

Four colours of carbon sinks in terrestrial ecosystems

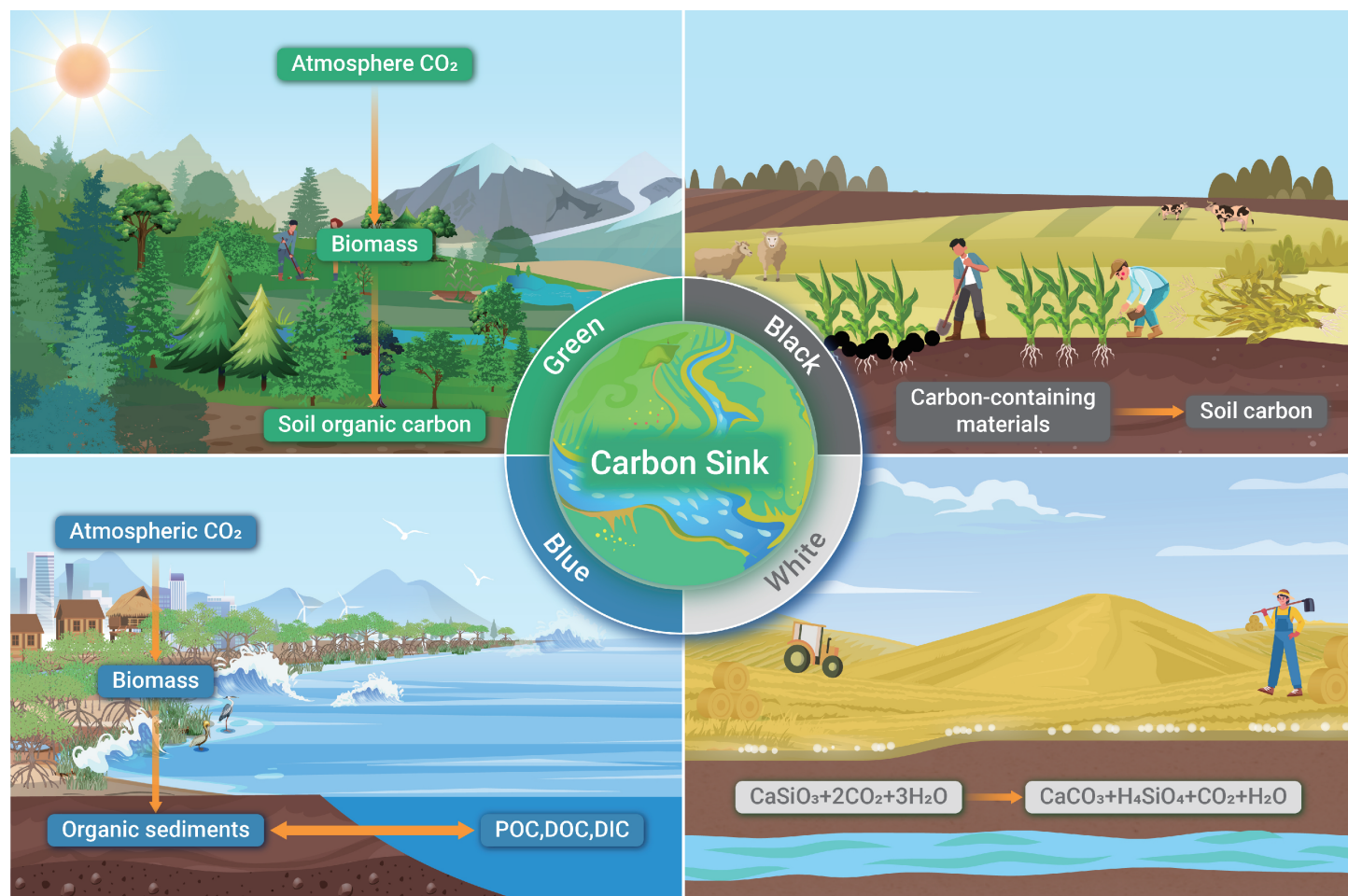
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GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- Enhancing terrestrial ecosystem carbon sinks is an effective strategy for achieving carbon neutrality.
- Previous classifications of carbon sinks are often abstract and lack systematic descriptions.
- This review introduces a new concept of four colours of carbon sinks across different ecosystems.
- Nature-based solutions and their potential for enhancing the four colours of carbon sinks are identified.
- Potential, costs, risks, and social acceptance of carbon sinks of these colours in China are also discussed.

Four colours of carbon sinks in terrestrial ecosystems

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Terrestrial ecosystems are important carbon (C) sinks that absorb 31% of anthropogenic carbon dioxide (CO₂) emissions. Understanding the formation mechanisms and enhancement strategies of terrestrial carbon sinks is necessary for assessing their magnitude, spatiotemporal dynamics, and potential. This knowledge is also the foundation for implementing effective management measures and technological approaches to enhance terrestrial carbon sinks, which is essential for achieving carbon neutrality and limiting global warming to less than 1.5°C. Here we propose that the terrestrial carbon sinks can be systematically conceptualized into four colours, specifically green carbon, black carbon, blue carbon, and white carbon. We elucidate the definition, current distribution, and approaches for enhancing carbon sinks of these four colours. Our results indicate that the current four-colour carbon sink globally is 4.4 Pg C yr⁻¹. The global potential to enhance the four-colour carbon sinks is estimated to be 11.9 ± 2.2 Pg C yr⁻¹. Using China as a case study, where its current four-colour carbon sink amounts to 0.74 Pg C yr⁻¹, we also introduce the approaches to enhancing carbon sinks of these colours, along with their mitigation potential, costs, environmental risks, and social acceptance. Finally, we highlight priority research areas for future studies to advance the scientific and practical understanding of terrestrial carbon sinks.

INTRODUCTION

Human activities, primarily through emissions of greenhouse gases, have unequivocally caused global warming, with the global surface temperature reaching 1.1°C greater than that in 1850–1900 from 2011–2020.¹ Human-caused climate change is already affecting Earth's material cycles, energy balance, and ecological processes, while intensifying the frequency of extreme climate events, such as drought, heatwaves, heavy rainfall, and floods. These impacts pose serious threats to social, economic, and ecologically sustainable development. In response, the Paris Agreement set a global temperature target of “well below 2°C” and encouraged efforts to “limit increase to 1.5°C above pre-industrial levels”.² Carbon dioxide (CO₂) serves as the primary greenhouse gas in the atmosphere, with the concentration increasing from 278 parts per million (ppm) prior to the Industrial Revolution to 419.3 ppm in 2023.³ To limit warming to 1.5°C above preindustrial levels with no or limited overshoot, global net zero CO₂ emissions, i.e., carbon neutrality, must be reached in the early 2050s.⁴

Achieving carbon neutrality necessitates both anthropogenic emission reductions, and enhancing ecosystem carbon sinks to remove carbon from the atmosphere.⁵ Carbon sequestration in terrestrial ecosystems represents a crucial pathway towards attaining this goal.^{6–9} Terrestrial ecosystems are the

main absorbers of CO₂, with a global carbon storage of approximately 3478 Pg C.¹⁰ In the past decade (2012–2021), the terrestrial carbon sink was estimated at 3.2 ± 0.9 Pg C yr⁻¹, offsetting 30% of the total CO₂ emissions from fossil fuel combustion (9.7 ± 0.5 Pg C yr⁻¹) and land-use change (1.1 ± 0.7 Pg C yr⁻¹).³ Moreover, the terrestrial carbon sink has consistently increased in recent years and continues to play a key role in mitigating climate change.^{3,11}

Previous studies have focused predominantly on natural carbon sinks in various terrestrial ecosystems. These studies have estimated the spatial-temporal dynamics and formation mechanisms of carbon sinks based on ecosystem type, with an emphasis on forest ecosystems and approaches to enhancement, such as afforestation initiatives (e.g., the One Trillion Trees Project).^{12,13} However, there has been relatively little focus on enhancing carbon sinks in croplands, wetlands, and other ecosystems. To address the managerial and technological requirements for achieving carbon neutrality systematically, further clarification of the definitions and formation mechanisms of carbon sinks in terrestrial ecosystems is essential.¹⁴ This clarification will enable targeted evaluations of both the magnitude and spatiotemporal dynamics of terrestrial carbon sinks. Additionally, further exploration is needed regarding approaches to enhancing carbon sinks along with the potential magnitude of those sinks in these ecosystems, as well as the associated social costs and ecological risks.

