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REVIEW

Pursuing the goal of carbon neutrality in China: path for realization of carbon sequestration in planted forests

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KEYWORDS

Planted forest, carbon stock, carbon sequestration, carbon management, climate change, promotion path

HIGHLIGHTS

- Analyzes the current situation of planted forests construction in China.
- Summarizes the dynamic and benefit of C sequestration in plantation forest.
- Proposes the enhancement path of C sequestration for planted forests in China.
- Provides the path for realization of forest C sink trading in China.
- Suggests some insights for C sequestration and emission reduction in planted forests.

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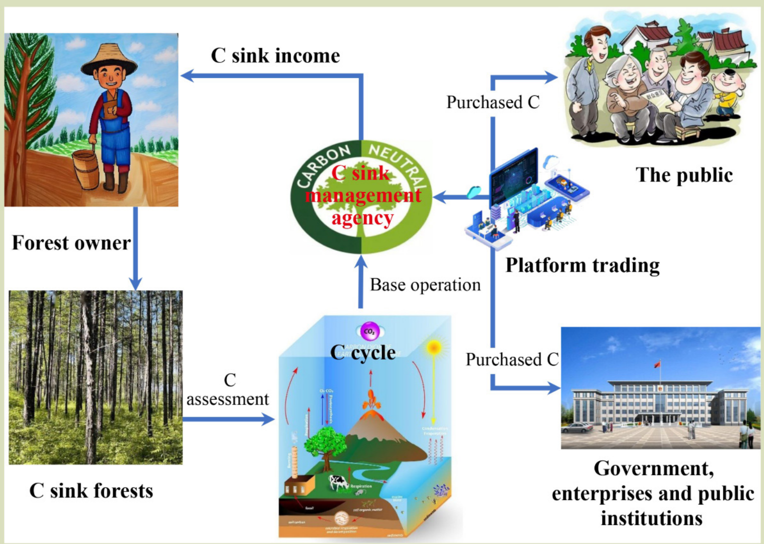
GRAPHICAL ABSTRACT



ABSTRACT

Tree plantations are an important forest resource that substantively contributes to climate change mitigation and carbon sequestration. As the area and standing volume of tree plantations in China have increased, issues such as unreasonable structure, low productivity, limited ecological functionality and diminishing ecological stability have occurred, which hinder the ability of tree plantations to enhance carbon sequestration. This study outlined the trajectory of carbon sequestration and its associated benefits in tree plantations by examining the current state of tree plantation establishment and growth, elucidated the strategies for advantages of carbon sequestration and climate change mitigation in planted forests, and summarized the existing problems with tree plantations. This paper underscores the pressing need for concerted efforts to boost carbon sequestration within planted forests and proposes management and development strategies for Chinese tree plantations. In the future, it will be necessary to apply scientific theories to practice and develop multi-objective management optimization models for the high-quality development of tree plantations. This will involve establishing a cohesive national carbon trading market, improving the prediction of carbon sequestration, and identifying priority zones for afforestation and reforestation, to better serve China's national strategy for achieving peak carbon and carbon neutrality.

1 Introduction

Carbon (C) emissions from ecosystems have intensified the greenhouse effect, increasing the severity of global warming. Global warming continues to escalate because of the inadequacy of C reduction measures[1]. Since the 1990s, the international community has collaborated to address climate change through mitigation and adaptation efforts[1,2]. From the Kyoto Protocol to the Paris Agreement, the diplomatic measures of countries worldwide have progressed, albeit with challenges. Regardless of the changing international context, China has been a consistent and active advocate and practitioner of global climate governance. After years of targeted actions, China has successfully curtailed its rapidly increasing CO_2 emissions. C emission intensity in China has decreased by 48.1% to 2005 levels, and non-fossil energy accounts for 15.3% of total energy consumption. China has achieved, ahead of schedule, the goals promised to the international community by Chinese authorities in 2020. At the 75th session of the United Nations General Assembly in 2020, President Xi Jinping announced that China will strive to peak carbon emissions before 2030 and achieve carbon neutrality before 2060[3]. This declaration provides guidance for China in addressing climate change and promoting green and low-C development. Therefore, achieving C neutrality has emerged as a pivotal objective for China in addressing future climate change.

C neutrality refers to net-zero CO_2 emissions attained by balancing the emissions of CO_2 with its removal from atmosphere, thereby reducing its contribution to global warming[4]. According to the United Nations Intergovernmental Panel on Climate Change (IPCC), anthropogenic CO_2 emissions are caused by human activities including fossil fuel combustion, industrial processes, agriculture and land-use activities. Measures for anthropogenic removal of CO_2 from the atmosphere include afforestation, which increases C absorption and capture[2,4]. When anthropogenic emissions are offset by anthropogenic removals, the net increase in CO_2 emissions is zero. Currently, China emits about 12.5 Pg of CO_2 annually, ranking first in the world. China is facing enormous pressure to substantially reduce emissions in the future. In addition to vigorously reducing C emissions, implementing nature-based solutions (NbS) can help achieve C neutrality goals. Unlike current methods that rely on industrial technology for ecological protection and governance, NbS utilize natural features and processes to address the challenges of sustainable development[5]. Forestry can be a crucial component of NbS. For example, increasing forest area and quality can aid in mitigating climate change and achieving China's C neutrality goal. Expansion and improved management of forests can also contribute to improving the national ecological environment, achieving sustainable development, and creating an ecologically beneficial and aesthetically pleasing civilization in China[6]. In the report of the International Union for Conservation of Nature (IUCN) submitted to the Fifteenth Conference of the Parties of the United Nations Framework Convention on Climate Change (UNFCCC), the IUCN established a framework for reducing C emissions from deforestation and forest degradation as a strategy for protecting the global forests and mitigating climate change[7].

Since the 1970s, China has initiated six key ecological forestry projects: the Three-North Shelterbelt Forest Program, Yangtze River and Zhujiang River Shelter Forest Projects; Grain for

Green Program; and the Beijing-Tianjin Sand Source Control Project, Returning Grazing Land to Grassland Project. These projects have made critical contribution to the restoration of terrestrial ecosystem functions, including C sequestration, and support the goals of sustainable development and C neutrality[8]. However, a comprehensive analysis of the C sink function, benefits of the C sequestration, and strategies for augmenting C sinks and diminishing C emissions in tree plantation ecosystems is currently lacking. No consensus has been reached regarding the role of forest C sinks in achieving C neutrality, and a systematic theoretical system has not yet been developed. Therefore, in this study, we summarized and analyzed the construction of existing tree plantations with the aim of evaluating the dynamic evolution of C sequestration in plantations and the path and benefits of increasing C sinks and reducing C emissions. Additionally, we summarized the challenges posed by increasing C sinks and reducing C emissions with tree plantations and proposed future solutions. This work promotes a greater understanding of the potential of C sequestration in the forestry field and provides a valuable reference that supports China's goal of achieving C neutrality.

