zhou Guomo

INBAR

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The International Network for Bamboo and Rattan (INBAR) is an intergovernmental organization dedicated to reducing poverty, conserving the environment and creating fairer trade using bamboo and rattan. INBAR was established in 1997 and represents a growing number of member countries all over the world. INBAR's headquarters are in China and there are regional offices in Ghana, Ethiopia, India and Ecuador. INBAR connects a global network of governmental, non-governmental, corporate and community partners in over 50 countries.

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Technical Report No. 32

Bamboo and Climate Change Mitigation : a comparative analysis of carbon sequestration

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Foreword

The challenges brought on by Climate Change have been succinctly described by Professor John Schellnhuber[1] as a MAD Challenge; one which requires simultaneous action on Mitigation, Adaptation and Development. Forests are recognized as having a crucial contribution to meeting these challenges due to the multiple services that they provide, notably carbon sequestration, timber provision and income generation. The growing literature on bamboo repeatedly confirms the importance of this multifunctional forest resource in providing livelihoods, as well the important environmental services that it provides at a local level-including erosion control, watershed maintenance and a habitat for biodiversity.

Bamboo's ability to provide global environmental services through carbon sequestration is also now receiving high levels of interest, and is the subject of research by INBAR and partners. Due to its fast growth rate, bamboo has long been supposed to be a plant with a high sequestration capability, and the research to date indeed confirms that bamboo outperforms fast growing trees in its rate of carbon accumulation. However, important questions remain, especially on how much carbon a bamboo forest can absorb, and how to store this carbon over longer time periods. An overview of these multiple and complex issues is presented in this report.

Whilst more research in this area is undoubtedly needed, it is important to recognize the multiple benefits that bamboo can provide on all three fronts of the MAD Challenge. At INBAR we aim to leverage these benefits through local and global initiatives, so that bamboo can continue to provide development and adaptation at the local level, while simultaneously contributing to tackling climate change at the global level.

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Executive Summary

Within the range of options available to mitigate high levels of carbon dioxide in the atmosphere, forests and forestry practices have received a lot of attention. While global deforestation is one of the most important sources of carbon emissions, it is thought to be relatively easy to halt compared with other options. Through forestry practices including the expansion of forest area and improvements in forest management, forests can act as important carbon sinks. Although botanically bamboo is a woody grass and not a tree, bamboo forests have comparable features to other types of forest regarding their role in the carbon cycle. They sequester carbon through photosynthesis, and lock carbon in the fibre of the bamboo and in the soil where it grows. However, there are also important differences between bamboo forests and other forests. Bamboo has a rapid rate of early growth and high annual re-growth when managed. The lifecycle of individual bamboo culms (between 5-10 years) is comparatively short. The products derived from bamboo are commonly used in lower durability applications than those from timber forests. Consequently, INBAR and partners set out to determine how bamboo behaves in terms of carbon storage, and how it compares to trees in its carbon sequestration performance.

This report attempts to address the main issues which influence how bamboo should be seen within the climate change context. Chapter 1 gives a global overview of bamboo and its importance to global and local economies, societies and environments and its potential in dealing with the climate change challenge, and Chapter 2 describes the mechanisms that have been created to tackle climate change, and examines how bamboo fits within these. Chapters 3 to 5 analyse to what extent bamboo could contribute to carbon storage at the plantation stand, ecosystem, and national level using calculations based on field data of bamboo and comparable tree species. Chapters 6 and 7 look at issues of management and product durability which could affect carbon storage performance.

The findings and conclusions are summarized as follows.

The comparative analysis of carbon sequestration between a monopodial Moso bamboo plantation and fast growing Chinese Fir plantation modelled for subtropical growing conditions in South East China showed that a Moso bamboo (*Phyllostachys pubescens)* plantation at a density of 3,300 culms/ha and a Chinese Fir (*Cunninghamia lanceolata*) plantation at a density of 2,175 trees/ha have comparable features regarding their rapid growth rates and climatic requirements. The study analysed their growth patterns and used dynamic biomass and carbon models to ascertain their relative rates of carbon sequestration. The research concluded that both species had a comparable sequestration rate, but followed a different pattern.

- The calculation of the annual net carbon storage for a newly afforested Moso bamboo plantation showed a peak of 5.5 t C/ha in the 5th year. The bamboo sequestered more carbon than the Chinese Fir in the first 5 years, but less than the Chinese Fir during the next 5 years. Under regular management practices (which include stand and soil management combined with common harvesting regimes) the study found that the Moso bamboo plantation sequestrated an equal or greater amount of carbon than the Chinese Fir plantation within the latter's first 30 years harvesting rotation as well as the second 30 year rotation.
- In contrast, if the bamboo forest wasn't managed through annual harvesting practices, it would be significantly less effective at carbon sequestration. Compared with the first 30 year of the Chinese Fir plantation, the bamboo plantation only sequestered about 30% of the total carbon that the fir plantation sequestered. In other words, fir is likely to be much more effective at sequestering carbon than bamboo when a bamboo plantation is unmanaged and un-harvested.

A literature review confirmed that the level of carbon stored in Moso bamboo forests and in Chinese Fir in various provinces of China are indeed comparable.

For tropical conditions, the carbon sequestration capacity of Eucalypt plantations was compared to sympodial Ma bamboo (*Dendrocalamus latiflorus*) in the same area. This is a suitable comparison due to their relative rapid growth rates and similar climatic requirements. The study analysed their respective growth patterns and calculated their relative carbon sequestration capacity. The results indicated that both plantations had comparable carbon sequestration capacity and performance.

- Under regular management practices with annual harvesting for the bamboo, the Eucalypt plantation outperformed the bamboo in the first 5 years until it was cut, to be replaced by a new Eucalypt plantation. In the second 5 years, the Ma bamboo started to outperform the Eucalypt plantation.
- The results indicate that sympodial bamboo in the tropics is likely to sequester equal or more carbon than Eucalypt plantations. The review of the data calculated and collected from the literature also has clearly shown that more carbon is likely to be sequestered by species growing in tropical areas (both bamboo and trees), than by species growing in sub-tropical areas.

A literature review indicated that the carbon stock in vegetation (including understory species and other mixed vegetation) of Moso bamboo is within the range of 27-77 t C/ha. The majority of carbon appears to be sequestered in the arbour layer accounting for 84-99%; the shrub layer and the herbaceous layer accounted for very small contributions, especially in intensively managed bamboo forests. When looking at the whole ecosystem, including the soil, Moso bamboo forest ecosystem carbon storage capacity was reported to be between 102 t C/ha and 289 t C/ha, of which 19-33% was stored within the bamboo culms and vegetative layer and 67-81% stored within the soil layer (rhizomes, roots and soil carbon). This indicates that the soil layer carbon content is likely to be about 2-4 times greater than the vegetative layer. Bamboo ecosystems were found to have an equal or somewhat lower carbon stock (between 102- 288 t C/ha) when compared with other forest types (between 122 - 337 t C/ha). The total carbon stock in bamboo forests is obviously affected by climatic factors. The carbon stock of bamboo in Fujian province (Qi, 2009), where the climate is more suitable for bamboo growth than in Zhejiang province (Zhou, 2004), surpassed *Pinus elliottii* in its 19th year, Chinese Fir in its 15th year, and showed comparable carbon stock to broad-leaved forest (262.5 t C/ha) and tropical forest (230.4 t C/ha).

At the national level in China, the carbon stock in bamboo forests has been estimated by combining carbon density data with inventory data on bamboo resources in China. The results varied greatly between different studies. The total carbon stock in bamboo forests in China was estimated between 605.5 - 837.9 Tg C and carbon density for bamboo between 130.4 -173.0 t C/ha.

The effects of management regimes on carbon storage were also studied. Intensive management of Moso bamboo seems to be able to increase the carbon storage capacity in above ground biomass. It was also noted that the carbon in rhizomes, roots and soil may be lower under intensive management. The role of management practices on carbon sequestration by bamboos needs further study.

As with other forest products, bamboo products retain their carbon content until they either biologically deteriorate or are burnt. Although bamboo has many advantageous features over many timber species such as high tensile strength, flexibility and hardness, it is argued that bamboo products are not as durable as many wood based products, therefore having a shorter life cycle. However, this appears to be more due to customs than to technical limitations, and in recent years many more durable bamboo products have entered the market. This investment in producing more high quality, durable bamboo products needs to continue, because it is a key issue in order to optimize and prolong carbon storage. Prolonged storage of carbon is only possible when the culms are processed into durable products with long lifecycles, such as construction materials, panel products and furniture.

An alternative is to utilise bamboo as a bio- energy resource as an alternative for fossil fuel, or for charcoal products, including biochar. The promotion and development of bamboo management and utilization for such purposes could provide additional opportunities to mitigate climate change.

In conclusion, within this comparative analysis considering Eucalypt and Chinese Fir, rapid growing trees from tropical and subtropical regions respectively, bamboo plantations seemed to be highly comparable to fast-growing trees. Moreover, the benefits appear to extend to the ecosystem and regional level due to bamboo's carbon sequestration capacity, stemming from its re-growth capacity and annual harvesting regimes. Sustainable management and appropriate utilization of bamboo resources can increase the amount of carbon sequestered, through management changes which increase storage capacity within the ecosystem in the short-term, and through transformation of carbon into durable products in the long-term. Bamboo is managed and utilized by hundreds of millions of people globally, who rely on it for many different uses, from household uses and protection of riverbanks to being a source of income. Many bamboo farmers live in less developed regions and are affected by poverty. The promotion of bamboo as a sustainable carbon sequestration tool will not only create new opportunities for mitigating climate change but can improve and protect millions of rural livelihoods through investment in sustainable bamboo management, industry and technology.

List of Acronyms

AFOLU:	Agriculture, forestry and other land use
AGB:	Above ground biomass
A/R:	Afforestation/ Reforestation
CA:	Carbon accumulation
CAF:	Chinese Academy of Forestry
CDM:	Clean Development Mechanism
CO_2e:	Carbon dioxide equivalent
COP:	Conference of the Parties
FAO:	Food and Agriculture Organization
GHG:	Greenhouse gas
GIS:	Geographical Information System
HBP:	Harvested Bamboo Products
HWP:	Harvested Wood Products
INBAR:	International Network for Bamboo and Rattan
IPCC:	Intergovernmental Panel on Climate Change
JI:	Joint Implementation
MAD:	Mitigation, Adaptation and Development.
MBC:	Microbial biomass carbon
MC:	Mineralizable carbon
Pg:	Petagram (a unit of weight equal to 10^{15} grams)
REDD:	Reduce Emissions from Deforestation and Degradation
REDD+:	"REDD+" goes beyond deforestation and forest degradation, and includes the role of conservation, sustainable management of forests and enhancement of forest carbon stocks
SBFM:	Sustainable Bamboo Forest Management
SFM:	Sustainable forest management
Tg:	Teragram (a unit of weight equal to 10^{12} grams)
TOC:	Total organic carbon
UNFCCC:	United Nations Framework Convention on Climate Change
WSOC:	Water-soluble organic carbon
YNC:	Yearly net carbon

Introduction: Purpose of the report

The challenge involved in addressing the concurrent needs of Mitigation, Adaptation and Development - the MAD Challenge (Schellnhuber, 2009) requires an investigation into the interaction between all natural systems and people to determine how natural systems can be better utilised.

Bamboo's ability to sequester carbon at high rates based upon its fast growth has long been an important part of its green credentials. However, given the complexities of establishing models for vegetative sinks, there are a number of questions regarding bamboo's ability to sequester and store carbon over different time horizons. Among the complications of quantifying carbon sequestration, there are important questions regarding bamboo's comparative advantage when compared to other fast growing trees, the length of time over which it sequesters carbon at higher rates than competing species, the role of a bamboo ecosystem in acting as a carbon store, the role that management of bamboo plays in its performance, and the durability of bamboo-derived products[2].

This publication examines these questions through modelling studies and a review of the existing work that has been carried out on quantifying carbon sequestration of bamboo systems.

