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Technological Approaches to Enhance Ecosystem Carbon Sink in China: Nature-based Solutions

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Abstract

Carbon peak in 2030 and carbon neutralization in 2060 has been established as one of the important strategic goals of China's economic and social development. During 2010-2020, the capacity of terrestrial ecosystems in China to sequester carbon dioxide (CO2) varied from 1.0 to 1.3 Gt/a, with high uncertainty. To enhance the carbon sink capacity of Chinese terrestrial ecosystems, the combination with land space planning and ecological protection is essential. It is necessary to first stabilize the existing carbon storage in these ecosystems, such as forest, grassland, wetland, coast, and others, and then implement some important ecological protection and ecological restoration projects at large scale. In addition, new technologies of carbon capture, utilization, and storage based on biological CO2 fixation principles (Bio-CCUS) or ecological CO2 fixation principles (Eco-CCUS) should be developed and applied. Through integrated regional ecosystem management and spatial planning, as well as multiple technologies to enhance carbon sink, it is possible to double the carbon sink capacity, both natural and human-made, arriving at 2.0-2.5 Gt/a during 2050-2060. In practice, we need to scientifically assess the key technologies of ecosystem carbon sink improvement in view of effectiveness, economic feasibility, and durability, and then comprehensively integrate these technologies into different regions for demonstrations at regional scale.

Keywords

ecosystem carbon sink carbon storage ecologically critical zone carbon cycle carbon neutrality

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Technological Approaches to Enhancing Ecosystem Carbon Sink in China: Nature-based Solutions

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Abstract: Carbon peak by 2030 and carbon neutrality by 2060 have become important strategic goals for China's long-term development. From 2010 to 2020, China's terrestrial ecosystems can capture and store about 1.0–1.3 Gt/a of carbon dioxide (CO_2). To enhance the carbon sink capacity of terrestrial ecosystems in China, it is essential to combine national land planning and ecological protection and stabilize the existing carbon sinks in forests, grasslands, wetlands, coasts, and others, so as to implement ecological protection and restoration projects. In addition, new technologies of carbon capture, utilization, and storage based on biological CO_2 fixation principles (Bio-CCUS) or ecological CO_2 fixation principles (Eco-CCUS) should be developed and applied. Through integrated regional ecosystem management and spatial planning, as well as multiple technologies, it is possible to double the natural and human-made carbon sink capacity, namely, 2.0–2.5 Gt/a of CO_2 during 2050–2060. In practice, we need to systematically analyze key technologies to enhance ecosystem carbon sink, scientifically assess their effectiveness, economic feasibility, and durability, and then achieve the technological integration in different regions and conduct regional demonstrations. **DOI:** 10.16418/j.issn.1000-3045.20220121002-en

Keywords: ecosystem; carbon sink; carbon storage; ecologically critical zone; carbon cycle; carbon neutrality

Carbon peak by 2030 and carbon neutrality by 2060 have become important strategic goals for China's long-term development. Therefore, it is necessary to carry out an overall macro-layout of technological approaches related to emission reduction, carbon conservation, carbon sink enhancement, and carbon storage and coordinate the development of new ecological economies and industries regarding energy transformation by decarburization, structural adjustment to emission reduction industry, and ecological environment development for carbon sink enhancement. The terrestrial ecosystem has a huge carbon sink capacity, and it is one of the important ways to achieve the goals of carbon peak and carbon neutrality (hereinafter referred to as 30–60 goals) by consolidating and improving its carbon sink [1, 2]. Therefore, it is urgent to promote the demonstration and application of key technologies and optimized models for protecting and improving ecosystem carbon sink and develop new technologies for biological and ecological carbon capture, utilization, and storage (CCUS) [3], so as to implement carbon neutrality in China.

Extensive research has focused on the process of the ecosystem carbon cycle, carbon sequestration mechanism, and the principle of carbon sink enhancement in recent years [4]. The previous studies on ecological processes at the site and landscape scales as well as feedback studies on the regional ecosystem and climate system have laid a theoretical foundation for studying and developing regional carbon sequestration and carbon sink enhancement technologies [5]. Currently, the main scientific and technological tasks to consolidate and improve the ecosystem carbon sink are as follows: (1) strengthening national land planning and controlling its use, strictly enforcing the ecological protection red line, and stabilizing the carbon storage of existing forests, grasslands, wetlands, coasts, frozen soils, and other ecosystems; (2) implementing nature conservation and ecological restoration projects to improve ecosystem quality and carbon sink; (3) coordinating the existing natural ecosystem, naturally restored secondary ecosystem, and artificially rehabilitated ecosystem to comprehensively improve the carbon sink capacity [6, 7].

Researchers have developed effective technologies for carbon conservation and carbon sink enhancement for different ecosystems through long-term research. However, under the background of national 30–60 goals, how to effectively evaluate the economic feasibility of these technologies and the stability and sustainability of carbon sinks and achieve the integrated application and demonstration regionally and nationally has not been solved [8]. This study aims to provide a reference for national land planning and the control of land use, implementation of major ecological

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conservation and restoration projects, and integrated application of regional carbon sink technologies.

