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Managing planted forests for multiple uses under a changing environment in China

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Abstract

Background: Planted forests are expanding throughout the world, and now account for 7% of global forest cover and provide more than 60% of global industrial round wood. Negative ecological and social impacts of the establishment of planted forests and the challenges of their multi-purpose management have also given rise to concern. China has been playing an important role in global expansion of planted forests while reducing emission from deforestation and forest degradation.

Methods: This article attempts to conduct an overall analysis and review of the current status, challenges and future perspectives of planted forests in China to obtain a better understanding on how to manage planted forests for multiple uses under a changing environment. Data from several national forest inventories and other sources, as well as new empirical data, were used for a statistical analysis on the dynamics of planted forests in China.

Results: Planted forests in China have undergone a continuous expansion in the past 20 years, which has significantly contributed to an increase in total forest cover and timber supply as well as other ecosystem services like carbon sequestration. The three key driving forces for this expansion were government programmes, and market and technology development. However, the predominance of very few tree species in the plantations, uneven spatial distribution, skewed age-class distribution, and low volumes in growing stock, coupled with increasing complexity of multiple purpose forestry management under a changing environment, have generated several major challenges confronting planted forests in China.

Conclusions: A strategic transition in the management of Chinese planted forests is needed, with a shifting emphasis from area expansion to stand productivity and quality enhancement, from traditional timber production to multi-purpose management for forest goods and services, and from monoculture plantations to biodiversity rich mixed forests. A landscape-design approach and adaptive management practices should be put in place to meet the diversified demands of stakeholders for different goods and ecosystem services while enhancing forest resilience under the changing climate.

Background

Planted forests are composed of trees established through planting and/or through deliberate seeding of native or introduced species for productive and protective purposes. Such forests have been expanding rapidly in all regions of the world reaching 264 million ha in 2010 (FAO, 2010), of which nearly 48% was established within the past 20 years. These planted forests are mainly distributed in Asia, accounting for 46% of the total world planted forest area, followed by 26% in Europe and 14% in North America. China alone accounts for 23% of the total planted forest area in the world, with a rapid expansion rate of 1.76 million ha annually, contributing significantly to the offsetting of annual net global loss of 6.77 million ha in the past 20-year period (FAO, 2010). Besides the expansion of the planted forests, the natural forests in China have been also increasing with a net gain of 9.57 million ha since 1998 when China launched the Natural Forest Protection

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Program (State Forestry Administration (referred as SFA below), 2014).

Although planted forests represent only 7% of the global forested area, their contribution to the global industrial round wood production exceeds 60% (Carle and Holmgren, 2008). It is expected that the expansion of planted forests will continue or even accelerate in many parts of the world in order to meet the increasingly diversified demands on forest goods and services from the society. Given the current expansion trend, a further rise in the area of planted forests up to 300 million hectares by 2020 can be anticipated (FAO, 2010). Planted forests are therefore expected to increasingly contribute to the world's supply of wood, fibre, fuel and non-timber forest products (NTFPs), as well as provide environmental and social services. In particular, the central role of planted forests in mitigating climate changes, conserving biodiversity, combating land degradation and developing green economy has been increasingly recognised in the evolving international processes and financing mechanisms (Winjum and Schroeder, 1997; Paul et al, 2012). At the same time, negative ecological and social impacts of planted forests and the challenges confronting planted forests have also given rise to serious concern across the globe (Winjum and Schroeder, 1997; Booth, 2013; Ferraz et al, 2012).

Due to its important role in global expansion of planted forests, China's experience provides a deep insight into the mechanisms underlying the successful development of planted forests. The impacts of planted-forest development on timber markets and the environment are of significance to policy-makers, planners and forest managers. A number of studies carried out in the world predict the future contribution of planted forests to economic, environmental and social services. However, there have been no comprehensive analyses on the development of planted forests in China so far, even though global assessments of planted forest resources and outlook studies for wood from planted forests, best practice guidelines and many interesting cases of country applications from around the world have been documented (FAO, 2006a, 2006b; Kröger, 2012; Carle and Holmgren, 2008; Cossalter and Barr, 2005; FAO, 2010). This paper presents an overview on the current status and driving forces of planted forest development in China, and describes the major challenges and future perspectives of China's planted forests. The authors' aim is that this article will provide useful information and experiences for other developing countries, and assist with understanding the overall situation of the planted forest resource in China and its future development strategies under climate change.