2 Role of the forestry industry in achieving carbon neutrality

Forests have emerged as the largest C pool in terrestrial ecosystems owing to their large biomass[9]. The global terrestrial ecosystem stores about 2480 Pg of C, of which 1150 Pg is stored in forest ecosystem. In global forests, the average biological C stock is 71.5 m^3. When accounting for C in the soil, coarse woody debris, and leaf litter is accounted for, the C stock of forest reaches 161 m^3[10]. The C sink function of forests has the advantages of being more economical and efficient than other methods in terms of emission reduction. The annual C exchange between forest photosynthesis, respiration and the atmosphere accounts for about 90% of the annual C exchange in terrestrial ecosystems[11], making a considerable contribution to the global C cycle and C balance, as well as in regulating the global climate. Therefore, forests are a crucial element of climate change mitigation efforts.

To better improve the C sink function of forest ecosystem, it is necessary to develop C sink forestry management and afforestation. For example, C sink forestry refers to forestry activities that focus on coping with climate change and accumulating C sinks. In addition to increasing C sinks, it is also necessary to improve the stability, adaptability and ecosystem service functions of forests. C sequestration afforestation is implemented on land where the baseline has been determined, with specific activities conducted to increase C sequestration and monitor afforestation during stand growth. Compared with ordinary afforestation efforts, C sequestration afforestation emphasizes the C sink function of forests, has specific technical requirements, such as C sink measurement and monitoring, and highlights the multiple benefits of forests. Notably, only forests planted in accordance with the C sink afforestation technical requirements that conduct measurements and monitoring according to the regulations and are officially recognized according to the C sink afforestation inspection and acceptance method can be labeled as C sink forests.

3 Analyses of the current status of planted forests in China

According to a report published by the National Aeronautics and Space Administration and the journal *Nature* in 2019, the green area of Earth increased by 5% over the past 20 years, and the largest contribution to this change was afforestation in China[12]. China has implemented several key afforestation and forestry ecological construction projects, the Three-North Shelterbelt Forest Program (1978), Grain for Green Program (1999), Natural Forest Protection Program (2000), Beijing-Tianjin Sandstorm Source Control Project (2001), and Wildlife Protection and Nature Reserve Construction Project (2001), Consequently, China's forest coverage increased from 8.6% in 1949, when the People's Republic of China was established, to 21.6%. The area and stock of planted forests has experienced substantial growth, securing China's position as a global leader in planted forests.

According to the findings of the Ninth National Forest Inventory (2014–2018), the total area of planted forests in China is 79.5 Mha, and the total volume of standing stock is 3.4×10^9 m^3. The forest area in China can be categorized into three distinct types: 71.2% is covered by arbor forests, which occupy an area of 57.1 Mha; 3.15% is covered by bamboo forests, which occupy an area of 2.51 Mha; and 25.0% is covered by special shrubbery forests, which occupy an area of 19.9 Mha[13]. Comparing and analyzing the results of the National Forest Inventory over time, the area and standing stock of China's planted forests have increased continually over 40 consecutive years (Fig. 1). According to a comparison of the results of the first to ninth inventories, the area of planted forests has increased by 56.0 Mha, which is 2.4 times the original area, and the standing stock has increased by about 20 times (Fig. 1). However, the two most recent inventories show that the growth rate of planted forest areas has slowed.

The net increase in the area of planted forests in the ninth inventory was 6.73 Mha, a decrease of 1.66 Mha, or 19.8%, compared with the net increase of 8.39 Mha in the eighth inventory (Fig. 1). The dynamic changes in the area of planted forest in various regions were consistent with overall trends in China.

The distribution of planted forests in China shows that the regions with the largest area of planted forests (accounting for more than 5% of the national area) are Fujian, Guangdong, Guangxi, Hunan, Sichuan and Yunnan. The combined area and standing stock of planted forests in these six regions account for 42% of the country. Guangxi has the largest area of planted forests in China, accounting for 9% of the country, while Fujian has the largest standing stock of planted forests, accounting for 10% of the country. The tree species data composition of planted forests in China shows that the top 10 tree species in terms of area are Chinese fir (*Cunninghamia lanceolata*), poplars (*Populus* spp.), eucalyptus (*Eucalyptus robusta*), larch (*Larix gmelinii*), Masson's pine (*Pinus massoniana*), Chinese pine (*Pinus tabulaeformis*), slash pine (*Pinus elliottii*), radiata pine (*Pinus radiata*), loblolly pine (*Pinus taeda*), and oak (*Quercus* spp.), with a total area of 34.4 Mha, accounting for 73% of the planted forests area. The total standing stock composed of these species is 1.9×10^9 m^3, accounting for 75% of the total planted forest stock[14]. Of the China's planted forests, the area was gradually decreased from the young forest to the post mature forests (Fig. 2). The area structure of the age group showed a typical inverse "J" shape distribution (Fig. 2). The total standing stock of young and middle-aged forest is 1.69 billion m^3, which is slightly larger than that of nearly mature and over-mature forest 1.68 billion m^3 (Fig. 2).

Despite the consistent expansion of China's forest resources in terms of area and standing stock, challenges remain regarding overall adequacy, quality, and distribution of these resources. First, the management of planted forests is extensive, resulting in low-unit-standing stock with limited productivity and economic benefits. Planted forests have the contradiction of expanding in area while substantially decreasing in quality[15]. Second, China's planted forests are generally monocultures consisting of one species, leading to a decline in biodiversity, soil degradation caused by continuous cropping over multiple generations and gradual degradation of ecosystem functions.

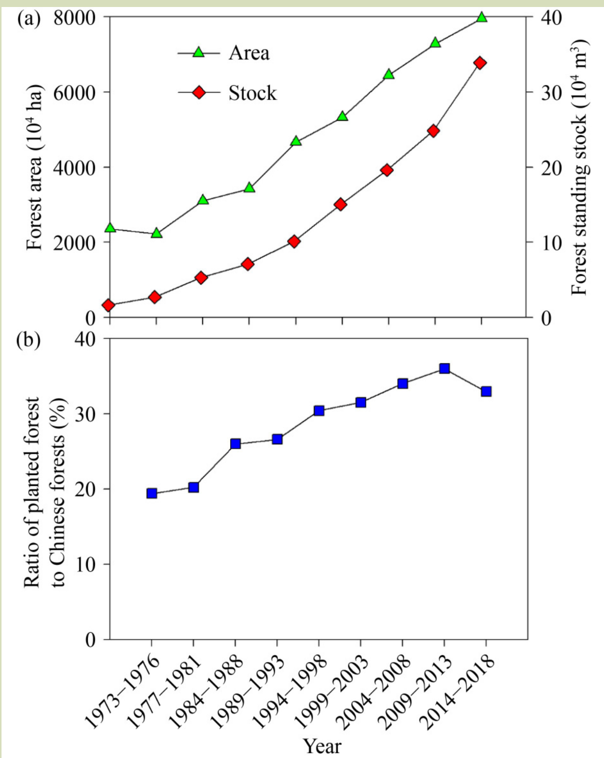


Fig. 1 Planted forest area and standing stocks (a) as well as the percentage of planted forest area to forest area in China (b) during the previous National Forest Inventories.

