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Evaluate the differences in carbon sink contribution of different ecological engineering projects

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Abstract

China has implemented a series of ecological engineering projects to help achieve the 2060 carbon neutrality target. However, the lack of quantitative research on ecological engineering and the contribution of climate change to terrestrial carbon sinks limits this goal. This study uses robust statistical models combined with multiple terrestrial biosphere models to quantify the impact of China's ecological engineering on terrestrial ecosystem carbon sink trends and their differences according to the difference between reality and nonpractice assumptions. The main conclusions include the following: (1) since 1901, 84% of terrestrial ecosystem carbon sinks in China have shown an increasing trend, and approximately 45% of regional carbon sinks have increased by more than 0.1 g C/m^2 every 10 years. (2) Considering the impact of human activities and the implementation of ecological engineering in China, approximately 56% of carbon sinks have improved, and approximately 10% of the regions whose carbon sink growth exceeds 50 g C m^{-2} yr^{-1} are mainly in the southeast coastal of China. (3) The carbon sequestration potential and effect of the Sanjiangyuan ecological protection and construction project are better than others, at 1.26 g C m^{-2} yr^{-1} and 14.13%, respectively. The Beijing–Tianjin sandstorm source comprehensive control project helps alleviate the reduction in carbon sinks, while the southwest karst rocky desertification comprehensive control project may aggravate the reduction in carbon sinks. This study clarifies the potential of China's different ecological engineering to increase carbon sink potential, and distinguishes and quantifies the contribution of climate and human activity factors to it, which is of great significance to the system management optimization scheme of terrestrial ecosystems and can effectively serve the national carbon neutral strategy.

Highlights

- Reality and nonpractice assumptions are used to evaluate the impact of ecological engineering on terrestrial ecosystems.
- Multiple terrestrial biosphere models show 45% of China's carbon sinks increase by more than 0.1 g C m^{-2} every 10 years.
- SEPCP is more helpful in improving terrestrial carbon sinks compared to the other two ecological projects.

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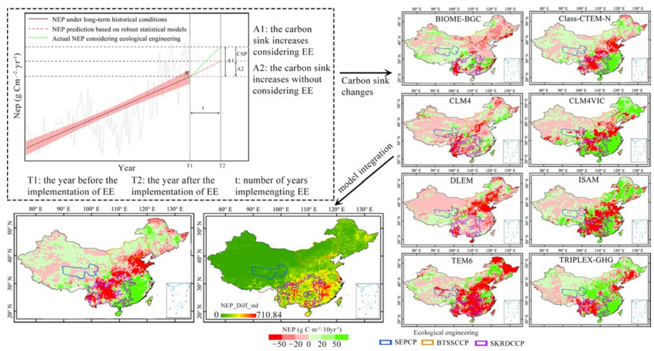
Keywords Carbon sink, Terrestrial biosphere model, Mann, Kendall trend test, Ecological engineering, Carbon sequestration potential

Graphical Abstract



1 Introduction

Terrestrial ecosystems have always been an important natural carbon sink (Sharma et al. 2022), especially since the 1960s, and they have stored more than a quarter of anthropogenic carbon emissions on average (Friedlingstein et al. 2019). The carbon sink potential also significantly affects the concentration of CO_2 and other greenhouse gases in the atmosphere, as well as key ecosystem services such as forest and crop productivity (Li et al. 2020; Cavan and Hill 2022). Considering their importance in curbing climate change, studying the spatiotemporal evolution trends and impact mechanisms of carbon sinks is crucial for formulating climate change mitigation policies (Schimel et al. 2015; Zeng et al. 2023c).

The United Nations International Panel on Climate Change emphasizes the urgency of achieving the emission targets set in the December 2015 Paris Climate Agreement (Pilpola et al. 2019; Li et al. 2022b). As the largest carbon emitter, China has recently proposed the goal of achieving carbon neutrality (Li et al. 2021b). China has formulated and implemented a series of national megaprojects aimed at protecting the environment and restoring degraded ecosystems (Lu et al. 2018). Ecological engineering can help improve the carbon sequestration of terrestrial ecosystems in multiple ways. Firstly, by protecting vegetation areas, especially the area of forests and grasslands, the carbon storage of ecosystems can be increased (Tong et al. 2018). Ecological engineering may also enhance the resistance and resilience to environmental stress by protecting advantageous tree species in the area (Lu et al. 2018). In addition, ecological engineering can also slow down the impact of limiting factors on vegetation growth by regulating microclimate and increasing regional water input, thereby helping to increase vegetation vitality and carbon sink (Xiao et al. 2023). These projects are of great significance for achieving carbon neutrality goals (Wu et al. 2022; Zhou et al. 2022).