Methodology

The method applied in this paper is basically analysis of the available data and other information. The data used are publicly available except where specifically stated. Most of data used for the analysis originate from the Food and Agriculture Organization (FAO) statistics, the national forest inventories and the forestry statistics by the Chinese Government referenced herein. The FAO statistics, mainly the Global Forest Resources Assessment 2010, provide a good database for global and regional analysis. Forest resources inventories have been conducted periodically in China for about 40 years. The data from eight times national forest inventories have been used to explore the dynamics of planted forests in China using information on tree species, age structure and spatial distribution and so on. The data on planting area, investments and so on have been derived from the Chinese Forestry Statistical Yearbook published annually by the Government. In order to explore the forces driving establishment of new forests at local level, an economic investigation was conducted in 2011 for a comparative cost-benefit analysis through interviews with 50 farmers from the Banqiao village and the Guantang village in the city of Qinzhou in the Guangxi region of China where *Eucalyptus* spp. plantations have been greatly expanded in the last decade.

Current status of planted forests in China

Historically, China was rich in forest resources and biodiversity due to its vast geographical areas and highly diversified climate conditions that provided favourable environments for widely varying forest ecosystems ranging from boreal forests in the north to tropical rain forests in the south. Most forests were public assets and strong centralised governance ensured their strict protection against unauthorised occupation and illegal logging except during the declining period of Qing dynasty in the latter part of nineteenth century and the first half of the twentieth century. Post revolution, China's forestry development has experienced an oscillating process, as in most places across the world (Lane and McDonald, 2002), characterised by three distinct phases of: (i) over-logging and deforestation resulting in reduction in the extent and quality of forest cover, (ii) massive reforestation and afforestation across the country with a few species for increased production of timber and other forest products, and (iii) shifting focus of management from production-centred forestry towards higher emphasis on ecological rehabilitation, environmental amelioration and provision of ecosystem services (S. Liu et al., 2011).

During the latter two phases, afforestation and reforestation have played a dominant role in promoting the rapid and massive expansion of planted forests in China (Figure 1). The most recent national forest inventory places China's forest cover at 21.63% of the country's geographical area, up from just about 10% at the end of 1970s. China today has about 208 million ha of forested

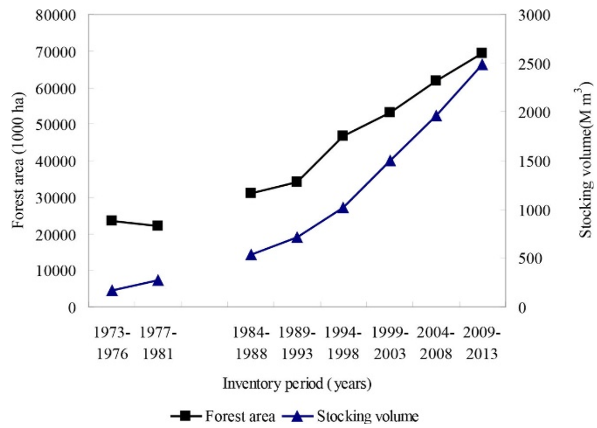

Figure 1 Area and volume of planted forests in China over the last forty years. Sources: Data from the eight national forest inventories in China, including General Bureau of State Forestry, 1977; Ministry of Forestry 1983 1989 1994; SFA 2000 2005 2009 2014.

land and 15.14 billion m^3 of stocking volume, of which the total planted forests account for 69.33 million ha (36%) of the total forest area and 2.48 billion m^3 (17%) of the total forest stocking volume of the country (SFA, 2014).