[2] This report approaches the question of climate change mitigation by looking at the rate carbon sequestration and carbon storage in the bamboo ecosystems, as determined by growth models. It does not address rates of removal of carbon dioxide from the atmosphere directly, or the flux in carbon dioxide within the bamboo ecosystem. It focuses rather on carbon sequestration based upon volumes of carbon stored in bamboo over its growth period, and compares the effects of different management practices on this process. This is the only area which has been researched in detail for bamboo to date, although it is hoped that this work can be built upon to look at the other aspects of carbon dynamics in the bamboo ecosystems

1. Bamboo and Climate Change

1.1 Bamboo and the MAD Challenge

Bamboo holds significant importance for humanity on numerous levels. Throughout history, its properties have been repeatedly used by different cultures to provide the goods and services needed for their lives. Today, it remains highly important as a basic livelihood crop and material for rural people living in Asia, Latin America and Africa, as well as a growing number of higher-income people who purchase green bamboo products throughout the world. Bamboo should be seen as a useful tool to tackle the MAD Challenge of Mitigation of, Adaptation to and Development in the face of Climate Change. Whilst the main focus of this publication is on the mitigation potential of bamboo systems, this section briefly describes the importance of bamboo to human development and adaption.

1.1.1 Bamboo botany, distribution and use

The way bamboo grows and its wide distribution throughout the world makes it an important natural resource for hundreds of millions of people across the globe (INBAR Strategy, 2006). Taxonomically a grass, bamboo has properties of fast growth and rejuvenation after cutting, which means it can provide a harvestable yield every 1-2 years once maturity is reached. This makes it a quick and reliable source of bamboo fibre; a versatile material which lends itself to processing into many different forms and products (Scurlock, 2000). Its ability to rejuvenate itself from its below-ground rhizome stock means that it does not require replanting, needs little tending, and generally has little need for capital, labour or chemical inputs to provide adequate levels of fibre. As such it is highly suited to a diversified agricultural system, constituting one of several livelihood resources for farmers (INBAR, 2004).

The wide distribution of bamboo across the tropics and subtropics of Asia, Africa and Latin America, with an annual production estimated at between 15-20 million tonnes of fibre implies that it is highly significant as a livelihood material (Williams, 1994). Although traditionally associated more closely with Asian cultures, a number of economically important species are found in Latin America and Africa, where they too constitute important crops for local inhabitants. Dual characteristics of lightweight and high tensile strength of *Guadua angustifolia* have resulted in its main use as a building material throughout its range in Colombia, Ecuador and Peru. *Arundinaria alpine*, which is distributed in mountainous parts of East Africa, is an important source of construction material and fuel. With the highest concentration of species occurring in South and Southeast Asia, bamboo has occupied a central role in the development of culture and civilisation there with both a utilitarian, functional as well as spiritual significance. Used for food, clothing and shelter, infusing writing, spoken language and art, bamboo has traditionally contributed to the multiple physical and spiritual requirements of mankind.

1.1.2 Bamboo and development

Bamboo is relied on heavily by some of the world's poorest people, and can be a significant pathway out of poverty (Belcher, 1995). It is commonly available as a common-pool resource and relatively easy to harvest and manage. Low investment costs for processing inputs and flexible time requirements for undertaking seasonal work means that bamboo-based employment is suitable to both full and part-time employment opportunities (INBAR, 2004). The development of the bamboo industry has lead to job creation and raising rural incomes with associated benefits. For example, a conservative estimate indicates that there are 5.6 million people working in China's bamboo sector, 80% of whom are working in forest cultivation (Jiang, 2002a). Case studies on 'bamboo counties' in Eastern China demonstrate the important role that the development of the bamboo sector can have in reducing rural poverty, maintaining high levels of rural employment. Impact assessments of INBAR project communities in northern India show that bamboo-based interventions have high value-addition through enhancing incomes, generating extra rural employment and empowering women in their communities (Rao et al., 2009). The expansion of global trade in bamboo is expected to contribute to development in bamboo growing areas. Currently bamboo contributes to between 4-7% of the total tropical and subtropical timber trade (Jiang, 2007).

1.1.3 Bamboo and Adaptation to Climate Change

Human beings are fundamentally dependent upon the flow of ecosystem services (MEA, 2005). Enhanced protection and management of natural ecosystems and more sustainable management of natural resources and agricultural crops can play a critical role in climate change adaptation strategies (World Bank, 2010; TEEB, 2009).

Bamboo is an important part of many natural and agricultural eco-systems, providing a number of crucial ecosystem services. It provides food and raw materials (provisioning services) for consumers in developing and developed countries. It regulates water flows, reduces water erosion on slopes and along riverbanks, can be used to treat wastewater and can act as windbreak in shelterbelts, offering protection against storms (regulating services).

As poor people will be worse hit by the effects of climate change, action plans for adaptation need to be tailored to their situation (UNFCCC, 2007). Investing in 'ecological infrastructure' is increasingly acknowledged to be a cost-effective means of adapting to climate-change related risks, in many cases surpassing the use of built infrastructure (TEEB, 2009). For instance, the use of mangrove forests to protect shorelines provides an equal level of protection at a lower cost. Using bamboo forests as part of a comprehensive approach to rehabilitating degraded hillsides, catchment areas and riverbanks has shown promising and quick results (Fu and Banik, 1995).

The light-weight and versatility of harvested bamboo also lends itself to innovations to cope with increased floods, such as raised housing in Ecuador and Peru and floating gardens in Bangladesh (Oxfam, 2010). Bamboo thus has a high potential to be used in adaptation measures to alleviate threats imposed by local changes in climate on vulnerable populations.

1.2 Current global issues -Introduction to climate change

Climate change is considered to be one of the greatest threats facing humanity. According to the IPCC, global warming is unequivocal, with evidence from increases in average air and ocean temperatures, melting of snow and ice and sea level rise (IPCC, 2007). If global emissions continue down the Business as Usual (BAU) trajectory, the scientific evidence points to increasing risks of serious, irreversible impacts (Stern, 2006). In order to avoid the most damaging effects of climate change, it is estimated that global levels of atmospheric greenhouse gases (GHGs) need to be stabilized at approximately 445-490 parts per million CO2e (CO2 equivalent) or less. To achieve this target, it is essential that urgent international action is taken. Forests will have a central role in meeting this target (Eliasch, 2008).

1.3 Climate change and the forestry sector

Forests have been discussed very specifically in the climate change research and discussions because of the high contribution that deforestation makes to increasing atmospheric stocks of carbon, and the potential to remove carbon from the atmosphere through improvement and expansion of forests.

i) Halting deforestation There is increased interest in reduced deforestation as a tool for climate change mitigation, as avoided deforestation is a relatively low-cost carbon abatement option (Gullison et al., 2007). Forests accounts for the largest store of carbon amongst terrestrial plant communities, and the reduction of this store through the process of deforestation is responsible for approximately 17 per cent of global emissions (Eliasch, 2008). This ranks it as the third largest source of GHG emissions after the burning of coal and oil (Brickell, 2009). The IPCC (2007) estimated emissions from deforestation in the 1990s were 5.8 GtCO2/year. Other estimates suggest that 1-2 billion tonnes of carbon were released from forestry during the 1990s (Mahli and Grace, 2000). McKinsey and Company (2009) mapped the costs of abatement practices on a greenhouse gas cost abatement curve showing that the costs within forestry are relatively low, with high benefits to be attained from carbon sequestration projects incorporated within carbon markets. In order to reduce deforestation it is estimated that a minimum annual cost of US$2.5 billion is needed to achieve significant reductions in emissions. This estimate is equivalent to approximately 500 Mt CO2e/year of reduced emissions at an average cost of US$5/tCO2e (Neeff et al., 2009). Recent technical research and policy proposals have focused on viable mitigation approaches using mechanisms to pay for keeping forests standing, which are collectively grouped under the Reduced Emissions from Deforestation and Degradation (REDD) initiative.

ii) Sequestering more carbon through vegetation Increasing the level of carbon sequestration- the process in which plant communities capture carbon dioxide through photosynthesis and transform the gas into solid biomass- is one of a range of viable options for reducing the total amount of carbon dioxide in the atmosphere and thus mitigating future dangerous climate change-related scenarios. By converting land containing relatively low levels of carbon (e.g. shrub and pasture lands, agricultural fields, or degraded forests) into forested land, which contains more carbon in the vegetation and soil, more atmospheric CO2 could potentially be sequestered in terrestrial ecosystems. This is the more relevant research area for bamboo, as bamboo forests are important for production, and are not at risk from deforestation to the same extent that primary tropical forests are.

1.4 Bamboo in a world of growing timber demand and climate change

The demand for timber and agricultural commodities will continue to increase as the global population expands and becomes wealthier. Global policies will need to shift towards more efficient and sustainable production methods in order to satisfy the rising demand for commodities. The sustainable management of forests will play a key role in meeting this demand.

Bamboo has an important role to play in reducing pressure on forestry resources. For instance, in China, since nationwide logging bans of certain forests came into effect in 1998, bamboo has increasingly been seen as a possible substitute to timber and has entered many markets traditionally dominated by timber. The successful use of bamboo in different product lines, ranging from furniture and flooring to paper and packaging demonstrates the high potential for bamboo as a more sustainable alternative material in production of many products.

As discussed in section 1.3, given the increasing levels of atmospheric carbon dioxide, another major environmental service that humans rely on forests to provide is carbon sequestration, and a major part of forestry research is now focussed on quantifying how different forests perform as sinks (i.e. whether they absorb more carbon than they emit, and for how long) and as stores (how much carbon do they hold in their standing static state).
Questions have similarly been raised over how well bamboo performs as a carbon sink. Although bamboo is a woody grass and not a tree, bamboo forests have comparable features and functions to other types of forests regarding their function in the carbon cycle. Bamboos have rapid growth rates, high annual re-growth after harvesting and high biomass production. Bamboos are believed to perform roughly equivalent to fast growing plantation species with an increment biomass of between 5 and 12 t C/(ha•yr) (Lobovikov et al., 2009). It is therefore hypothesised that bamboo has a capacity of carbon sequestration that is similar to that of fast growing forests.

However, given the complexity of natural systems, and the fact that scientific research in carbon cycle research in forests and especially in bamboo has started only recently, there are a number of issues which have been raised about factors which influence the performance of bamboo as a carbon sink.

1.) The relationship between rates of bamboo growth and carbon sequestration

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 carbon sequestration, but by sequestration in previous seasons in other parts of the bamboo system, and as such growth of new shoots is not an indicator of sequestration rate. On the other hand, Zhou (2009) argues that as the bamboo system requires more inputs in the shooting season of young culms (when new shoots grow), high growth in bamboo shoots can be equated with a high rate of carbon sequestration.

It can be argued of course that as long as carbon sequestration is determined by measuring the difference in standing carbon between Year(t+1) and Year(t) (a stock change approach), it doesn't matter whether and how the relocation of carbon between old and new culms occurs. Therefore in this study, we focus on carbon per unit area, rather than carbon/ culm.

2.) Storage length of carbon in a bamboo system

Bamboo culms of most species reach maturity after approximately 7-10 years, after which they deteriorate rapidly, releasing carbon from the above-ground biomass back into the atmosphere (Liese, 2009). Therefore in a natural state, bamboo will reach a stable level of above ground carbon relatively quickly, where carbon accumulation through sequestration is offset by carbon release through deterioration of old culms. In order for the bamboo system to continue to be a net sink, carbon has to be stored in other forms, so that the total accumulation of carbon in a solid state exceeds the carbon released to the atmosphere. Chapters 7 and 8 discuss these questions, amongst other issues that can affect the length of storage of carbon.

3.) The threat of bamboo flowering

As a member of the grass family, many (although not all) bamboos have a gregarious flowering characteristic where the plants die after flowering, with often all plants from the same species dying at the same time. As a risk typical to bamboo systems, this has received special attention in the literature. Such flowering in bamboo species results in the loss of all carbon in the biomass of the plant. Although little is known about the flowering determinants, relatively fixed flowering cycles are known for important species. For instance, *Melocanna baccifera* (the common species in Northern India) is known to flower ever 45-50 years. Whether or not bamboo flowering presents a threat to carbon sequestration is largely a question of risk assessment and based upon the state of the information known about the flowering cycle of the particular species in question. Of course, where mechanisms are designed for the use of bamboo in carbon offsets, careful consideration of the flowering risk should be made. For the species considered in Chapters 3-5 of this report, *Phyllostachys pubescens* has been observed to flower with intervals of at least 67 years (Watanabe, 1982), and Ma bamboo (*Dendrocalamus latiflorus*) has been observed to have sporadic flowering but only very occasionally resulting in a large area of the bamboo forest dying.