In previous studies, scientists have classified carbon into either organic carbon or inorganic carbon. Over the past two decades, numerous measures aimed at enhancing carbon sinks have been proposed by researchers; however, these measures have focused primarily on the increase in organic carbon in terrestrial ecosystems. To emphasize the role of different types of carbon in mitigating global change, researchers have also introduced a full spectrum of colour-based descriptions, such as blue carbon, green carbon, and teal carbon, to describe the properties and distribution of organic carbon in the Earth system.¹⁵ Nevertheless, these classifications of carbon sinks are often abstract and lack comprehensive and systematic descriptions. Moreover, different disciplines have their own definitions and understandings of types of carbon sinks, hindering effective communication and collaboration across different fields.

Here, we propose the concept of four colours of carbon sinks across different ecosystems: green carbon, black carbon, blue carbon, and white carbon. This concept is based on the initial sources of carbon sinks, the medium or specific ecosystem and ecosystem components of carbon sequestration, the properties of carbon sinks (organic or inorganic), and their colours. Specific definitions for each type of carbon sink are introduced (Table 1), along with their proposed history, magnitude, and enhancement strategies (Figure 1). We use China as a case study to explore the potential and related costs for

Table 1. Definitions, formation pathways, mechanisms, ecosystems, and relevant ecosystem components of the four colours of carbon sinks used in this study.

Carbon sink types	Definition	Formation pathways and mechanisms	Ecosystems	Ecosystem component
Green carbon	Carbon absorbed from the atmosphere through photosynthesis and stored in terrestrial ecosystems (plants and soil), including forests, grasslands, shrublands, and inland wetlands	Organic matter formed by plant photosynthesis is the initial source of carbon, which is then distributed between plants and soil	Forests, grasslands, shrublands, and inland wetlands	Plants and soils in forests, grasslands, shrublands, and inland wetlands
Black carbon	Carbon sink formed by the decomposition of dead substances by adding carbon-containing materials (such as straw and organic fertilizers) to croplands, or directly applying biochar to terrestrial soils for storage	Dead carbonaceous materials are used as carbon sources and then stored in the soil	Croplands and other terrestrial ecosystems with soil such as forests and grasslands	Soils
Blue carbon	Organic matter formed by photosynthesis in coastal ecosystems such as salt marshes, mangroves, and seagrass meadows, or captured from land and sea sources, and ultimately stored and buried in soil or sediment	Organic matter formed by photosynthesis or captured from land and sea sources is the carbon source in coastal ecosystems such as salt marshes, mangroves, and seagrass meadows	Salt marshes, mangroves, and seagrass meadows, excluding inland wetlands	Plants, soils, and sediments in coastal ecosystems
White carbon	Carbon sinks formed by chemical processes, such as silicate weathering, carbonate weathering of karst, weathering of alkaline building materials, and inorganic carbon in desert	Inorganic carbon (carbonates) formed by chemical weathering and then ultimately stored in soil, groundwater, or downstream water	Deserts, karst areas, urban, forests, grasslands, and croplands	Desert saline alkali land, alkaline building materials, and terrestrial soils

enhancing carbon sinks of these four colours of carbon. This comprehensive review contributes to a visual understanding of the distribution, formation mechanisms, and approaches to enhancing carbon sinks in terrestrial ecosystems. In addition, guidance is offered for communication among scientists and for governments to effectively implement measures to enhance different carbon sinks and manage them efficiently.

CONCEPT OF FOUR COLOURS OF CARBON SINKS

Green carbon

Green carbon typically refers to CO₂ in the atmosphere that is absorbed through photosynthesis and stored in vegetation and soil (Table 1), and this process is a vital part of the global carbon cycle. The 1997 Kyoto Protocol proposed afforestation as an important means to enhance the carbon sink, which implies the concept of “green carbon”. While numerous international classifications of carbon based on colour have been proposed,¹⁵ the definition of “green carbon” has remained fundamentally consistent. In this work, we continue to use the concept of “green carbon” and further define it as the carbon sink formed by photosynthesis in forests, shrublands, grasslands, and inland wetlands (Table 1).

Forests are primary components of terrestrial ecosystems, constituting approximately 30% of the global land area.³⁴ The carbon stored in global forests in 2020 was 870 ± 61 Pg C, accounting for 25% of the total terrestrial carbon pool (Figure 2). Most forest carbon is stored in live biomass (43%) and soils (45%), with smaller proportions stored in dead wood and litter (12%).¹⁸ Managing the forest carbon sink is important for achieving carbon neutrality.^{16–19} The average global forest net carbon sink was 1.4 ± 0.7 Pg C yr⁻¹ from 2010 to 2019,¹⁸ and forests globally possess significant additional carbon sequestration potential within their natural distribution areas.³⁵ Among this, the carbon sink in harvested wood products (HWPs) was estimated at 0.21 Pg C yr⁻¹, with carbon stored for years to hundreds of years, effectively delaying emissions.¹⁸ Shrublands constitute approximately 10% of the global terrestrial area,²¹ with carbon stored in vegetation and soil amounting to 24.2 Pg C and 123.8 Pg C, respectively.¹⁴ The global shrubland carbon sink is estimated to be 0.3 Pg C yr⁻¹ on the basis of shrubland areas and mean C sequestration rates.^{14,21} Grasslands account for 40% of the global land area. The global grassland carbon storage is approximately 486 Pg C, with vegetation accounting for approximately 63 (50–120) Pg C and soil accounting for approximately 423 (279–592) Pg C.¹⁴ However, whether grasslands are net sinks or sources is uncertain, as global estimates have ranged from -1.9 Pg C yr⁻¹ to 0.37 Pg C yr⁻¹.^{14,36} Inland wetlands are also important parts of the organic carbon pool in terrestrial ecosystems. According to the Ramsar Convention, inland wetlands include swamp and peat wetlands, river and riparian wetlands, lake and lakeshore wetlands, saline lakes, and reservoirs. Although inland wetlands cover only approximately 6% of the land surface,

they are critical carbon reservoirs that store 30% of the total global soil organic carbon stock of 1500 Pg C.³⁷ The carbon sink of global inland wetlands is approximately 0.75 Pg C yr⁻¹.²² Considering the residence time of carbon in these four ecosystems, the carbon stored in the woody biomass of forest ecosystems and the soil organic carbon pools of forests, grasslands, shrublands, and inland wetlands can persist for decades to centuries, thereby significantly aiding in the goal of carbon neutrality.^{38–40}

The primary strategies used to enhance green carbon sinks include ecological protection and restoration, afforestation and reforestation, and forest management (Figure 1), among which increasing the forested area is an important approach.^{41,42} Human intervention measures in terrestrial ecosystems such as forest protection and the transformation of cropland to forest and grassland can significantly improve green carbon sinks.^{43,44} Afforestation and forest protection are two excellent approaches for enhancing forest carbon sequestration and mitigating climate change.^{45–49} The World Economic Forum launched the “One Trillion Tree Initiative” in 2020 to conserve, restore, and grow one trillion trees by 2030. Under current climate conditions, the global forest area could be increased by 900 million hectares, which represents a greater than 25% increase in forested area, equivalent to 205 Pg of additional carbon at maturity.⁵⁰ The forest carbon sink can be increased by 0.06 Pg C yr⁻¹ to 3.3 Pg C yr⁻¹ through natural forest protection, forest management, and afforestation and reforestation (Figure 3). For grasslands, carbon sinks can be enhanced by management such as natural grassland conservation, enclosures, and artificial improvements.⁵¹ The carbon sink contributed by natural grassland conservation and artificial management (such as improving grazing management and sowing legumes in pasturelands) is estimated to be 0.01 Pg C yr⁻¹ to 0.34 Pg C yr⁻¹ and 0.01 Pg C yr⁻¹ to 0.7 Pg C yr⁻¹, respectively. Moreover, the achievable carbon sequestration potential in global grasslands is 0.63–1.99 Pg C yr⁻¹, which should also benefit biodiversity objectives.⁵¹ For inland wetlands, protecting natural wetlands and developing constructed wetlands are effective ways to increase their carbon sink strength. This carbon sink potential could increase by 0.38 ± 0.05 Pg C yr⁻¹ (Figure 3).

