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Carbon Sequestration Capacity of Terrestrial Vegetation in China based on Satellite Data

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Abstract: Achieving carbon neutrality depends on carbon emission reduction and sequestration. However, research on vegetative carbon sequestration in China remains preliminary. In this study, we calculated the total carbon sequestration of terrestrial vegetation and that of different vegetation types in China from 2001–2019 using satellite data. Total vegetative carbon sequestration slowly increased but its increase was significantly lower than that of carbon emissions over the same period. Provinces with the strongest carbon sequestration capacity were mainly distributed in the south, whereas those with the lowest capacity were mainly in the west of Heihe-Tengchong Line. Woody grassland achieved the largest amount of carbon sequestration and grassland experienced the fastest growth. As sequestration ability varies by vegetation type and region, we suggest adopting a holistic regional approach that optimizes local vegetation growth environments, improves ecological compensation protection mechanisms (especially in urban areas) and develops other carbon sequestration pathways.

Keywords: carbon neutrality, satellite data, carbon sequestration of terrestrial vegetation, vegetation types

Introduction

The effects of climate warming, including increasingly frequent extreme weather, constrain global economic development (Nanda et al. 2016) and threaten human survival, leading countries and regions to attach increasing importance to relevant international issues, such as energy conservation and emission reduction. To mitigate climate warming, the 2015 Paris Agreement reached at the 21st United Nations Climate Change Conference achieved a historic consensus that global temperature rise should be controlled to within 2 °C (preferably within 1.5 °C) by the end of this century. Subsequently, at the Climate Ambition Summit held in late 2020, leaders of all countries clearly put forward the goal of controlling global temperature rise within 1.5 °C by the end of this century.

The core of temperature control is carbon control, because climate warming is mainly caused by excessive anthropogenic CO_2 emissions, which account for a major share of greenhouse gases. Therefore, global warming can be effectively curbed by achieving carbon neutrality, including reducing carbon emissions and increasing carbon sequestration, as soon as possible (Liu et al. 2021; Xu et al. 2021). Compared to the former, the latter is more cost-effective (Richards and Stokes 2004). Vegetation plays an important role in carbon sequestration by converting carbon dioxide into carbohydrates (e.g., glucose), thereby reducing the carbon dioxide content in the atmosphere (Liu et al. 2021), which has attracted widespread attention. For example, the 1992 United Nations Framework Convention on Climate Change clearly stated the importance of forest carbon sequestration in controlling global warming, and the 1997 Tokyo Protocol re-emphasized the role of forests in carbon sequestration. While further specifying the urgency of addressing climate change and controlling excessive greenhouse gas emissions, the Montreal and Copenhagen Conferences put forward initiatives to enhance the carbon sequestration capacity of vegetation. The Paris Agreement formalized the status of the Reducing Emissions from Deforestation and Forest Degradation (REDD) mechanism and created a new pattern that deeply integrates national economic development with the ability to control carbon emissions. And many scholars have carried out empirical researches on the carbon sequestration capacity of vegetation. For instance, Luo et al. (2021) taken the Guangdong-Hong Kong-Macao Greater Bay Area as an example to explore the contribution of vegetation to fossil fuel related CO_2 emissions in urban agglomerations. Xu et al. (2021) explored the determinants of the carbon sequestration capacity of vegetation. If global vegetation is considered as a collective carbon sequestration sink, international cooperation on achieving carbon neutrality can provide vegetative carbon control an important role in combating climate change.

At present, China is the largest energy consumer and carbon emitter (Ma et al. 2018). As a responsible major country, China has been actively addressing climate change (Ge and Lin 2021) and promoting vegetative carbon sequestration for decades. For example, China launched several ecological restoration projects, such as the Three North Shelterbelt Project, the world's largest artificial forestation program (Chu et al. 2019), the Yangtze River and Zhujiang River Shelter Forest Project, the Natural Forest Protection Project, the Grain for Green Program, and the Returning Grazing Land to Grassland Project. According to a report by the National Forestry and Grassland Administration in 2019, one-third of the world's artificial forests are in China. Although China's vegetation coverage only accounts for 6.6% of the global total, China's leaf area increments from 2000 to 2017 accounted for 25% of the global increase over that period, largely due to the increase in China's artificial afforestation area. According to the 8th China Forest Resources Inventory, China has 15.1 billion m^3 of forest stock and 21.63% forest cover. The continuous growth of forest stock and cover in the past 20 years has made China the fastest growing country in the world in terms of forest resources. Due to these ecological restoration projects, the carbon sequestration in relevant regions was increased (Xu et al. 2021).

However, compared to developed countries, such as European nations and the United States, China's road toward energy conservation, emission reduction, and carbon neutrality is more difficult. Industrialization and urbanization in such countries started in the first industrial revolution and lasted for two hundred years, while China's industrialization did not really start until 1953. For China, the completion of industrialization and urbanization in the future may take a long time (Du et al. 2019), and it still faces huge pressures on emissions. China's large population and land area make its scale of industrialization and urbanization already comparable to that of Europe as a whole. Of particular concern, accelerated industrialization and urbanization will inevitably damage vegetation while continuously increase carbon emissions, such that the amount of carbon sequestered by vegetation may decrease significantly compared to carbon emissions. Therefore, achieving carbon neutrality during a period of accelerating urbanization and industrialization is a difficult problem that the Chinese government is facing.