In order to explore the potential of bamboo sequestration, and address the concerns raised above, this study has identified the following key questions which currently shape the debate on bamboo sequestration:

1) Does the higher rate of rapid canopy closure and plantation maturation of bamboo equate to a higher absorption rate of CO2 from the atmosphere compared with other comparable fast growing trees in subtropical and tropical regions? In other words, does a bamboo plantation have a higher rate of carbon sequestration than other species?
2) A special feature of bamboo stands is the annual harvesting and re-growth pattern. How does this feature relate to accumulation of biomass and thus carbon sequestration?
3) Are there any significant differences between carbon uptake by bamboo forests and by fast growing tree species in the long term?
4) What is the difference between carbon storage in a bamboo forest ecosystem and other comparable forest ecosystems?
5) How does a bamboo forest perform in terms of carbon sequestration at a landscape and regional level compared to other forest types?
6) What are the impacts of current bamboo forest management on the carbon sequestration capacity of bamboo forests? Do current management practices improve or worsen the carbon sequestration capacity in bamboo forests?
7) To what extent are the management options able to fulfil the multiple goals of the bamboo industry, local communities and sustainability of bamboo forests?

2. Mechanisms used for addressing Climate Change

2.1 Carbon accounting

Scientists have raised the issue of carbon sinks' permanence within the terrestrial biosphere (Schlamadinger and Marland, 2000), since carbon storage in forests is finite and therefore not permanent, whereby after a period of time, carbon locked in vegetation and soil is released into the atmosphere through respiration, decomposition, digestion, or fire (Locatelli and Pedroni, 2004). Nevertheless, carbon sequestration through forestry is commonly considered to contribute to mitigating climate change.

Carbon offsetting involves the purchase of carbon credits from greenhouse gas reduction projects to negate the equivalent of a ton of CO_2 emitted in one area by avoiding the release of a ton of CO_2 or sequestering a ton of CO_2 in another place. Often these are equated using so-called CO_2 equivalents (CO_2e) Carbon markets allow CO_2e to be traded as a commodity. The key characteristic of carbon offsets is additionality. Additionality refers to emissions reductions being additional to what occurs under a business-as-usual scenario (Taiyab, 2006).

2.2 Carbon markets

2.2.1 Kyoto Protocol and the Clean Development Mechanism

The Kyoto Protocol was the first legally binding agreement to reduce GHG emissions, which aimed to curb GHGs by 5% of 1990 levels (Boyd, 2009). The Protocol created two classes of countries with different obligations and opportunities for greenhouse gas emissions and trading of emissions credits. Countries listed as Annex I of the Protocol (developed countries and economies in transition) have commitments to limit GHG emissions, while those countries not listed (developing countries) have no such commitments.

The Kyoto Protocol provides three 'flexibility' mechanisms to reduce the cost of meeting emissions targets.

1) Emissions Trading
   Countries that have satisfied their targets can sell their excess carbon allowances to other countries.
2) Joint Implementation (JI)
   Purchase of emissions credits from GHG offset projects in Annex I countries (industrialized countries)
3) The Clean Development Mechanism (CDM)
   Purchase of emission credits from projects in non Annex-I countries (Taiyab, 2006). Under the protocol, the Clean Development Mechanism (CDM) allows developed countries to offset carbon dioxide through industry or forestry projects (reforestation or afforestation), which allows developing countries to voluntarily participate in reducing CO_2 through receiving payments from developed countries (Boyd 2009). In 2006, CDM projects were estimated at US $5.3 billion (EcoSecurities, 2007).Presently there are 8 registered forestry CDM projects.

2.2.2 Voluntary carbon credits

A voluntary market for carbon has emerged as an alternative to CDM, operating outside of international agreements. The voluntary market is driven by Corporate Social Responsibility (EcoSecurities, 2007), involving companies, governments, organisations, organizers and individuals, taking responsibility for their carbon emissions by voluntarily purchasing carbon offsets. These voluntary offsets are often bought from retailers or organisations that invest in offset projects and are sold to customers in relatively small quantities. The voluntary market is

not required to adhere to the strict guidelines of CDM, therefore voluntary offset projects tend to be smaller, have a greater sustainable development focus, have lower transaction costs and involve a wider range of methods or techniques (House of Commons Environmental Audit Committee, 2007).

The voluntary carbon offset market grew by 200% between 2005 and 2006. In 2007 there were over 150 retailers of voluntary carbon credits worldwide, with a record 65 million tonnes of carbon being traded, worth US $330 million (Hamilton et al, 2008). A key difference between regulatory and voluntary markets is the variety of forestry related carbon abatement activities in the latter. Forest conservation projects have been traded on voluntary markets since the early 1990's (EcoSecurities, 2007).

There are two categories of carbon credits within voluntary carbon markets:

CDM/JI: These projects are registered with CDM or JI projects and aim to generate CERs (Certified Emissions Reductions) and ERUs (Emissions Reduction Units)
Non CDM/JI: These projects are registered under CDM/JI, but are considered VERs (Verified Emission Reductions)

A buyer can voluntarily purchase credits from a CDM or a non-CDM project, however voluntary credits cannot be used to meet regulatory targets (Taiyab, 2006).

2.2.3 REDD

The first commitment period of the Kyoto Protocol (ending in 2012) considered addressing industry and energy-related emissions as more important than emissions related to agriculture, forestry and other land uses (AFOLU). Although rewarding reforestation and afforestation, the CDM did not address emissions stemming from 'avoided deforestation' as a project class, therefore leaving the largest source of GHG emissions in many developing countries unaddressed (Neeff et al., 2009). Since 2005 international GHG abatement talks have focused on producing a mechanism that could reduce emissions from deforestation and degradation (REDD) in developing countries. The 13th Session of the Conference of the Parties of the UNFCCC, held in Bali in December 2007, addressed a post-Kyoto framework which encourages the implementation of demonstration activities to sequester carbon through forestry (Neeff, 2009). A number of policy options on how to incentivize REDD are being proposed, including both market-based and non-market-based approaches (Streck, 2008). REDD primarily intends to provide financial incentives to help developing countries voluntarily reduce national deforestation rates and associated carbon emissions (Gibbs et al., 2007).

2.2.4 REDD+

REDD focuses only on reducing emissions from deforestation and forest degradation. REDD+ intends to go further by rewarding activities that improve forest health; including better forest management, conservation, restoration, and afforestation. This could potentially improve environmental services and biodiversity whilst enhancing carbon stocks. The REDD+ model may be more suitable for smallholders who can be rewarded for forest conservation activities. The activities that can contribute to mitigation under a REDD+ mechanism are reducing emissions from deforestation, reducing emissions from forest degradation, conservation of forest carbon stocks, sustainable management of forests; and enhancement of forest carbon stocks (Bleaney et al., 2010). Although "enhancement of forest carbon stocks" generally refers to afforestation, reforestation and restoration activities on deforested and degraded lands, it can also be interpreted to include the sequestration of carbon in healthy standing forests (Bleaney et al., 2010).

2.3 Carbon Credits for Bamboo

Since bamboo is botanically a grass and not a tree, many carbon accounting documents fail to include bamboo, or don't consider bamboo within forestry. Bamboo therefore does not adequately fit under the terminology for a 'forest' in either the Kyoto Protocol, Marrakech Accords or IPCC. If bamboo were to be adequately recognized within 'forestry,' bamboo could potentially occupy an important position in climate change mitigation, adaptation, and sustainable development (Lobovikov et al., 2009).

Forest definitions are myriad. However, common to most definitions are threshold parameters including minimum forest area, tree height and level of crown cover. Under the Kyoto Protocol, a "forest" is defined according to these three parameters as selected by the host country. To be eligible for voluntary credits and REDD, project forests must meet internationally accepted definitions of what constitutes a forest, e.g., based on UNFCCC host-country thresholds or FAO definitions (UNFCCC, 2009).

Discussions are ongoing on the acceptance of tall and medium height woody bamboos as trees under UNFCCC and the Kyoto Protocol, and in the future, under REDD and REDD+. The Executive Board of the CDM, in its 39th meeting, decided that "Palm (trees) and bamboos can be considered equivalent to trees in the context of A/R". However, the final decision on what constitutes a 'forest' lies with the country Designated National Authorities (DNAs), therefore potentially affecting whether CDM or other schemes include palms and/or bamboos (Lobovikov et al., 2009).

Since bamboo is often managed by rural households with little financial capital for investment, monitoring A/R projects or REDD+ would be impossible without external project funding. Moreover, due to bamboo being outside conventional forestry projects, bamboo projects would face considerable challenges regarding sampling designs, carbon assessment methods and default parameters devised for timber trees (Lobovikov et al., 2009). Any mechanism which generates payments for forest carbon, whether through a fund or a market, will not function effectively unless consistently and effectively regulated. Well-aligned policies depend on well-coordinated institutions and effective governance practices. Coordination depends on information flow and participation particularly at the grassroots level (Saunders et al., 2008), and such policies are currently not yet common for, and not yet adapted to bamboo.

However, bamboo forests constitute an important livelihood source for millions of rural people; the current extent of bamboo forests and area of potential distribution justifies amending the IPCC guidelines and additional methodological tools to allow for the inclusion of bamboo in carbon schemes (Lobovikov et al., 2009). To make this happen, more insights are needed in the potential contribution of bamboo to mitigating climate change.

2.4 Permanence and leakage

As vegetation is an unstable dynamic system, emission credits generated by carbon offsets face the risks of premature expiration due to unforeseen shocks which can destroy standing carbon. A cause for concern is the leakage associated with mitigation projects. The magnitude of leakage can be large enough to negate the carbon benefits of a project (Dutschke, 2003).

Due to the potential magnitude of natural disturbance events at the individual project level, integrated approaches to address forest offset project reversal risk need to be considered adequately. Bamboo forests face the same types of risk as many other types of forest, including fire, pest attacks, drought and extreme weather events, as well as gregarious flowering (see Chapter 1).

In addition, climate change is predicted to affect forestry and agriculture in a number of ways, thus potentially debilitating the efficiency of forests to act as a carbon sink. There is general agreement amongst climate scientists that natural disturbances are highly likely to increase in frequency and intensity and extreme climate events will become more frequent with an increase in spring temperature fluctuations and summer drought (IPCC, 2007). Climate extremes and higher average temperatures will negatively affect forest ecosystems and increase their susceptibility to pests and diseases (Hemery, 2008)

Policymakers should ensure that forest offset policies and programmes do not provide an incentive to maximize carbon storage at the expense of risk management (Galik and Jackson, 2009).

3. Carbon sequestration at the stand level

As part of the analysis of how bamboo can play a role in fulfilling demand for timber and sequestering atmospheric carbon, this chapter looks at how the carbon sequestration (levels and patterns) of bamboo compares with other fast growing trees which are commonly used for providing timber. The analysis concentrates on the situation in China, because it is the only country for which sufficient data could be found for both bamboo and comparable fast growing species. The models deal with the accumulation of carbon in the bamboo plant, and do not describe the flux in carbon dioxide between the plant and the atmosphere.

From the literature, data were collected for growth patterns of Moso bamboo, Ma bamboo, Chinese Fir and Eucalypt plantations. The longest period covers 60 years, which is the typical length of a Chinese Fir plantation in China, consisting of two rotations of 30 years. The harvest method for Chinese Fir and Eucalypt plantation are clear cutting, which removes all above ground carbon stock, while for bamboo, cutting takes place every year, which is equivalent to leaving a fixed amount of carbon stock standing every year (for Moso bamboo 5/6, for Ma bamboo 2/3 of the above ground carbon stock) which is replaced in the year following the harvest.

3.1 Data sources

The section is based on an extensive literature review, focusing on biomass and carbon sequestration in the biomass of the whole plant of bamboo (above and below ground) and rapid growing tree species such as Eucalypt and Chinese Fir plantations. The methodology for calculating carbon sequestration was based on techniques used within the cited literature. In order to verify data, authors were contacted on occasion.