1 Principles of consolidating and enhancing ecosystem carbon sink capacity with nature-based solutions (NbS)

It is a huge ecosystem project involving political, economic, social, and ecological development to implement 30–60 goals in a trans-regional and cross-industry way within national lands and coasts. Therefore, it is necessary to carry out the spatial optimization layout with NbS and the systematic engineering concept of rationally allocating resources and environment and popularize key technologies for protecting ecosystem carbon pool and enhancing carbon sink. The core concept of NbS is to respect the laws of nature, be in line with natural conditions, and make use of natural processes. It develops schemes for enhancing carbon sinks of typical ecosystems based on ecosystem approaches in accordance with local conditions. NbS also help to formulate schemes for protecting carbon pool and enhancing carbon sink regionally based on the macro ecosystem approach and can optimize the regional nature-economy-society complex ecosystem to achieve the coordination and unification of social, economic, and ecological and environmental benefits. NbS are scientifically based on the evolution principle of the biosphere and environment system, the coupling principle between macro systems, the integrity principle of the ecosystem, and the harmonious coexistence theory between human and nature. They also highlight a community with a shared future between humankind and mountains, rivers, forests, fields, lakes, grass, sand, and ice to optimize the spatial and temporal allocation between the water-soil-climate-biology environment and resources. Therefore, the following four principles should be obeyed when carbon sink enhancement schemes with NbS are developed for different regions to achieve carbon neutrality.

1.1 The coordination of carbon sink enhancement with the main function zones of national lands

The carbon sink enhancement scheme must be coordinated with the existing main function zones of national lands. It should identify important zones with natural carbon sinks and zones with artificially enhanced carbon sinks, integrate them into national ecological protection areas, ecological red line areas, and major ecological restoration project areas, and strengthen the overall management of mountains, rivers, forests, fields, lakes, grass, sand, and ice and oceans, seas, bays, islands, reefs, and banks in China's specific areas. The geographical pattern and natural regionalization of China's carbon sinks are the basis for formulating the spatial layout of the carbon neutrality action. In light of natural and geographical conditions, carbon sink areas within the territory should be planned as a whole, and priority should be given to the ecologically critical zones to demonstrate the integrated models of carbon sink enhancement technologies.

1.2 The integration of carbon sink enhancement and nature conservation and ecological development

The national carbon sink consolidation and improvement strategy must be implemented in all areas across China. Additionally, the technological model for improving carbon sink regionally must be based on the ecosystem productivity and economic and social development determined by regional natural and geographical conditions, and the ecological project should match natural and geographical conditions, economic and social status, and scientific and technological capabilities [1]. China's macro landform, geography, and climate patterns determine the basic spatial pattern of major carbon sink areas [9, 10]. The vast mountain forests have a strong carbon sequestration function, and most of the mountain forests in China are still in the stage of ecological restoration, with potential carbon sink enhancement ability. In addition, China's coastal zones, riparian zones, traffic lines (road zone), and urban green spaces (green belts) are important areas of land greening in recent years, with great carbon sink enhancement potential. "Three Eco-zones" (Qinghai-Tibet Plateau Eco-zone, Yellow River Eco-zone, Yangtze River Eco-zone,) and "Four Shelterbelts" (Northeast Shelterbelt, North Shelterbelt, South Shelterbelt, and Coastal Shelterbelt), which have been proposed by the Master Plan for the Major Projects for the Protection and Restoration of National Key Ecosystems (2021–2035), are the basis for guiding the planning of national carbon sink areas and provide an important reference for improving the macro decision of carbon sink enhancement.

1.3 The combination of carbon sink enhancement with historical and cultural heritage and rural revitalization

The layout of the national carbon sink enhancement projects should be combined with natural and cultural heritage protection, biodiversity protection, and regional development. China has a long history and rich cultural heritage, and many geographical spaces are not only distributed with natural and cultural heritage but also important function zones for biodiversity and ecosystem carbon sinks. The protection of natural and cultural heritages such as famous mountains and rivers, shrines and temples, and relics distributed in different regions of China must be based on the protection and restoration of natural landscapes, ecosystems, and cultural environment, so as to combine carbon sink conservation with human civilization continuation. In addition, China's social development needs to consolidate and expand poverty alleviation achievements and comprehensively advance the rural revitalization strategy. About 41.74% of national lands are covered by the 14 former concentrated poverty-stricken areas, including Ta-pieh Mountains, Southern Greater Khingan

Mountains, the karst rocky desertification areas of Yunnan, Guangxi, and Guizhou, border mountains of western Yunnan, Tibet, and the four prefectures of southern Xinjiang, and these areas are characterized by high carbon storage and high per capita carbon sink. Therefore, the coordination between economic development, resource exploitation and utilization, ecological and environmental protection, and consolidation and enhancement of carbon sinks in poverty-stricken areas has attracted the attention of the government and the public, and it is necessary to establish a mechanism for valuing ecosystem carbon sink products. Efforts must be made to ensure a win-win situation between the economic development and environmental coordination in poor areas and realize the coordination of 30–60 goals with ecological restoration, the beautiful China initiative, and rural revitalization through mechanisms such as carbon sink trading, carbon sink tax, and fiscal transfer payment.

1.4 The combination of carbon sink enhancement with regional ecosystem management

The core technology to consolidate and enhance the carbon sequestration in carbon sink function zones indicates the nature-based comprehensive management of the regional ecosystem, and the popularization and application of the multi-objective and compatible regional ecological management model involving ecological protection, ecological restoration, rural revitalization, and carbon conservation and carbon sink enhancement. For the past few decades, China, after studying typical ecosystem structure-process-function mechanisms, has developed carbon sequestration and carbon sink enhancement technologies for ecosystems including farmland soils, artificial forests, natural secondary forests, grasslands, wetlands, and desert oasis and designed ecosystem management models for different geographical regions, which provide carbon sink function zones with rich technologies for carbon conservation and carbon sink enhancement (Table 1). Most of these technologies or models are based on long-term observations and tests and validated by observational data. However, some actions that ignore natural laws and pursue man-made carbon sinks deserve attention. For example, the blind and large-scale planting of forests or shrubs in arid and semi-arid deserts cannot significantly enhance carbon sink and should cause soil loss and carbon pool loss [11]. In addition, some areas convert massive wetlands to woodlands on the grounds that forests are important carbon sinks. Such conversion (especially in high altitude or high latitude areas) should accelerate the decomposition of soil organic matters, resulting in the loss of carbon sink in soil, and its comprehensive ability to enhance carbon sink is debatable [5].