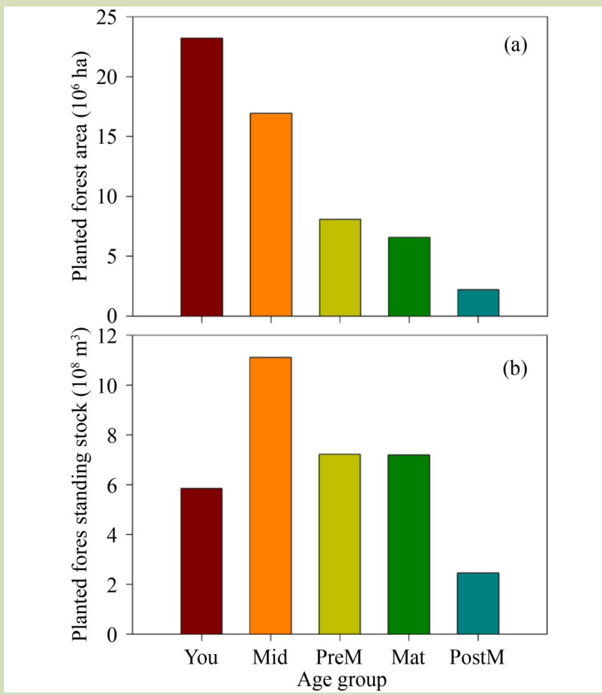


Fig. 2 Distribution of planted forest area (a) and standing stock (b) by age groups. You, young age group; Mid, middle age group; PreM, near-mature age group; Mat, mature age group; PostM, over-mature age Group.

Thus, these factors affect the sustainable and stable development of planted forest ecosystems[16]. Third, the expansion of China's planted forest area is limited by available land resources, land conditions and the impact of climate change, leading to finite space for constant expansion[17]. Also, planted forests generally consist of stands of trees of the same age, and their natural renewal and ecosystem self-regulation functions are poor. To date, there have been no successful cases of natural regeneration or near-natural succession in planted forests in China.

4 Dynamics and benefits of carbon sequestration in planted forests in China

The biomass C stock of forests typically increases as afforestation efforts continue. Based on the area and accumulation data for each stand age group of different forest types (represented by dominant tree species) in the forest resource inventory data of China, the relationship between biomass density and stand age of the 36 major forest types in China was constructed[18]. In addition, the relationship between biomass C stock and forest age was combined with the C content coefficients of each tree species (Table 1). The stand age of each tree species ranges from young, medium, near-mature and mature to over-mature. The C stock of forests increased rapidly in the early growth stage and then gradually stabilized, following a logistic growth curve. Taking *P. massoniana*, the main tree plantation species in China, as an example, the C stock of the young, medium, near-mature, mature, and over-mature age groups was 15.1, 21.7, 25.3, 32.5 and 38.1 Mg·ha^{-1} C, respectively. The C stock of *Abies fabri* stands was 14.8, 22.5, 26.7, 31.8 and 33.7 Mg·ha^{-1} C in each age group, respectively. The C stock of *Quercus* spp. was 24.1, 49.7, 65.8, 87.5 and 95.6 Mg·ha^{-1} C in each age group, respectively. The C stock of *Caragana korshinskii* was 3.8, 6.3, 7.0, 14.1 and 11.2 Mg·ha^{-1} C in each age group, respectively. In general, forest C stock increases with the continuous growth of plantations, and the proportion of underground biomass to total forest biomass (root ratio) also increases. Additionally, the C stock of understory litter increases over time, showing a trend of first increasing and then gradually stabilizing[19].

Table 1 Logistic equation between biomass C stock and forest age of 36 forest types in China

Forest type	C stock calculation
Pinus koraiensis	$111.75/(1 + 7.9541e^{-0.0360\ Age})$
Abies fabri	$178.71/(1 + 5.7382e^{-0.0295\ Age})$
Picea asperata	$142.94/(1 + 7.9541e^{-0.0360\ Age})$
Tsuga chinensis	$101.98/(1 + 4.8039e^{-0.0201\ Age})$
Cupressus funebris	$78.39/(1 + 10.5681e^{-0.0443\ Age})$
Larix gmelinii	$67.85/(1 + 2.6594e^{-0.0696\ Age})$
Pinus sylvestris	$105.35/(1 + 10.8787e^{-0.1059\ Age})$
Pinus densiflora	$25.26/(1 + 2.3436e^{-0.0985\ Age})$
Pinus thunbergii	$30.88/(1 + 3.36e^{-0.0823\ Age})$
Pinus tabuliformis	$45.81/(1 + 12.2360e^{-0.1144\ Age})$
Pinus armandii	$47.58/(1 + 3.2828e^{-0.0678\ Age})$
Keteleeria fortunei	$33.59/(1 + 0.6470e^{-0.0238\ Age})$
Pinus massoniana	$37.53/(1 + 2.1735e^{-0.0522\ Age})$
Pinus yunnanensis	$75.61/(1 + 5.3342e^{-0.0736\ Age})$
Pinus kesiya	$49.99/(1 + 2.0674e^{-0.0878\ Age})$
Pinus densata	$81.25/(1 + 3.6259e^{-0.0578\ Age})$
Cunninghamia lanceolata	$36.2/(1 + 2.4369e^{-0.0963\ Age})$
Cryptomeria fortunei	$58.06/(1 + 2.5125e^{-0.1113\ Age})$
Metasequoia glyptostroboides	$70.18/(1 + 12.3200e^{-0.2046\ Age})$
Fraxinus mandschurica (or Juglans mandshurica)	$102.73/(1 + 8.0670e^{-0.0607\ Age})$
Cinnamomum camphora	$58.99(1 + 5.4000e^{-0.0566\ Age})$
Phoebe zhennan	$104.16/(1 + 9.1857e^{-0.0615\ Age})$
Quercus	$98.62/(1 + 8.4907e^{-0.0422\ Age})$
Betula	$80.27/(1 + 7.4789e^{-0.0516\ Age})$
Hard broadleaf	$77.82/(1 + 10.3130e^{-0.0492\ Age})$
Tilia tuan	$117.14/(1 + 7.8232e^{-0.0586\ Age})$
Sassafras tzumu	$101.81/(1 + 24.99e^{-0.1708\ Age})$
Eucalyptus robusta	$46.94/(1 + 7.1493e^{-0.1432\ Age})$
Casuarina equisetifolia	$77.69/(1 + 6.4432e^{-0.0698\ Age})$
Populus	$35.07/(1 + 1.4920e^{-0.1434\ Age})$
Aluerites fordii	$51.84/(1 + 4.0946e^{-0.0505\ Age})$
Soft broadleaf	$65.54/(1 + 5.2755e^{-0.1302\ Age})$
Other broadleaf	$96.27/(1 + 20.7297e^{-0.3534t})$
Mixed Conifer	$77.88/(1 + 20.8042e^{-0.1017\ Age})$
Mixed Conifer and broadleaf	$145.48/(1 + 8.5774e^{-0.0560\ Age})$
Mixed broadleaf	$116.41/(1 + 12.2721e^{-0.1677\ Age})$