Emission reduction and carbon sequestration are the primary approaches for achieving carbon neutrality (Liu et al. 2021; Xu et al. 2021). At present, most research has focused on the former through optimizing energy structures, improving energy efficiency, strengthening awareness of emission reduction, enhancing capacity transfer, strengthening organization and leadership, improving assessment mechanisms, and developing and applying low-carbon technologies. For example, from the perspective of industrial optimization, Zuo et al. (2012) considered achieving carbon neutrality through emission reduction strategies in the construction industry, and Tozer and Klenk (2018) explored carbon neutrality development in cities by simulating different urban emission reduction strategies (including industrial layout and technological innovation). However, energy conservation and emission reduction may have a negative impact on economic growth (Shimizu 2017). Therefore, emission reduction will not be worthwhile if it comes at the expense of economic growth. For example, in 2020, global carbon emissions were cut by 7–7.5% from the previous year due to the COVID-19 pandemic, but this came at the expense of the world economy (Climate Transparency 2020; Earth System Science Data 2020). Only developing a comprehensive understanding of carbon sequestration capacity can we calculate the spatial extent of emissions for a given carbon neutrality target and determine an emission reduction path that balances economic development and climate goals. Therefore, carbon neutrality targets cannot be achieved without research on carbon sequestration capacity. However, current research is limited by the technology and data and focuses more on emission reduction, neglecting carbon sequestration.

Primary carbon sequestration methods include both anthropogenic and natural carbon capture and storage (Gibbins and Chalmers 2008; Sohi 2012). The technological approach comes with high risk (Cherepovitsyn et al. 2020), high cost, and technical complexity, making its large-scale adoption unfeasible at present. Natural carbon sequestration primarily depends on both marine and terrestrial resources, with terrestrial vegetation a primary factor on carbon sequestration capacity of land. Existing literature on the carbon sequestration capacity of terrestrial vegetation was mostly limited to a local region (Fu et al. 2019; Chen et al. 2019; Vaccari et al. 2013) or a special vegetation type (He et al. 2017; Liu et al. 2014). For instance, Fu et al. (2019) investigated the carbon sequestration capacity of roadside vegetation along Shanghai-Nanjing G42 expressway, and He et al. (2017) estimated the carbon sequestration capacity of forest vegetation in China. Insufficient understanding of vegetative carbon sequestration hinders a complete understanding of Earth's carbon cycle, preventing objective examinations of the challenges posed by global warming and making reasonable emission reduction targets and room impossible to determine. Therefore, estimating the carbon sequestration capacity of terrestrial vegetation is of great practical significance for achieving future carbon neutrality.

In this study, we estimated the total carbon sequestration of terrestrial vegetation and that of 11 distinct vegetation types in China from 2001–2019 using satellite data widely applied in carbon emission and sequestration research (Chen et al. 2021), with the following contributions: (1) The first measurement of total carbon sequestration by Chinese terrestrial vegetation during this period, providing relevant basic data for future research on carbon sequestration and neutrality as such data are lacking currently; (2) An estimation of the carbon sequestered by different vegetation types during this period, providing a reference for optimizing vegetation type distribution for improved carbon sequestration capacity; (3) A division of the results by Chinese administrative region to better evaluate local changes in vegetative carbon sequestration capacity and the implementation effects of policies, such as "returning farmland to forest" and "returning pasture to grassland"; (4) An effective supplement to the Chinese vegetation census, significantly reducing human, financial, and material input.

This rest of paper is organized as follows: Section 2 describes the methods and data sources, Section 3 presents the measurement results of vegetative carbon sequestration, and Section 4 presents the conclusions and relevant policy suggestions.

Method and data resources

Method

Based on the carbon sequestration capacity and land cover area of each vegetation, the carbon sequestration amount of vegetation in a certain region can be calculated as follows:

$$\begin{aligned} CS_i &= \sum_{j=1}^{11}\left(CSC_{i,j} \times La_{i,j}\right) \\ &= \sum_{j=1}^{11}\left(Trans \times NPP_{i,j} \times La_{i,j}\right) \end{aligned} \tag{1}$$

where CS_i indicates the carbon sequestration in province i; $CSC_{i,j}$ indicates the carbon sequestration capacity of vegetation j in province i; $La_{i,j}$ indicates the land cover area of vegetation j in province i. $CSC_{i,j}$ can be expressed by $Trans \times NPP_{i,j}$, where $Trans$ indicates the transformation coefficient, presented by the ratio of the amount of CO_2 needs to be absorbed for producing per unit of dry matter via photosynthesis to the carbon content in vegetation's dry matter; $NPP_{i,j}$ indicates the net primary productivity (NPP) of vegetation j in province i, which reflects the mass of net dry matter of vegetation per unit area after photosynthesis and respiration (Cao et al. 2020).

According to formula (1), the carbon sequestration of vegetation depends on three factors: the transformation coefficient, land cover area, and NPP. With regard to the transformation coefficient, it can be presented by the ratio of the amount of CO_2 needs to be absorbed for producing per unit of dry matter via photosynthesis to the carbon content in vegetation's dry matter. The carbon content in vegetation's dry matter is about 45%. The amount of CO_2 needs to be absorbed for producing per unit of dry matter can be calculated according to the chemical equation of photosynthesis, which is presented by formula (2):

$$6CO_2(264\,g)+6H_2O(108\,g)\rightarrow C_6H_{12}O_6(180\,g)+6O_2(192\,g)\rightarrow polysaccharides(162\,g) \quad (2)$$

According to formula (2), vegetation will absorb about 1.62 g of CO_2 when producing 1 g of dry matter through photosynthesis. Thus, the amount of CO_2 needs to be absorbed for producing per unit of dry matter is set as 1.62 in this study. Therefore, the transformation coefficient is $1.62/0.45$.