2 Approaches to enhancing carbon sink and key technologies

Ecosystem carbon conservation and carbon sink enhancement are considered to be the most environment-friendly, cost-optimal, and beneficial technological approaches in the Kyoto Protocol (1997), Copenhagen Accord (2009), and Glasgow Climate Pact (2021) [12, 13]. For the past decades, China has made great achievements in ecological and environmental development, which lays a foundation for ecological carbon pool protection and carbon sink enhancement and is significant for developing the theoretical system, application technology, and model of coordinated ecological development and carbon sequestration and carbon sink enhancement. On this basis, the carbon cycle of the earth system and the artificial control system that support the 30–60 goals should be established from the coupling of carbon cycles of the geological system, surface system, ecological system, and humanistic society system. More attention should be paid to the development and application of new CCUS (Bio-CCUS or Eco-CCUS) based on biology or ecology in developing CCUS theory and technologies in geological engineering [2].

2.1 Traditional agricultural and forestry technologies to reduce emissions and enhance carbon sink

Traditional agricultural and forestry technologies to reduce emissions and enhance carbon sink mainly consist of afforestation, reafforestation and forest management, agricultural conservation tillage, animal husbandry emission reduction, grassland and wetland management, coastal ecological projects (such as blue carbon breeding), and other low-carbon technologies to reduce emission or enhance carbon sink [8, 12]. Currently, the following technologies should be applied and developed: ① Implementing major ecological protection and restoration projects, carrying out integrated protection and restoration of mountains, rivers, forests, fields, lakes, grass, sand, and ice in different regions, and continuously increasing forest areas and stock volume; ② Vigorously promoting land greening, consolidating the achievements of returning farmlands to forest and grasslands, and implementing the projects to improve forest quality accurately. ③ Adopting diversified forest management measures, such as the extension of forest intermediate cutting time, planted forest fire prevention and pest control. ④ Strengthening the protection and restoration of the grassland ecosystem, and intensifying the protection of inland river banks, lakes, marshes, and wetlands. ⑤ Comprehensively promoting the ecological protection and restoration of coastal (wetland), especially the protection of mangroves, sea grass beds, and salt marshes. ⑥ Changing the farming system and improving cultivated land quality, implementing the protection projects of black soils, loess and red soils, and enhancing the soil carbon pool and its stability. ⑦ Strengthening the research and development of geological carbon sink in inland saline-alkaline soils and karst regions (Table 1).

According to studies, agricultural conservation tillage and the use of organic fertilizer can capture and store about

Table 1 Effect of artificial management on carbon sequestration of ecosystems and their qualitative evaluation

		Technological measures	Carbon sink effect	Technology maturity	Environmental fitness	Social adaptability	Current application scale	Evaluation difficulty of carbon sequestration	Comprehensive evaluation index	IPCC commitment (Yes/No)
Forest ecosystem	1	Afforestation and reafforestation	***	***	**	**	***	*	***	Yes
	2	Returning farmland to forests	***	**	***	**	**	*	***	Yes
	3	Natural forest protection	**	***	***	**	**	*	***	No
	4	Forest tending	**	**	**	***	**	**	**	No
	5	Intermediate cutting of forests	**	**	**	**	*	***	**	No
	6	Naturalization of planted forests	**	**	**	*	*	***	*	No
	7	Planting of fast-growing and high-yield forests	*	**	**	**	*	**	*	No
	8	Stand optimization/transformation measures	*	*	*	*	*	***	*	No
Grassland ecosystem	1	Natural grassland enclosure	***	***	***	**	***	**	***	No
	2	Returning farmlands to grasslands	***	***	***	**	**	*	***	Yes
	3	Restoration measures for deteriorated grasslands	**	**	**	**	*	***	**	No
	4	Perennial mixed pasture planting	*	**	*	***	*	**	**	No
	5	High-yield artificial grassland planting	*	**	*	**	*	**	*	No
	6	Rational control of grazing intensity	*	*	**	**	*	***	*	No
	7	Rotational grazing system/delayed grazing	*	**	*	**	*	***	*	No
Farmland ecosystem	1	Straw turnover	***	***	***	**	*	*	***	Yes
	2	Organic fertilizer application	***	***	***	**	*	*	***	Yes
	3	Minimal tillage	**	***	**	**	***	**	**	Yes
	4	Non-tillage	**	**	**	**	*	**	**	Yes
	5	Crop rotation	*	***	**	***	**	***	*	Yes
	6	Irrigation management	*	**	*	**	*	***	*	Yes
Wetland ecosystem	1	Wetland conservation	***	***	***	**	***	**	***	No
	2	Returning farmlands to lakes	***	**	***	*	*	*	**	Yes
	3	Degraded wetland restoration	**	**	**	*	*	**	**	No
	4	Wetland management	*	*	*	*	*	***	*	No
	5	Conversion of wetland types	*	*	*	**	*	***	*	No
	6	Constructed wetlands	*	**	*	**	**	**	*	No
Coasts (wetlands)	1	Wetland vegetation restoration	***	***	**	***	*	*	***	No
	2	Shellfish culture	***	***	**	***	***	**	***	Yes
	3	Algal cultivation	***	***	**	**	***	***	**	No
	4	Coral reef reconstruction	**	**	*	*	*	***	*	No

Note: carbon sink effect refers to the carbon sequestration rate after implementing management measures; technology maturity indicates whether the measures are technically mature; environmental fitness tells whether the measures are highly adaptable to the environment; social adaptability demonstrates whether the measures are suitable for expansion from the perspective of social regulations, public behavior, and economy. Current application scale represents the application or promotion of the measures in China's ecosystems; the difficulty of carbon sequestration evaluation refers to the difficulty of accurately evaluating the carbon sequestration effect based on existing technologies; comprehensive evaluation index shows the comprehensive evaluation of the carbon sequestration effect with measures based on the foregoing six evaluation indexes; IPCC commitment indicates whether the measures can be listed in the current inventory of the IPCC (Intergovernmental Panel on Climate Change). The carbon sink effect of all measures has three levels in terms of qualitative evaluation, and measures for each ecosystem are valued with asterisks. More asterisks signify that the measure has a stronger carbon sink effect or is more suitable for expansion in terms of qualitative evaluation items except for the evaluation difficulty.