Black carbon

Black carbon is typically defined as the product of the incomplete combustion of fossil fuels and biomass. It is found in soil, ice, sediment, and the atmosphere.⁹⁹ Black carbon aerosols are an important component of fine particulate pollutants in the atmosphere, where they pose a threat to human respiratory health. In addition, black carbon can strongly absorb short-wave radiation in the atmosphere, contributing to regional warming effects. The black carbon deposited on the surface of ice and snow reduces the albedo of ice and snow, leading to the melting of surface ice and snow.^{15,100} Under its original definition, black carbon is considered a carbon source. In this study, we redefine black carbon as an organic carbon sink formed by either the

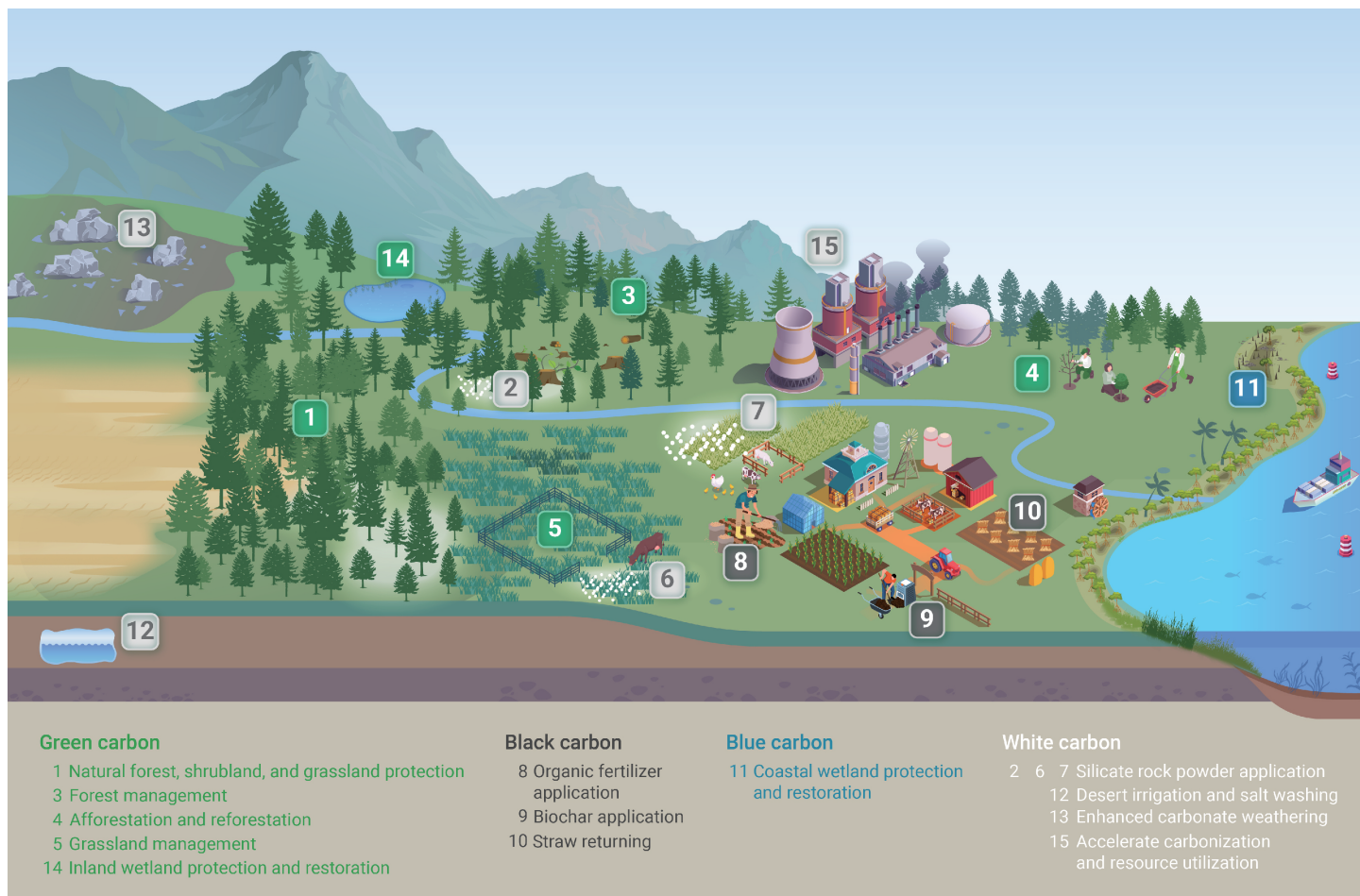


Figure 1. Approaches to enhancing carbon sinks of four colours in terrestrial ecosystems.

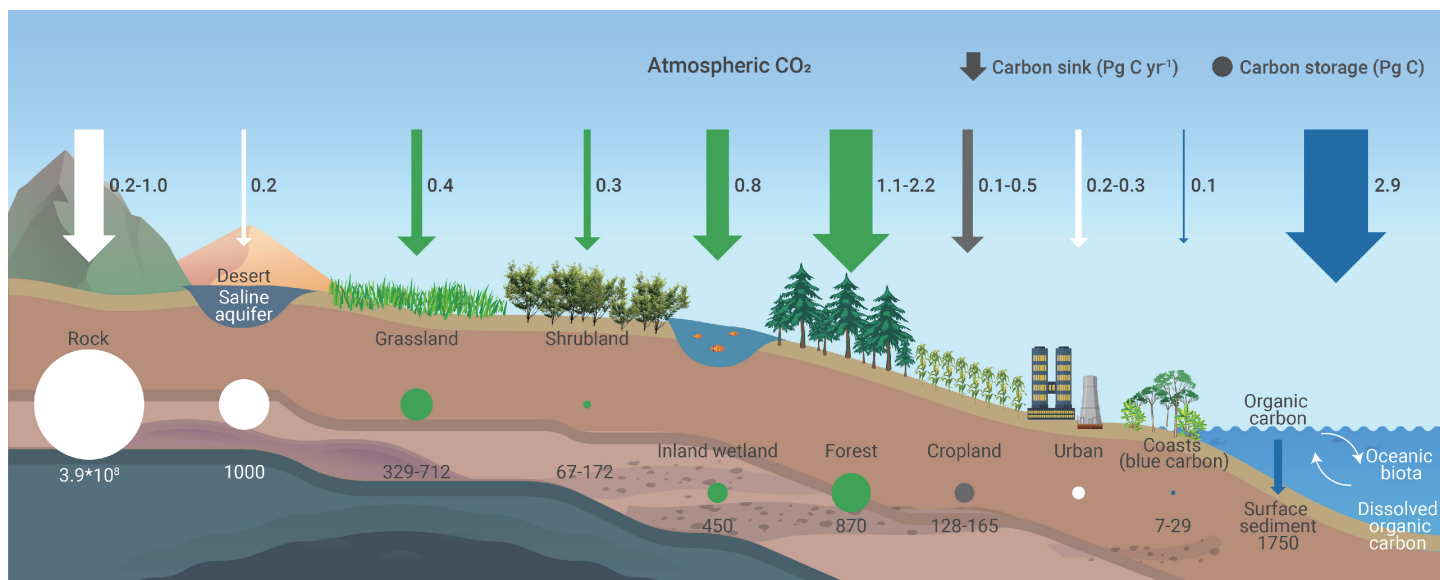


Figure 2. Four colours of carbon sinks and their carbon storage in various terrestrial ecosystems globally. Green carbon: carbon sinks and storage in forests,¹⁶⁻¹⁹ grasslands,^{14,20} shrublands,^{14,21} and inland wetlands (these data are derived from the global wetland carbon sink,²² excluding the coastal blue carbon sink²³).^{14,22} Black carbon: soil organic carbon storage and carbon sinks in croplands.¹⁴ Blue carbon: carbon sinks and storage in coastal ecosystem,²³⁻²⁵ carbon storage in coastal sediments.²³ White carbon: carbon sinks via rock weathering²⁶⁻²⁸ and carbon storage in rocks,²⁹ carbon sinks and storage in deserts³⁰ and urban areas.³¹⁻³³

decomposition of carbon-containing materials, such as straw, manure, and other dead substances, added by human activities to cropland or the direct application of biochar (the carbon-rich solid product produced by the pyrolysis of biomass under anoxic conditions) to soil in terrestrial ecosystems such as croplands, grasslands, and forests (Table 1).