The land cover areas of 11 terrestrial vegetation were obtained from the MCD12Q1 product according to the classification on terrestrial vegetation of the University of Maryland. Specifically, we first pretreated the MCD12Q1 product by splicing its tiles data with the MODIS Reprojection Tool (MRT); Secondly, we extracted classification band of 11 terrestrial vegetation of the University of Maryland and convert the tile format from hdfeos file to GeoTIFF file. At the same time, the fill value of the blind area was deleted. Thirdly, to obtain the remote sensing images with 500 m resolution, the original image was resampled by the Nearest Neighbor method, and the grid data coordinate was transformed into Mollweide coordinate projection. Finally, based on the attribute extraction and area statistics, the land cover areas of various vegetation were obtained using vector map provided by the National Geomatics Center of China.

With regard to NPP of different terrestrial vegetation, it was estimated by employing MOD17A3H product. We first spliced the MOD17A3H tile data using the MRT and converted the images of the band of NPP from hdfeos to geotiff. Next, we removed the fill values from the grid data (32766 in NPP) according to the guidance document and multiplied remaining NPP by a scaling factor of 0.0001. Then, we adopted the same sampling and projection to match the images of NPP with that of land cover, and consequently obtained the images of NPP with the resolution of 500 m in Mollweide coordinate. To obtain the NPP of different types of terrestrial vegetation, the land cover of each type vegetation was selected as a mask to extract the distribution of NPP. Finally, based on the zone statistics, 11 vegetation's NPP was estimated. The estimated values of NPP for each province in 2001 and 2019 were shown in Table 1.

Our method has some obvious advantages. First, this is the simplest method currently available for measuring the carbon sequestration capacity of terrestrial vegetation in a large area (globally or in countries and regions with a large land area). Second, it can be combined with different vegetation classification methods for broader analysis. Third, it allows easier and low-cost annual updates to terrestrial vegetation sequestration data as compared to other methods, such as the first National Geoinformation Survey, which required three years and > 50,000 people. Fourth, it allows studies tracing back to the past. For example, publicly available Landsat data can be traced back to the 1980s. Fifth, it is mainly based on satellite data, which have uniform standards and exclude interference from subjective factors.

There are a variety of criteria for classifying terrestrial vegetation types, and the resulting statistics may vary considerably. For example, data provided by the National Forestry and Grassland Administration include some of the same types mentioned above, but also consider trees in woody grasslands and savannas. As a result, familiarity with the conversion relationships between datasets is a prime prerequisite for comparisons.

Data resources

This study is based on relevant data of 31 provinces in Chinese mainland during 2001–2019. NPP is used to estimate the carbon sequestration of terrestrial vegetation in this study, since it is usually regarded as a vital indicator for measuring the carbon sequestration of the ecosystem (Zhang et al. 2019). The NPP data estimated by MOD17A3H product from 2001 to 2019 were adopted as the basic data, which were derived from the Modis sensor. These data are widely accepted in research due to their long-time span, wide spatial coverage across most of the world, similarity to results estimated by other methods (such as Casa model data and Ecosystem Model-Data data), and relatively low errors as shown by ecosystem flux tower and yield estimations (Turner et al. 2006; Hong et al. 2020).

MCD12Q1 product was used to obtain the land coverage of 11 terrestrial vegetation types[1] during 2001–2019 based on classification criteria of land cover type defined by the University of Maryland. This product maps global land cover at 500 m spatial resolution at annual time steps to allow analyses of changes in different land-cover types. Other surface cover classifications include water, towns, wetlands, non-vegetated growth areas (e.g., deserts and bare rocks), and mosaic areas (not identified by satellite sensors). Moreover, there are still a few areas that are not covered due to the orbit of the satellites. The spatial distribution of different types of land in Chinese mainland is shown in Figure 1. Given that terrestrial vegetation in wetlands and towns is difficult to identify, our estimates did not include terrestrial vegetation in these areas, nor areas that cannot be identified and covered by satellite sensors, so the results may underestimate the carbon sequestration capacity of terrestrial vegetation to some extent. We estimated that terrestrial vegetation covered 6.668 million km^2 of China,

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[1] The 11 terrestrial vegetation types include evergreen coniferous forest, evergreen broad-leaved forest, deciduous coniferous forest, deciduous broad-leaved forest, mixed forest, closed shrubland, open shrubland, woody grassland, savanna, grassland, and cultivated land.

88.13% of the official data value (7.566 million km^2) provided by the first National Geoinformation Survey.