0.14–0.17 Gt/a of CO_2 [14], and for measures such as grassland fencing and grass planting, the number is approximately 0.06–0.08 Gt/a [8, 15, 16]. However, estimates have been deduced based on the small-scale and short-term research, and thus there are still great uncertainties, with the economic feasibility to be studied.

2.2 Approaches to enhancing carbon sink by ecological projects

For approaches to enhancing carbon sink by ecological projects, we need to coordinate the national land greening and ecological and environmental governance, improve the ecosystem carbon sink of forests, farmlands, grasslands, deserts, inland wetlands, lakes, coastal wetlands, offshore aquaculture, etc., explore the existing mature technologies, and integrate them into systematic technological models suitable for landscapes, basins, and regions. It is necessary to fully summarize the research, development, and demonstration achievements of all kinds of technologies related to ecosystem location, observation, research, and carbon sink enhancement, and collect technologies for improving carbon sink to support the comprehensive demonstration of regional carbon sinks.

Scientists have developed and summarized effective measures to enhance carbon sink in the past decades (Table 1), such as afforestation and reforestation, returning farmlands to forests, and natural grassland enclosure [6, 8]. However, in implementing the carbon neutrality strategy, it is urgent to scientifically evaluate the carbon sink effect, durability, spatial applicability, and economic feasibility of carbon sink enhancement technologies and recommend corresponding measures to enhance carbon sink by ecological projects that can be implemented in a large scale. The ecological construction of new afforestation, road and riparian zones, and green belts is still expanding in China. According to the national statistics of new afforestation and green belt areas in each province and the analysis of the corresponding carbon sequestration rate of each region, the implementation of new ecological restoration and land greening projects are of huge carbon sequestration potential. New afforestation and greenbelt are expected to capture and store about 0.03–0.08 Gt/a of CO_2 [17].

2.3 New Bio-CCUS/Eco-CCUS approaches

Bio-CCUS/Eco-CCUS refers to that more CO_2 can be captured by increasing the productivity of the terrestrial ecosystem, and they can be converted into organic biomass which serves as energy, chemical, or building materials instead of fossil products or is directly buried or geologically stored. Photosynthesis is the largest energy and matter conversion process on earth. It is a natural process for efficient conversion of light energy and carbon sequestration, which provides sufficient raw materials for Bio-CCUS/Eco-CCUS.

(1) Research and development of high-tech biological carbon sequestration technologies by molecular biology principles. The transgenic and molecular design technologies in molecular biology are rapidly developing, which has provided potential technologies for developing biological carbon storage and can be widely used in constructing an integrated system of technologies for efficient CO_2 bio-utilization or storage. The potential technological breakthroughs are as follows. ① Using molecular biology technologies to improve photosynthetic organisms' light capture, carbon sequestration, and metabolic pathways and enhance photosynthetic carbon sequestration efficiency. ② Improving and screening trees and grass with efficient carbon sequestration, saline-alkali tolerance, or drought-resistance performance. ③ Developing microorganisms or aquatic plants with efficient carbon sequestration and pollution reduction effect.

(2) Development of artificially simulated photosynthesis technologies based on modern biosynthesis principles. The development of modern biotechnology provides conditions for technological breakthroughs in biological improvement and simulation of photosynthesis. Breakthroughs that sunlight, water, and CO_2 are converted into carbohydrates by artificial utilization and simulated photosynthesis may provide key technologies for Bio-CCUS/Eco-CCUS. Potential technological breakthroughs include the following aspects. ① Developing chemical and biocatalysis coupling technologies to construct a starch synthetic pathway of carbon sequestration [18]. ② Exploring biological enzyme catalysts to break through the complex regulation barriers of starch synthesis in nature. ③ Developing module assembly optimization and spatial-temporal separation strategies to solve the problems of substrate competition and product inhibition in the artificial carbon sequestration pathway. ④ Breaking through the cost limitation of applied technologies to improve the application value and industrialization of artificial carbon sequestration technologies.

(3) Development of biological/ecological carbon sequestration technologies by land resources such as polluted or abandoned lands. China has polluted lands and wetlands and abandoned mining areas. Although these lands are not suitable for planting crops for humans and livestock, they can be planted with high-light efficiency and high biomass plants (such as poplar, Achnatherum splendens, castor bean, maize, sweet sorghum, and sugarcane). The biomass produced by these plants can be used as bio-energy and bio-chemical raw materials, and their harvest can be compressed into particles or buried directly after carbonization, which realizes long-term carbon sequestration. Taking maize or sorghum as an example, each hectare of land produces 30 tons of straws and grains per year, and the annual net carbon sequestration rate can reach 49.4 tons per hectare. If the price of CO_2 per ton from the CCUS pathway is 1 300–2 000 yuan, the economic effect of carbon sink per unit area will even exceed the economic value of traditional agricultural planting.