The dynamics of soil C stock with tree plantations has not been extensively analyzed, yet there are three likely conditions: increase, decrease or no change[20,21]. However, some studies have found that after returning farmland to forests, soil C stock has shown a trend of first decreasing and then increasing[19,22]. Through integrating 844 observations from 181 sample sites across China[21], one study found that the change rates of C stock in 0–20 cm soil of stands aged 0–5, 6–10, 11–30, 31–40 and > 40 years were –0.93, 0.89, 1.30, 0.13 and

0.05 Mg·ha^{-1}·yr^{-1}, respectively. Meanwhile, the change rates of C stock in 0–100 cm soil were –3.15, 0.83, 3.59, 1.15 and 0.02 Mg·ha^{-1}·yr^{-1}, respectively. Also, mixed-species forests had a better soil C sequestration capacity than single-species forests. Especially in the early stages of tree plantation construction, planting mixed forests can reduce the degree of soil organic C loss and even provide a greater C sink benefit. Through integrating 218 observations from 48 sites across China[23], one study reported that the rates of C sequestration in 0–20 cm soil of single and mixed species tree plantations by aged (Table 2). Overall, the soil organic C sequestration capacity of mixed-species forests is 2–3 times higher than that of single-species forests[23]. Also, the rate of C sequestration in tree plantations was affected by land use prior to afforestation. For example, the higher the initial soil organic C content, the lower the average soil C sequestration rate after afforestation[21,23]. However, soil organic C is typically reduced after the reforestation of logged land[23].

Six ecological construction projects have been successively implemented in China since the 1970s, impacting about 16% of the total land area[8]. From the 1970s to 2000s, China's forest biomass C stocks increased by 40%[24]. It is predicted that by 2050, the C stock of forest biomass in China will increase by 9.97–13.1 Pg C, and the annual average C sequestration rate will be 85–154 Tg C[18,25]. From 2001 to 2010, the average annual C sequestration in the implementation areas of the six ecological construction projects was 132 Tg, of which 56% (74 Tg) of this C sink contribution was derived from the six ecological construction projects[8]. During this time, the ecosystem C stocks in the implementation areas of the major ecological projects increased considerably. The average annual increase in forest biomass C stock and soil C stock in the project areas was 6.6–22.0 and 1.0–9.7 Mg·ha^{-1}, respectively[8]. The Natural Forest Protection, Grain for Green, Three-North Shelterbelt Forest, China Rapid-Growing and High-Yield Forest Construction, and Beijing-Tianjin Sandstorm Source Control projects accounted for 44.8% of the national forest cover, and the average annual increase in forest biomass C stock was 72.8 Tg, accounting for 63.4%–71.2% of the national forest biomass C sequestration rate[26,27]. Of these, the project of returning farmland to forest land (grassland) had the largest increase in its C pool among all ecological construction projects, with an average annual C sequestration rate of 24.6 Tg·yr^{-1} from 2000 to 2010[8]. By 2020, the entire project of converting farmland to forest land (grassland) sequestered 1700 Tg of C, and it is predicted to sequester 4120 Tg of C by 2050[22]. Compared to the total C sequestration of global vegetation restoration projects during the same period[28], the C sequestration attributed to China's conversion projects accounted for 25% of the total C sequestration by all vegetation restoration projects worldwide[22]. Additionally, there are differences in the C sequestration rate and potential of tree plantations in different regions, and the rate is generally higher in eastern and southern regions with humid climates and lower in north-western regions with dry climates. Therefore, vegetation restoration through the construction of tree plantations in China has delivered considerable C sink benefits.

Table 2 C sequestration rate of afforestation age groups in pure forests and mixed forests

Forest age (yr)	Pure forests (Mg·ha^{-1}·yr^{-1})	Mixed forests (Mg·ha^{-1}·yr^{-1})
< 5	–0.43	0.54
6–10	0.89	1.47
11–20	0.45	1.02
> 20	0.18	0.34

5 Methods and benefits of using planted forests to increase C sinks and reduce C emissions

The C sink functions of ecosystems can be enhanced through NbS. The IPCC Special Report on Climate Change and Land revealed that greenhouse gas emissions from agriculture, forestry and other land use (AFOLU) activities related to NbS accounted for 23% of global greenhouse gas emissions[29]. The IPCC Special Report on Global Warming of 1.5 °C stated that the C sink potential of afforestation and reforestation can reach 3.6 Gt·yr^{-1} CO_2 in the emission reduction path of AFOLU measures[30]. According to IPCC estimates, the technical potential for avoiding deforestation and forest degradation is 0.4–5.8 Gt·yr^{-1} CO_2[29]. Thus, NbS have great emission reduction potential in forestry.

C sequestration in planted forests is mainly achieved through technical and institutional methods. Advancing C sequestration through technological innovation involves expanding the forest area and increasing forest coverage through afforestation and increasing the volume and growth of forests per unit area (Fig. 3). The former method is mainly used under suitable land and hydrological conditions for afforestation whereas the latter is used in the case of limited afforestation space. Decades of afforestation in China have limited the potential to continually expand forest areas and increase forest coverage. According to data from the Ninth Forest Resource Inventory[14], more than 30 Mha of barren hills and wastelands are suitable for afforestation in China.

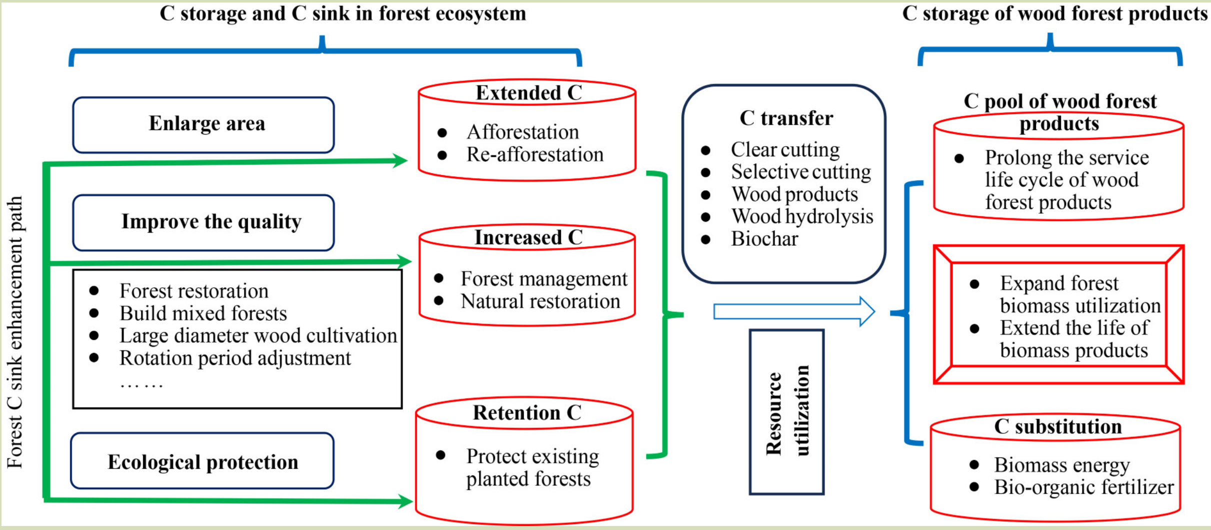


Fig. 3 Path for enhancement of C sequestration for planted forests in China.