[Figure 1 near here]

Estimated carbon sequestration of terrestrial vegetation

Sequestration nationwide

Both the carbon sequestration and the carbon sequestration capacity of vegetation were quite different between different provinces (Table 1). From 2001 to 2019, the carbon sequestration and the carbon sequestration capacity of vegetation in most provinces increased, the top five provinces with the growth rate were Ningxia, Beijing, Shanxi, Shaanxi, Inner Mongolia, respectively, with the growth rate of more than 50%. The carbon sequestration of vegetation in five provinces (Tibet, Shanghai, Jiangxi, Fujian, Guangxi, and Hainan) and the carbon sequestration capacity of vegetation in four provinces (Tibet, Shanghai, Jiangxi, Fujian, and Hainan) have decreased. Yunnan and Sichuan provinces had the largest amount of carbon sequestration due to their wide range of vegetation coverage and higher carbon sequestration capacity. Provinces with the strongest carbon sequestration capacity, such as Fujian, Guangdong, Guangxi, Hainan, and Yunnan, were primarily located in the south as these regions are particularly suitable for evergreen broad-leaved forests and mixed forests (Wen and Zhou, 2006), which have high carbon sequestration capacity. Vegetation in provinces west of the Heihe-Tengchong Line, such as Xinjiang, Tibet, Ningxia, and Qinghai, had the lowest carbon sequestration capacity due to their higher altitude. The above findings are consistent with the conclusions of He et al. (2015) to a certain extent, they argued that southern region is one of important regions of carbon storages in China, and the shares of carbon storages in total amount in Xinjiang, Tibet, Ningxia, and Qinghai are smaller.

[Table 1 near here]

The total carbon sequestration of terrestrial vegetation in China increased in fluctuation slowly, increased from 9,463 million t in 2001 to 10,834 million t in 2019, indicating an increase of 14.49% (Figure 2). The reason may be that although China's urbanization process is accelerating, which may lead to the loss of vegetative carbon sequestration, at the same time, China has implemented a series of national ecological restoration projects, such as the Three North Shelterbelt Project, the Yangtze River and Zhujiang River Shelter Forest Project, the Natural Forest Protection Project, the Grain for Green Program, and the Returning Grazing Land to Grassland Project, which contributed to the increase in carbon sequestration of terrestrial vegetation. The change trend of three phases (2003 to 2009, 2009 to 2013, and 2013 to 2018) was similar: a "U" shape defined by a peak, fall, and subsequent rise, which may be due to the joint action of the phased implementation of national ecological restoration projects, such as the Three North Shelterbelt Project, the Yangtze River and Zhujiang River Shelter Forest Project, and the Natural Forest Protection Project, and the change in carbon sequestration capacity of 11 vegetation and their land cover areas.

[Figure 2 near here]

There was a continuous and significant increase in carbon emission and net carbon emissions from 2001 to 2013, slowing afterward and continuing to rise (Figure 2). The increase in sequestered carbon was significantly lower than the increase in carbon emissions over the same period. This is consistent with the finding of Luo et al. (2021). Net carbon emissions provide a direct representation of the gap between carbon emissions and sequestration. The apparent gap between the two derives from the acceleration of industrialization and urbanization in China since the beginning of the century, inevitably causing damage to terrestrial vegetation, resulting in the slower expansion of terrestrial vegetation area compared with industrialization and urbanization.

To better understand the importance of China achieving carbon neutrality through vegetative carbon capture, we compared the increase in total vegetative carbon sequestration with carbon emissions in the same period. The ratio of the increase in vegetative carbon sequestration to carbon emissions from 2002–2019 was generally small (up to 17.64% in 2002) and both the ratio of the increment of vegetative carbon sequestration to carbon emissions and net carbon emissions from 2002–2019 were <6%.

As the world's largest carbon emitter, China's energy intensity and carbon emissions intensity remain 17% and 18.5% above the global average, respectively, as of 2019 (Enerdata 2020; BP 2020). Therefore, to achieve the dual goals of economic growth and carbon neutrality, China must pay more attention to building its vegetative carbon sequestration capacity alongside significantly reducing carbon emissions.

Sequestration by vegetation type

During 2001–2019, the total contributions of woody grassland, grassland, cultivated land, and savanna to the carbon sequestration of terrestrial vegetation were the greatest, about 75%, followed by broad-leaved forests, whereas that of coniferous forests and shrublands were the weakest (Figure 3). Grassland, deciduous broad-leaved forest, and mixed forest had the fastest growth in total carbon sequestration over the same period.

The Chinese government has continually promoted farmland conversion to forest and grassland, active grassland restoration, and desert management, leading to expanded grassland ecosystems. Most grassland plants, have a short life cycle and vigorous metabolisms, are located in areas with long cumulative sunshine hours. This is conducive to photosynthesis, such that the total amount of carbon sequestered by grasslands has consistently increased. In addition, broad-leaved forest trees are generally taller and have high energy demand during growth, making them naturally more capable of sequestering carbon. At present, most Chinese artificial afforestation projects primarily consist of broad-leaved trees, and the planted area has increased significantly; therefore, the total amount of carbon sequestered by broad-leaved forests has increased accordingly. The world is gradually transitioning from simple forest to mixed forest, and China is working to expand the area planted with mixed forest, therefore, the total amount of carbon sequestered by mixed forest has increased significantly. Coniferous forests are mainly located at higher altitudes and latitudes where it is colder, resulting in smaller leaf area and relatively weaker energy demand; therefore, their carbon sequestration capacity is limited. Although shrublands are widely distributed in China, this vegetation type occupies less land and has weaker carbon sequestration capacity, especially open shrublands (Table 2) and are only equivalent to 7–15% of the carbon density of forest vegetation.