Types of planted forests

China's Forest Law (1998) classifies the five major types of forests based on their management objectives, namely: (i) timber forest, with the main purpose of producing timber, including bamboo forests which are utilised for bamboo wood; (ii) economic forest, with the main management emphasis on forest products other than timber, such as fruit, nuts, herbs, bark, leaves, tree sap, flower buds and tender sprouts, and raw materials for forestry chemical industries etc. (In China's forest inventory system, economic forest is measured only in terms of area, but not stocking volume.); (iii) fuel-wood forest, with the main purpose of producing fuel wood; (iv) protection forest, with the main emphasis on protection and provision of services; and (v) special use forest, with the purpose of special use such as national defence, environmental conservation, scientific experiments etc.

The first three types are categorised as commercial forests, which are predominantly managed for economic purposes, and the latter two are categorised as ecological forests predominantly managed for ecological purposes. Among the five types, timber forest accounts for 43% of the total planted forest area, followed by economic forest and protection forest. In terms of stocking volume, timber forest accounts for 63% of total planted forests, followed by protection forest (Table 1).

Dominant tree species in planted forests

According to the characteristics of trees in terms of height and trunk, the planted forests are classified as

Table 1 Composition of types of planted forests in China

Forest type	Area		Stocking volume	
	1000 ha	%	1000 m^3	%
Timber	29,753	42.9	1,551,938	62.5
Protection	17,993	26.0	840,375	33.8
Special use	1,473	2.1	87,288	3.5
Economic	19,855	28.6	-	0.0
Fuelwood	260	0.4	3,647	0.1
Total	69,334	100	2,483,248	100

Sources: The Eighth China's National Forest Inventory (SFA, 2014).

high forests, economic forests and bamboo forests in China's forest inventory (Xiao, 2005). High forest is the one that originates from seed or from planted seedlings, with standalone trunks and height over six metres. Economic forest as one of the five major types of forests is separated from the high forest when describing the dominant tree species. Bamboo forest refers to the forest land spanning more than 0.067 ha (one Chinese moo) and growing bamboo species with a diameter at breast height of over 2 cm. The latest national forest inventory shows that the planted forests consist of 47 million ha of high forests, 19.8 million ha of economic forests and 2.4 million ha of bamboo forests.

Ten tree species dominate the 34.3 million ha of planted high forests and they contain 1.87 billion m^3 of stocking volume according to the latest National Forest Inventory, Table 2. The remaining 12.7 million ha consists of more than 60 tree species. Among these dominant species, the top five are Chinese fir (*Cunninghamia lanceolata* (Lambert). Hooker), poplars (*Populus* spp.), eucalyptus (*Eucalyptus robusta* Smith), larch (*Larix gmelinii* Rupr.) and Masson's pine (*Pinus massoniana* Lamb.), accounting for 60% of total area of planted high forest and 66% of total volume of planted high forest (Table 2) respectively. Following attempts to broaden the ecological base of plantations in recent years, mixed plantations now cover 16% of planted forests while the rest is monoculture.

Age classes of planted forests

In the forest inventory of China, there are five age classes that are young, middle- aged, pre-mature, mature, and over-mature. The classification of age class follows national guidelines for forest resources survey (SFA, 2011a). The age class interval can be divided by 20 years, 10 years, 5 years, or 1~2 years depending on the growth rate and life time of various tree species. Since major reforestation and afforestation work in China began in the 1970s and gathered momentum thereafter, the young and middle-aged classes dominate the forest landscape accounting for nearly 72% of the total area of planted high forest and 52% of the total

Table 2 Composition of dominant tree species (group) in Chinese planted high forests