However, these areas are mainly located in the west, making afforestation difficult. For example, in north-western China, where annual rainfall is less than 400 mm, vegetation restoration mainly depends on the shrub species, and the potential for increasing C sinks is relatively limited. Therefore, to achieve the goals of achieving peak C and C neutrality, the focus of forest C sequestration should be shifted to increasing the volume and growth of forests per unit area. Implementing multifunctional, near-natural, full life-cycle management technology in tree plantations has improved the composition and structure of forests, thereby improving the C sink capacity of forest ecosystems. Through a pilot demonstration of forest management, the average growth of trees in China reached 7 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ and exceeded 9 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ in South China. If the average volume of tree plantations increases from the current 59.3 $m^3 \cdot ha^{-1}$ to between 300 and 800 $m^3 \cdot ha^{-1}$ in developed countries, the C sink capacity would be increased by several times. Through such enhancement, forest ecosystems can further contribute to climate change mitigation and achieving the goals of achieving peak C and C neutrality.

Increasing C sequestration through institutional innovation is crucial. In maintaining a C balance, increasing the capacity of C sinks is theoretically equivalent to reducing the contribution of C sources. Incorporating forest C sinks in the C market distinguishes it from other resource and environmental markets. For example, the water, emissions and energy rights markets are all single property rights markets whereas the C market is a composite property rights market that includes C emission rights and C sinks. Once the C market is reasonably mature, the anticipated income from forest C sequestration will become relatively transparent, allowing for the assessment of costs as either profit or loss. Accordingly, relevant departments can decide whether to provide compensation for forest C sinks. At the beginning of the 21st century, the former State Forestry Administration successively established the C Sink Management Office and the China Green C Sink Fund and actively explored the development and voluntary trading of forest C sinks. Subsequently, over 1.2 Mha of C sink afforestation projects have been funded and managed in more than 20 regions across the country. In March 2022, Anji County in Zhejiang Province, established the China's first county-level forestry C sink management bureau. In cooperation with financial institutions such as the China Development Bank, Anji County obtained 11 billion yuan in long-term, low-interest loans and established the country's first provincial-level bamboo forest C sequestration and stock trading platform. With bamboo forest C sequestration and stock transactions as the starting points, a complex system involving forest land circulation; C sequestration; and stock-base, operation-platform, and transaction-income feedback has been established (Fig. 4). The entire project is expected to have a C sink area of more than 33,333 ha and annual C sequestration of more than 300 Gg. Based on the 6000 $CNY \cdot ha^{-1}$ price of bamboo forests, this system has the potential to increase farmer income by more than 200 million $CNY \cdot yr^{-1}$.

Technical C sequestration focuses on solving the problem of reducing the costs of C sequestration in tree plantations whereas institutional C sequestration focuses on solving the income problems associated with C sequestration in tree plantations. As long as the income from the planted forest is

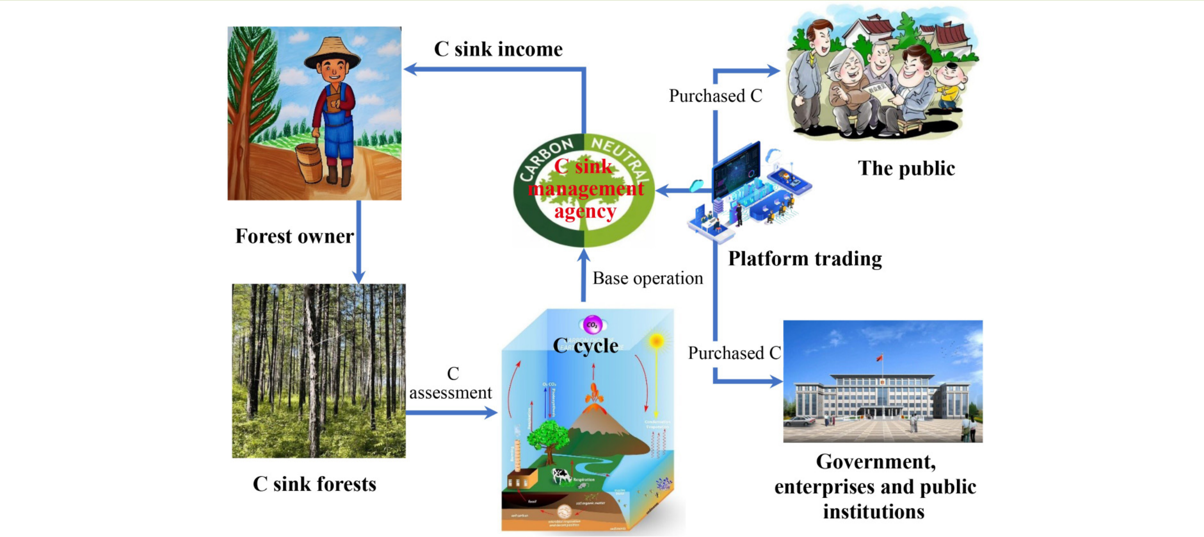


Fig. 4 Path for realization of forest C sink trading.

greater than its costs, people will be motivated to engage in forest C sequestration. In contrast to the paths of C emission reduction and C neutralization, the path of forestry C emission reduction not only helps mitigate climate change but also protects biodiversity and ecosystem health, supporting livelihoods and alleviating community poverty. Of the UN sustainable development goals proposed, the forestry C emission reduction and C sink enhancement paths contribute to poverty eradication (SDG1); taking urgent action to cope with climate change and its impact (SDG13); and protecting, promoting, and sustainable use of terrestrial ecosystems (SDG15). Also, these measures have a synergistic effect in promoting the realization of these goals in terms of climate change mitigation, biodiversity conservation and poverty reduction.