It is unclear to what extent ecological engineering has a positive impact on terrestrial carbon sinks (Tong et al. 2018). The change in carbon sequestration potential in China may be influenced by both ecological engineering (EE) and climate change (Gong et al. 2021; Zeng et al. 2023a), especially in some climate sensitive areas such as the Qinghai Tibet Plateau and the Southwest Kast region (Xiao et al. 2023). Research based on ground inventory data shows that the terrestrial carbon storage of the regions involved in the national megaproject increased significantly from 2001 to 2010 (Lu et al. 2018; Cai et al. 2022). The carbon density of ecosystems in different project areas increased between 2.1 and 29.4 Mg C ha^{-1}, and the carbon sink within the scope of the national megaproject reached 132 Tg C yr^{-1} (Lu et al. 2018). To achieve the 2060 carbon neutral target, the terrestrial ecosystem plays an important role in winning time for industrial emission reduction (Zhou et al. 2022). In conclusion, China has played a crucial role in guiding the ultimate achievement of the Sustainable Development Goals by formulating a series of ecological plans to restore regional vegetation cover (Lu et al. 2018) and prevent and control land degradation (Cowie et al. 2018), and relevant actions are instructive for mitigating global warming and achieving carbon neutrality (Yu et al. 2022).

However, in addition to ecological engineering, climate change has a significant impact on carbon sinks/sources

(Li et al. 2021a). Climate warming may prolong the phenology of vegetation and increase carbon sequestration capacity (Liu et al. 2019). The changes in precipitation and solar radiation may have an impact on the growth conditions of vegetation, which is reflected in changes in carbon sinks (Chen et al. 2019b). Studies have also found that 64% of photosynthetic period of Chinese vegetation is controlled by temperature (Xue et al. 2023). Generally speaking, climate change and human activities are interdependent (Kou et al. 2021), and previous studies have typically not fully distinguished the contributions of the two to carbon sink change (Liu et al. 2018). Although studies have delved into how ecological engineering affects terrestrial ecological carbon sinks from a mechanistic perspective, there is still relatively little analysis on the differences in identifying the carbon sink potential of different ecological engineering by distinguishing climate factors, which hinders the implementation of China's carbon sink enhancement plan (Zhou et al. 2022).

Exploring the impact of China's ecological engineering on terrestrial ecosystem carbon sinks is of great significance for global climate governance and extending the service time of ecosystem carbon sinks. To achieve this goal, this study used robust statistical models combined with multiple terrestrial biosphere models to identify the response of vegetation to climate change, and analyzed the differences of multiple ecological engineering projects in China and their impact on terrestrial ecosystem carbon sink trends based on the differences between reality and nonpractice assumptions. We propose a research framework that eliminates factors such as climate change to explore the impact of ecological engineering on carbon sinks in terrestrial ecosystems, which can provide reference for research in other regions or evaluating the impact of human activities. At the same time, this study analyzed and quantified the contributions of climate and human activity factors to the potential increase of ecosystem carbon sinks, which is of great significance for optimizing the management of terrestrial ecosystems and can effectively serve the national carbon neutrality strategy.

2 Materials and methods

2.1 Data sources

The global Net Ecosystem Production (NEP) data used in the study was derived from simulation results of Terrestrial biosphere models (TBMs). The TBMs have become an integral tool for extrapolating local observations and understanding land–atmosphere carbon exchange to larger regions. In order to ensure comparability of the NEP used, the selected TBMs in the study were all derived from Multi–scale synthesis and Terrestrial Model Intercomparison Project (MsTMIP) (Huntzinger et al. 2018). The MsTMIP protocol specifies standard model inputs, simulations and simulation setup procedures, as well as required model output and format to ensure a valid and fair comparison of model results against one another and against available observations. TBMs are process models based on biogeochemistry and biophysics, which output large–scale carbon cycle results by combining environmental variables (including climate, land use, atmospheric CO_2, nitrogen deposition, etc.) with model preheating and simulation periods. TBMs typically include different simulation scenarios (Table 1). Due to the need to consider the impact of ecological engineering in this study, where ecological functions have an important impact on the protection of forest and grassland, time–varying in input land use data, atmospheric carbon dioxide content and nitrogen deposition data are required. The 8 TBMs in MsTMIP contain BG1 simulation scenarios and were selected for this study (Table 2). The specific input data of the model can be viewed in the supplementary information. Site level data (e.g., eddy covariance observations), inventory data (e.g., forest carbon stocks), regional gridded observations (e.g., aboveground biomass) and model–data products (e.g., data–driven spatially distributed Gross Primary Production products) have be used to evaluate TBM model, and these models have been extensively studied and proven to be effective means of estimating carbon sinks at a large scale and in a long–term.