Croplands, one of the three major systems of terrestrial ecosystems, play a

crucial role in ensuring food security. Given that most plant-derived carbon in croplands returns to the atmosphere as CO₂ within a short time, research on the carbon balance in croplands has focused primarily on changes in the soil carbon pool. Soil organic carbon storage in global croplands is 128-165 Pg,¹⁴ which is approximately 10% of the global storage of soil organic carbon (1500 Pg C to a soil depth of 1 m) (Figure 2). Croplands are heavily managed, and

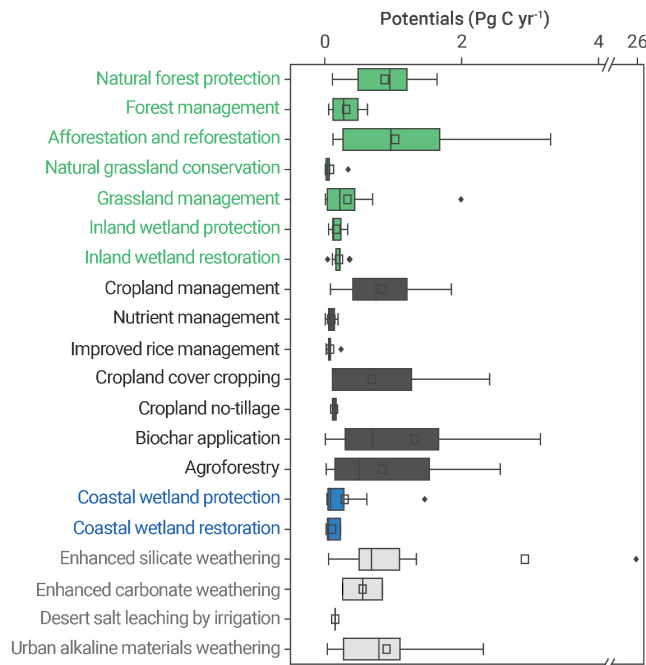


Figure 3. Global potential for increasing carbon sinks of the four colours via different pathways The error bars, boxplot edges, black lines, squares, and diamonds represent the maximum and minimum values, upper and lower quartiles, medians, means, and outliers of all the data, respectively. Note: Natural forest protection;⁵²⁻⁵⁸ Forest management;^{52,54,56-58} Afforestation and reforestation;^{52,54,56-58} Natural grassland conservation;^{54,56,58,67} Grassland management;^{51,54,56,58,68,69} Inland wetland protection;^{54,56-58,70,71} Inland wetland restoration;^{54,56-58,71} Cropland management;^{69,72,73} Nutrient management;^{54,56-58,74} Improved rice management;^{54,56-58,75} Cropland cover cropping;^{54,56,58,75,76} Cropland no-tillage;⁷⁷ Biochar application;^{54,56,58,60,63,67,69,70,74,78-83} Agroforestry;^{54,56,58,67,68,70,74,84,85} Coastal wetland protection;^{54,56,58,67,70,86-88} Coastal wetland restoration;^{56,58,67,70,86,89} Enhanced silicate weathering;^{60,64,65,90-93} Enhanced carbonate weathering;^{28,94} Desert salt leaching by irrigation;⁹⁵ Urban alkaline materials weathering;^{33,96-98}

the soil organic carbon in croplands is consequently the most active part of the soil carbon pool in terrestrial ecosystems.¹⁰¹ Changes in soil organic carbon in croplands significantly affect the global carbon cycle and climate change.¹⁰² In addition, soil organic carbon in croplands, as the most important component of soil, is closely related to soil fertility, crop production, and food security. Therefore, maintaining and increasing soil organic carbon in croplands is essential for improving soil quality and promoting sustainable agricultural development.

The soil carbon sink of global croplands is 0.11-0.48 Pg C yr⁻¹ (Figure 2). Furthermore, adding carbon-containing materials to croplands by returning crop residues to soil (straw returning), applying manure and biochar, and implementing other management measures can increase soil carbon storage and form additional carbon sinks (Figure 1). Applying biochar to cropland soil (including other terrestrial soils) could significantly reduce carbon emissions, potentially increasing the black carbon sink by 0.01-3.15 Pg C yr⁻¹ (Figure 3). By the year 2100, the maximum potential of biochar could reach between 5.5 and 9.5 Pg C yr⁻¹.⁸⁰ The most significant characteristic of biochar in relation to climate protection is its stability in soil, which allows it to persist for decades to thousands of years.^{60,103} The application of manure in cropland soil is even more conducive to carbon sequestration, potentially increasing the soil organic carbon content by 33-35%.^{104,105} Other practices, such as nutrient management of cropland soils, conservation tillage, improving rice management, and straw returning, can promote the accumulation of soil organic carbon and increase the black carbon sink by 0.01-1.85 Pg C yr⁻¹ (Figure 3). In addition, developing agroforestry systems is an effective strategy to increase soil organic carbon storage, and is considered an important method of reducing greenhouse gas emissions by the United Nations Intergovernmental Panel on Climate Change (IPCC).¹⁰⁶ The global development of agroforestry systems can sequester 0.02-2.56 Pg C yr⁻¹ of carbon (Figure 3), with increased black carbon sinks accounting for approximately 40% of the total carbon sink.⁶⁷

Blue carbon

Blue carbon refers to carbon captured by oceanic and coastal ecosystems. In 2009, the United Nations Environment Programme, the Food and Agriculture Organization, and the Intergovernmental Oceanographic Commission of United Nations Educational, Scientific, and Cultural Organization (UNESCO) jointly issued a report entitled "Blue Carbon: The Role of Healthy Oceans in Binding Carbon", which proposed that blue carbon refers to organic carbon captured and stored by oceanic and coastal ecosystems and noted that coastal blue carbon systems such as salt marshes, mangroves, and seagrass meadows, are more manageable than oceanic ecosystems.^{87,89,107-109} In 2013, the IPCC formally incorporated the coastal blue carbon into the relevant mechanisms of "the United Nations Framework Convention on Climate Change" and indicated in the "Special Report on oceans and cryosphere in a changing climate" that whether coastal blue carbon is easy to manage is a necessary condition for defining blue carbon.¹¹⁰ In this study on terrestrial ecosystems, we refer to "blue carbon" as a carbon sink in coastal ecosystems including salt marshes, mangroves, and seagrass meadows. Coastal blue carbon ecosystems contribute to more than 46% of the total C buried in global ocean sediments; however, they constitute only 0.5% of the seafloor area.^{111,112} Global carbon stored within coastal blue carbon ecosystems is estimated to be 28.7 Pg C (Figure 2), with salt marshes accounting for 1.4 Pg C, mangroves accounting for 15.2 Pg C, and seagrass meadows accounting for 12.1 Pg C.²⁴ Globally, these coastal blue carbon ecosystems contribute relatively little to climate change mitigation, with a carbon sink of approximately 0.08 Pg C per year,²³ comprising 0.013 Pg C per year for salt marshes, 0.024 Pg C per year for mangroves, and 0.044 Pg C per year for seagrass meadows.