6 Insights from and challenges of carbon sequestration and mitigation in planted forests

As artificially regulated ecosystems, the selection of tree species, planting methods and management measures in tree plantations can have direct or indirect effects on the C sequestration. First, afforestation models have been shown to directly affect C stocks in aboveground and belowground ecosystems. The biomass C of the tree layer can be determined by the biomass accumulation rate and C density of the tree species. Tree species, community composition, and stand age have marked effects on soil C stocks[31,32] and the persistence of C sequestration[33]. Second, management measures can increase the diameter at breast height, tree height, crown width and stand volume growth of individual trees, increase the number of species, and cover of understory vegetation (Fig. 5); and change the rates of litter decomposition and soil C accumulation, thus affecting the vegetation C stock in tree plantation ecosystems[34,35]. In addition, tree harvesting methods and intensity may affect stand biomass and productivity, the structure of planted forests and soil moisture and temperature, which will affect the growth of trees and their C stocks. Also, harvesting changes the rate of soil organic matter decomposition and the rate of soil C emissions[36,37].

Although China ranks first in the world in terms of both vegetation restoration and average annual scale of afforestation, there are still significant challenges to address. Examples include the quality of forest resources, prevalence of monocultures, uneven spacing and low utilization rate of forested land. China’s forest volume is 94.8 $m^3 \cdot ha^{-1}$, which is only 72.4% of the global average. In particular, tree plantations are dominated by a single tree species. The poor structural stability of planted forests makes effective C sequestration difficult. According to the Ninth Forest Resource Inventory data set, young and middle-aged forests, which account for nearly 61% of the forest area, have the greatest potential for increasing C sinks in China. Young and middle-aged forests grow rapidly and have high C sequestration rates. However, as planted forests gradually approach maturity, the rate of increase in C sequestration tends to slow. In addition, the available afforestation space becomes increasingly smaller,

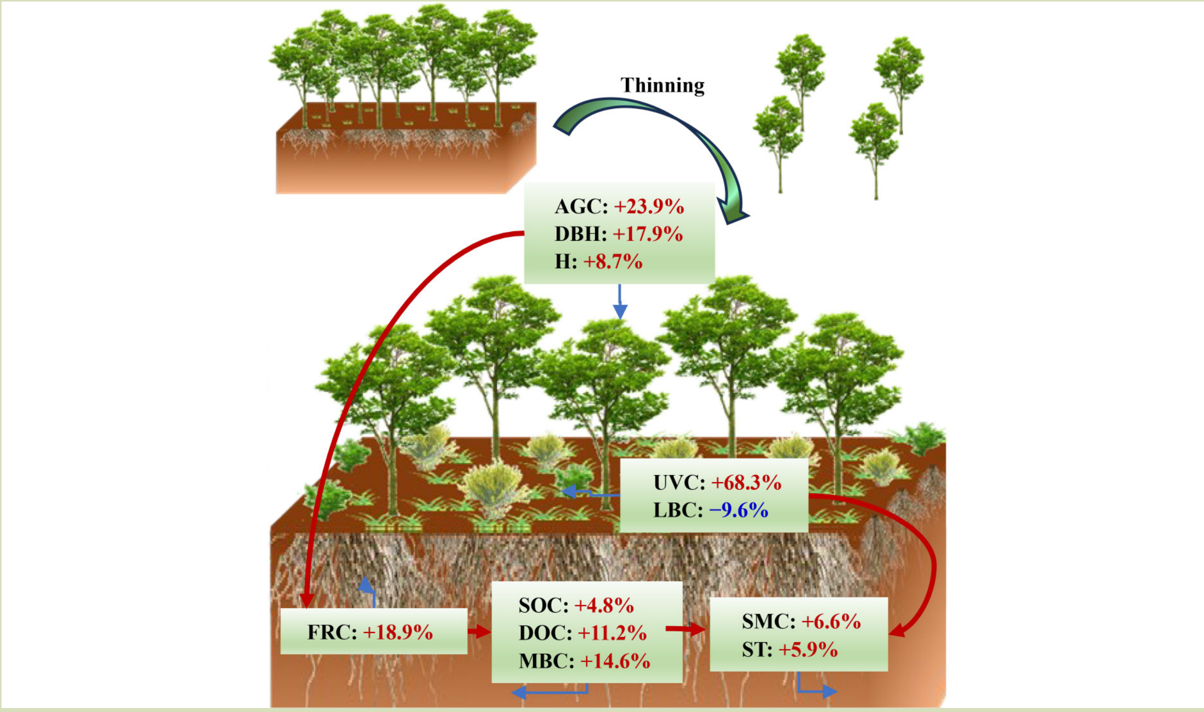


Fig. 5 Positive and negative forest thinning effects on vegetation and soil. SMC, soil moisture content; ST, soil temperature; SOC, soil organic carbon; DOC, soil dissolved organic carbon; MBC, soil microbial biomass carbon; AGC, aboveground biomass carbon stock of trees; DBH, average diameter at breast height of stand; H, average stand height; UVC, carbon stock of understory vegetation biomass; LBC, carbon stock of litter biomass; and FRC, fine root biomass carbon stock.

making it difficult to expand the afforestation area. Continuously increasing C sequestration in tree plantations is a major challenge. First, the space for high-quality afforestation is reduced, and the difficulty of expanding the total area is increased. Second, the cultivated land afforestation area is large and faces the risk of reversal. Third, the overall quality of the plantations is not high, and unit productivity is low. Fourth, dependence on plantation wood increases, and the discrepancy between supply and demand is prominent. Last, the loss of plantation area increases, and high-intensity logging remains serious.

To better develop and protect planted forests and continuously enhance their C sequestration functions, urgent response measures are required[38,39]. First, there must be further promotion of land-greening actions and expansion ecological development. It is necessary to fully explore the potential of existing forest land and improve its utilization rate. At present, China has 52,402,800 ha of land available for afforestation. For plots of land in the western region with poor ground conditions, appropriate trees or shrubs should be selected. Second, there must be a strengthen scientific forest management and an improvement the quality of tree plantation resources. It is necessary to promote the construction of forest management planning and systems, especially in key state-owned forest areas and farms. Third, there must be optimization of the structure of tree plantations and enhancement their wood-supply capacity. By adjusting the horizontal distribution pattern of single-species tree plantations and mixed-species forests, low-quality and low-efficiency monoculture plantations can be transformed into high-quality and high-efficiency forests. Fourth, it is imperative to enhance oversight and ensure safeguarding of afforestation. In response to the current situation of over-intensive and unstandardized harvesting of tree plantations, there need to be accelerated reform of logging management, improved logging management policies, application of targeted policies in different regions, and rational allocated and strictly implemented logging quotas consistent with regional logging situations.

7 Future outlook

In the context of global climate change, this study aimed to address the problems in the management of C sequestration in

China's tree plantations considering society's demand for increased forest area. China's tree plantation management, development strategies, and countermeasures are undergoing transformation. Emphasis has shifted from the expansion of tree plantation areas to improving the quality and efficiency of plantation ecosystem services and the development of high-quality, efficient, stable and sustainable multifunctional plantations[17]. In addition, to support China's goal of C neutrality, China should not only build a national unified C trading market but also improve the prediction of the C sequestration potential of different forest types in different regions. Also, afforestation and reforestation priority areas should be identified to better serve China's goal of achieving peak C and C neutrality. The following conclusions were drawn.