[Figure 3 near here]

As shown in Table 2, both the land cover area and the carbon sequestration capacity of different vegetation were quite different. Grassland and cultivated land covered the largest area, together totaling > 4 million km^2, followed by woody grassland and savanna (with forests 700,000–800,000 km^2), deciduous broad-leaved forest, mixed forest and evergreen broad-leaved forest (together totaling >800,000 km^2), whereas closed shrublands and open shrublands covered the smallest area (just over 13,000 km^2). From 2001 to 2019, the land cover area of evergreen coniferous forest, evergreen broad-leaved forest, deciduous broad-leaved forest, mixed forest, and open shrubland increased, among which, the fastest increase was in the land cover area of open shrubland and evergreen broad-leaved forests. Because the former's total area was very small, its increase in its real area was very limited. The increase in the latter and the increase in other different forest types (except deciduous coniferous forest) were obvious, and this may be related to the artificial afforestation and conversion of farmland to forest policies. There was little change in the land cover area of savanna and grassland. The land cover area of cultivated land remained almost unchanged, mainly related to adherence to the bottom line of 1.8 billion mu of cultivated land and the implementation of the permanent basic farmland protection system. The land cover area of deciduous coniferous forest, closed shrubland, and woody grassland decreased. Although the land cover area of closed shrubland decreased by 28%, its impact on the total land cover of vegetation was negligible due to its small absolute area.

Evergreen broad-leaved forests, had the strongest carbon sequestration capacity overall and with its expanded area, contribute significantly to the overall carbon sequestration. Evergreen coniferous forest, mixed forest, deciduous broad-leaved forest, woody grassland, and savanna will most enhance sequestration capacity in future because their mean carbon sequestration capacities were relatively large, more than 0.5 kg/m^2. However, the carbon sequestration capacities of deciduous coniferous forest, closed shrubland, cultivated land, grassland, and open shrubland were relatively weak.

The carbon sequestration capacity of closed shrubland, grassland, and deciduous coniferous forest increased clearly, over 20%, despite their weak carbon fixation ability. The carbon sequestration capacity of deciduous broad-leaved forest, cultivated land, mixed forest, woody grassland, and savanna increased 20%, 15%, 7%, 6%, and 6%, respectively, whereas that of evergreen broad-leaved forest and open shrubland decreased slightly, less 5%. The carbon sequestration capacity of forests can be affected by the age of trees (Zhu et al. 2019), thus, the former may be due to the rapid expansion of planting, such that trees are in a growth period. According to the results of the 9th National Forest Resources Inventory, young and middle-aged forests accounted for 64% of total forest area, near-mature forests 16%, mature forests 14%, and over-mature forests 6%. Therefore, the carbon sequestration capacity per unit area weakened, but a large number of young and middle-aged forests indicate that China's forests have great carbon sequestration potential to a certain extent, which is consistent with the viewpoint of Liu et al. (2014). The largest decline in carbon sequestration capacity was the evergreen coniferous forest, which decreased by 23%.

[Table 2 near here]

Given the great potential of forests in carbon sequestration (Liu et al. 2014; He et al. 2017), at the Climate Ambition Summit, President Xi Jinping pledged to increase China's forest stock by 6 billion m^3 by 2025 (compared to 2005). The 7th and 9th National Forest Resources Inventory showed that China's forest volume was 13.721 billion m^3 in 2005 and 17.56 billion m^3 in the first half of 2018. To meet the declared target, China's forest stock would need to reach 19.721 billion m^3 by 2025 (an increase of approximately 3 billion t of carbon sequestration compared with 2005 and approximately 1 billion t compared with 2018). We used two methods to calculate the volume of China's forests in 2025: the average growth rate of major forest types from 2001–2019 and trends in area and carbon sequestration capacity per unit area of major forest types during that period. Both methods estimated that China would achieve this goal by 2025, possibly earlier if afforestation is sped up and forestry structure is optimized. The planting of evergreen broad-leaved forest should be further promoted during the return of farmland to forest and urban greening because of its superior carbon fixation and extensive adaptability to the environment of the Yangtze River Basin and southern China, for the promotion of vegetative carbon sequestration.

Conclusions and policy suggestions

From the perspective of terrestrial vegetation, this paper analysed the total carbon sequestration of terrestrial vegetation and that of different types of vegetation in China from 2001–2019 using the satellite data of MOD17A3H and MCD12Q1. The results showed that southern Chinese regions, such as Fujian, Guangdong, Guangxi, Hainan, and Yunnan, are especially suitable for the growth of vegetative types with high sequestration ability, such as evergreen broad-leaved forests and mixed forests. Sequestration ability was lowest in provinces west of the Heihe-Tengchong Line due to geographical factors. Evergreen broad-leaved forest, which had the strongest sequestration ability of all types considered, has expanded its area and has had a significant contribution to the increase in total carbon sequestration. The carbon sequestration capacities of evergreen coniferous forest, mixed forest, deciduous broad-leaved forest, woody grassland, and savanna were also strong; therefore, these should be emphasized in future plantings. The carbon sequestration ability of deciduous coniferous forest, closed shrubland, cultivated land, and grassland was relatively weak.

Climate factors and landscape management have great impacts on the carbon sequestration of vegetation (Chen et al. 2019; Smith 2014). Compared to the former, the latter is more adjustable and controllable. To promote the optimal distribution of vegetation for improved sequestration, a holistic approach to Chinese landscape management should emphasize adaption to local conditions by considering differences in sequestration ability, growth needs, terrain attributes, regional characteristics, and production and development needs. This would improve the overall carbon sequestration of terrestrial vegetation, diversify regional ecological and industrial patterns, and promote the coordinated development of environment-related industries, such as tourism, planting, and aquaculture.