While blue carbon plays a critical role in climate change and the global carbon cycle, it does not function as a mitigation measure in itself. In coastal ecosystems, effective natural mitigation measures must be achieved through human influence or management.⁸⁹ Blue carbon forms primarily through plant carbon sequestration and sediment carbon burial, together with the exchange of particulate organic carbon, dissolved organic carbon, and inorganic carbon with coastal waters through tidal action. Compared with other terrestrial ecosystems with saturated carbon sequestration capacity, coastal blue carbon ecosystems present high primary productivity, burial rates, and long-term sustainable capacity for carbon sequestration.¹¹³ From the carbon burial rate per unit area, the carbon burial rate of coastal blue carbon ecosystems is estimated to be 15 times greater than that of terrestrial ecosystems and 50 times greater than that of oceans.^{114,115} Furthermore, tidal action distributes sulfate horizontally, which inhibits organic matter decomposition and methane emission.¹¹⁶ In addition, with rising sea levels, sediment production increases, and the sediment is buried in deeper sediment layers. This process stabilizes organic matter and inhibits its degradation, allowing carbon within sediments to remain stable for hundreds to tens of thousands of years without being reintroduced into the atmosphere.^{113,117,118} Consequently, coastal blue carbon ecosystems have greater carbon sequestration potential per unit area than terrestrial and ocean ecosystems do. Technological approaches to reduce carbon emissions and enhance blue carbon involve mainly the ecological restoration of degraded ecosystems, reductions in soil carbon emissions, plant carbon sequestration, sequestration of soil microbial carbon, carbon deposition, and carbon burial.¹¹⁹ The increased conservation of coastal blue carbon ecosystems could avoid 0.03-1.46 Pg C yr⁻¹ of carbon emissions, whereas restoration efforts could draw down an additional 0.02-0.23 Pg C yr⁻¹ (Figure 3).

White carbon

White carbon was originally referred to as a silver-white allotrope of carbon and was discovered in the graphite gneiss of the Ries Crater in Germany in 1968. In the four-colour classification of carbon sinks proposed in this study, white carbon is redefined for the first time as a carbon sink formed by chemical processes, particularly inorganic carbon formed by carbonate (white in appearance), including silicate weathering and carbonate weathering; weathering of alkaline building materials, such as concrete and cement; and soil inorganic carbon formed under saline and alkaline conditions in deserts (Table 1).

In 1981, Walker proposed that silicate weathering is the only negative feed-

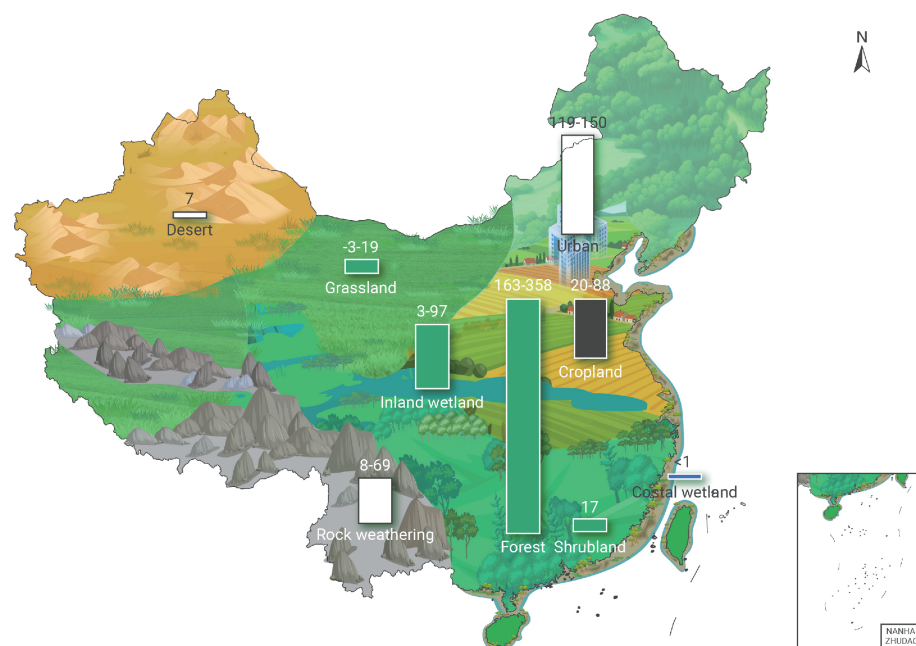


Figure 4. Four colours of carbon sink (Tg C yr^{-1}) in various terrestrial ecosystems in China Green carbon: carbon sink in forests,^{44,137,138} grasslands,^{14,43,139} shrublands,^{14,43} and inland wetlands.^{140,141} Black carbon: carbon sink in cropland.^{43,142} Blue carbon: carbon sink in coastal ecosystem.^{112,143} White carbon: carbon sink by silicate weathering,²⁶ and carbon sink in karst ecosystem,¹⁴⁴⁻¹⁴⁷ desert,³⁰ and urban.³¹⁻³³

back mechanism that balances atmospheric CO_2 over a million-year time scale, thereby maintaining the relative stability of atmospheric CO_2 concentrations and temperatures throughout geological history.^{120,121} Silicate weathering could store atmospheric CO_2 for millions of years (0.5 to 1 Myr time scale). Although silicates are the most abundant minerals and are widely distributed on continental surfaces, their relatively slow dissolution kinetics limit the rate of their CO_2 removal. The carbon sink flux for global silicate weathering has been estimated to be $0.04\text{--}0.17 \text{ Pg C yr}^{-1}$.²⁶ In recent years, numerous studies have confirmed that the carbon sink from carbonate weathering in karst ecosystems plays a vital role in the global carbon budget because carbonate weathering has faster dissolution kinetics than silicates.^{27,28,122-124} The estimated carbon sink from global carbonate weathering is approximately $0.15\text{--}0.89 \text{ Pg C yr}^{-1}$ (Figure 2). However, importantly, this carbon sink influences the global climate primarily on shorter time scales than silicate weathering does, ranging from centennial to millennial periods.¹²²

The weathering of alkaline building materials has also attracted scientific attention. The global carbon sinks generated by lime and cement weathering are estimated to be $0.03 \text{ Pg C yr}^{-1}$ and $0.2\text{--}0.3 \text{ Pg C yr}^{-1}$, respectively, and these sinks can remove CO_2 from the atmosphere for several years or decades.³¹⁻³³ The final sources for white carbon sinks are the saline aquifers beneath deserts, which constitute significant active carbon pools in terrestrial ecosystems.³⁰ Soil-respired CO_2 dissolves into saline and alkaline soil solutions, and the dissolved inorganic carbon is subsequently washed down into saline aquifers underneath large deserts, forming a carbon sink of 0.2 Pg annually (Figure 2). Considering that saline aquifers are covered by thick layers of sand and may not overflow once the carbon enters the saline aquifers, this process can be characterized as predominantly unidirectional: once incorporated, carbon becomes an integral part of the geological fabric.³⁰ However, research on carbon sequestration derived from alkaline weathering of building materials and desert saline aquifers is still limited.

Owing to the slow rate of natural rock weathering, its contribution to achieving carbon neutrality has generally been considered small, and its carbon sink has not been included in the global carbon budget. However, enhanced rock weathering has recently been recognized as an important means to increase white carbon, and enhanced rock weathering was acknowledged as a potential option for atmospheric CO_2 removal by the IPCC Sixth Assessment Report on Climate Change (AR6).^{4,60,90-92,125,126} To enhance rock weathering, crushed silicate rock powders are applied to terrestrial soils to accelerate chemical weathering, thereby promoting chemical reactions among silicates and soil CO_2 . Atmospheric CO_2 is converted into dissolved inorganic carbon (principally bicarbonate ions, HCO_3^-), which is removed via surface runoff to the ocean and potentially stored for more than 100,000

years.¹²⁵ In 1990, Seifritz proposed the use of mineral transformations to store CO_2 . This technique, also known as CO_2 mineralization or mineral carbonation, mimics and accelerates the natural weathering of rocks, where CO_2 reacts with minerals containing calcium or magnesium to form stable carbonates and permanently store CO_2 .¹²⁷ In 1995, Lackner et al. proposed a chemical method to permanently store CO_2 as carbonate minerals.¹²⁸ In a recent study by Beerling et al.,⁹⁰ enhanced silicate rock weathering in global croplands could remove $0.14\text{--}0.55 \text{ Pg C yr}^{-1}$ from the atmosphere. Goll et al.⁹¹ estimated that applying basalt powder to soils in appropriate natural

ecosystems worldwide could generate a carbon sink of approximately $0.055\text{--}0.68 \text{ Pg C yr}^{-1}$ (Figure 3), with an estimated carbon sequestration cost of $100\text{--}500 \text{ US\$}$ per tonne (10^6) of CO_2 . Furthermore, enhanced silicate rock weathering can be utilized in coastal systems, which can not only remove atmospheric CO_2 to combat global warming but also enhance ocean alkalinity.¹²⁹ Nevertheless, its effectiveness, safety, and feasibility require validation through experimental studies.