Dominant tree species	Area		Stocking volume	
	1000 ha	%	1000 m^3	%
Cunninghamia lanceolata	8,946	19.0	625,404	25.0
Populus spp.	8,538	18.1	502,958	20.1
Eucalyptus robusta	4,455	9.5	160,334	6.4
Larix gmelinii	3,137	6.7	184,142	7.4
Pinus massoniana	3,062	6.5	171,552	6.8
Pinus tabulaeformis Carr.	1,608	3.4	66,072	2.6
Cupressus funebris	1,462	3.1	61,042	2.4
Pinus elliottii Engelm.	1,344	2.9	40,560	1.6
Robinia pseudoacacia L.	1,226	2.6	26,992	1.1
Quercus spp.	541	1.1	34,396	1.4
Others	12,745	27.1	631,735	25.2
Total	47,064	100	2,505,187	100

*Sources: The Eighth China National Forest Inventory (*SFA, 2014*).*

stocking volume of planted high forest (Table 3), respectively.

Spatial distribution of planted forests

The planted forests in China are unevenly distributed across the whole country, with greater concentration in the warmer and wetter south and southwest regions, accounting for 63% of the total area and 62% of the total stocking volume of planted forests, respectively (Table 4). The top five provinces are Guangxi, Guangdong, Hunan, Sichuan and Yunnan, reaching 25.3 million ha, accounting for 37% of the total area and 31% of the total stocking volume of planted forests, respectively.

Ecosystem goods and services from planted forests

Planted forests, like natural forests and many other types of vegetation, provide ecosystem goods and services that significantly contribute to human well-being. Currently, the annual harvest from planted forests reaches 155 million cubic metres, accounting for 46% of the total wood production (SFA, 2014). Being one of the leading timber consumers in the world, China's wood demand has been rapidly growing with the increasing national economy and population. The increasing gap between China's timber supply and demand has to be mostly fulfilled from its own planted forests although some timber is imported from planted forests in countries such as New Zealand.

Table 3 Age structure of planted high forests

Age class	Area		Stocking volume	
	1000 ha	%	1000 m^3	%
Young	18,662	39.6	357,099	14.4
Middle-aged	15,147	32.2	927,257	37.3
Close to mature	6,679	14.2	581,627	23.4
Mature	5,099	10.8	483,939	19.5
Post-mature	1,483	3.2	133,327	5.4
Total	47,070	100.0	2,483,249	100.0

*Sources: The Eighth China National Forest Inventory (*SFA, 2014*).*

Table 4 Spatial distribution of planted forests in China

Region and province	Area		Stocking volume	
	1000 ha	%	1000 m^3	%
South and southwest region	**43,962**	**63.3**	**1,546,271**	**62.3**
Guangxi	6,345	9.2	222,722	9.0
Guangdong	5,579	8.0	154,677	6.2
Hunan	4,746	6.8	140,945	5.7
Sichuan	4,493	6.5	159,645	6.4
Yunan	4,141	6.0	110,203	4.4
Fujian	3,777	5.4	248,532	10.0
Jiangxi	3,386	4.9	111,219	4.5
Zhejiang	2,585	3.7	68,318	2.8
Guizhou	2,373	3.4	115,574	4.7
Anhui	2,251	3.2	93,748	3.8
Hubei	1,949	2.8	60,071	2.4
Hainan	1,362	2.0	23,132	0.9
Chongqing	926	1.3	35,917	1.4
Tibet	49	0.1	1,568	0.1
North and East Plain region	**10,357**	**15.0**	**351,726**	**14.1**
Shandong	2,445	3.5	87,093	3.5
Henan	2,271	3.3	104,658	4.2
Hebei	2,209	3.2	56,838	2.3
Jiangsu	1,568	2.3	63,209	2.5
Shanxi	1,318	1.9	26,658	1.1
Beijing	372	0.5	7,857	0.3
Tianjin	106	0.2	3,549	0.1
Shanghai	68	0.1	1,864	0.1
Northeast region	**10,459**	**15.1**	**461,068**	**18.5**
Inner Mongonia	3,317	4.8	97,982	3.9
Niaoning	3,071	4.4	94,875	3.8
Jilin	2,465	3.6	164,237	6.6
Heilongjiang	1,606	2.3	103,974	4.2
Northwest region	**4,558**	**6.6**	**124,187**	**4.9**
Shaanxi	2,370	3.4	28,121	1.1
Gansu	1,030	1.5	28,318	1.1
Xinjiang	940	1.4	60,267	2.4
Ningxia	144	0.2	3,174	0.1
Qinghai	74	0.1	4,307	0.2
Total	**69,336**	**100.0**	**2,483,252**	**100.0**