The ecological engineering dataset (Table 3, Fig. 1) is provided by National Ecosystem Science Data Center, National Science & Technology Infrastructure of China. (http://www.nesdc.org.cn) (Shao et al. 2022). The data of the three ecological engineering projects are independent of each other, without spatial overlap, and the underlying surface is mainly grassland, with high comparability. Among them, the Sanjiangyuan ecological protection and construction project (SEPCP) is located in the Qinghai Tibet Plateau (QTP), with a high altitude, consisting

Table 1 Eight terrestrial biosphere models

Number	Model	Year	Spatial resolution	Country
1	BIOME–BGC	1901–2010	0.5°	USA
2	CLASS–CTEM–N	1901–2010	0.5°	Canada
3	CLM4	1901–2010	0.5°	USA
4	CLM4VIC	1901–2010	0.5°	USA
5	DLEM	1901–2010	0.5°	USA
6	ISAM	1901–2010	0.5°	USA
7	TEM6	1901–2010	0.5°	USA
8	TRIPLEX–GHG	1901–2010	0.5°	Canada

The Eight terrestrial biosphere models were provided by the North American Carbon Program

Table 2 Description of variables input for five simulation scenarios

Simulation name	Climate forcing	Land–use history	Atmospheric CO_2	Nitrogen deposition
RG1	Constant	Constant	Constant	Constant
SG1	CRU + NCEP	Constant	Constant	Constant
SG2	CRU + NCEP	Time–varying	Time–varying	Constant
SG3	CRU + NCEP	Time–varying	Time–varying	Constant
BG1	CRU + NCEP	Time–varying	Time–varying	Time–varying

Table 3 Three major ecological engineering projects in China

Number	Name	Abbreviation	Area	Implementation time
1	Sanjiangyuan ecological protection and construction project	SEPCP	57.08 *10^4 km^2	2004–present
2	Beijing Tianjin sandstorm source comprehensive control project	BTSSCCP	127.2*10^4 km^2	2002– present
3	Southwest karst rocky desertification comprehensive control project	SKRDCCP	133.0*10^4 km^2	2008– present

The ecological engineering dataset was provided by National Ecosystem Science Data Center, National Science & Technology Infrastructure of China