Several other approaches could be used to increase fluxes to white carbon sinks. Zeng et al.^{28,94} proposed that applying carbonate rock powder in non-karst areas could reduce carbon emissions. This technology could increase the global carbon sink by approximately $0.26\text{--}0.84 \text{ Pg C yr}^{-1}$ (Figure 3). Alkaline waste from industrial applications could also be used to accelerate mineral carbonization processes. This process can be viewed as “permanent” storage of inorganic carbon.¹³⁰ Using alkaline waste to manufacture building materials and optimize building designs could yield a carbon sink of $0.04\text{--}2.32 \text{ Pg C yr}^{-1}$ (Figure 3). In addition, cultivating and irrigating saline lands in arid zones can accelerate the process of soil-respired CO_2 dissolving into saline and alkaline soil solutions and then being washed down into saline desert aquifers, resulting in an additional carbon sink of 0.152 Pg per year (Figure 3).

APPROACHES AND POTENTIAL FOR ENHANCING CARBON SINKS OF THE FOUR COLOURS OF TERRESTRIAL ECOSYSTEMS IN CHINA

The carbon stored in terrestrial ecosystems in China is 100 Pg C ,¹³¹ with carbon sink ranging from 0.058 to 1.1 Pg C yr^{-1} ,¹³²⁻¹³⁶ which is equivalent to $14\text{--}46\%$ of CO_2 emissions from fossil fuel combustion in China during the same period. The potential terrestrial carbon sink in China is large and plays a crucial role in mitigating global warming (Figure 4). In the following sections, we review the current carbon storage and carbon sinks of terrestrial ecosystems in China for the four colours of carbon sinks outlined above. Furthermore, we discuss the approaches, potential, costs, environmental risks, and social acceptance for enhancing carbon sinks of these four colours in different terrestrial ecosystems (Table 2).

Green carbon

Forests, accounting for 23% of China's total land area,³⁴ constitute the largest carbon storage and sink in China's terrestrial ecosystems. The carbon storage of China's forest ecosystem was estimated to be 30.8 Pg C in 2011–2015,¹⁵⁵ which accounts for 31% of the total carbon storage of China's terrestrial ecosystem. The average rate of carbon sequestration in forests is $0.163 \text{ Pg C yr}^{-1}$ (Figure 4),⁴⁴ which contributes 80% of the total carbon sink of China's terrestrial ecosystem. As the area of planted forests (or young

Carbon Type	Ecosystem	Management Practices		Benefits	Challenges	Potential
		Practice	Scale (GtC)			
Green carbon	Forests	Natural forest protection				
		Forest management				
	Grasslands	Afforestation and reforestation	86–169 ^{148,149}	Enhances biodiversity; improves air quality; regulates hydrology; prevents soil erosion	Large-scale afforestation may lead to biodiversity loss, water shortages, soil degradation, nutrient loss, decreased albedo and radiation, fires, and social economic risks such as violent conflict, poverty, hunger, food price increases, and disruption of local cultures	High, but dependent on local involvement and education
		Natural grassland protection		Enhances soil fertility; conserves biodiversity; prevents soil erosion		
		Grassland management	7–22 ^{150,151}	Conserves biodiversity; prevents soil erosion; increases plant cover; increases grassland productivity; improves air quality		
Shrublands	Ecological protection		Enhances biodiversity; regulates hydrology; prevents soil erosion			
	Inland wetlands	Ecological protection and restoration		Conserves biodiversity; improves water and air quality	Water management challenges; risk of methane emissions; potential habitat disturbance	High, particularly with visible water quality improvements
Black carbon	Croplands	Straw returning		Increases soil nutrient contents; enhances soil microbial activity; reduces nutrient runoff; improves soil fertility and quality; increases crop yields	High cost, reduces germination rate, prone to pests and diseases	
		Organic fertilizer application		Increases crop yields	Increases heavy metals and organic pollutants; affects soil health, plant growth, and crop yields	High, if economic benefits and long-term gains are communicated effectively
		Biochar application	32–122 ^{90,152,153}	Improves soil quality; enhances soil fertility; removes soil pollutants	Increases heavy metals and organic pollutants	
		Agroforestry		Provides habitats; improves air quality; reduces soil erosion	Water management challenges; fires; prone to pests and diseases	
Blue carbon	Coastal ecosystems	Ecological restoration and protection	15–74	Increases blue carbon sequestration; improves coastal protection; enhances marine biodiversity; improves water and air quality; prevents soil erosion	Risk of habitat loss; challenges in managing human activities; vulnerability to climate change impacts	High, with strong community involvement and visible coastal protection benefits
White carbon	Silicate	Silicate rock powder application	100–130 ⁹⁰	Mitigates soil acidification; improves soil health; increases essential nutrients for plants	Mining, grinding, and transport may cause vegetation damage, biodiversity loss, groundwater and air pollution, and tailings accumulation	Low
		Vegetation restoration		Mitigates soil erosion and loss; improves environment quality	Landscape changes; potential water pollution	
	Karst regions	Carbonate rock powder application	235 ¹⁴⁴	Mitigates soil acidification; improves soil health	May exacerbate frost and drought damage in forests, increase invasive species risk; changes in groundwater/surface water quality in non-karst areas require further evaluation	Moderate to high, if agricultural benefits and environmental improvements are demonstrated
		Desert saline alkali lands	Irrigation and desalination of saline-alkali lands	15–100	Increases carbon storage in soils and potential new areas for cultivation	Water wastage, fertilizers and pesticides used in improvement process may cause environmental pollution
		Alkaline building materials	Resource utilization Accelerated carbonation	180–1100 ¹⁵⁴	Reduces pollutant emissions; promotes resource recycling; increases environmental capacity	High costs; potential production of toxic and hazardous substances during implementation

influence of extreme events and human disturbance. If the effects of natural disasters, deforestation, and tree mortality are included, the estimated carbon sink of China's forests decreases to 0.28 Pg C yr⁻¹.¹³⁷ In addition, China is a leading producer and trader of HWP and possesses significant mitigation

potential associated with these products. The amount of carbon stored in HWP in China is estimated to be between 0.7 and 1.3 Pg C,¹⁵⁷⁻¹⁶⁰ with a carbon sink ranging from 14.9 to 150.5 Tg C yr⁻¹.^{157,160,161}

Shrublands constitute 7% of China's total land area,⁴³ with carbon stored in vegetation and soil amounting to 6.7 ± 0.32 Pg C.^{14,155} The carbon sink in shrublands in China is estimated to be 17.1 Tg C yr⁻¹.⁴³ Grasslands account for 30% and inland wetlands account for 4% of China's total land area. Estimates of grassland carbon storage range widely from 17.3 Pg C to 59.5 Pg C, with soil carbon storage accounting for more than 90% of the total carbon storage.¹⁶² Due to differences in data sources and estimation methods, estimates of grassland carbon sinks in China vary widely, ranging from -3.4 to 19.4 Tg C yr⁻¹.¹³⁹ China's inland wetland accounts for 34 million hectares, with carbon stored in vegetation accounting for approximately 0.16 ± 0.03 Pg C and that in soil accounting for approximately 16.2 ± 1.2 Pg C.¹⁴¹ The estimated carbon sink of inland wetlands varies greatly, ranging from 3.36-96.7 Tg C yr⁻¹ (Figure 4).