In addition, China's mechanisms for ecological compensation and long-term protection should be further improved. At present, these policies are mainly concentrated in low-population-density areas, such as natural reserves, important ecological function zones, mineral resource development zones, and river basin water environment protection zones. As urbanization accelerates, it will be increasingly important to enhance the carbon sequestration capacity of terrestrial vegetation in densely populated urban areas. Therefore, these mechanisms should be creatively extended to urban greening policies to stimulate the enthusiasm of the population and managers participating in urban green development. The goal should be to increase terrestrial vegetation cover in urban areas. At the same time, although southern China (such as Guangxi and Yunnan) is suitable for vegetation with strong carbon fixation capacity (such as evergreen broad-leaved forests), these vegetated areas are also at risk of urban encroachment; consequently, the carbon sequestration of vegetation in these regions may have a great loss due to urban expansion (Page et al. 2021). Therefore, there is a need to establish long-term sustainable development protection mechanisms in these regions to avoid the decline in vegetation carbon sequestration caused by deforestation.

Finally, investment should be increased for carbon capture, transport, and storage technologies to supplement any deficiency in vegetation carbon sequestration. Although the latter is beneficial for absorbing and reducing atmospheric carbon dioxide, it is still unable to cope with the huge amount of carbon dioxide emitted by human activities, as the annual increase in carbon sequestration only accounts for 11% of the total amount of emissions on average. Therefore, it is necessary to develop other methods for carbon sequestration as a supplement to vegetation carbon sequestration. In addition to the role of the government and market, technology plays an indispensable role in the process of emission reduction. High-energy-consuming enterprises, such as power generation, iron, steel, building material, and chemical producers, and scientific research institutions, should increase their investment in appropriate technology, such as carbon capture (e.g., organic ammonia, pre-combustion treatment, combustion efficiency improvement, and chemical cycle reaction) and carbon storage (e.g., geological, marine, and chemical). Key problems, such as the high cost of such technology and possible leakages in the storage process, should be researched and resolved. Breakthroughs in carbon capture, transport, and storage could leave more room for carbon emissions in the future and increase the chances of achieving carbon neutrality on schedule.

The main limitation of this study lies in the resolution of the satellite data used is only 500 m. There may be some errors if the calculation results in this study is used to estimate the carbon sequestration capacity of vegetation in a smaller area. Therefore, in the future, we will focus on using satellite data with higher resolution (e.g., 30 m) to explore the carbon sequestration capacity of vegetation in smaller areas.

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Table 1. Amount and capacity of vegetative carbon sequestration, and NPP in 31 provinces of Chinese mainland in 2001 and 2019.

Province	Carbon sequestration (million t)		Carbon sequestration capacity (kg/m^2)		NPP (kg/m^2)	
	2001	2019	2001	2019	2001	2019
Heilongjiang	597.35	723.00	1.35	1.64	0.375	0.456
Inner Mongolia	615.01	931.43	0.72	1.09	0.200	0.303
Xinjiang	262.70	313.38	0.56	0.67	0.156	0.186
Jilin	279.72	330.17	1.50	1.77	0.417	0.492
Liaoning	194.21	220.12	1.39	1.58	0.386	0.439
Gansu	237.33	348.95	1.01	1.48	0.281	0.411
Hebei	157.32	220.68	0.89	1.24	0.247	0.344
Beijing	9.90	17.38	0.69	1.22	0.192	0.339
Shanxi	126.06	209.33	0.83	1.37	0.231	0.381
Tianjin	7.17	9.59	0.75	1.00	0.208	0.278
Shaanxi	233.62	360.06	1.15	1.77	0.319	0.492
Ningxia	24.68	46.21	0.49	0.91	0.136	0.253
Qinghai	233.22	295.22	0.48	0.60	0.133	0.167
Shandong	169.60	204.93	1.19	1.44	0.331	0.400
Tibet	564.63	556.77	0.66	0.65	0.183	0.181
Henan	171.92	213.93	1.09	1.35	0.303	0.375
Jiangsu	144.28	158.60	1.67	1.83	0.464	0.508
Anhui	213.58	229.68	1.63	1.75	0.453	0.486
Sichuan	783.12	951.35	1.64	1.99	0.456	0.553
Hubei	295.62	333.22	1.69	1.90	0.469	0.528
Chongqing	158.09	191.18	1.97	2.38	0.547	0.661
Shanghai	7.15	6.70	2.02	1.89	0.561	0.525
Zhejiang	242.02	252.58	2.59	2.70	0.719	0.750
Hunan	443.65	459.95	2.19	2.27	0.608	0.631
Jiangxi	382.76	375.24	2.43	2.38	0.675	0.661
Yunnan	1330.22	1435.89	3.57	3.83	0.992	1.064
Guizhou	473.36	512.26	2.74	2.95	0.761	0.819
Fujian	375.65	370.45	3.26	3.21	0.906	0.892
Guangxi	729.73	728.61	3.16	3.16	0.878	0.878
Hainan	136.56	135.54	4.20	4.16	1.167	1.156
Guangdong	107.44	108.02	3.27	3.29	0.908	0.914

Data source: MOD17A3H and MCD12Q1 products; Carbon sequestration capacity refers to the amount of carbon sequestered in one region divided by the area.