3.2 Methodology

Bamboo biomass data were used to calculate the bamboo forest carbon stock increases, based on the compiled data and research findings from various authors. Through screening, comparison and verification of the compiled research, we selected the most credible biomass formula and models:

(1) The development of newly afforested Moso bamboo (*Phyllostachys pubescens*) plantations
Simulations of the changes in biomass from the initial shooting to canopy closure within bamboo stands were modelled using observational data (number of newly grown bamboo culms, diameter at breast height (DBH), and biomass). The simulation model on DBH changed simultaneously with the age of the plantation (Chen et al, 2004a, 2004b):

$$D=5.2000+0.5722\,y+0.0452\,y^2-0.0056\,y^3 \quad (R=0.9990,\ y\in[1,7]) \qquad [1]$$

$$H=0.5702+1.6426D-0.0465D^2 \quad (R=0.727,\ D\in[D\ (y=1),\ D\ (y=7)]) \qquad [2]$$

Where D represents the DBH of bamboo stands (cm), y presents afforestation years (years), H is the height of bamboo stand in metres (m). The bamboo forest that was used to collect the data from 1997 to 2003 is located in a hilly area of Zhejiang province (28°31′-29°20′N, 118°41′-119°06′E).

(2) Living individual biomass of Moso bamboo model [3] and whole bamboo stand living biomass [4] (Chen 1998):

$$W=213.4164D^{-0.5805}H^{2.3131} \quad (R=0.8321) \qquad [3]$$
$$Bw=W*DS \qquad [4]$$

Where W is the biomass of the whole individual bamboo culm including rhizomes and roots (g/ culm), D is the DBH (cm), H is the height of the bamboo stand (m); the data from year 1 to year 7 reported by Chen (2004b) are used for calculations using formula [3]. DS is the density of the bamboo (culms per hectare), a common density of 3,300 culms/ha for a mature bamboo forest is used in the calculations using [4]. Bw is the biomass of the forest (t/ ha). The bamboo forest that was used to collect the data for the formula (in 1998) is located in northern Fujian province (26°14'-28°20'N, 117°02'-119°07'E).

(3) Chinese Fir (*Cunninghamia lanceolata*) biomass model (Tian, 2005):

$$W_1=217.8639(1-e^{-0.118053t})^{3.3402} \quad (R=0.99) \qquad [5]$$
$$W_2=168.91357(1-e^{-0.13344t})^{3.4170} (R=0.999) \qquad [6]$$

W_1 and W_2 are respectively the first and second cycle of the total living biomass of Chinese Fir in a plantation, t is the Chinese Fir trees age. The data for the formula were collected from Hunan Huitong Forest Ecosystem Research Station [1979-2004] (26°50'N, 109°45'E). Equation [4] is used to calculate total biomass in the Chinese Fir forest, using the common density of 2,175 trees/ha.

(4) DBH module for Ma Bamboo *(Dendrocalamus latiflorus)* afforestation (Chen, 2002):

$$D=1.960772+1.039603\,X \quad (R=0.5324, X \in [1, 5]) \qquad [7]$$

D is the DBH of Ma Bamboo(cm), X is the afforestation years. Data for the formula were collected from 1995 to 1999 in a forest in southern Fujian province (24°31'N, 117°21'E).

(5) Total biomass of Ma Bamboo (Liang, 1998):

$$W=0.540093D^{1.9305} \quad (R=0.945) \qquad [8]$$

W is the biomass (kg); D is diameter at breast height (cm). Data for the formula were collected in 1997 in a Ma bamboo stand in Fujian province (25°24'-25°29'N, 118°23'-118°50'E). Equation [4] above is used to calculate the whole stand biomass, using a density of 1728, 1612, 1504, 1750 and 1723 culms/ha respectively for the first five years.

(6) The *Eucalyptus urophylla* forest living biomass:

Equation [4] above is used to calculate the *Eucalyptus urophylla* forest living biomass. Where W is the total biomass of an average individual *Eucalyptus urophylla* tree (kg/ individual tree) as measured per year during a 5 year rotation, DS is the density of the *Eucalyptus urophylla* forest (1,350 trees per hectare).The data were collected from 1996 to 2000 in an *Eucalyptus urophylla* forest located in Fujian province (24°37'N, 117°28'E) (Lin, 2003) .

(7) Carbon stock in biomass (Xu et al., 2007)

$$C=0.5B \qquad [9]$$

Where C is the carbon stock in biomass, 0.5 is the carbon fraction commonly used for trees and bamboo (Xu et al., 2007; Zhou at al., 2004; Xu et al., 2009; Qi et al., 2009).

3.3 Comparative analysis of the carbon sequestration patterns of a newly afforested Moso bamboo plantation and a Chinese Fir plantation in subtropical locations

3.3.1 Dynamics of carbon sequestrated in a newly-established Moso bamboo plantation in the first 10 years

In subtropical regions, monopodial bamboo species (such as *Phyllostachys pubescens* and *P. bambusoides*) can achieve canopy closure within 6-8 years after planting and can reach maturity for regular harvesting from the 9th or 10th year. One of the most frequently asked questions regarding bamboo carbon sequestration is to what extent the rapid canopy closure and early harvest influences the creation of biomass and carbon sequestration.

The pattern of net annual carbon increment in the first 10 years after planting is shown in Figure 3-1 and Table 3-1, demonstrating the fluctuations in bamboo carbon sequestration during stages of growth. The figure is based on the bamboo growth pattern formula [1, 2], bamboo biomass formula [3, 4] and bamboo carbon formula [9]. From the 6th year onwards bamboo culms are harvested. The harvested culms are included in the total carbon sequestration of the Moso plantation.

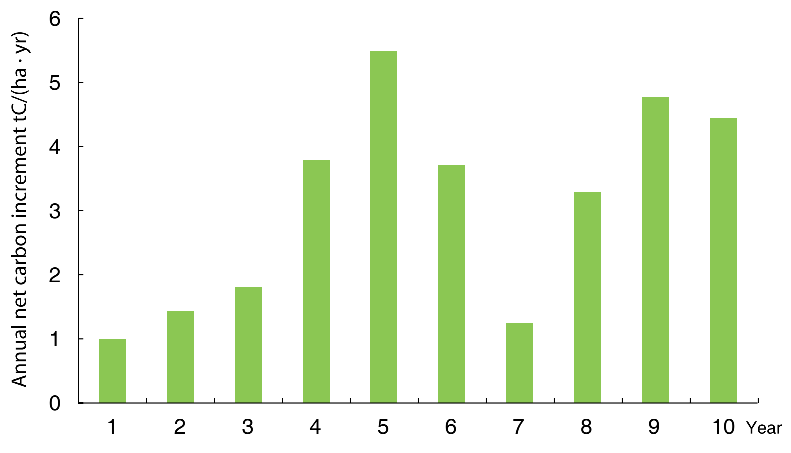

Fig. 3-1 Change in annual net carbon sequestrated in the Moso plantation in the first 10 years t C/(ha • yr)

Year	1	2	3	4	5	6	7	8	9	10
YNC	1.0	1.4	1.8	3.8	5. 5	3.7	1.2	3.3	4.8	4.4
CA	1.0	2.5	4.3	8.1	13.5	17.2	18.5	21.8	26.5	31.0

Table 3-1 Yearly net carbon (YNC) sequestration and carbon accumulation (CA) in the Moso plantation in the first 10 years

Figure 3-1 and Table 3-1 demonstrate that within the initial ten year period there are two peaks of carbon sequestration at years 5 and 9. The increase in culms reaches its peak at Year 5, when there are approximately 2,175 culms/ ha, and reaches a constant level of 3,300 culms/ ha in year 10, which is a common density of a mature Moso forest. In the year 5, the net annual carbon stock increase is about 5.5 tonnes. The increase in growth is smaller in the 6th and 7th year due to less culms being added every year, but increases again from the 8th year onwards because new culms have increasingly bigger diameters during this phase. In the first ten years, the annual average net carbon stock in the new bamboo plantation is approximately 3.1 tons/ha.

3.3.2 Comparative analysis of the carbon sequestration trends of a newly-established Moso bamboo and a Chinese Fir plantation in the first 10 years

Chinese Fir *(Cunninghamia lanceolata)* is one of the most rapidly growing plantation species in subtropical China. Chinese Fir and Moso bamboo forests naturally grow at similar sites and require similar climatic conditions[3]. Due to similarities in distribution and use, a comparison of carbon sequestration between Chinese Fir and Moso bamboo can reveal how bamboo's ability to sequester carbon compares with that of a fast growing tree.

The growth patterns of Chinese Fir (Tian, 2005) and Moso bamboo are very different, as shown in Table 3-2. The Chinese Fir plantations are even-aged whereas Moso is uneven-aged. Whilst a plantation of Chinese Fir younger than 10 years resides in the 'young forest' phase, a Moso bamboo plantation achieves canopy closure and maturation already in its 8th year. Normally, after 8 years, an individual Moso bamboo culm ages and dies, and therefore it should be harvested before that time in order to provide utility and store carbon for a longer period.

Species \ Age		<=10	11-20	21-25	26-35	>=36
Chinese Fir		Young stand	Medium age	Close to maturity	Matured	Old
Moso	Individual Culm	Matured	Dying			
	Stand	Young to mature	Matured			

Table 3-2 The growth patterns of Chinese Fir and Moso bamboo plantations

[3] Since the calculations for bamboo and 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.

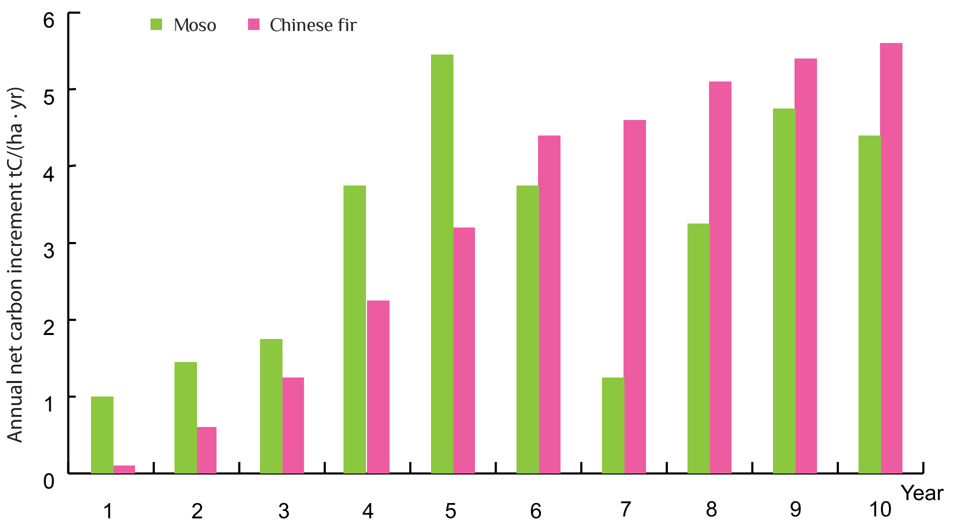

Fig. 3-2 Comparison of modelled carbon sequestration patterns of the Chinese Fir and Moso bamboo plantations during the first 10 years.
(The bars show net annual carbon sequestration t C/ (ha•yr))

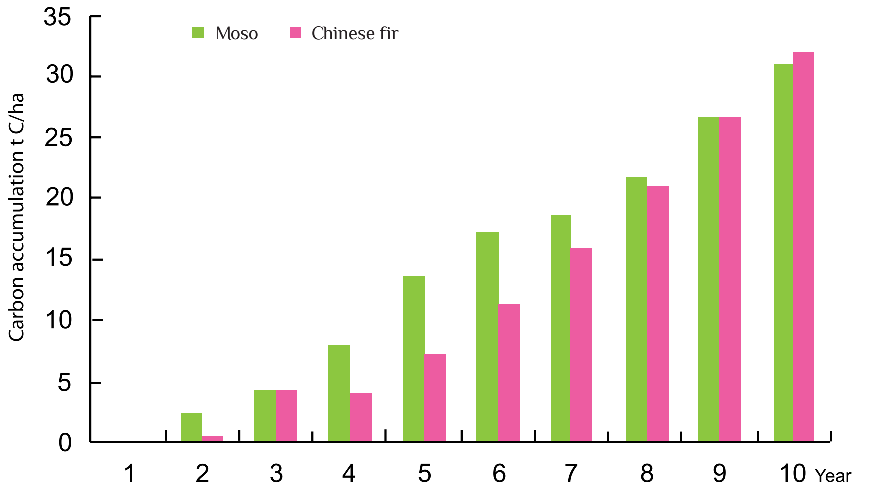

Fig. 3-3 Patterns of modelled aggregate carbon accumulation during the first 10 years of the Chinese Fir and Moso plantations t C/ha

Fig. 3-2 shows that Moso bamboo sequesters carbon rapidly in the first 5 years, and then slows down with a 2nd peak at 8 and 9 year, while Chinese Fir starts relatively slowly but increases steadily during the initial growth period. Fig. 3-3 indicates that by the 9th and 10th year the carbon sequestrated by both plantations presented here would be comparable.