*Sources: The Eighth China's National Forest Inventory (*SFA, 2014*).*

Besides timber products, planted forests also contribute to economic development and livelihood by providing NTFPs. Of the total economic forests of the country, 96% is planted forests, producing 133.8 million tons of NTFPs in 2011 (of which, 114.7 million tons of fruits, 9.3 million tons of dry fruits/nuts, 1.4 million tons of tea, 1.6 million tons of woody oil and etc), accounting for 23% of the total output value of forestry industry (SFA, 2011b).

At the same time, planted forests play a key role in ecological improvement by enhancing environmental services of biodiversity conservation, carbon sequestration and hydrological regulation greatly contributing to the China's strategic goals of ecological restoration, ecological security and ecological civilisation (SFA, 2009). The monetary value of the major forest ecosystem services such as water conservation, soil conservation, carbon sequestration and oxygen release, nutrient accumulation, atmosphere environment purification, and biodiversity conservation, was estimated to be about 10.01 trillion CNY/year (approximately 1.48 trillion US$/year) and is equivalent to one third of China's annual gross domestic product (GDP) (Niu et al, 2012). Of these, carbon (C) sequestration by planted forest is the most important service with about 0.3 Pg C having been sequestrated by planted forests in China since the mid-1970s. The rapidly increasing C stock (and C density) in China's planted forests has been a major contribution to the increase in the global forest C sink over the period (Fang et al., 2001; Piao et al., 2009; Pan et al., 2011). Since most of these planted forests are still very young and have not always benefited from the greatly increased public investment in forest technology and management in China, it is reasonable to assume that the full potential of planted forests in China to accumulate additional biomass in living trees and in forest soils has not yet been achieved (Fang *et al.*, 2007).

Factors sustaining the massive afforestation and reforestation in China

Since the 1970s, the planting area has been increasing rapidly with more than 5 million ha per year in average (Figure 2) without showing any signs of slowing even after almost four decades of continuous run, a rate so huge even for a country of the size of China that it could only have happened in an environment in which political, economic, ecological, social and aesthetic factors coalesced in resonance. In the beginning it was essentially government-initiated programmes that stimulated tree planting across the country in the face of severe depletion of forests after decades of mismanagement, severe misuse and complete neglect. Growth in urban and global markets for forest products, coupled with demographic migration from rural areas into urban zones, spurred the conversion of abandoned crop fields into tree farms. Quantitative, cross-national analyses suggest that many of these forces work jointly in regionally distinctive ways to facilitate the expansion of planted forest (Zhang et al, 2006; Rudel, 2009).

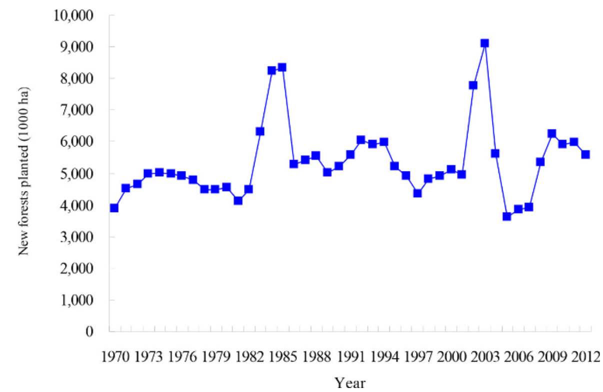

Figure 2 Annual amount of new forests planted in China from 1970-2012. *Sources: China Forestry Statistical Year Book, 2013a*