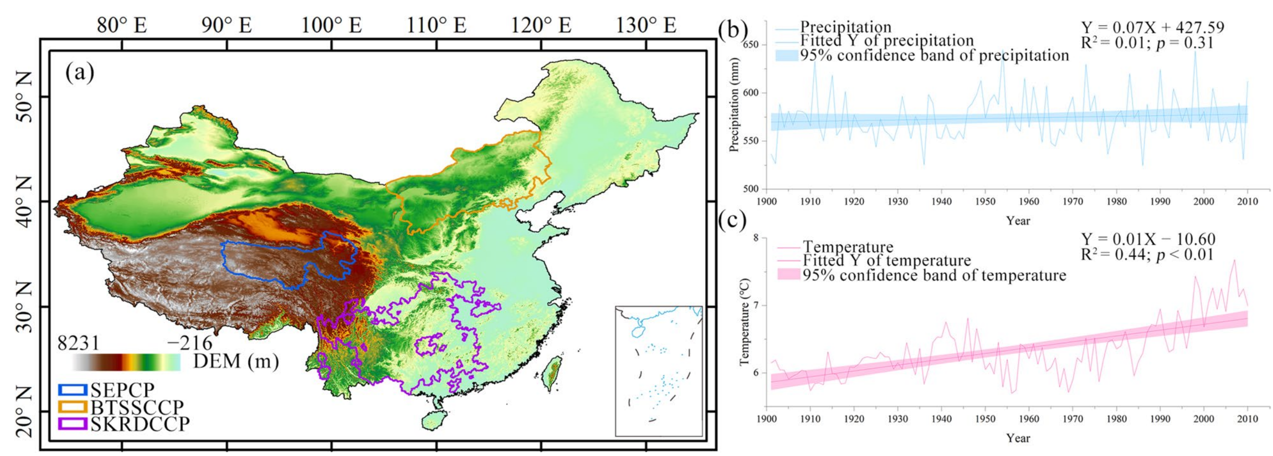


Fig. 1 **a** Spatial location and scope of three major ecological engineering projects in China, **b** precipitation change trend in China from 1901–2010, and **c** temperature change trend in China from 1901–2010

mainly of grassland and unused land (Fig. 1). The Beijing-Tianjin sandstorm source comprehensive control project (BTSSCCP) is located in northern China and consists mainly of grasslands. The Southwest karst rocky desertification comprehensive control project (SKRDCCP) is located in southwestern China, and it has the most complex terrain, mainly woodland, grassland and agricultural land.

This study also utilized multiple environmental factors to further analyze the mechanisms of ecological engineering's impact on carbon sinks, including climate factors, soil factors, vegetation factors, and terrain features. The precipitation, temperature, soil temperature, and soil moisture data used in the study are sourced from ERA–Interim reanalysis data, with a spatial resolution of 0.1°. The Vegetation Health Index (VHI) data used is from the improved product by Zeng et al. 2023a, with a spatial resolution of 4 km°. The Leaf Area Index (LAI) data used is from Liu et al. (2012), with a spatial resolution of 0.08°. The dem data used is from National Centers for Environmental Information, with a spatial resolution of 1 km°, and the SOC data used is from the Soilgrid product, with a spatial resolution of 1 km. The land use type data is MODIS product (MCD12Q1), with a spatial resolution of 500m. We resampled these environmental data using bilinear interpolation to match the NEP spatial resolution (0.5°). In addition, environmental data is further analyzed by synthesizing monthly data into annual data. Precipitation is synthesized into annual data by accumulating monthly data, while other elements obtain annual data by averaging monthly data.

2.2 Methods

2.2.1 Mann–Kendall trend testing

As a robust trend analysis method, Mann–Kendall (MK) trend test has been widely used in ecological environment research (Zhang et al. 2015; Saadi et al. 2023). This is a robust nonparametric test method that does not require a normal distribution of data series (Pandey and Khare 2018). Therefore, we used this method to analyze the trend of carbon sink changes in long–term terrestrial ecosystems. Specific information can be found in Supplementary Information.

2.2.2 Pearson correlation analysis

Pearson correlation analysis is commonly used to study the degree of correlation between variables and determine whether they have a significant response relationship. At present, this method has been widely used in the fields of climatology, ecology, and agroforestry. This study used Pearson correlation analysis to help identify the main environmental factors that affect the carbon sink function of terrestrial ecosystems during the implementation of ecological processes, and conducted an F–test. When $p < 0.05$, the correlation was significant.

$$\mathrm{r} = \frac{\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \overline{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \overline{y})^2}} \tag{1}$$

where r is the correlation coefficient, which ranges from −1 to 1, x_i and y_i are the values of factors x and y during the i period, $\overline{x}$ and $\overline{y}$ are the average values of factors x and y, and n is the length of the time series.

2.2.3 Estimating the CSP of ecological engineering

Based on the global NEP data estimated from 8 terrestrial biosphere models from 1901 to 2010, combined with the MK trend test method, the carbon sequestration potential (CSP) and carbon sequestration effect (CSE) of ecosystems were estimated. First, 1901–2010 was divided into two periods, namely, the historical scenario period before the implementation of ecological engineering and the ecological engineering period after the implementation of ecological engineering. Then, based on the annual NEP data in the historical scenario period and the MK trend test method, the 2010 NEP after excluding the impact of ecological engineering was estimated. The key assumption of this study is that the NEP obtained by using the MK trend test method based on long–term historical scenarios is the result of considering a series of environmental factors, such as climate change, atmospheric CO_2 content change and nitrogen deposition, without considering the impact of ecological engineering implementation. Finally, the 2010 NEP estimated by assumption was compared with the NEP obtained by model simulation under actual conditions to analyze the CSE and CSP of ecological engineering. Based on the above ideas, the CSE and CSP of ecological engineering were determined (Fig. 2). The CSE of ecological engineering can be estimated by the following equation:

$$\mathrm{CSE} = \frac{CSP}{B} \times 100\% \tag{2}$$

where CSE is the carbon sequestration effect of ecological engineering, and B is the carbon sink level of the terrestrial ecosystem before the implementation of ecological engineering. CSP is the difference between the carbon sink level after the implementation of ecological engineering and the carbon sink level estimated based on long–term historical conditions and robust statistical methods, which can be calculated by the following formula:

$$\mathrm{CSP} = A1 - \mathrm{A2} \tag{3}$$

where A1 is the difference between the carbon sink level of the terrestrial ecosystem in the T2 period and that in the T1 period based on the model simulation under actual conditions. A2 is the difference between the carbon sink of the terrestrial ecosystem estimated based on long–term historical conditions and robust statistical methods in the T2 period and T1 period. A2 can be obtained by the formula:

$$\mathrm{A2} = NEP_{predict,trend} * n \tag{4}$$

where $NEP_{predict,trend}$ is the annual change in NEP estimated based on historical scenario periods using the MK trend test, the unit is g C m^{-2} yr^{-1}, and n is the T3 time range (set in this study from 2005 to 2010, i.e., n is 6).

3 Results

3.1 The spatiotemporal characteristics of environmental conditions and carbon sinks in different ecological engineering regions

The study first compared the environmental characteristics of three ecological engineering implementation areas, including temperature and precipitation, soil, vegetation, and elevation (Fig. 3). The water and thermal conditions in the SKRDCCP area are usually better than those in the other two ecological engineering implementation areas, and the local vegetation conditions in the SKRDCCP area are also significantly higher than those in the other two areas, with an average LAI of around 2.0. The vegetation