3.3.3 Comparative analysis of carbon sequestration trends of a newly-established Moso bamboo and a Chinese Fir plantation in two harvesting rotations (1-60 years)

Chinese Fir plantations are composed of even-aged stands which are commonly clear-felled as they reach maturity at approximately 30 years. A managed Moso bamboo forest has an annual continuous production of biomass. The first 'mature' culms are harvested after 3 years, and thereafter 1/3 of all the culms are harvested biannually after the 5th year[4]. A Moso bamboo stand is considered to be in biological balance when 1/3 new biomass re-grows after 1/3 of the total biomass is harvested and removed from a bamboo plantation.

The formula used for the Chinese Fir plantation is based upon a 2 x 30 year harvesting rotation cycle, after which the land is put to other use. This is currently the most common practice in China. Fig. 3-4 shows that the annual carbon increase for the Moso bamboo peaks at year 5 and for the Chinese Fir at year 13, at a similar level of 5.5 t C/(ha • year). For the Moso bamboo, carbon increase becomes level at 3.8 t C/ha at year 10. For the Chinese Fir, the calculations show diminishing increases until the end of the first cycle, at 30 years, when all the carbon in the fir is removed (and for the purpose of this study assumed to be converted to durable products) and a new plantation is established that follows a similar pattern. Due to some level of soil degradation, the second cycle of Chinese Fir produces a lower amount of biomass and therefore carbon in comparison with the first cycle[5]. At the end of the first cycle of Chinese Fir (year 30), the carbon calculated to be sequestered by both plantations is roughly equal, while after 60 years the calculated total carbon accumulation for the Moso bamboo plantation was 217 t C/ha and for the Chinese Fir 178 t C/ha[6].

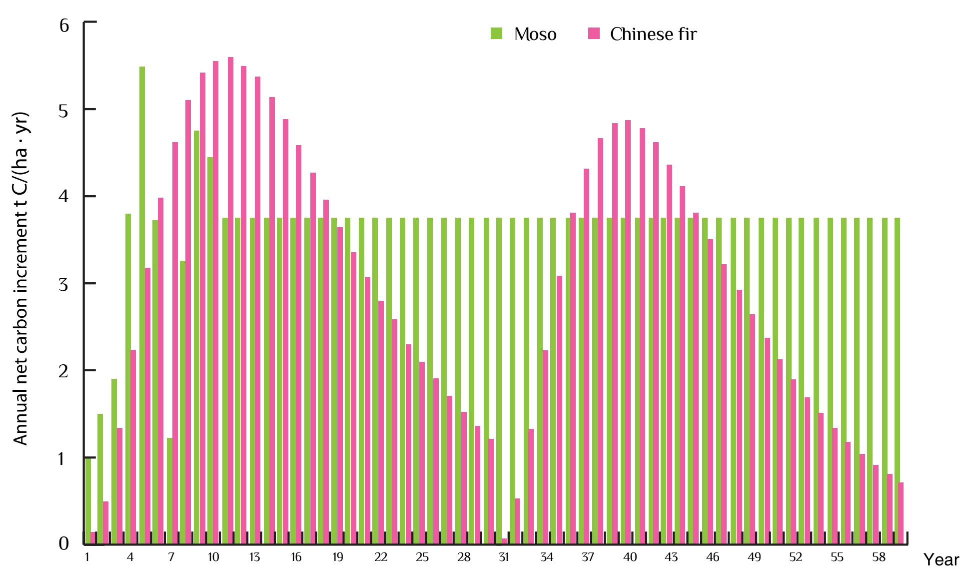

Fig. 3-4 Annual net carbon sequestration patterns adopting regular harvesting patterns within a 60 year period t C/(ha • yr)

[4] For the purposes of this study, this has been converted to annual harvests of 1/6 of the culms. This is shown in the graphs presented in this study.
[5] No studies were found that reported soil degradation and therefore less biomass production for a regular Moso forest between the 30th and 60th year.
[6] For both Moso bamboo and Chinese Fir in the model, harvested culms and stems are included in the total amount of carbon sequestered.

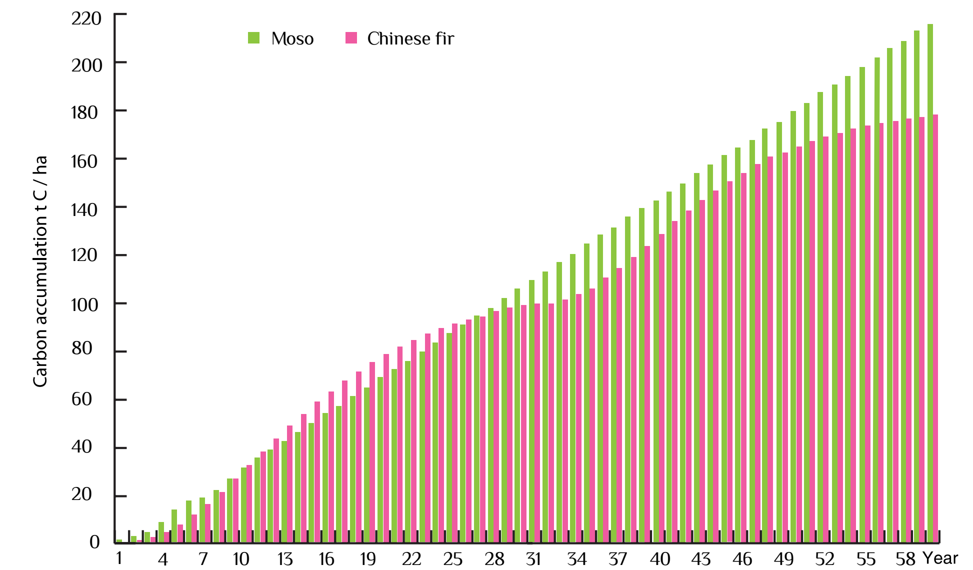

Fig. 3-5 Calculated accumulation of carbon sequestration patterns with regular bamboo harvesting within a 60 year timescale t C/ha

3.3.4 Carbon sequestration by unmanaged bamboo forest (without regular harvesting)

Moso forests without human interventions, or Moso plantations that are planted but not managed are rare in China. However, for the benefit of this analysis, it is important to compare and contrast the differences between carbon sequestration between managed and unmanaged bamboo stands.

Liese (2009) states that an unmanaged, naturally regenerating bamboo forest contains culms of all ages, including many dying and dead ones. The underground rhizome system also may suffer from deterioration. Such forests are often situated far from human settlements and have not been researched. According to FAO (2005), in Asia about 30% of bamboo forests are planted and 70% are natural, and only a part of that is managed by communities or forestry entities.

For the calculations a complete biological deterioration of the dead bamboo culms was assumed so that these would not contribute anymore to plant carbon stock.

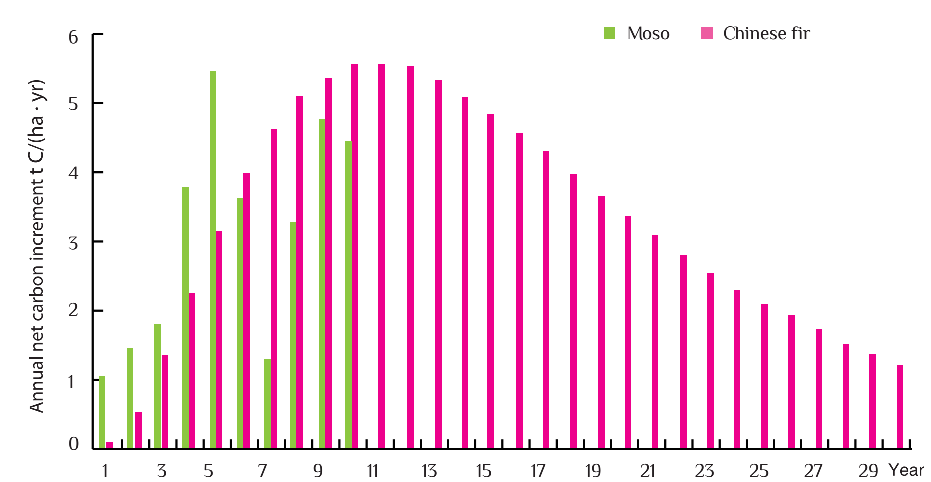

Fig. 3-6 Modelled annual net carbon sequestration patterns without regular bamboo harvesting over a 30 year time period t C/(ha • yr)

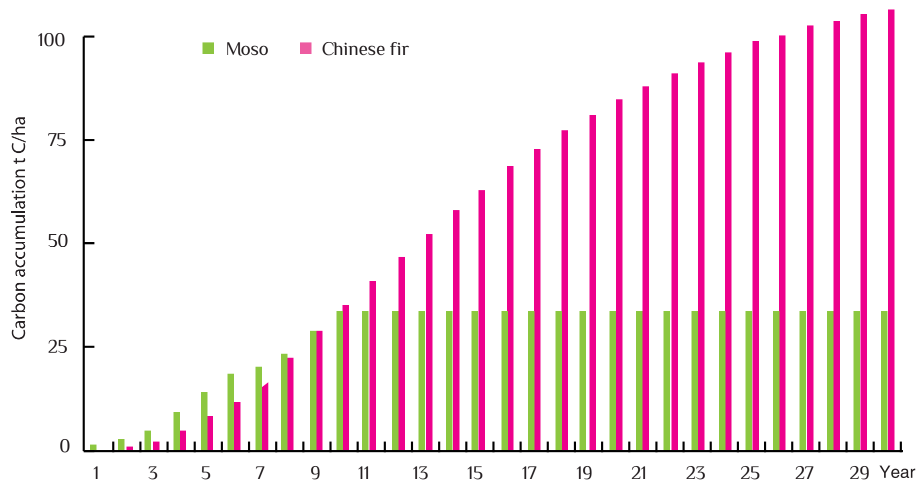

Fig. 3-7 Calculated accumulation patterns of carbon stock without regular harvesting within a 30 year time period t C/ha

Figure 3-6 and Figure 3-7 show that the patterns of the accumulated above-ground carbon in the Chinese Fir plantation is about 3.2 times greater than the accumulation of carbon in an unmanaged Moso bamboo plantation within a 30 year period[7]. Xiao et al. (2007) reported that the carbon stock in Chinese Fir at 15 years is 2.13 times higher than Moso bamboo at 10 years. Figure 3-7 shows that carbon in the Chinese Fir at 15 years is 1.9 times higher than the Moso bamboo equilibrium level (which is reached at 10 years).

These data indicate that carbon sequestered in Moso bamboo forests only would be comparable or exceeding that of Chinese Fir forests when managed with regular harvesting cycles. Where Moso bamboo forests are not managed with regular harvesting, the carbon sequestration of Chinese Fir is likely to be higher. This identifies the need for Moso bamboo management to be encouraged and developed for carbon stock management, and suggest Moso bamboo plantation carbon projects merit inclusion under initiatives such as CDM A/R and potentially the inclusion of management of currently unmanaged Moso bamboo stands under a REDD+ scheme.