Table 2. Acreage and carbon sequestration capacity of different terrestrial vegetation types.

	Mean area (km^2)	2019/2001 (area)	Mean carbon sequestration capacity (kg/m^2)	2019/2001 (Carbon fixation capacity)
Evergreen coniferous forest	57216	1.12	0.770	0.770
Evergreen broad-leaved forest	169479	1.36	1.050	0.960
Deciduous coniferous forest	19328	0.79	0.470	1.270
Deciduous broad-leaved forest	381659	1.15	0.590	1.200
Mixed forest	250200	1.14	0.720	1.070
Closed shrubland	4065	0.72	0.390	1.540
Open shrubland	9044	1.39	0.070	0.990
Woody grassland	889378	0.91	0.720	1.060
Savanna	697945	1.00	0.720	1.060
Grassland	2912267	0.98	0.210	1.310
Cultivated land	1277144	1.00	0.400	1.150

Data source: MOD17A3H and MCD12Q1 products

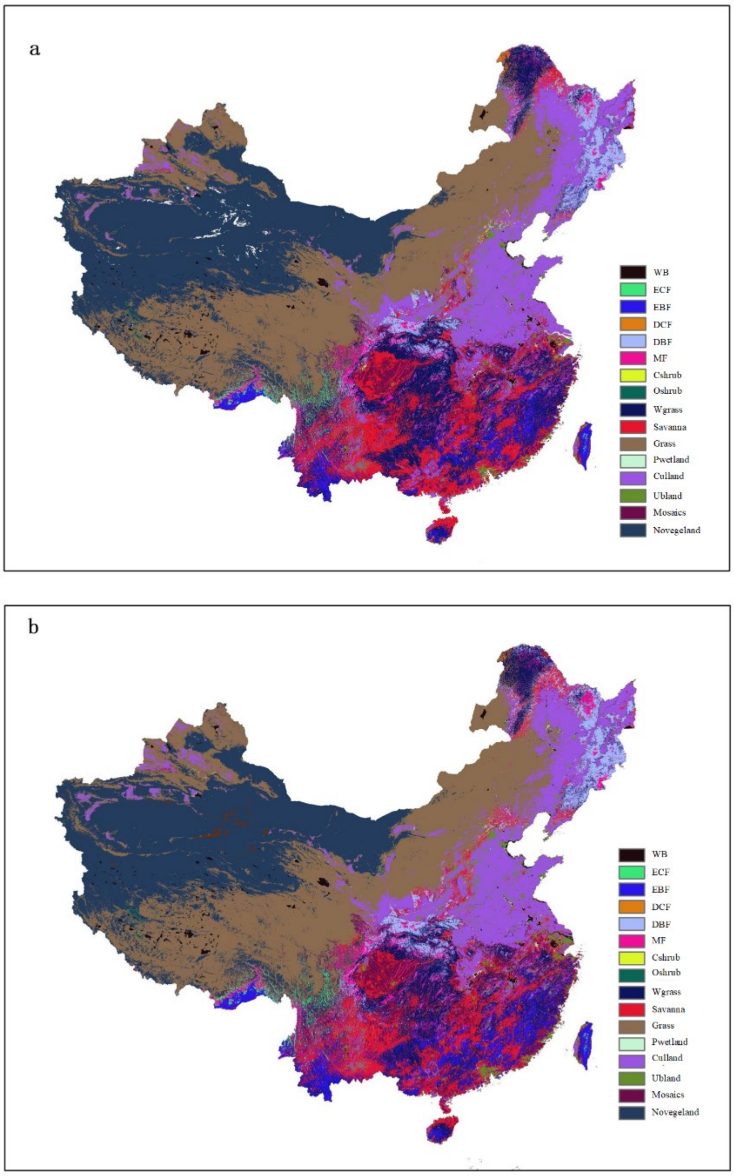

Figure 1. The spatial distribution of different types of land in Chinese mainland

Note: a and b present the spatial distribution of different types of land in Chinese mainland in 2001 and 2019, respectively. WB indicates water bodies, *ECF* indicates evergreen coniferous forests, *EBF* indicates evergreen broad-leaved forests, *DCF* indicates deciduous coniferous forests, *DBF* indicates deciduous broad-leaved forests, *MF* indicates mixed forests, *Cshrub* indicates closed shrublands, *Oshrub* indicates open shrublands, *Wgrass* indicates woody grasslands, *Grass* indicates grasslands, Pwetland indicates permanent wetlands, *Culland* indicates cultivated lands, *Ubland* indicates urban and built-up lands, *Mosaics* indicates cultivated land/ natural vegetation mosaic areas, *Novegeland* indicates non-vegetated lands.