(1) Plantation ecosystem management will retain a diversified development pattern in the process of transformation from single objective to multi-objective management.

According to natural geographical division, climate differentiation, strategic positioning of forestry, and regional economic and social development needs, the utmost potential of distinct plantation ecosystem types can be achieved by implementing structural refinements and landscape optimizations. In river headwaters, water sources, important ecological functional areas and areas with complex terrain, the main objectives of plantation ecosystem management are to enhance ecological functions, improve the ecological environment, and maximize the ecological benefits of the plantation. In areas characterized by abundant water and heat, fertile soil and relatively flat terrain, a diversified approach to plantation management is pursued. This involves establishing distinct types of plantations for different purposes such as oil production, commercial timber, energy production and C sequestration. Composite management sites encompassing forest-based cultivation of tea, fruits, medicines and other agricultural products have also been developed. These endeavors aim to achieve highly intensive, large-scale, high-quality and high-yield plantation management. Leveraging the capacity of wood-based forest product supplies is crucial for achieving substantial economic gains. Multi-objective management of plantation ecosystem service functions should be continuously improved to better meet value, use, product and service needs of the country[17].

(2) Long-term observations and research on the response and adaptation of planted forest ecosystems to global climate change are required to explore scientific theories and optimization paths for sustainable management.

To effectively balance and coordinate multiple ecosystem service functions, it is necessary to advocate for and adopt forest landscapes. This involves adopting a mosaic of natural or artificially planted forest patches, reasonable allocation of different geographical provenance/genetic clones, mixed-age stands, and a multi-tree species management combination of long and short rotation periods[23], to enhance forest biodiversity, heterogeneity and ecological stability[39]. Plantation ecosystem management is a continuous process involving planning, monitoring, evaluation, adaptation and adjustment. Developing adaptive strategies for ecosystem management depends on the response of forest plants, animals, microorganisms and other biological elements to environmental factors such as water, heat and nutrients. Therefore, it is necessary to conduct long-term observational research on the response and adaptation of planted forest ecosystems to global climate change. This will entail ongoing experimentation and investigation into the scientific theory of sustainable management of planted forests in China and an optimization model of multi-objective forest management.

(3) A unified C sink price should be formulated for planted forests, the C sink trading compensation mechanism for planted forests should be improved, and the liquidity of domestic and international markets should be enhanced.

Currently, China is at a juncture where local pilot C markets and the national C market coexist. However, the C price establishment in local markets across the country lacks uniformity, which leads to constrained market trading liquidity. Although China's C market aligns with international trends, its prevailing C trading prices remain relatively low. As China prepares to restart its Certified Voluntary Emission Reduction (CCER) project, it signifies a progressive move toward incorporating C sink forestry initiatives into the national C trading market. Several measures can be undertaken to accelerate the integration of C sinks in tree plantations into the national C trading market. Strengthening the regulatory framework for trading C sinks in tree plantation, identifying the market demand for such sinks, enhancing the compensation mechanisms for these transactions, streamlining the CCER development filing process, and providing clarity on the property rights system for tree plantation sink projects are essential steps in this process. Therefore, it is necessary to establish a unified C sink price for planted forests to ensure that it resonates both domestically and internationally.

(4) An improved prediction model is required to accurately estimate the C sequestration potential of forest ecosystems under climate change and human disturbance.

The estimation of forest C stocks is essential within the realm of research on global climate change and strategies for bolstering sinks while curbing emissions. Currently, projections of forest C sequestration potential within a given region exhibit considerable variability based on the modeling approach, scale, applicability range, and foundational data employed in the prediction process. The predictions may be influenced by the level of subjectivity owing to the assumptions and simulations of the future area and tree species. Often, these models oversimplify complex interactions, disregarding numerous influential factors that can affect the results. Therefore, it is necessary to consider abiotic environmental factors (e.g., climate, soil and topography), tree stand characteristics, future forestry policies, social development, human interference or management, and other influencing factors. This will contribute to refinement of prediction models for the C sequestration potential of planted forests.

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Compliance with ethics guidelines

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REFERENCES

1. Intergovernmental Panel on Climate Change (IPCC). 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4, chapter 4: Forest Land. *IPCC*, 2019
2. Intergovernmental Panel on Climate Change (IPCC). Climate Change 2014: Mitigation of Climate Change. Cambridge: *Cambridge University Press*, 2014
3. Wu H. For green network. *China Daily*, 2023
4. Chen J M. Carbon neutrality: toward a sustainable future. *Innovation*, 2021, **2**(3): 100127
5. Le Gouvello R, Cohen-Shacham E, Herr D, Spadone A, Simard F, Brugere C. The IUCN Global Standard for Nature-based Solutions™ as a tool for enhancing the sustainable development of marine aquaculture. *Frontiers in Marine Science*, 2023, **10**: 1146637
6. Tian H L, Zhu J H, Li C Y, Xiao W F. Nature-based Solution: potential and economic benefits of carbon removal or carbon emission reduction through forestry approaches. *Climate Change Research*, 2021, **17**(2): 195–203 (in Chinese)
7. Sowińska-Świerkosz B, García J. A new evaluation framework for nature-based solutions (NBS) projects based on the application of performance questions and indicators approach. *Science of the Total Environment*, 2021, **787**: 147615
8. Lu F, Hu H, Sun W, Zhu J, Liu G, Zhou W, Zhang Q, Shi P, Liu X, Wu X, Zhang L, Wei X, Dai L, Zhang K, Sun Y, Xue S, Zhang W, Xiong D, Deng L, Liu B, Zhou L, Zhang C, Zheng X, Cao J, Huang Y, He N, Zhou G, Bai Y, Xie Z, Tang Z, Wu B, Fang J, Liu G, Yu G. Effects of national ecological restoration projects on carbon sequestration in China from 2001 to 2010. *Proceedings of the National Academy of Sciences of the United States of America*, 2018, **115**(16): 4039–4044
9. Bastin J F, Finegold Y, Garcia C, Mollicone D, Rezende M, Routh D, Zohner C M, Crowther T W. The global tree restoration potential. *Science*, 2019, **365**(6448): 76–79
10. Nesha K, Herold M, De Sy V, Duchelle A E, Martius C, Branthomme A, Garzuglia M, Jonsson O, Pekkarinen A. An assessment of data sources, data quality and changes in national forest monitoring capacities in the Global Forest Resources Assessment 2005–2020. *Environmental Research Letters*, 2021, **16**(5): 054029
11. Zhang H. Research on effect of forest management on the forest carbon sequestration and the promotion strategies. *Forestry Construction*, 2020, (3): 20–23 (in Chinese)
12. Chen C, Park T, Wang X, Piao S, Xu B, Chaturvedi R K, Fuchs R, Brovkin V, Ciais P, Fensholt R, Tømmervik H, Bala G, Zhu Z, Nemani R R, Myneni R B. China and India lead in greening of the world through land-use management. *Nature Sustainability*, 2019, **2**(2): 122–129
13. State Forestry and Grassland Administration. China Forest Resources Report (2014–2018). Beijing: *China Forestry Publishing House*, 2019 (in Chinese)
14. Wang Y L. Review on China's plantation development since the reform and opening up. *Forest Resources Management*, 2019, (1): 6–11 (in Chinese)
15. Liu S R, Dai L M, Wen Y G, Wang H. A review on forest ecosystem management towards ecosystem services: status,

challenges, and future perspectives. *Acta Ecologica Sinica*, 2015, **35**(1): 1–9 (in Chinese)