(4) Development of biological/ecological carbon sequestration technologies by agricultural and forestry residual biomass. Forest and farmland ecosystems produce a large amount of waste or straw biomass every year, which is a huge biological resource. Yan et al. [19] have found that the annual accumulation of newly added organic matters in China's terrestrial ecosystems was huge through a study on biomass's calorific value. Therefore, the full utilization of the biomass removed by forest regeneration, deforestation, and tending will provide huge alternative energy and help to realize the 30–60 goals. According to studies, the biomass growth rate of China's existing forest vegetation is likely to reach a peak during 2035–2040 [11, 20]. Therefore, secondary forest tending and proper cutting are necessary to stabilize and improve productivity and prevent carbon leakage caused by forest fires and pests. The study results provide a theoretical basis for the selective cutting or cultivation of forests in the future

and indicate prospects for developing power generation or biological carbon sequestration technologies of forest biomass. If a quarter of the annual forest productivity is removed from the ecosystem, the forest may have around 300 million cubic meters of wood (or the equivalent leaves and branches). In other words, the forest biomass of about 0.27–0.3 Gt/a of CO_2 could be used for Eco-CCUS. Moreover, China's annual grain output is about 650 million tons, and the crop straw produces about 1.07 billion tons of CO_2. If the straw amount consumed by straw turnover, energy utilization of rural households, and livestock is deducted (about 70%), and the remaining 30% of straw is used for Eco-CCUS, its carbon sink may be enhanced to 0.32 Gt/a. Similarly, the sequestration and storage of discarded furniture and construction materials are also significant carbon sink measures.

3 Overall goals and approaches to enhancing carbon sink in China

It is challenging to determine the goals and approaches to improving the carbon sink in China. Here, we propose a potential goal for enhancing China's ecosystem carbon sink through the carbon neutrality concept with NbS and existing data. Although the goal has high uncertainty and needs to be validated by subsequent scientific research and social practice, it can serve as a reference for consolidating and enhancing the carbon sink in China.

3.1 Enhancement targets of the existing ecosystem carbon pool, carbon sink capacity, and function

China's ecological construction has greatly improved the carbon sink of the terrestrial ecosystem over the past 30 years. According to the census data, China's forest area increased from 117.12 million hectares in 1973–1976 to 179.89 million hectares in 2014–2018, and the CO_2 of forest biomass has increased by 14 billion tons in the past four decades [21]. As outlined in the 14th Five-Year Plan (2021–2025) on the protection and development of forests and grasslands, the forest stock volume in China is expected to reach 19 billion cubic meters in 2021–2025, which attracts worldwide attention. The report based on remote sensing data has shown that the global green space areas increased by 5% from 2000 to 2017, and China's contribution rate was about 25% [22].

The prediction of carbon storage and carbon sequestration capacity and potential of ecosystems is a complex scientific issue. Based on the present findings, the organic carbon storage of terrestrial vegetation, litter, and soils at 0–1 m depth in China is estimated at 363.3 ± 20.9 billion tons of CO_2. Specifically, the organic carbon storage of vegetation is 49.8 ± 11.9 billion tons, and that of soils is 298.8 ± 18.6 billion tons. Currently, the organic carbon of unconfirmed deep soils, peatlands, and various animals is about 266.7 billion tons, 55.1 billion tons, and 100 million tons of CO_2, respectively. In addition, the inorganic carbon of the soil at 1 m depth and 0–2 m depth is about 172.7 billion tons and 195.4 billion tons of CO_2, respectively (Figure 1).

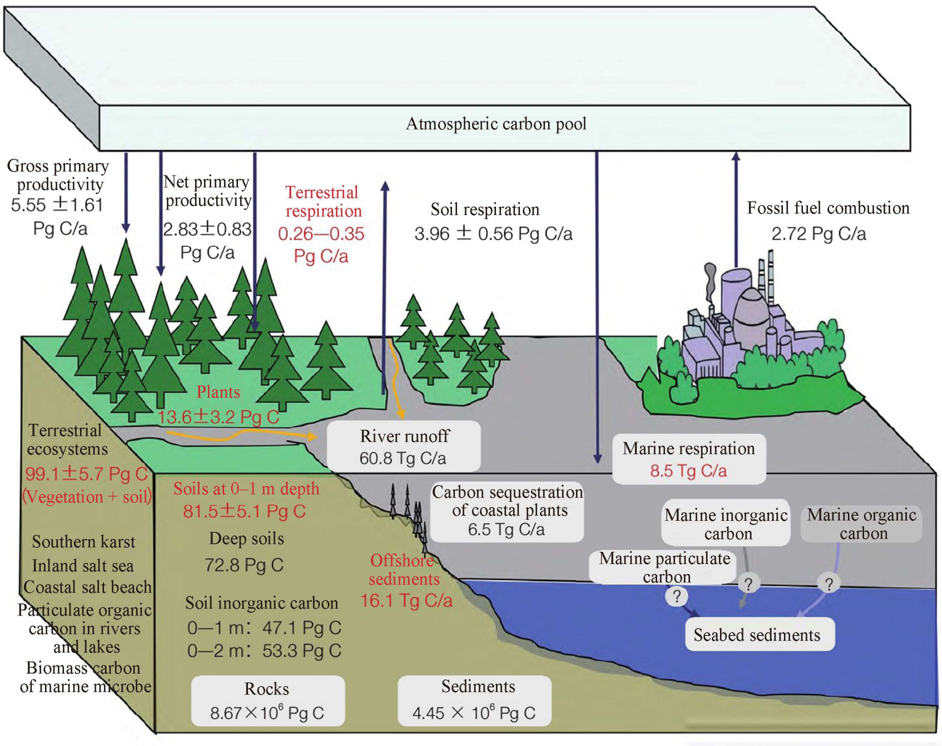

Figure 1 Estimates of ecosystem carbon storage, carbon sink, and carbon sequestration potential of lands and coasts in China

The carbon sink effect of terrestrial ecosystems estimated by different statistical methods varies greatly. The existing terrestrial organic carbon sink is confirmed about 1.0–1.5 Gt/a [15, 23–25] or about 1.0–1.3 Gt/a in a conservative way. Reliable information reveals that the regional comprehensive carbon sink in China will increase to 2.0–2.5 Gt/a by 2050 by carrying out carbon sink certification, carbon sink enhancement projects, ecological management, and comprehensive application of measures such as Bio-CCUS/Eco-CCUS, with coordinating organic and inorganic carbon sinks in land-river-ocean spaces, and on the basis of existing carbon sink capacity.