The main approaches for enhancing green carbon include afforestation, reforestation, forest management, grassland restoration, grazing management, and inland wetland protection and restoration (Table 2). In recent decades, China has implemented several major projects to protect natural ecosystems and restore degraded ecosystems, such as natural forest protection, the return of cropland to forest or grassland (the Grain for Green Program), the return of cropland to lakes, and grazing exclusion practices.^{44,163} These projects have protected forest, grassland, and wetland ecosystems while increasing the carbon sink of China's terrestrial ecosystems by an estimated 74 Tg C yr⁻¹, which represents more than half of the total ecosystem C sink for project regions.^{43,44}

In forests, the maximum carbon sink potential can reach 120-430 Tg C yr⁻¹ via afforestation, reforestation, natural forest protection, forest management, and other measures.^{54,58,164,165} The cost of carbon sequestration through afforestation and reforestation is US\$10-800 per tonne of CO₂, with an average cost of US\$86-169 per tonne of CO₂ (Table 2).^{148,149} However, large-scale afforestation can lead to biodiversity loss, water scarcity, reduced surface albedo, etc., and the potential impacts of afforestation should also be considered in afforestation projects (Table 2). Protecting natural grasslands and returning grazing lands to grasslands has significantly improved the capacity and potential of grassland carbon sinks. Through natural grassland protection, the grassland carbon sink could increase by 14.7 Tg C yr⁻¹,⁴⁴ while altering the grazing intensity and planting grasses could increase the grassland carbon sink by 12.1 Tg C yr⁻¹.^{54,58} If grazing lands are returned to grasslands on a large scale in China, the carbon sink in Chinese grassland ecosystems could increase by up to 0.21 Pg yr⁻¹.¹⁶⁶ Moreover, the cost of carbon sequestration in grassland ecosystems is relatively low (Table 2). The average cost of carbon sequestration is US\$7-22 per tonne of CO₂ through comprehensive measures such as using enclosures, replanting and improving grasslands.^{150,151}

The protection and restoration of inland wetland ecosystems is the easiest method of increasing their carbon sink capacity. The carbon sink could increase approximately 0.06-0.33 Pg C yr⁻¹ and 0.04-0.37 Pg C yr⁻¹ through peatland protection and restoration, respectively.^{54,56-58,70} Nevertheless, further research is essential to assess the costs associated with enhancing carbon sinks in inland wetlands and to evaluate the potential magnitude of such enhancements across various types of inland wetlands, including forested wetlands, lakes, reservoirs, and other inland wetland types.

Black carbon

China's croplands store approximately 16.3 Pg of soil organic carbon and account for 16% of China's terrestrial carbon storage.¹⁵⁵ The soil carbon storage per unit area in China's croplands is estimated to be 43.9 Mg C ha⁻¹ (0-30 cm),¹⁵⁵ which was about 49% lower than the values reported for global croplands (86.0 Mg C ha⁻¹).⁷³ Therefore, over the next 40 years, if the soil organic carbon content in China's cropland is increased to match or exceed the current level observed in global cropland, an additional carbon sink of 5.5 Pg could theoretically be achieved. In addition, the development of new agronomic techniques could reduce emissions of CH₄ and N₂O by approximately 50%, which is equivalent to sequestering 50-80 Tg C yr⁻¹. These findings indicate that despite high-intensity human disturbance in croplands, manage-

ment changes could increase soil carbon sequestration and reduce greenhouse gas emissions sufficiently to offset more than 10% of China's carbon emissions over the next 40 years, thereby contributing substantially to the goal of carbon neutrality.

Returning crop residues to the soil after harvesting (straw returning) is a common approach to increase soil carbon sequestration. Straw returning and replacing chemical fertilizers with organic fertilizers are two primary ways to increase black carbon,¹⁶⁷ potentially increasing the carbon sink by 48 Tg C yr⁻¹ by 2060. Although straw returning can increase soil organic carbon storage, it may also pose risks such as pest outbreaks and greenhouse gas emissions (Table 2). Additionally, the effectiveness of straw returning is influenced by factors such as the quantity and frequency of straw returning, tillage measures, fertilization methods, and environmental conditions, which often result in limited carbon sequestration.

Improving soils by adding biochar is a novel technique for carbon sequestration, emission reduction, and sustainable use of cropland.¹⁶⁸ Using biochar to increase carbon sequestration and reduce emissions of greenhouse gases can advance the goal of carbon neutrality, with an annual carbon sequestration rate of 2.07 tonne ha⁻¹.^{168,169} In a recent study, biochar had a negative emission potential of up to 0.25 Pg C yr⁻¹.¹⁷⁰ This finding demonstrates that applying biochar could substantially increase soil carbon storage and reduce greenhouse gas emissions, making it essential to include biochar in future studies on enhancing soil black carbon. However, the cost of biochar fixation is high, ranging from US\$32-122 per tonne of CO₂, so the economic feasibility of adding biochar is uncertain (Table 2).^{90,152}

Rice, together with maize and wheat, account for 90% of the crops produced in China. Because of high methane emissions from rice paddies, rice cultivation contributes about half of the greenhouse gas emission equivalents of these three crops.¹⁷¹ Improving rice cultivation practices is a nature-based solution to mitigate climate change, with minimal costs.⁷⁴ In China, improved rice cultivation could increase the carbon sink by 9-14 Tg C yr⁻¹.^{54,58}

Blue carbon

Blue carbon plays an important role in mitigating climate change and improving the oceanic environment. The Chinese government has increasingly valued blue carbon and in 2016, it included the development of blue carbon ecosystems in official reports on climate change.¹⁷² The total area of coastal blue carbon ecosystems in China is approximately 1,670 to 3,950 km²,¹¹² with total carbon storage ranging from 0.038 Pg C to 0.095 Pg C.^{25,173} In addition to carbon sequestration through photosynthesis, the high carbon deposition rates and burial rates of coastal blue carbon ecosystems are important factors influencing their strength as a carbon sink. The rates of carbon burial in coastal blue carbon ecosystems in China are approximately 0.273-0.835 Tg C yr⁻¹ (Figure 4). Salt marshes account for approximately 80% of this carbon sink, which is significantly greater than that of mangroves and seagrass meadows.¹⁴³ Coastal blue carbon ecosystems export a substantial amount of carbon to adjacent coastal waters through lateral tidal flows and groundwater. The lateral carbon fluxes from China's mangroves and salt marshes are estimated to be 0.2 Tg C yr⁻¹ and 0.9 Tg C yr⁻¹, respectively.¹¹²

In recent years, human activities such as beach reclamation, excessive resource use, and water pollution have degraded coastal blue carbon ecosystems in China, reduced vegetation cover, and reduced carbon sinks. Global warming and rising sea levels have increased the risk of inundation in these ecosystems.¹⁷⁴ Therefore, the government needs to protect and manage existing coastal blue carbon ecosystems and restore degraded areas to achieve synergy among ecological protection, restoration, and carbon sink enhancement.

Nature-based solutions, such as ecological protection and restoration, could enhance coastal blue carbon sinks in China by approximately 0.47-1.79 Tg C yr⁻¹.^{25,112} and could cause these sinks to reach 3.8 Tg C yr⁻¹ by 2060.¹⁶⁴ Given that coastal blue carbon areas in China are relatively limited, protecting and restoring coastal blue carbon systems while enhancing their carbon sink potential through management measures and technologies represent cost-effective approaches for China to achieve carbon neutrality by 2060. Protection and restoration measures should fully consider site suitability, public awareness, local economic conditions, and management policies. Establishing an appropriate ecological compensation standard is also necessary to

ensure the maximization of economic benefit incentives for residents.^{112,143}

White carbon

The carbon sink created by rock weathering is an effective approach to achieve carbon neutrality in China. In 2013, the IPCC Fifth Assessment Report on Climate Change (AR5) concluded that “enhanced weathering” was an effective solution for removing atmospheric CO₂. In 1997, China proposed that karst regions were large carbon sinks (subsequently termed karst carbon sinks).^{175,176} In 2021, the Chinese government recognized the importance of the karst carbon sink for China's journey towards carbon neutrality.^{177,178} Carbonate weathering is considered the main carbon sink from rock weathering over short time scales,¹⁷⁹ with carbon sink ranging from 3.2 Tg C yr⁻¹ to 64.2 Tg C yr⁻¹ (Figure 4). This large variability can be attributed to significant differences in data sources and estimation methods across studies. In China, the total carbon sink of silicate weathering is 4.5 Tg C yr⁻¹ (Figure 4).²⁶ The vast desert areas in China also offer substantial potential for inorganic carbon sinks via dissolution and absorption of CO₂ by saline and alkaline soil water, and the value is estimated to be 6.6 ± 2.2 Tg C yr⁻¹ (Figure 4). Furthermore, China has great carbon sink potential because of the weathering of lime and cement materials, estimated to be 10.1 Tg C yr⁻¹ and 109.1–140.0 Tg C yr⁻¹, respectively (Figure 4).