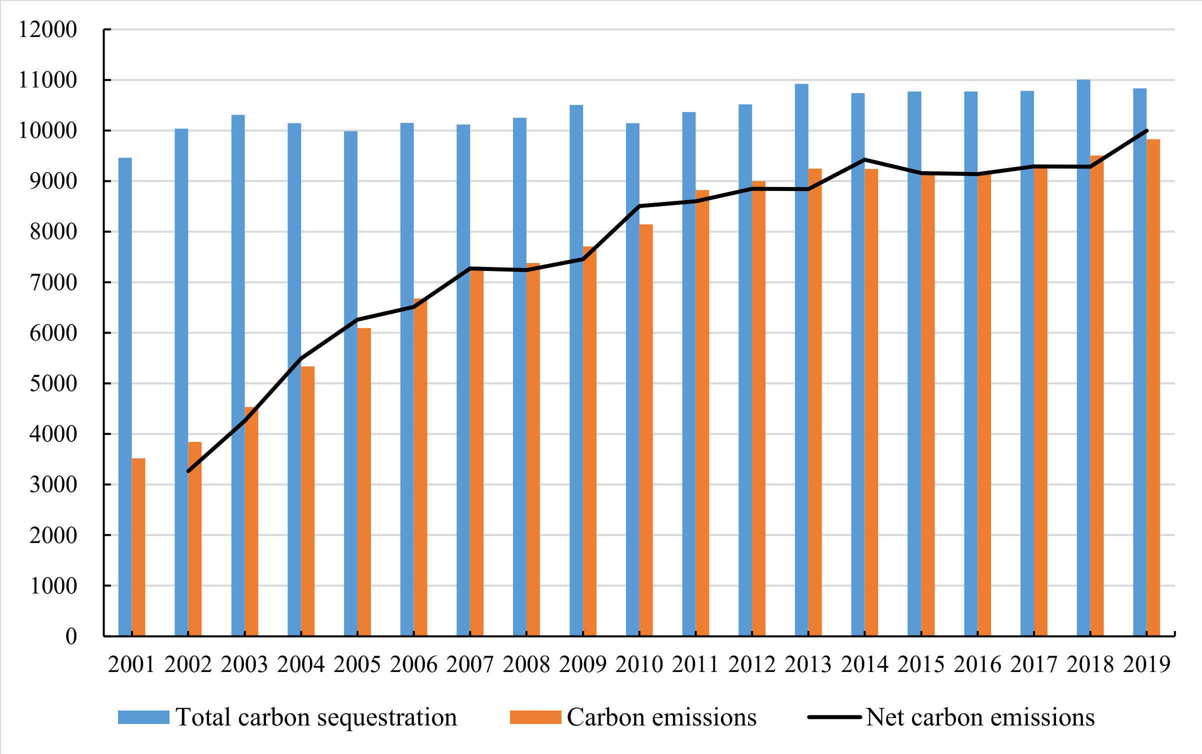

Figure 2. Carbon emissions and vegetative sequestration in China, 2001–2019 (million t). Data source: Total carbon sequestration is calculated based on data obtained from MOD17A3H and MCD12Q1 products, and data on carbon emissions is derived from the BP Statistical Review of World Energy 2020. Net carbon emissions refer to carbon emissions minus the increment of total carbon sequestration (i.e. the difference between the total carbon sequestration in the reporting period and the base period).

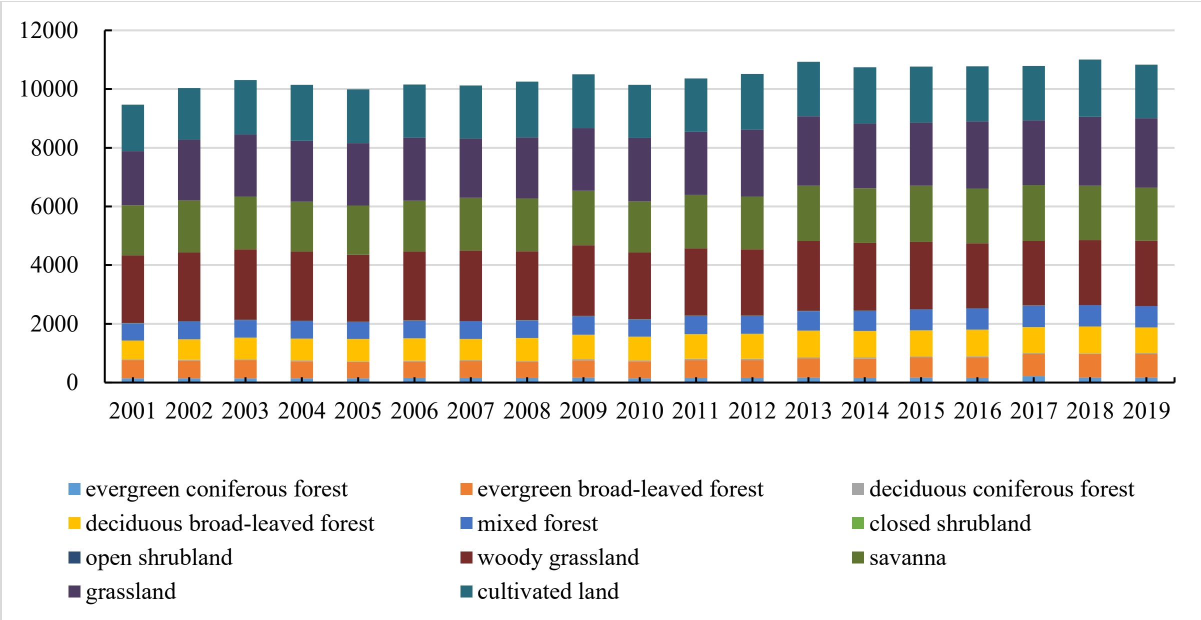

Figure 3. Carbon sequestration of 11 Chinese vegetation types (million t). Data source: MOD17A3H and MCD12Q1 products