(a) Government-initiated programmes

This is by far the most important driving force for stimulating the rapid and massive expansion of planted forests in China. Government initiated programmes either offer adequate financial supports or create an enabling environment for private investment in tree planting through attractive incentives. The implementation of the six key national forestry programmes in the past three decades, including the Key Shelterbelt Development Programs (SDP), the Natural Forest Protection Program (NFPP), the Conversion of Cropland to Forest Program (CCPF), the Sandification Control Program for Areas in the Vicinity of Beijing and Tianjin (SCP), the Wildlife Conservation and Nature Reserves Development Program, and the Forest Industrial Base Development Program (FIBDP), generated a great momentum for developing planted forests (S. Liu et al., 2011). Data for the period 1990 to 2012 showed that these six key forestry programmes have funded afforestation area of 78.2 million ha, contributing 62% of the total planted area (SFA, 2013a).

Over the last decade deep changes encompassing social, economic, ecological and political aspects have occurred in China generating an enabling environment for forest resource management at local, county, provincial and national levels. Among these perhaps the most important and far-reaching is forest tenure reform through which the management control right over 180 million ha of collective forestlands has already been passed into the hands of the individual households (SFA, 2013b). The Government hopes that this step will prove to be a great incentive and impetus to forest owners to further expand fast-growing and high-yielding planted forests for maximising economic benefit for themselves and, in the process, bring a wide range of ecological and social benefits to the larger society around them. While it is still too early to make informed judgments about the ecological outcome of one of the greatest steps ever undertaken in the ecological history of mankind, the interim indications are positive in nature, especially in south and southwest China where more favourable climatic conditions for tree growing occur. In addition to these land reforms, private investment in the forestry sector has also been increasing in all regions of China from 22% of the total forestry investment in 2004 when the reforms initiates at pilot scale to 63% of that in 2012 (SFA, 2013a), with private owners now managing more than 60% of the total planted forest area (SFA, 2014).

(b) Market growth

Two key factors have stimulated tree planting campaign. These are the development of international and local markets for forest products and progressive urbanisation processes that bring improved transportation infrastructure and demographical immigration from rural areas to cities. In turn, this leads to the increased abandonment of farm lands due to less available labour. Also, Sohngen & Sedjo (1999) suggested that, under a varying price assumption, the increased demand for wood would be mostly met from planted forests due to the significantly lower cost of extraction. From a local perspective too, fast-growing planted forests have obvious cost-benefit advantages over cultivating annual agricultural crops. Data obtained from an economic investigation in Qinzhou city of Guangxi show that growing a single five-year-rotation of *Eucalyptus* spp. could yield 10,320 CNY/ha (1650 US$/ha) more net profit than cultivating annual crops over the same period (Table 5).

(c) Technology development

Wider application of new technology is helping to improve the quantity and quality of trees, including improvement of growth rates, disease and pest resistance, tree form and wood-fibre quality, and ease of processing. It is also helping to expand the use of resources previously considered uneconomic (lesser known species, small piece sizes) and non-forest fibre resources such as wood residues and recycled materials (Wijewardana, 2005). Tissue culture and clonal reproduction are widely used in China as the most effective ways of providing a large quantity of high-quality seedlings for developing massive planted forests in relatively short periods (Lan and Gu, 2002). Increased yields can offer major economic advantages to planted forests based on biotechnology (Sedjo, 2004). Depending on the relative final returns of growing trees or wood processing, growing large trees over long rotations may be replaced with short-rotation management of small trees for production of fibre and biomass. Market competitiveness will be significantly influenced by the application of either traditional genetic and silvicultural-improvement practices, and wood processing techniques in planted forest development, or some new technical innovations beyond traditional forestry areas, such as new composite materials and bio-energy.

Challenges confronting planted forests in China

Like many other countries in the world, planted forests in China have been exposed to huge challenges in terms of ecological sustainability and environmental changes. In particular, climate change has been regarded as a main disturbance driving force for the past several decades and future years to come.