16. Tian D L, Shen Y, Kang W X, Xiang W H, Yan W D, Deng X W. Characteristics of nutrient cycling in first and second rotations of Chinese fir plantations. *Acta Ecologica Sinica*, 2011, **31**(17): 5025–5032 (in Chinese)
17. Liu S R, Yang Y J, Wang H. Development strategy and management countermeasures of planted forests in China: transforming from timber-centered single objective management towards multi-purpose management for enhancing quality and benefits of ecosystem services. *Acta Ecologica Sinica*, 2018, **38**(1): 1–10 (in Chinese)
18. Xu B, Guo Z, Piao S, Fang J. Biomass carbon stocks in China's forests between 2000 and 2050: a prediction based on forest biomass-age relationships. *Science China. Life Sciences*, 2010, **53**(7): 776–783
19. Deng L, Han Q S, Zhang C, Tang Z S, Shangguan Z P. Above-ground and below -ground ecosystem biomass accumulation and carbon sequestration with *Caragana korshinskii* Kom plantation development. *Land Degradation & Development*, 2017, **28**(3): 906–917
20. Niu X Z, Duiker S W. Carbon sequestration potential by afforestation of marginal agricultural land in the Midwestern U.S. *Forest Ecology and Management*, 2006, **223**(1–3): 415–427
21. Deng L, Liu G B, Shangguan Z P. Land-use conversion and changing soil carbon stocks in China's 'Grain-for-Green' Program: a synthesis. *Global Change Biology*, 2014, **20**(11): 3544–3556
22. Deng L, Liu S G, Kim D G, Peng C H, Sweeney S, Shangguan Z P. Past and future carbon sequestration bene fits of China's grain for green program. *Global Environmental Change*, 2017, **47**: 13–20
23. Yu Z J, Wang K B, Li J W, Shangguan Z P, Deng L. Mixed plantations have more soil carbon sequestration benefits than pure plantations in China. *Forest Ecology and Management*, 2023, **529**: 120654
24. Fang J, Guo Z, Hu H, Kato T, Muraoka H, Son Y. Forest biomass carbon sinks in East Asia, with special reference to the relative contributions of forest expansion and forest growth. *Global Change Biology*, 2014, **20**(6): 2019–2030
25. Hu H, Wang S, Guo Z, Xu B, Fang J. The stage-classified matrix models project a significant increase in biomass carbon stocks in China's forests between 2005 and 2050. *Scientific Reports*, 2015, **5**(1): 11203
26. Pan Y, Birdsey R A, Fang J, Houghton R, Kauppi P E, Kurz W A, Phillips O L, Shvidenko A, Lewis S L, Canadell J G, Ciais P, Jackson R B, Pacala S W, McGuire A D, Piao S, Rautiainen A, Sitch S, Hayes D. A large and persistent carbon sink in the world's forests. *Science*, 2011, **333**(6045): 988–993
27. Guo Z, Hu H, Li P, Li N, Fang J. Spatio-temporal changes in biomass carbon sinks in China's forests from 1977 to 2008. *Science China: Life Sciences*, 2013, **56**(7): 661–671
28. Zomer R J, Neufeldt H, Xu J, Ahrends A, Bossio D, Trabucco A, van Noordwijk M, Wang M. Global tree cover and biomass carbon on agricultural land: the contribution of agroforestry to global and national carbon budgets. *Scientific Reports*, 2016, **6**(1): 29987
29. Shukla P R, Skea J, Calvo Buendia E, Masson-Delmotte V, Pörtner H O, Roberts D C, Zhai P, Slade R, Connors S, van Diemen R, Ferrat M, Haughey E, Luz S, Neogi S, Pathak M, Petzold J, Portugal Pereira J, Vyas P, Huntley E, Kissick K, Belkacemi M, Malley J. Climate Change and Land: an IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems. *IPCC*, 2019
30. Masson-Delmotte V, Zhai P, Pörtner H O, Roberts D, Skea J, Shukla P R. Global Warming of 1.5 °C: IPCC Special Report on Impacts of Global Warming of 1.5 °C above Pre-industrial Levels in Context of Strengthening Response to Climate Change, Sustainable Development, and Efforts to Eradicate Poverty. Cambridge: *Cambridge University Press*, 2022
31. Wang H, Liu S R, Mo J M. Correlation between leaf litter and fine root decomposition among subtropical tree species. *Plant and Soil*, 2010, **335**(1–2): 289–298
32. Liu Y, Lei P F, Xiang W H, Yan W D, Chen X Y. Accumulation of soil organic C and N in planted forests fostered by tree species mixture. *Biogeosciences*, 2017, **14**(17): 3937–3945
33. Ekholm T. Optimal forest rotation age under efficient climate change mitigation. *Forest Policy and Economics*, 2016, **62**: 62–68
34. Aun K, Kukumägi M, Varik M, Becker H, Aosaar J, Uri M, Morozov G, Buht M, Uri V. Short-term effect of thinning on the carbon budget of young and middle-aged Scots pine (*Pinus sylvestris* L.) stands. *Forest Ecology and Management*, 2021, **492**: 119241
35. Meng Y, Zhang Y, Li C, Wang Z, Li Y. The effect of thinning management on the carbon density of the tree layers in Larch-Birch mixed natural secondary forests of the Greater Khingan Range, Northeastern China. *Forests*, 2022, **13**(7): 1035
36. Dore S, Kolb T E, Montes-Helu M, Eckert S E, Sullivan B W, Hungate B A, Kaye J P, Hart S C, Koch G W, Finkral A. Carbon and water fluxes from ponderosa pine forests disturbed by wildfire and thinning. *Ecological Applications*, 2010, **20**(3): 663–683
37. Pang X, Hu B, Bao W, de Oliveira Vargas T, Tian G. Effect of thinning-induced gap size on soil CO_2 efflux in a reforested spruce forest in the eastern Tibetan Plateau. *Agricultural and Forest Meteorology*, 2016, **220**: 1–9
38. Du Z, Hu J, Xiao Q H, Feng Q, He P, Li R. Analysis on characteristics and development countermeasures of plantation resources in China. *Central South Forest Inventory and Planning*, 2020, **39**(1): 5–10 (in Chinese)
39. Deng L, Shangguan Z P. High quality developmental approach for soil and water conservation and ecological protection on the Loess Plateau. *Frontiers of Agricultural Science and Engineering*, 2021, **8**(4): 501–511