China could enhance rock weathering to increase the carbon sinks of terrestrial ecosystems on a large scale. First, China has a large land area, including 220 million hectares of forests (80 million hectares of planted forests), 120 million hectares of cropland and 390 million hectares of grassland. Second, China has abundant silicate and carbonate mineral resources. For example, China contains the world's most abundant source of wollastonite, and basalt is plentiful and widely distributed, providing a robust foundation for implementing a strategy of spreading alkaline material in diverse habitats. China could increase white carbon by 40–220 Tg C annually by enhancing silicate weathering,¹⁸⁰ while spreading carbonate powder in non-karst areas could add approximately 39 Tg C annually to the carbon sink.¹⁴⁴ The cost of enhanced rock weathering in China is about US\$100–130 per tonne of CO₂ (Table 2),¹⁸⁰ which is lower than that of direct air capture and storage but higher than that of afforestation and biochar application.

Unlike other approaches, enhanced rock weathering can not only increase white carbon sinks but also release nutrients, alleviate soil acidification, improve soil properties, and therefore increase plant biomass.^{90,91,125,181,182} Due to the intensity of food production in China's croplands, farmers face numerous issues, such as soil acidification and declining organic matter contents, leading to reduced crop yields. Bicarbonate (HCO₃⁻) produced during weathering, which is weakly alkaline, can ameliorate soil acidification.¹²⁵ Nutrients released during weathering, such as calcium, magnesium, silicon, and potassium, are essential for plant growth. Therefore, enhanced rock weathering can significantly improve crop yield and quality, ensuring China's food security. The application of wollastonite powder to enhance rock weathering in China's paddy soils increased rice yields by 3–31% (average of 12.6%). Considering the benefits of increased crop yields, the cost of these approaches can be greatly reduced. Thus, widespread implementation of these approaches in China's croplands could help achieve food security and carbon neutrality goals.

Despite this promise, many uncertainties and potential risks remain in implementing enhanced rock weathering in China (Table 2). First, the rate of rock weathering is affected by factors such as temperature, moisture, soil type, and vegetation type. Field trials of silicate weathering are still limited, so accurately evaluating the capacity of this approach to offset carbon emissions remains challenging. Second, field and pot experiments have demonstrated that nutrients released during silicate weathering can increase plant biomass. However, the large-scale addition of silicates has not been fully verified or accepted by the public. Third, mineral mining and grinding may lead to various ecological and environmental issues, such as landscape destruction, biodiversity loss, groundwater and air pollution, and tailings accumulation. Fourth, it is necessary to further evaluate the costs associated with mineral mining, grinding, transportation and other processes. Before the large-scale application of this technology, field trials and demonstration projects are needed. In addition, it is crucial to garner public support, focus on the commercial feasibility of this approach, and formulate policies to protect

the relevant interests of agroforesters and farmers.

Socioeconomic considerations for enhancing the four-colour carbon sinks in China

The technical potential to enhance the four-colour carbon sinks in China's terrestrial ecosystems is well documented. However, the translation of technical potential into actionable strategies necessitates a thorough consideration of cost-effectiveness. Different strategies for enhancing carbon sinks present varying levels of cost effectiveness (Table 2). For example, while afforestation and reforestation have high technical potential (120–430 Tg C yr⁻¹), they entail substantial costs (US\$10–800 per tonne CO₂) and are constrained by limitations in land and water resources,^{47,183} which may ultimately result in diminishing marginal benefits. In contrast, ecosystem protection and restoration demonstrate superior economic viability (Table 2) and lower implementation risks. Moreover, to optimize cost-benefit ratios, the co-benefits of these strategies must be integrated into assessments (Table 2). For example, emerging technologies, such as enhanced silicate weathering, are promising but costly (US\$100–130 per tonne CO₂). However, considering their additional benefits, such as improving soil acidification and increasing agricultural productivity,^{125,184} can increase their economic feasibility.

Furthermore, given the marked spatial disparities in economic development, ecological resources, and carbon emissions across China's regions,¹⁸⁵ a one-size-fits-all policy is not feasible, and equity must be fully considered.¹⁶⁴ For example, provinces with abundant forest cover should focus on forest protection and fire management to prevent carbon loss and enhance their carbon sink function. Regions dominated by agriculture need to emphasize sustainable agricultural practices, such as straw returning, organic fertilization, and nutrient management, to balance carbon sequestration with food security. Additionally, while the eastern and central regions present higher carbon emissions coupled with relatively weak carbon sink capacities, the southwestern and northeastern regions, despite their lower levels of economic development, possess abundant ecological resources. To address these regional disparities in environmental characteristics and resource distribution, a diversified ecological compensation mechanism could be established nationwide to promote balanced ecological sustainability across different regions.¹⁸⁶ One potential solution is the implementation of interprovincial carbon sink trading, which would enable industrialized regions to offset their emissions by investing in carbon sink projects in underdeveloped areas. This mechanism could foster interregional cooperation and promote shared responsibility for emissions reduction.

LIMITATIONS AND PROSPECTS

The differing mechanisms of formation and variable approaches for enhancing carbon sinks in terrestrial ecosystems has led us to introduce the concept of the four colours of carbon sinks in terrestrial ecosystems. This concept aids in understanding the spatial-temporal distribution, formation mechanisms, and approaches for enhancing carbon sinks. Our results revealed that the current “four-colour” carbon sink is 4.4 Pg C yr⁻¹. The potential for enhancing the “four-colour” carbon sinks globally by 11.9 ± 2.2 Pg C yr⁻¹ is greater than that estimated in previous studies.^{54,56,58} This discrepancy may be attributed to the fact that, in addition to considering nature-based climate solutions (including protecting, restoring, and managing terrestrial ecosystems), this review also encompasses other measures for enhancing carbon sinks, such as enhanced rock weathering, accelerated carbonization and utilization of urban alkaline materials, and irrigation to wash out salt in deserts.

However, significant uncertainties exist in the estimation of the status and future potential of carbon sinks in these terrestrial ecosystems. For example, the carbon sink of grasslands varies between -1.9 Pg C yr⁻¹ and 0.37 Pg C yr⁻¹, resulting in uncertainty as to whether grasslands act as net sinks or sources. These uncertainties in the results of estimation arise from variations in methods, data sources, and sample sizes across different studies. Furthermore, previous research on terrestrial carbon sinks has focused primarily on ecosystems, such as forests, grasslands, and wetlands. A notable lack of studies has addressed carbon sinks associated with saline aquifers underneath deserts and the utilization of urban alkaline material due to insufficient data. Therefore, a unified carbon accounting system utilizing

multiple data sources, processes, scales, and methods is needed to account for the carbon budgets of terrestrial ecosystems.

Furthermore, approaches for enhancing carbon sinks of four colours exhibit certain overlapping characteristics. For example, forest carbon sinks are classified as green carbon; however, the application of biochar and wollastonite powder in forests can enhance black carbon and white carbon, indicating that forest soil may also serve as a medium for both types of carbon. Notably, applying biochar and wollastonite to forest soil can improve the soil environment and promote an increase in forest biomass, thereby enhancing green carbon. Nevertheless, this study does not account for the integrated effects of applying multiple approaches to enhance carbon sinks within the same ecosystem. In addition, the potential for enhancing the four-colour carbon sinks associated with different enhancement measures under different future climate change scenarios has not been considered. Consequently, future research should not only focus on the integrated effects of applying multiple approaches to increase carbon sequestration within the same ecosystem but also explore how the potential for enhancing carbon sinks may respond to future climate change.

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AUTHOR CONTRIBUTIONS

A. W., Z. L., X. L., S. N., J. H., C. Z., G. H., Dejun L., G. Y., and Y. F. conceived, organized, and wrote the manuscript. A. W., R. K., Z. Q., C. S., Y. W., J. W., F. L., P. D., and Deze. L. wrote and revised the section on white carbon. X. L., Y. L., F. Z., H. Z., and J. H. wrote and revised the section on green carbon. L. S., X. W., and C. Z. wrote and revised the section on black carbon. G. H. wrote and revised the section on blue carbon. All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DATA AND CODE AVAILABILITY

Data are available from the corresponding author upon reasonable request.

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