3.4 Comparative analysis of field data for Moso bamboo and Chinese Fir

The results of the calculations and the studies of the pattern of carbon sequestration for Moso bamboo and Chinese Fir as presented above are compared with field data from a large variety of Chinese studies in Table 3-3. Total standing biomass carbon for Moso plantations at a similar density as that used for the calculations vary between 25 t C/ha to 91 t C/ha. The figures for Chinese Fir range from 17 to 48 t C/ha (at approximately 10 years); from 37 to 62 t C/ha (at 15 years); and from 70 to 81 t C/ha (at maturity-approximately 25 years). Chinese Fir plantations older than 30 years contain around 195 t C/ha in standing biomass. These field data are in the same range as the ones presented in Figures 3-1 to 3-6, and support the conclusion that Moso bamboo can contribute to carbon sequestration in a similar way as Chinese Fir, provided that the harvested product is turned into durable products that continue to store carbon for long periods.

[7] The sharp drop in carbon increment from 4.5 to 0 tC/(ha•yr) in Fig. 3-6 is due to the calculation used, which provides incremental growth only in the first 10 years. Following this, an equilibrium is maintained as loss due to dying plant material is matched by new growth. Whilst in the field, lower levels of incremental growth may be seen in the first few years after the 10 year mark in some situations, a zero-net gain equilibrium for bamboo forests around the 10 year mark is common.

Type	Location	Density	Above ground Carbon	Below ground Carbon	Total	Age (years)	Ref.
		Culms/ha	(ton/ha)	(ton/ha)	(ton/ha)		
Moso	Nanjing, Fujian (24°52'N, 117°14'E)	\	28.29	10.68	38.97	\	Li,1993
	Fujian (26°14'-28°20'N, 117°02'-119°07'E)	\	29.39	11.49	40.88	\	Chen, 1998
	Yongchun, Fujian (26°14'-28°20'N, 117°02'-119°07'E)	\	23.38	8.99	32.37	\	Peng, 2002
	Wuyishan, Fujian (27°33'-27°54'N, 117°27'-117°51'E)	\	35.47	19.88	55.35	\	He, 2003
		\	29.38	11.49	40.87	\	
	Yongan, Fujian (25°21'-25°31'N, 117°40'E)	2,551~2,801	51.18	22.97	74.15	\	Qi, 2009
		2,251~2,776	44.61	16.69	61.30	\	
		2,201~2,751	37.33	13.70	51.03	\	
	Miaoshanwu, Fuyang, Zhejiang (30°04'N)	\	36.65	34.00	70.65	\	Huang, 1987
	Miaoshanwu, Fuyang, Zhejiang (30°04'N)	3,750	64.63	26.57	91.19	24	Huang, 1993
		2,700	29.09	30.97	60.06	24	
	Lin' an, Zhejiang (30°14'N, 119°42'E)	2,000~4,500	19.08	11.50	30.58	\	Zhou, 2004
	Tianmushan, Lin an, Zhejiang (30°18'-30°24'N, 119°23'-119°28'E)	4,642	26.81	8.88	35.69	\	Hao, 2010
	Changning, Sichuan	\	17.55	8.21	25.76	\	He, 2007
	Huitong, Hunan (26°50'N, 109°41'E)	2,100	15.54	27.31	42.85	10	Xiao, 2007
Modelling Moso With harvesting	Quzhou, Zhejiang	3,300	22.3	8.7	31.00	10	This study, 2010
			\	\	105.20	30	
Chinese Fir	Nanping, Fujian (117°57'E, 26°28'N)	1,061	153.09	37.69	190.78	40	Zhong, 2008
		1,316	169.03	29.20	198.23	87	
	Huitong, Hunan (26°48'N, 109°30'E)	1,530	43.59	8.95	52.54	15	Xiao, 2007
	Nandan, Guangxi (24°58'-25°01'N, 107°29'-107°30'E)	2,200	14.54	2.54	17.08	8	He, 2009
		2,000	21.82	5.41	27.23	11	
		1,967	30.74	6.54	37.28	14	
	Dagangshan, Fenyi, Jiangxi (27°30'-27°50'N, 114°30'-114°45'E)	1,667	42.26	5.34	47.60	12	Duan, 2005
		1,667	48.58	6.20	54.78	14	
		1,667	54.72	6.99	61.71	16	
	Sichuan	\	\	\	23.30	<10	Hou, 2009
		\	\	\	47.45	11~20	
		\	\	\	70.85	20~25	
		\	\	\	81.23	26~35	
		\	\	\	194.22	>36	
Chinese Fir modelling	Huitong, Hunan (26°48'N, 109°30'E)	1,530	\	\	32.00	10	This study, 2010

Table 3-3 Carbon sequestration reported for Moso bamboo and Chinese Fir plantations

3.5 Comparative analysis of carbon sequestration in a new Ma bamboo and an Eucalyptus plantation under tropical growing conditions

Ma bamboo (*Dendrocalamus latiflorus*) is a medium-large-sized sympodial bamboo plantation species distributed extensively across tropical regions, particularly South Asia. Ma bamboo's rapid growing forest counterpart is Eucalypt. Eucalypt is one of the fastest growing plantation species on the planet, demonstrating high yielding characteristics. Introduced to China from Eastern Indonesia in 1890, the rapid development of Eucalypt plantations has led to a current coverage of 1.4 million hectares, which ranks China second only to Brazil in terms of the national Eucalypt plantation area. (Wen, 2000). This section will compare the carbon sequestration patterns of Ma bamboo and *Eucalyptus urophylla*, the most commonly grown Eucalyptus species in tropical China. Because of the rapid growth patterns of these tropical species, the analysis has been limited to differences during the first 10 years.

3.5.1 Comparative analysis of carbon sequestration within a new Ma bamboo and a new Eucalypt (Eucalyptus urophylla) plantation under regular management practices with harvesting rotations within the first 10 years

The calculations for Ma bamboo have been made using equations [4], [7] and [8]. For Eucalypt, a model based upon a new plantation of *Eucalyptus urophylla* was used, with the density about 1,350 individual/ha.

Fig. 3-8 shows that annual carbon increment in the Ma bamboo plantation peaked at year 8 when the culms/ha start reaching a maximum, and the annual replacement of harvested culms becomes balanced. The Eucalypt is felled after 5 years, the calculated pattern for annual increment is similar for the two cycles (years 1-5 and years 6-10). The annual increments for the Eucalypt are both lower (e.g. years 1, 6, 7, 8 and 9) and higher (years 2,3,4,5 and 10) than the Ma bamboo. The pattern of accumulated carbon sequestered for both plantations is shown in Fig 3-9, and appears to be at similar levels, with the Eucalyptus rising earlier but levelling off in comparison with the Ma bamboo plantation in the second 5 year period.

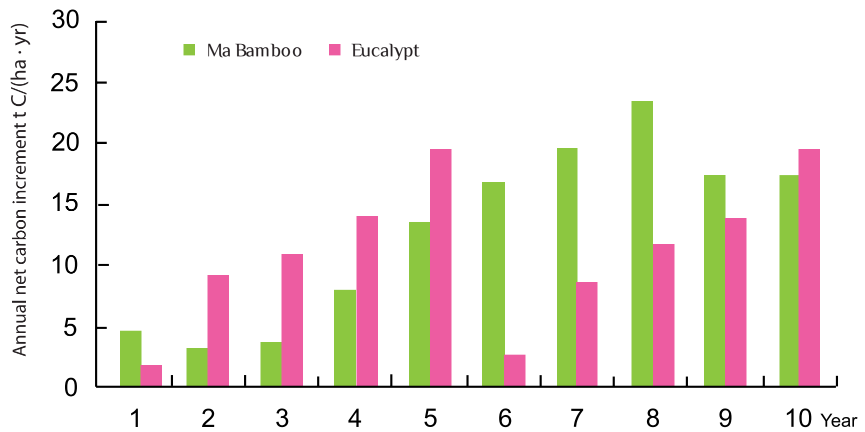

Fig. 3-8 Modelled annual net carbon sequestration patterns under regular harvesting Ma bamboo and Eucalypt plantation practices over a 10 year period t C/(ha · yr)

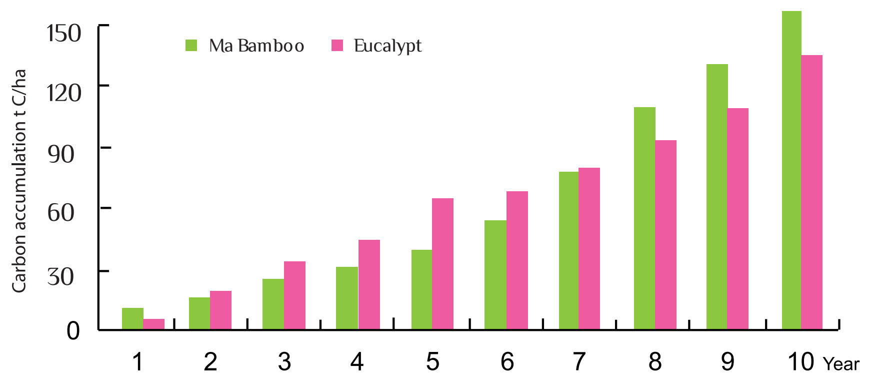

Fig. 3-9 Calculated patterns of accumulation of carbon sequestration under regular harvesting practices for the Ma bamboo and the Eucalypt plantation over a 10 year period t C/ha

3.6 Summary

Moso bamboo and Chinese Fir plantations have comparable features regarding their rapid growth rates and climatic requirements. The study analysed their respective growth patterns and used biomass and carbon calculations to ascertain their relative carbon sequestration patterns and capacity. The results indicate that bamboo and trees have very different sequestration patterns, but are likely to have comparable carbon sequestration capacity, as long as the bamboo forest is managed and the total amount of harvested fibre from both species is turned into durable products.

The Moso bamboo forest used for the modeling parameters in this study had an initial planting density of 315 culms/ha, then grew up to 2,550 culms/ha in year 7. This study assumes that the forest canopy closure and maximum density of 3,300 culms/ha is reached at the 10th year with an average DBH of 10cm. However, under intensive management practices in Moso bamboo forests in China, a density of 4,500 culms/ha and higher can be reached. In this case, the carbon stock and annual sequestrated carbon in the above ground biomass in an intensively management bamboo forest would be higher than the modelling data used in this study. However, the total effect is unclear, as it is expected that intensive management may reduce the sequestration capacity of the soil layer (see also Chapter 6). There may also be higher emissions resulting from the management practices, such as from fertiliser inputs. More research is needed on carbon models under different management regimes.

The carbon sequestration capacity of Eucalypt plantations were compared to sympodial Ma bamboo *(Dendrocalamus latiflorus)* due to the relative rapid growth rates and similar climatic requirements of both species. The study analysed their respective growth patterns and the results indicate that both species may have a comparable carbon sequestration capacity and performance.

Climate \ Species	Bamboo	Tree
Subtropical	31 (Moso bamboo)	32 (Chinese Fir)
Tropical	128 (Ma bamboo)	115 (Eucalypt)

Table 3-4 Modelled accumulated carbon at 10 years t C/ha

Table 3-4 lists the calculated accumulated carbon/ha after 10 years for the 4 plantations included in this study. As explained previously these two bamboo species and two tree species were chosen because they are commonly grown and recognised as having the highest rate of biomass accumulation amongst bamboos and tree species in tropical and subtropical China. It is clear that that in the tropics in Southern China, more carbon is sequestered by both trees and bamboo species. This is likely to be due to the climatic conditions that include higher temperatures, longer growing seasons, and more sunlight, all stimulating photosynthesis and thus carbon sequestration. Since Ma bamboo and Moso bamboo are grown under climatically different conditions, the comparison between the two bamboo species cannot be used as an indication of the importance of genotypic differences for carbon sequestration. For this, further experiments would be needed involving several high performing bamboo species that would be grown under comparable climatic conditions.

It is evident that sustainable bamboo management is the key to achieving sustained carbon sequestration within bamboo plantations, which then can compare at least with tree species. Management techniques should be advocated for both bamboo plantations and natural bamboo forests to realize the full potential of bamboo carbon sequestration.

4. Carbon sequestration capacity in bamboo forest ecosystems

The study has shown that when compared to Chinese Fir and Eucalyptus in managed plantation sites, bamboo is at least equal to the other species in terms of its carbon sequestration capacity. However, results from studies focusing on bamboo carbon sequestration capacity vary greatly as they adopt different methodologies and management practices. Recent research conducted in China indicates that Moso bamboo plays a significant role in regional and national carbon budgets in China. The adoption of Geographical Information Systems (GIS) and remote sensing has expanded the scope to attempt to estimate biomass stocks (Lu, 2006).