Coping with uncertainties of climate change

Warming temperatures, changing precipitation patterns and extreme meteorological events are among possible threats to planted forests in China. Changes in temperature and precipitation regimes have the potential to gradually affect forests in terms of forest structure, spatial distribution, growth and productivity. Some effects from rising temperature and increasing precipitation, particularly in the colder north, may be positive for forest growth and productivity, while others (e.g. increased fire occurrence and pest and disease outbreaks) may be negative (S. Liu et al., 2011). In addition, changing climate can affect hydrological processes and water yields of forested watersheds, as well as the downstream water availability for both people and wetland ecosystems (Minshal, 1988; Poff and Ward, 1989; Poff, 1996; Sun *et al*., 2008). Climate extremes can be highly detrimental to forest ecosystems. For instance, the icy-rain and snowfall that occurred during the early spring of 2008 caused severe forest losses and destroyed nearly 13% of China's total forested area (Shao et al., 2011), which resulted in habitat loss and starvation of many kinds of wildlife besides potential, cumulative, and long-term effects on natural ecosystems. The recent sustained drought in Southwest China affected more than 80% of the vegetation in three provinces of Yunnan, Guangxi and Guizhou (Wang et al., 2010). If, as anticipated, the growing concern with global warming spurs further expansion in planted forests in an effort to sequester atmospheric carbon, questions about their social and ecological effects would become more pressing. The adaptive management of planted forests needs to consider the uncertainties of climatic change and its effects on forests and environments in order to enhance the positive effects while reducing the negative effects.

Preventing forest pest, disease and fire damage

The methods of establishing (by clear felling of natural forest before planting) and managing (using slash and burn) fast-growing monoculture plantations, predominantly of Masson pine, Chinese fir and *Eucalyptus*

Table 5 A comparative cost-benefit analysis of annual crops (wheat and soybean) and *Eucalyptus* spp.

a) **Cost-benefit analysis of growing a wheat and soybean as an annual crop (Unit: CNY/ha)**		
Two crops in a year: wheat + soybean		
Cost	**wheat**	**Soybean**
Seed	750	750
Fertiliser	1800	900
pesticide/herbicide	225	225
Plough	600	0
Sowing	525	525
Harvesting	600	600
subtotal	4500	3000
Total cost	7500	
Benefit	**wheat**	**Soybean**
yield per ha (kg)	6000	1500
unit price	2	3.5
subtotal	12000	5250
Total benefit	17250	
Net profit per year per ha	**9750**	
Net profit over 5 years	**48750**	

b) **Cost-benefit analysis of growing Eucalyptus spp. (Unit: CNY/ha)**	
Costs of planting and management	
Seedlings(0.5 CNY/plant×1500 plant/ha, including 150 plants for replanting)	750
Planting(0.6 CNY/hole×1500 holes/ha)	900
fertilisers (3.5 CNY/plant×1500 plants/ha)	5250
tending/fertilising(525 CNY/ha×4 times)	2100
subtotal	9000
Costs of harvesting	
harvesting and transportation(50 CNY/m^3 ×150 m^3/ha)	7500
Taxes and dues	6930
subtotal	14430
Total cost (over 5 years)	23430
Benefits	
Yield per ha in 5 years (m^3)	150
unit price	550
Total benefit (over 5 years)	82500
Net profit	
Total over 5 years	59070

robusta in southern China and poplar species and larch in northern China, have caused a decline in biodiversity and consequential lowering of ecosystem stability and soil fertility. Many of these monoculture plantations are also in poor ecological health and are very vulnerable to exacerbating disturbances such as fire, insect and disease, hurricanes, drought, and wind storms under climate change (Peng et al., 2008). In particular, the disturbance agents of insect and pests, diseases and fire are expected to become the main challenges to forest managers. A total of 292 forest pests and diseases have been identified as of special concern to planted forests in China (SFA, 2008). Pine moth (*Dendrolimus* spp.) infest up to 3.30 million ha across China (Luo, 2002). Furthermore, the damaged area of poplar (*Populus* spp.) pests reached up to 2.67 million (Luo, 2002). In 2010, 11.64 million ha of forests were attacked by pests and diseases, and 7,723 forest fire events took place in planted forests (SFA 2011).