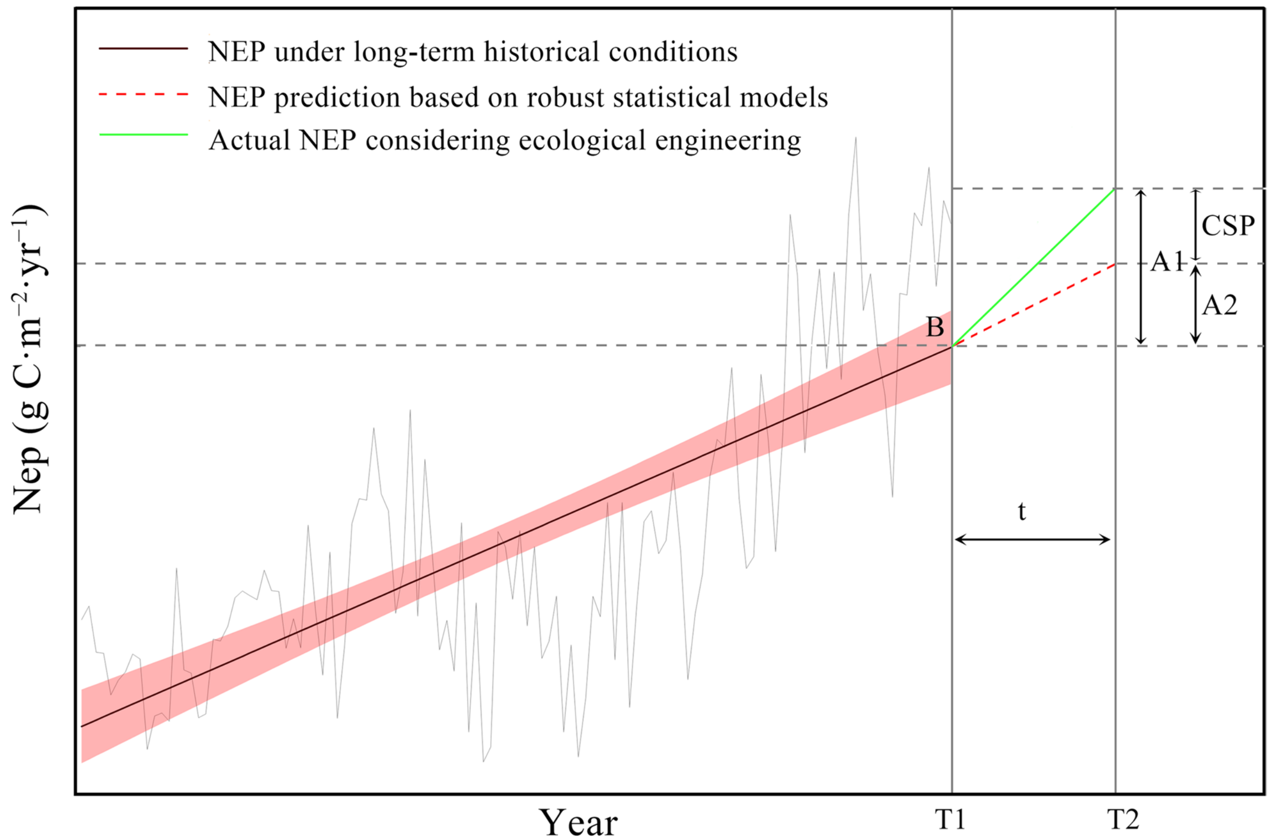


Fig. 2 Schematic diagram of the CSP and CSE of ecological engineering. The NEP with a solid green line is the NEP obtained from the model simulation based on reality after the implementation of ecological engineering. The NEP with a solid black line is the NEP obtained from the simulation of the model based on reality before the implementation of ecological engineering. The NEP with a red dashed line is the NEP estimated based on long–term historical conditions and robust statistical methods without considering the implementation of ecological engineering. T1 is the year before the implementation of ecological engineering (set as 2005 in this study), T2 is the year of assessment after the implementation of ecological engineering (set as 2010 in this study), t is the year span between T2 and T1, and B is the carbon sink of the terrestrial ecosystem at T1. A1 is the increase in NEP after implementing ecological engineering. A1 is the increase in NEP after implementing ecological engineering. CSP is the difference between A1 and A2. CSE is the ratio of CSP to B

drought risk in the SEPCP region is slightly lower than the other two regions, with a higher VHI and an average altitude of around 4500 m. The soil organic carbon is the lowest in the BTSSCCP region, while the soil organic carbon contents in the other two regions are similar.

The trend of changes in different environmental factors from 1980 to 2022 varies in different ecological engineering implementation areas (Fig. 4). The water conditions (precipitation and soil moisture) show a significant upward trend in the SEPCP region, with an average annual increase of 1.45 mm in precipitation, while showing a downward trend in the other two regions. The thermal conditions (temperature and soil temperature) have shown an upward trend in all three ecological engineering implementation areas, which is consistent with global warming. The vegetation health level in the SEPCP region shows a significant upward trend (increasing by 0.22 per year), indicating that the vegetation drought risk in the region may be reduced, while there is no significant change in the vegetation health level in other regions. The leaf area index shows an upward trend in all three regions, especially in the SKRDCCP region where the increase was the largest (an annual increase of 0.008 m^2/m^2).

The spatiotemporal evolution trend and significance of China's carbon sink during 1901–2010 were calculated for 8 models (Fig. 5). Most of the model results showed that China's carbon sink has generally increased since 1901, especially in the eastern and southeastern regions. Most models estimated that the average increase in NEP in these regions exceeded 0.5 g C m^{-2} every 10 years. However, there was a significant difference in carbon sink estimates for the western, southwestern, and northeastern regions of China. Over the past 100 years, the carbon sink in humid areas such as southeastern China showed a relatively clear upward trend, while the carbon sink changes in arid and semiarid areas such as the