The following section presents an analysis of Chinese research focusing on the capacity of bamboo forests to sequester carbon at the ecosystem level (including bamboo, vegetation, and forest soil carbon stocks). An attempt is made to compare the bamboo forest ecosystems with comparable forest ecosystems, whereby the carbon sequestration of each respective forest strata has been analysed to provide more comprehensive results.

4.1 Analysis of bamboo forests' carbon sequestration

Table 4.1 shows that above-ground carbon sequestration storage capacity of Moso bamboo forests including shrubs and litter has been reported at levels varying between 27-77 t C/ha. The majority of carbon was found to be sequestered in the arbour layer, accounting for 84-99% of the total. The shrub layer and the herbaceous layer accounted for very small contributions, especially in intensively managed forests.

Location	Stand management	Vegetation					Soil sampling depth and layer				Ecosystem	Ref.
		Arbor plant	Shrub	Grass	Litter	Sum	0-20 cm	20-40 cm	40-60 cm	Sum	Total	
Lin'an	Intensive	32.991	0	0	0.602	33.593	34.017	21.56	12.385	67.962	101.56	Zhou, 2004, 2006a
	Extensive	29.456	4.166	0.666	0.669	34.957	39.734	22.138	12.309	74.181	109.14	
	Medium	30.58	3.17	0.481	0.656	34.887	36.96	22.294	12.221	71.475	106.36	
Huitong	High-yielding	31.97	0	0.64	0.74	33.35	56.91	55.71	26.97	139.59	172.94	Xiao, 2007, 2009
	Medium -yielding	25.59	0	0.63	0.53	26.75	49.66	36.04	25.26	110.96	137.71	
Dagang shan		31.2	3.8	0.2	0.16	35.36	48.66	48.23	17.02	113.91	149.27	Wang 2007
Yong'an	Intensive management	74.15	0	0	2.59	76.74	45.34	52.2	53.1	150.64	227.38	Qi, 2009
	Medium	61.3	0	0	3.01	64.31	83.55	56.71	57.11	197.36	261.67	
	Extensive management	51.03	0	0	4.88	55.91	95.41	76	61.15	232.56	288.47	

Table 4-1 Carbon stock within Moso bamboo ecosystems (t C/ha)

Table 4-1 also shows that the distribution of carbon storage varies between different layers of soil. Within Moso bamboo forests, the carbon storage down to a depth of 60cm is reported to have a range between 68.0 -232.6 t C/ha, which includes rhizomes, roots and soil carbon. The carbon storage decreases with the soil depth. The soil layer between 0-20cm has the highest carbon stock.

The reported total bamboo forest ecosystem carbon storage capacity collected for this study ranges between 101.6 t C/ha and 288.5 t C/ha, amongst which 19-33% was stored within the bamboo and vegetative layer, and 67-81% was stored within the soil layer, which is about 2-4 times greater than the vegetative layer capacity. The shrub layer accounted for 3.3-5.6% of the carbon stock and the grass and the litter layer accounts for a very limited contribution.

The data in Table 4-1 are for forests where bamboo is the main species. However, many non-commercial species are found as minor species in forests dominated by trees. Very little data on the contribution of such bamboos to the carbon stored in those forests is available.

4.2 Comparison of carbon stock in bamboo and forest ecosystems (including bamboo, vegetation and soil carbon sequestration)

Parts / Forest	Arbor & Shrub	Litter	In soil	Total	Ref.
Moso bamboo in Lin'an (medium-intensity management)	34.2	0.66	71.48	106.34	Zhou, 2004; 2006a
Pinus elliottii at 19th year	86.78	8.86	26.30	121.94	Tu, 2007
Chinese Fir at 15th year	53.60	3.43	93.16	203.79	Xiao, 2009
Moso bamboo in Yong'an (medium- intensity management)	61.3	3.01	197.36	261.67	Qi, 2009
Deciduous broad-leaved forest	47.75	5.85	208.90	262.50	Zhou, 2000
Tropical forest	110.86	3.00	116.49	230.35	
Evergreen broad-leaved forest	73.68	5.43	257.57	336.68	

Table 4-2 Comparison of carbon stock in bamboo and tree forest ecosystems (t C/ha)

Table 4-1 and Table 4-2 indicate that managed bamboo ecosystems are likely to be a somewhat lower static carbon store (varying from 102 t C/ha to 288 t C/ha) when compared with other forest types-both managed and unmanaged (varying from 122 t C/ha to 337 t C/ha), although there is considerable overlap. The amount of carbon that all forest types can sequester is of course influenced by climatic and soil factors. However, it should be realised that the full potential of bamboo for sequestration can only be achieved if bamboo is sustainably managed and if the harvested culms are included in the carbon calculations for comparisons with other afforestation or sustainable forestry management options. This is further discussed in Chapter 7.

5. Bamboo carbon stock estimates at the national level of China

Moso bamboo is the most prevalent species of bamboo in China, accounting for about 3% of the total forest area. The total Moso bamboo area in China is 3.37 million ha, representing 70% of the total bamboo forest in China (according to the forestry inventory of SFA, China).

Carbon density is a key indicator of a forest's ability to sequester carbon, which is defined as the quantity of carbon in a unit area.

Chen (2008, 2009) used data from the 20th century on bamboo forest area, biomass accumulation, carbon storage, carbon density and soil organic carbon to calculate the average Chinese bamboo biomass, the average per plant biomass, soil organic matter content and the carbon density. Data from the period between 1950 and 2003 was used to calculate estimates of carbon storage, changes and area dynamics using two different types of bamboo; Moso and some small sized bamboo species which were grouped together. According to the research, Chinese bamboo forest carbon storage between 1950 and 2003 showed a rising trend. In the period from 1999-2003 the carbon storage capacity was 639.32 Tg C.

The data collected in Table 5-1 show that large variations exists in estimations of total bamboo carbon sequestration, depending on the different methodologies employed, area estimation and culm estimation. Chen (2008) reported that bamboo forest carbon storage in China during a period spanning 26 years (compiled from four of China's five-year national forest surveys) had increased. The initial period saw a rise of 6.5% -7.2% (1977-1981), followed by 7.8% - 9.8% (1984-1988), 9.3% -10.4% (1989-1993), 9.4% -10.6% (1994-1998), 10.6% -11.6% (1999-2003). During the same period the bamboo forest area only increased from 2.87% to 2.96%, and therefore this suggests that there has been a considerable increase of plant biomass per hectare of bamboo over that 26 year period.

Method	1950-1962	1977-1981	1984-1988	1989-1993	1994-1998	1999-2003	Ref.
Based on area	318.55	427.37	463.8	493	548.79	631.58	Chen, 2008
Based on the number of culms	286.59	341.81	414.54	436.28	504.82	605.5	
Based on carbon stock capacity at different ages & area	\	537.6	598.61 (168.798)	\	710.14 (168.647)	837.92 (173.031)	Wang, 2008
Based on area & average carbon density	\	\	\	\	\	1138.88* (258.818)	Li, 2003
Based on area & average carbon density	\	\	\	\	\	1425** (259.091)	Guo, 2005

Note: 1Tg=1012g , * Carbon storage in 2003,** Carbon storage in 2005

Table 5-1 Estimates of total carbon storage (Tg C) and carbon density ((t C/ha (in italics) in bamboo forests in the past 6 decades in China

Currently it is believed that forestry and forest vegetation sequesters a global average of 359 Pg C with an average carbon density of 86 t C/ha. China's forest carbon density at 38.7 t C/ha is below the global average (Wei, 2007). *Pinus sylvestris* forest carbon density is recorded at 31.1 t C/ha, larch forest at 60.2 t C/ha, Spruce-fir forest at 82.01 t C/ha, and tropical forest at 110.86 t C/ha (Zhou, 2000).

The carbon density in bamboo forests, as shown by the data included in table 5.1, is relatively high, ranging from 168.647 to 259.091 t C/ha. While this is within the range reported in Chapter 4, it is currently much higher than the average forest carbon density at the national level of China. One of the reasons for this could be that a large portion of China's forests are newly-planted young plantations with a low carbon stock, while most bamboo forests are mature secondary forests. It is expected that when the maturation stage for other forests is reached, the Chinese average will rise, and the carbon density of bamboo will be much closer to the Chinese average, as other forests are likely to sequester carbon to a level at least equal to bamboo, as was shown in Chapter 3 and 4.

Chen (2009) estimated that the carbon stocks in bamboo stands for 2010, 2020, 2030, 2040, and 2050 are expected to increase to 727.08 Tg C, 839.16 Tg C, 914.43 Tg C, 966.80 Tg C, and 1017.64 Tg C respectively. These data are based on government predicted trends over the next five decades which have been adjusted according to forest and bamboo variables, mainly because of an expected increase in bamboo area.

Increasingly studies are demonstrating that bamboo does have a role to play in carbon sequestration within forest ecosystems (Yang et al., 2008). The great variation in attempts to estimate total bamboo forest carbon identify a need to harmonize the measurements of carbon density across different sites, species, climates and conditions. While the case of China has been used above, this is only because data from other countries is lacking, both regarding the area of bamboo forests and estimates of bamboo carbon density in other countries. These would be needed before a reliable global estimation of bamboo carbon stock can be made.

6. Impact of management practices on carbon sequestration in Moso bamboo forests

Research indicates that bamboo has high productivity and, through management techniques, could sequester higher amounts of carbon, which could create a sink effect. A Moso bamboo forest requires approximately seven years to grow to maturity, which is significantly faster than tree species. Bamboo stands require more frequent management practices compared with other kinds of forestry stands. Due to its rapid growth and regeneration, bamboo can be harvested by annual selective cutting. Bamboo stands pass from the establishment stage through phases of tending, pre-commercial and commercial thinning, and harvesting. Each stage requires specific silvicultural interventions (Lobovikov et al., 2009).Therefore the impact of management practices on carbon sequestration capacity, the ecosystem and carbon distribution patterns of bamboo forest are key issues to be addressed. At present, this issue has received little attention from researchers (Zhou, 2006a; Qi, 2009).

Generally there are three management types that are utilized in China for bamboo forest silviculture practices: high intensive, intensive and extensive management (Table 6-1).

Types	Management practices	The general characteristics of forest land
High intensive	Fertilising, clearing the understory once a year, tending, cutting bamboo and harvesting bamboo shoots	Only bamboo in arbor layer (no other trees), no understory
Intensive	Fertilising once a year, tending, cutting bamboo and harvesting bamboo shoots	Limited understory
Extensive	Tending, cutting bamboo and harvesting bamboo shoots	There may be mixed species, with shrub and herb layers and tree seedlings

Table 6-1 bamboo forest silviculture types in China

The data presented in table 4-1 suggested that extensively managed bamboo forest ecosystems have a higher carbon stock (288.5 t C/ha) than intensive management systems (262-227 t C/ha). However, intensively managed plantations increase carbon stock in the arbor part of the bamboo (51-74 t C/ha) compared with extensively managed plantations (39-51 t C/ha). Therefore intensively managed bamboo forests appeared to store about 1.4 times more carbon in the tree layer than extensively managed forests, while the carbon stock in the litter layer and soil of extensively managed bamboo forests appeared to be higher than those of intensively managed bamboo forests, 1.6 and 1.3 times respectively (Qi, 2009). Similarly, the annual fixed-carbon stock of Moso bamboo was reported at 12.7 t C/(ha•yr) when intensively managed, which is about 1.6 times the capacity when extensively managed (8.1 t C/(ha•yr)), 3.6 times the rate of Chinese Fir plantations, and 2-4 times the rate of tropical rain forests and pine forests (Zhou, 2006b). Intensive management increases the density of the bamboo stands. Qi (2009) reports that Moso bamboo annually fixed-carbon stock can be as high as 20.1 to 34.1 t C/(ha•yr). For the carbon in the litter and shrub layer and in the soil, i.e. the rhizomes, the roots and other carbon present in the soil, the indications point in the other direction (i.e. that intensive management decreases carbon sequestration in the below ground pool). Within the understory of extensively managed bamboo forests, the annual carbon sequestration capacity can reach up to 0.546 t C/ha, and the litter layer up to 6.114 t C/ha, which is equal to about 2 times the capacity of intensively managed bamboo forests (3.049 t C/ha) (Zhou, 2006).