Literature analysis reveals that the unconfirmed terrestrial and marine organic carbon sink is about 0.346 Gt/a. Specifically, the carbon sink of urban green space, the blue carbon sink of coastal ecosystem, and the carbon sink of the offshore sea are 0.029 Gt/a, 0.07–0.09 Gt/a, and 0.22–0.24 Gt/a, respectively. Therefore, the actual organic carbon sink capacity of land and ocean was 1.5–1.6 Gt/a from 2010 to 2020 [26–29]. Moreover, extensive studies have shown that the inorganic carbon sinks of China's desert saline-alkali lands, karst areas and loess plateau, blue carbon sink in the coastal areas, and offshore marine carbon sink are of great functions. Preliminary estimates suggest that the inorganic carbon sink in China is about 0.16–0.19 Gt/a, and specifically 0.178 Gt/a is from carbonate weathering [30–32].

3.2 Approaches to enhancing China's regional ecosystem carbon sink function zones

In order to improve regional ecosystem carbon sink function zones in China, we should comprehensively utilize traditional agricultural and forestry emission reduction and carbon sink enhancement technologies, carbon sink enhancement by ecological projects, and Bio-CCUS/Eco-CCUS. We should also assess, select, and develop key innovative technologies of carbon sink and integrate them into compatible ecological development and management models that are technically feasible, operationally effective, and easily promotable. These models should be widely applied in different carbon sink function zones according to local conditions, so as to comprehensively demonstrate and apply national and regional nature conservation and carbon sink enhancement technologies.

The geographical pattern and natural regionalization of ecosystem carbon sink are the basis for formulating the spatial layout of carbon neutrality action. The tasks of comprehensive demonstration of technologies to enhance regional carbon sinks are as follows. ① Carrying out the regional comprehensive investigation to understand the background of carbon sink, and on this basis, setting the targets and implementation period of regional carbon sink enhancement by combining with the geographical conditions, social and economic development demands, and the existing ecological protection and restoration projects. ② Selecting technological models to enhance carbon sink for regional comprehensive integration according to geographical conditions, social and economic development, the positioning of ecological functions of the region, and the assessment of regional applicability, so as to form a demonstration system of regional carbon sink enhancement technological models. ③ Observing and assessing regional carbon sinks and obtaining the change process of the carbon sink effect and other ecological, economic, and social functions during the demonstration period of carbon sink enhancement technologies, with the support of a carbon sink three-dimensional monitoring system. ④ Comprehensively assessing the regional carbon sink enhancement effect, refining policy suggestions, and formulating technical standards at the end of the demonstration of carbon sink enhancement technologies, with carbon sink inventory, three-dimensional observation, and data model platform.

China's comprehensive demonstration of technologies to enhance carbon sink in important function zones is a practical application of a technology system integrating sites, landscapes, and regions under the interaction between social system and ecosystem. It is necessary to improve the situation that traditional carbon sink enhancement technologies are applied fragmentarily and cannot cover the whole process of carbon sink formation. Previous studies have demonstrated that planted forests and natural secondary forests tended in China in recent decades play an important role in carbon sink. Grassland is considered to be carbon neutral on the whole except for the alpine meadow. Wetland is regarded as a carbon source as a whole. whether farmland soil belongs to the carbon source or carbon sink mainly depends on agricultural technology patterns and regional environmental conditions [5, 14, 17]. At present, long-term scientific research and massive application have laid a foundation for developing carbon cycle regulation technologies in areas, such as ecosystem carbon sink enhancement and industrial emission reduction. However, great challenges still exist in integrating carbon sink enhancement technologies by following the spatial pattern of the regional carbon cycle.

3.3 Requirements of a systematic layout scheme for carbon sink enhancement at the national level

The Working Guidance for Carbon Dioxide Peaking and Carbon Neutrality in Full and Faithful Implementation of the New Development Philosophy clearly defines the working principle of the overall layout of all industries and the comprehensive governance of mountains, rivers, forests, farmlands, lakes, and grass and sets objectives for work in each period. For example, China's forest coverage rate is expected to reach 24.1% by 2025 and 25% by 2030. Previous work in China has laid a good foundation for promoting the national unified layout of carbon sink enhancement. Moreover, previous major ecological projects have also provided a guarantee for enhancing regional carbon sink capacity, including the Three-North Forest Shelterbelt Project and the red and yellow soil restoration areas in South China, which have played a vital role in increasing carbon sink. China's strategy of the Yangtze River Economic Belt to strengthen environmental protection rather than seeking rapid growth at the cost of the environment and the strategy of ecological protection and high-quality development in the Yellow River Basin has recently been implemented on the premise of protecting regional ecology. Ecological protection has also brought an opportunity to consolidate and improve carbon sinks.

However, the large-scale carbon sink project, which lasts for 50 years and covers the whole country, needs to interact with national strategies such as natural environment protection, ecological and environment governance, regional sustainable development, and rural revitalization, which will have a significant impact on water security, food security, and resource security patterns at national and regional levels. Strong scientific and technological support is needed to develop a multi-objective system scheme to enhance carbon sink, improve the ecological environment, and promote regional development. Thereinto, theoretical cognition, technological integration, observation certification, and accounting and assessment are four basic scientific and technological tasks.