Dealing with limitations of land availability for new planted forests

Further expansion of planted forests in China is increasingly constrained by land availability due to the limited land resources and the continuous competition with other land uses, such as agriculture, settlement and infrastructure development. At present, about 30 million ha of land area potentially available for planted forests suffers from poor climate and soil conditions and it would be a technologically and economically challenging task to bring them under tree-growing regimes (SFA, 2014). In particular, there is less land available for planted forests in eastern regions compared with western areas. Although land is available especially in north-western areas, water resources are very scarce there. Developing planted forests in water-limited areas where the annual precipitation is below 400 mm would potentially exacerbate water shortages due to the increased evapotranspiration, especially under climate-change scenarios. Some studies have shown that the vegetation composition in terms of forest, shrub and alpine meadows could affect the amount of water yield in a watershed (Jiang et al., 2004; Y. Liu et al., 2006) and that the annual mean runoff coefficient and evapotranspiration (ET) may be closely related to landscape structure of watersheds (Li et al., 2006; Jiang et al., 2004; Y. Liu et al., 2006, 2008). At a macro-scale, it is important to consider the natural climatic constraints of water availability as well as the appropriate choice of species/varieties and associated forest management options that are suitable for water conservation. At the meso-scale, the proportion of native forest plays an important role in the reduction and regulation of water use, and therefore a system of mosaic landscape management may be able to stabilise water flow across plantation landscapes (Ferraz et al., 2012).

Future perspectives

China's National Forestry Strategy sets a goal of further expanding 40 million ha of planted forests in 2020 against the baseline of 2005 (SFA, 2009a). However, there are a number of important challenges to overcome, including: the largely monoculture nature of the plantations with only a few tree species dominating the planted landscape; uneven spatial distribution; undesirable age-class distribution; relatively low volume in growing stock; coupled with the increasing complexity of managing planted forests for multiple uses under a changing environment. Changing the management strategy of planted forests from one of area expansion to one of productivity and quality enhancement cannot come too soon. This change would occur by transforming forest management regimes from those relying solely on massive artificial regeneration and afforestation to ones focusing more on tending and natural regeneration. Such a change would enable the forest managers to contribute to climate mitigation and adaptation, water and biodiversity conservation by implementing management plans that comprehensively integrate economic (productivity and growth), social (equity of access to water and land-use conflicts) and environmental (climate change and biodiversity impacts) benefits from planted forests.

Conclusions

Planted forests are increasingly playing an important role in China for wood and non-wood forest products, carbon sequestration, soil stabilisation, and a range of other ecosystem services. Sustainability of planted forests in terms of desired goods and ecosystem services, and diversified adaptive options for different stakeholders to cope with global change and land use conflicts is a growing concern. Understanding of the short-term and long-term impacts of climate change on trees and forests is of great importance to identify the adaptation potentials, and to find ways of improving vitality and resilience of planted forests. There is a need to undertake a wide range of adaptation actions at different management levels that seek to appropriately modify rotation length, tree species, stand structure and growth and yield models, and at the genetic level that prepare the planted forests to benefit from the pending changes in the climate. Adaptation and mitigation must be considered in parallel and should be integrated together into current management regime of planted forests. Recognition of the interrelationships among land use and balancing of trade-off among multiple ecosystem services should underlie the management of planted forest landscapes. There are considerable uncertainties about potential impacts of climate change on planted forests and this knowledge gap needs to be narrowed down through focused research in a wide range of ecological regions.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

Shirong Liu designed the study, participated in drafting the manuscript and significantly improved the writing of the whole manuscript; Shuirong Wu participated in the study design, performed the data collection and analysis, and drafted manuscript on the social and economic aspects; Hui Wang participated in the study design and drafted the manuscript on the ecological aspects. All authors read and approved the final manuscript.

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