Also, under intensive management, the soil total organic carbon (TOC), water-soluble organic carbon (WSOC), microbial biomass carbon (MBC) and mineralizable carbon (MC) were found to be significantly lower (Zhou, 2006c; Xu, 2003). The repeated use of annual chemical fertilizers (itself a source of GHG) led to the decrease in water soluble carbon and soil microbial biomass carbon storage, causing a reduction in soil carbon storage (Jiang 2002b; Zhou, 2006c). Five years after intensive management, the TOC, WSOC, MBC and MC were significantly lower than those in extensively managed bamboo, and the TOC continued to decline for 20 years before stabilizing.

It is clear that intensive management has mixed effects on the carbon sequestration capacity of bamboo stands, and that much more research is needed to establish the best management option for carbon sequestration.

There are many policies that advocate afforestation as a carbon offset option. The establishment of productive monoculture plantations of rapidly growing tree species are considered to contribute to the terrestrial carbon pool. However, afforestation in monocultures on a large scale can impact water resources, cause substantial losses in stream flow, and increased soil salinization and acidification (Jackson et al., 2005). There are further concerns regarding the decline in forest biodiversity due to the expansion of such monoculture plantations, leading to reductions in ecosystem services (Bunker et al., 2005). Policies that advocate carbon sequestration in forest ecosystems should also consider the protection of ecosystem services and biodiversity, rather than just advocating an increase in monoculture plantations (Lal, 2008). Similarly with bamboo plantations for carbon sequestration it is important to advocate sustainable bamboo management.

In China bamboo species have been successfully combined within agroforestry and agriculture systems (Lobovikov et al., 2009), and this should be explored further in other parts of the world in the context of the specific local conditions.

7. Carbon sequestration in durable products

The models used in Chapters 3 and 4 assume that for both wood and bamboo species, all the carbon which was sequestered was retained in a durable state, be it in standing biomass or harvested products. Clearly this is an assumption which is not realistic since in practice, some carbon is lost when wood is converted into other products. The transformation of carbon in biomass into carbon locked in products is discussed in this chapter.

7.1 Carbon in Harvested Wood Products (HWP)

A carbon pool is created through the use and disposal of harvested wood products (HWP). The management of the life cycle of HWP therefore affects the concentration of carbon in the atmosphere (Hashimoto, 2008). The IPCC HWP report classifies HWP as a 'carbon reservoir' (Pingoud et al., 2006). The IPCC Guidelines for National GHG Inventories (IPCC, 2006) provide four accounting approaches to HWP: the stock-change approach, the atmospheric-flow approach, the production approach, and the simple decay approach (Hashimoto 2008), which are all methods of estimating the HWP contribution regarding carbon sequestration (Pingoud et al., 2006).

In contrast to the approach used in Chapter 3, carbon within HWP is not often accounted for as being sequestered and it is assumed that either all of the carbon in harvested trees is released into the atmosphere, or that there is no increase in the stock of wood products (IPCC 1996; Marland et al., 2010). Skog and Nicholson (1998) estimated that wood and paper products in use and in landfills in the USA in 1990 accounted for approximately 2.7 Pg C (20% of the amount of carbon in forest trees in the USA) and that this was increasing by 0.06 Pg C per year. In 2000, the amount of carbon in HWP produced globally was 0.71 Pg C (Pingoud et al., 2003). The annual inventories of CO2 emissions for major wood producing countries can change by as much as 30% depending on how harvested wood products are treated in the inventory (Pingoud et al., 2003; Marland et al., 2010).
The continuous growth of the size of the pool of harvested products is thus a key determinant in whether the system acts as a sink. Gustavsson (2001) also noted that wood-based building materials can affect the carbon balance through relatively low levels of generated CO2 as shown in their life cycle analysis when compared to industrial materials which consume high levels of GHGs in their production and development.

7.2 Carbon in harvested bamboo products (HBP)

For the comparison between bamboo and rapid growing wood species such as Chinese Fir and Eucalyptus, a key question is whether bamboo can be considered on the same terms as Harvested Wood Products, based upon the characteristics of the material, and the uses of the products. An individual culm has a limited lifetime of 7-10 years in a natural forest, and thereafter its biomass and the carbon contained will biodegrade and CO2 will be released into the atmosphere. On the other hand, prolonged sequestration of carbon is provided through a great variety of bamboo products that range from construction materials to pulp (Liese, 2009).

Comparisons between bamboo species and wood species in Chapters 3-5 assume that there is an equal rate of conversion from living carbon to biomass. A number of factors may affect this assumption, amongst which the durability of products is of key concern. According to product longevity and durability, bamboo products may be divided into short-term products such as fuel, papers or other agricultural usages, medium-term products such bamboo baskets and bamboo panels, and long-term products such as furniture, laminated products and permanent bamboo houses or flooring. The longevity and durability of bamboo products may determine the carbon storage performance to a great degree. It is important to reduce by-products and waste and to produce durable bamboo products during bamboo processing.

Current processing technology innovations and product development have increased the proportion of durable bamboo products. The prolonged storage of carbon is possible whenever the culms are processed into products with long life cycles, such as construction materials, panel products and furniture. The development and promotion of durable products can also contribute to the global campaign to promote low-carbon industry.

7.3 Bamboo biochar

Biochar may be considered as a potential alternative to bamboo products as a durable carbon stock. Through a process of pyrolysis, up to 50% of the carbon can be transferred from plant tissue to the biochar, with the remaining 50% used to produce energy and fuels (Lehmann, 2007). Biochar is a highly stable carbon compound created when biomass is heated to temperatures between 350 and 600 °C in the absence of oxygen (Whitman and Lehmann, 2009), which is subsequently mixed into soil to raise productivity. Conversion of biomass into biochar increases the residence time of carbon in the soil (Lehmann and Joseph 2009), as well as also reducing emissions of other Green House Gases (GHG) such as methane and Nitrous Oxides from the soil (Yanai et al., 2007). Biochar not only presents a potential carbon sink, but was known by ancient cultures as an effective fertilizer (Glaser, 2007). Biochar provides an opportunity to enhance agricultural productivity in nutrient-poor soils, has proven long term benefits in terms of nutrient retention and availability, reduced leaching of nutrients and other contaminants, potentially increased water availability for plants and potential benefits to microorganisms (Lehmann and Joseph, 2009). Biochars are also known de-tanifiers and have been tested as additives in animal feed (Lehmann and Joseph 2009). Van et al. (2007) also found that when bamboo biochar was added to goat feed there were noted production benefits.

Hua et al (2009) found that bamboo biochar was an effective fertilizer when incorporated with sludge composing thereby effectively reducing nitrogen loses in the soil. The positive effect was related to the high adsorption capacity of biochar particles during composting (Dias et al., 2009). Asada et al. (2002) found that bamboo biochar was effective in absorbing ammonia in soils. This was attributed to acidic functional groups formed as a result of thermolysis of cellulose and lignin at temperatures of 400 and 500°C (Lehmann and Joseph, 2009).

Due to the complexities of many of the carbon trading mechanisms, biochar presents a viable, simple alternative to sequester carbon for many rural households. The UNFCCC included biochar in their 2009 draft for the Copenhagen meeting, stating "Consideration should be given to the role of soils in carbon sequestration, including through the use of biochar and enhancing carbon sinks in drylands" (UNFCC, 2009). Many developing countries could benefit from investment in technology to enable the production of biochar; biochar can be produced in small and large scale systems from small cooking stoves to larger bioenergy systems (Whitman and Lehmann, 2009). Studies have found that biochar has average residence times in excess of 1000 years (Lehmann and Joseph, 2009), indicating that biochar could be an effective method of storing carbon, and presenting a potential alternative to durable products which do not have such longevity. The stability of biochar is a key issue in evaluating the potential benefits of bamboo biochar. Studies show that residence times vary from 293 years in Russian ecosystems (Hammes et al., 2008) to 9529 years in Australian woodland calculations (Lehmann et al., 2009).

More research is needed to ascertain the potential for bamboo biochar; the long-term storage times contradict the fertilizer functions that require bio-degrabability of the material. Steinbeiss et al (2009) found that biochars produced by hydrothermal pyrolysis could contribute to the soil carbon pool, however the rate of degradation depends on the type of biochar which is related to the condensation grade and chemical structure. Biochars could be designed to act as fertilizers whilst simultaneously adding to the soil carbon pool on a decadal time scale. Tens of years however contradicts the hundreds to thousands of years cited in other studies. Further studies are necessary to design the best possible soil amendments and to investigate the long-term behavior of these biochars in natural systems (Steinbeiss et al., 2009).

8. Conclusions

Under regular management practices including stand and soil management and yearly harvesting regimes, this study, through an analysis of the carbon sequestration patterns, found that bamboo plantations are likely to sequester carbon at a similar level as comparable fast growing trees, but following a different pattern:

1. The modelled Moso bamboo plantation during the process of canopy closure in the first 5 years sequestered much more carbon than the Chinese Fir. The modelling of the Ma bamboo plantation indicated slower sequestration than the comparable Eucalyptus during the first 5 years. Later on, the situation for both sets of comparisons equalized. Based on these data, and an extensive overview of the literature on carbon and biomass production of plantation forests in China, bamboo appears to be a viable option for carbon sequestration within forestry.

2. Sustainable management and harvesting practices are essential for bamboo plantations and natural bamboo forests to exploit and sustain their capacity for carbon sequestration. If not properly managed or left un-managed, the quantity of carbon sequestered in Moso bamboo was calculated to be only about 30% of the Chinese Fir in 30 years in subtropical regions. Thus to achieve higher levels of carbon sequestration, sustainable bamboo management, regular harvesting and utilization for durable products should be advocated.

3. At the ecosystem level, the carbon stock of a mature bamboo forest appears to be equal or somewhat lower than most other natural forests and plantations. However, in a mature bamboo forest, the annual net carbon sequestration is constant due to the practice of full re-growth after regular harvesting. About 2/3rds of the above ground total carbon and all of the below-ground carbon stays on site for a much longer period of time than other plantations, which are subject to clear felling when the plantation reaches maturity. Substantial amount of carbon are stored in the bamboo forests of China, and the total amount is expected to increase in the future primarily as a result of the planned increase of the area under bamboo due to afforestation programmes.

4. Since harvested bamboo and plantation wood are counted as stored carbon in the models used, the importance of Harvested Wood Products (HWP) and their potential to contribute to carbon sequestration has been briefly analysed. The new generation of bamboo products with long life spans is positive for prospects that carbon in biomass can be sequestrated for a longer period before they biodegrade, and further innovations should be encouraged to enhance the number of durable bamboo products.

5. Conversion of biomass into biochar is thought to stimulate carbon with a long residence time in soil. Biochar is considered to provide an opportunity to enhance agricultural productivity in nutrient-poor soils, has proven long term benefits in terms of nutrient retention and availability, reduced leaching of nutrients and other contaminants, potentially could increase water availability for plants and may have potential benefits to microorganisms. Biochar made out of bamboo offers interesting prospects but still requires a lot of research.

6. The calculations presented in this study are based on current climate conditions. Climate change will probably change the way bamboo and the other tree species used for comparisons grow, photosynthesises, and may alter their resilience to increased precipitation, temperature variability, pests and diseases as well as exposure to extreme weather events and fires. Scenario studies are needed to try to understand how climate change will affect the capacity of bamboo and the other trees to mitigate climate change.

This study underlines the similarities and differences in carbon sequestration between bamboo and other rapid-growing tree plantations. This study is based on data from China, because very little data are available from other parts of the world. It is hoped that research in other countries and regions will be carried out in the future to complement the work presented here.

While recognising that much more work needs to be done, the results from this report provide an indication that that bamboo forests potentially contribute significantly to meeting the three distinct components of the MAD Challenge brought about by Climate Change. As the importance of bamboo forests in providing both development needs and adaptation opportunities for local communities is already recognised, the role that they can play in providing global carbon sequestration services, as explored in this study, suggests that bamboo deserves more recognition as a plant of considerable importance in meeting the demands of a planet in need of both prosperity and sustainability.

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