(1) Theoretical cognition of ecosystem cycle and carbon sink enhancement principles. Understanding the principles of formation mechanism, dynamic evolution, geographical distribution, and management of ecosystem carbon sink is the ecological basis for consolidating and enhancing ecosystem carbon sink. National carbon sink management should be guided by ecosystem carbon cycle theory and rely on the dynamic monitoring of carbon sink, quantitative certification of carbon sink enhancement potential, and application evaluation of technological models, so as to promote social practices at local, regional, and national levels. The basic scientific issues mainly include three aspects. ① The effectiveness, feasibility, and economy of technological measures to consolidate or enhance carbon sinks. ② The certainty of carbon sink assessment, the variability of spatial and temporal patterns, and the sustainability of technological effects. ③ Ecosystem stability, sensitivity to human factors, and adaptability to environmental changes (Figure 2).

(2) Integration of technologies to consolidate and enhance carbon sinks. To consolidate and enhance carbon sinks in the vast Chinese territory requires the application and demonstration of various key technologies and ecosystem management models. The traditional technologies to enhance carbon sink by agricultural and forestry emission reduction and ecological projects are considered to be the ecological carbon sequestration systems with the most mature technologies, lowest cost, easiest popularization, and highest effect.

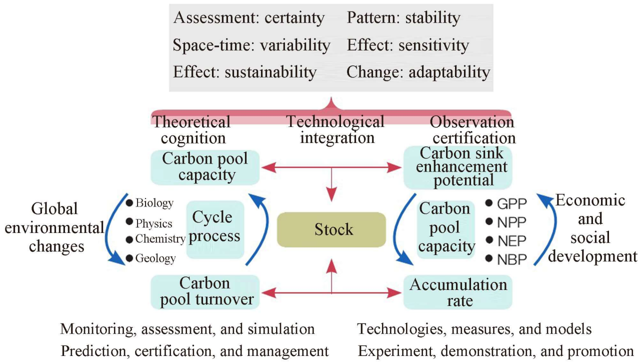

Figure 2 Ecological theories and frontier technologies to protect carbon storage and enhance carbon sink in China's ecosystems

GPP, gross primary productivity; NPP, net primary productivity; NEP, net ecosystem productivity; NBP, net biome productivity

However, it is necessary to demonstrate the effectiveness, feasibility, and economy of potential technologies to enhance carbon sink in accordance with local conditions, so as to form effective technical models and make them widely used through experiments and demonstrations [8]. Moreover, it is necessary to develop Bio-CCUS or Eco-CCUS technology with great potential in a forward-looking way to make technological reserves for doubling the carbon sink.

(3) Observation certification of consolidating and enhancing carbon sinks. For developing and implementing effective system plans, efforts must be made to develop the regional and national dynamic three-dimensional network monitoring system, establish the monitoring technologies of the typical ecosystem, regional, and national carbon sinks, construct the simulation analysis system for natural and social complex ecosystem process, and find theories and methods to predict the evolution of the ecology-climate-society complex ecosystem. Faced with China's complicated geographical patterns and regional differences in economic and social development, we should comprehensively analyze the ecological and environmental issues at different development stages in regions, predict the carbon sink benefits and ecological and environmental effects of various carbon sink projects, recognize the particularity of regional ecosystem carbon cycle and its mechanism, and certify the technical and economic feasibility, carbon sink effect, and potential impact of ecological environment of carbon sink projects, in a bid to provide a scientific basis for assessing the optimized layout and implementation effect of ecological projects in China.

(4) Accounting and assessment of consolidating and enhancing carbon sinks. Effect assessment, carbon sink certification, and regional and project management of carbon sink technologies, measures, and models are important for enhancing regional carbon sinks. It is urgent to develop and improve methods for assessing different carbon sinks in regions and establish methodological and technical standard systems for measuring, evaluating, and verifying carbon sink

effects of technologies, measures, and models to enhance carbon sinks in different ways. Additionally, special attention should be paid to the establishment of carbon sink accounting methods, climate effect certification and technical assessment standards for man-made technologies and measures, the development of reportable, measurable, and verifiable technical systems, and the construction of a common system for measuring, accounting and valuing carbon sink trading worldwide.

4 Conclusion

China's ecosystem has a huge carbon sink effect with much room for improvement and will play an important role in realizing the country's 30–60 goals. By consolidating and improving carbon sinks, it is expected to keep the CO_2 emitted by China's industries at 2.0–2.5 Gt/a, which can be regarded as the ballast stone and regulator of China's 30–60 goals. This is because ecosystem carbon sink can not only win precious time for the innovation and development of clean energy and green technologies but also provide a basic energy security guarantee for the stable operation of the country's economic and social system. However, the assessment of China's future ecosystem carbon storage, carbon sequestration capacity and potential, and the formulation of the action plan for enhancing ecosystem carbon sink, is not only a complex scientific issue but also a long-term economic and social development and social practice issue involving the overall situation, entire population, and territory. Although China has obtained great achievements in ecological restoration in the past 30 years, with substantial improvement in the ecosystem carbon sink, it is still a major and arduous task to double the carbon sink capacity as set in the national 30–60 goals, and the strong science and technologies, national guidance, public participation, and financial input are required.

References

1 Yu G R, He N P, Wang Q F. Carbon budget and carbon sink of ecosystems in China: Theoretical basis and comprehensive assessment. Beijing: Science Press, 2013. (in Chinese)

2 Wang F, Harindintwali J D, Yuan Z Z, et al. Technologies and perspectives for achieving carbon neutrality. The Innovation, 2021, 2(4): 100180.

3 Mallapaty S. How China could be carbon neutral by midcentury. Nature, 2020, 586: 482–483.

4 IPCC. Climate Change 2021: The Physical Science Basis//Masson-Delmotte V, Zhai P, Pirani A, et al. (Ed). Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press, 2021.

5 Yu G R, Zhao X Q, Liu G H. Approaches for Increasing Carbon Sink of Terrestrial Ecosystems in China and Its Potential. Beijing: Science Press, 2018. (in Chinese)

6 Yu G R, Wang Q F, Liu Y C, et al. Conceptual framework of carbon sequestration rate and potential increment of carbon sink of regional terrestrial ecosystem and scientific basis for quantitative carbon authentification. Progress in Geography, 2011, 30 (7): 771–787. (in Chinese)

7 He H L, Wang S Q, Zhang L, et al. Altered trends in carbon uptake in China's terrestrial ecosystems under the enhanced summer monsoon and warming hiatus. National Science Review, 2019, 6 (3): 505–514.

8 He N P, Wang Q F, Liu Y H, et al. The approaches to enhance carbon sequestration of terrestrial ecosystem at regional scales, and their feasibility. Progress in Geography, 2011, 30 (7): 788–794. (in Chinese)

9 Chen Z, Yu G R, Ge J P, et al. Temperature and precipitation control of the spatial variation of terrestrial ecosystem carbon exchange in the Asian region. Agricultural and Forest Meteorology, 2013, 182/183: 266–276.

10 Yu G R, Chen Z, Piao S L, et al. High carbon dioxide uptake by subtropical forest ecosystems in the East Asian monsoon region. PNAS, 2014, 111 (13): 4910–4915.

11 Cai W X, He N P, Li M X, et al. Carbon sequestration of Chinese forests from 2010 to 2060: Spatiotemporal dynamics and its regulatory strategies. Science Bulletin, 2022, doi: 10.1016/j.scib.2021.12.012.

12 IPCC. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Kanagawa: Institute for Global Environmental Strategies (IGES), 2006.

13 Rogelj J, den Elzen M, Höhne N, et al. Paris Agreement climate proposals need a boost to keep warming well below 2 °C. Nature, 2016, 534: 631–639.

14 Zhao Y C, Wang M Y, Hu S J, et al. Economics- and policy-driven organic carbon input enhancement dominates soil organic carbon accumulation in Chinese croplands. PNAS, 2018, 115 (16): 4045–4050.

15 He N P, Yu Q, Wu L, et al. Carbon and nitrogen store and storage potential as affected by land-use in a *Leymus chinensis* grassland of Northern China. Soil Biology and Biochemistry, 2008, 40 (12): 2952–2959.

16 Hu Z M, Li S G, Guo Q, et al. A synthesis of the effect of grazing exclusion on carbon dynamics in grasslands in China. Global Change Biology, 2016, 22 (4): 1385–1393.

17 Lu F, Hu H F, Sun W J, et al. Effects of national ecological restoration projects on carbon sequestration in China from 2001 to 2010. PNAS, 2018, 115 (16): 4039–4044.

18 Cai T, Sun H B, Qiao J, et al. Cell-free chemoenzymatic starch synthesis from carbon dioxide. Science, 2021, 373: 1523–1527.

19 Yan P, Xiao C W, Xu L, et al. Biomass energy in China's terrestrial ecosystems: Insights into the nation's sustainable energy supply. Renewable and Sustainable Energy Reviews, 2020, 127: 109857.

20 He N P, Wen D, Zhu J X, et al. Vegetation carbon sequestration in Chinese forests from 2010 to 2050. Global Change Biology, 2017, 23 (4): 1575–1584.

21 Zhang C H, Ju W M, Chen J M, et al. Disturbance-induced reduction of biomass carbon sinks of China's forests in recent years. Environmental Research Letters, 2015, 10 (11): 114021.

22 Chen C, Park T, Wang X H, et al. China and India lead in greening of the world through land-use management. Nature Sustainability, 2019, 2: 122–129.

23 Piao S, Fang J, Ciais P, et al. The carbon balance of terrestrial ecosystems in China. Nature, 2009, 458: 1009–1013.

24 Tang X L, Zhao X, Bai Y F, et al. Carbon pools in China's terrestrial ecosystems: New estimates based on an intensive field survey. PNAS, 2018, 115 (16): 4021–4026.

25 Xu L, Yu G R, He N P, et al. Carbon storage in China's terrestrial ecosystems: A synthesis. Scientific Reports, 2018, 8: 2806.

26 Wang J, Feng L, Palmer P I, et al. Large Chinese land carbon sink estimated from atmospheric carbon dioxide data. Nature, 2020, 586: 720–723.

27 Wang F M, Sanders C J, Santos I R, et al. Global blue carbon accumulation in tidal wetlands increases with climate change. National Science Review, 2020, 8 (9): nwaa296.

28 Gao Y, Zhou F, Ciais P, et al. Human activities aggravate nitrogen deposition pollution to inland water over China. National Science Review, 2019, 7 (2): 430–440.

29 Gao Y, Jia J J, Lu Y, et al. Determining dominating control mechanisms of inland water carbon cycling processes and associated gross primary productivity on regional and global scales. Earth-Science Reviews, 2021, 213: 103497.

30 Li H W, Wang S J, Bai X Y, et al. Spatiotemporal distribution and national measurement of the global carbonate carbon sink.Science of the Total Environment, 2018, 643: 157–170.

31 Li H W, Wang S J, Bai X Y, et al. Spatiotemporal evolution of carbon sequestration of limestone weathering in China. Science China Earth Sciences, 2019, 62 (6): 974–991.

32 Bai X Y, Wang S, Cao J H, et al. Carbon Sink of Rock Weathering and Climatic Change. Beijing: Science Press, 2021. (in Chinese)

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