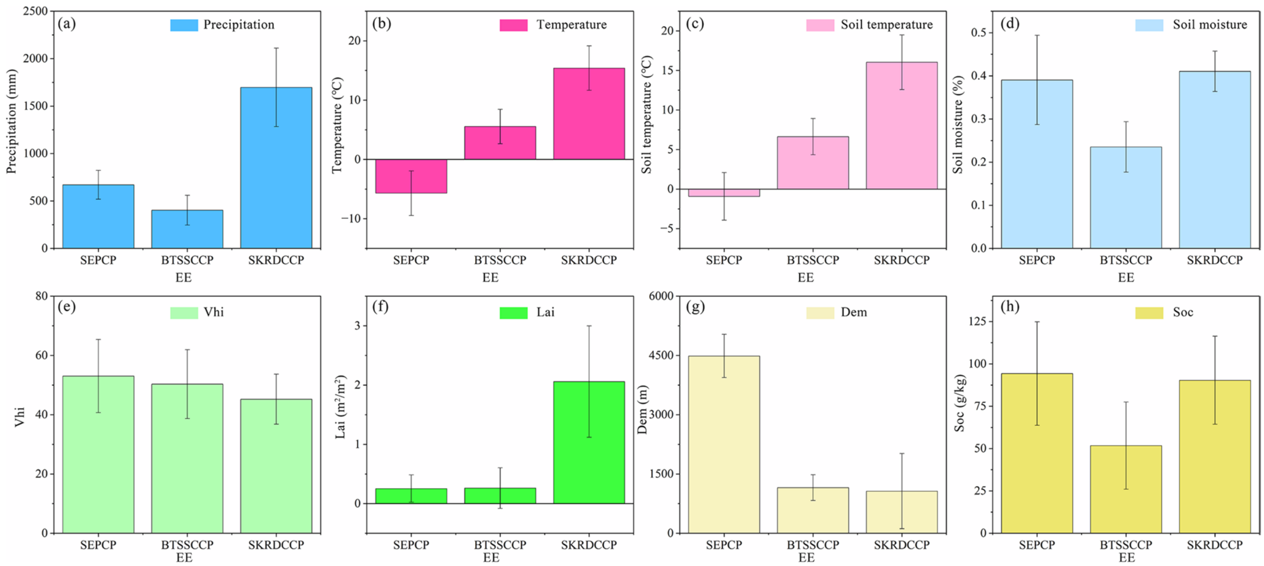


Fig. 3 Comparison of environmental conditions in three ecological engineering implementation areas over the past 40 years. **a** Precipitation. **b** Temperature. **c** Soil temperature. **d** Soil moisture content. **e** Vegetation health index. **f** Leaf area index. **g** Elevation. **h** Soil organic carbon

western and northern regions were more complex. Based on the significance test, the regions in China where NEP changes have passed the significance test are generally regions where carbon sinks have increased. Except for the BIOME–BGE model, all other models indicate significant growth in NEP in southern China.

Based on the 8 models, the carbon sink in most regions of China showed an increasing trend (Fig. 6). Since 1901, 84% of carbon sinks in China have increased, while 16% of regional carbon sinks have declined. Nearly half of the regions with a growth rate greater than 0.1 g C m^{-2} every 10 years, i.e., approximately 45%, were concentrated mainly in the eastern region of China, and the trend of change basically passed the significance test. The regions with declining carbon sinks were distributed mainly in parts of southwest, northwest, and northeast China. The standard deviation of China's terrestrial ecosystem carbon sink change trend showed that the estimates of the 8 models for the western, southwest and northern regions of China were relatively consistent, and the regions with large differences were concentrated mainly in the southern and southeastern regions of China.

3.2 Impact of human activities and ecological engineering on carbon sinks

By comparing the carbon sink differences of China's terrestrial ecosystem estimated based on historical conditions and an actual simulation in 2010, the potential of ecological engineering and human activities to increase sinks was analyzed. The impact of ecological engineering on the carbon sink obtained by the 8 models after excluding the impact of historical climate change was quite different (Fig. 7). Most models indicated an increase in carbon sink in the southeastern region of China after excluding the impact of climate change, especially the Class–CTEM–N, CLM4VIC, and TRIPLEX–GHG models, which indicated that the 2010 NEP estimated based on realistic conditions was generally 50 g C m^{-2} yr^{-1} higher than the 2010 NEP estimated based on long–term time series NEP. The Southwest region, on the other hand, performed the opposite, with many regions having differences exceeding –50 g C m^{-2} yr^{-1}.

Combining the 8 models, it was found that human activities and ecological engineering in more than half of China have helped improve the carbon sink (Fig. 8). Considering the impact of human activities and the implementation of ecological engineering in China, approximately 56% of terrestrial ecosystem carbon sinks have increased, while approximately 44% of regional carbon sinks have declined. Approximately 10% of the regions with carbon sink growth exceeding 50 g C m^{-2} yr^{-1} were concentrated mainly in the southeastern coastal areas of China. The regions with high carbon sink declines were distributed mainly in southwestern and central eastern China. Among them, the SEPCP in the QTP had the highest carbon sink increment, the BTSSCCP had no obvious CSE, and the SKRDCCP reduced the NEP instead. Based on the standard deviation of the impact of ecological engineering and human activities on China's terrestrial ecosystem carbon sink, it was found that the 8 models had a high consistency in the assessment of carbon sequestration of ecosystems in western and northern China. The regions with significant

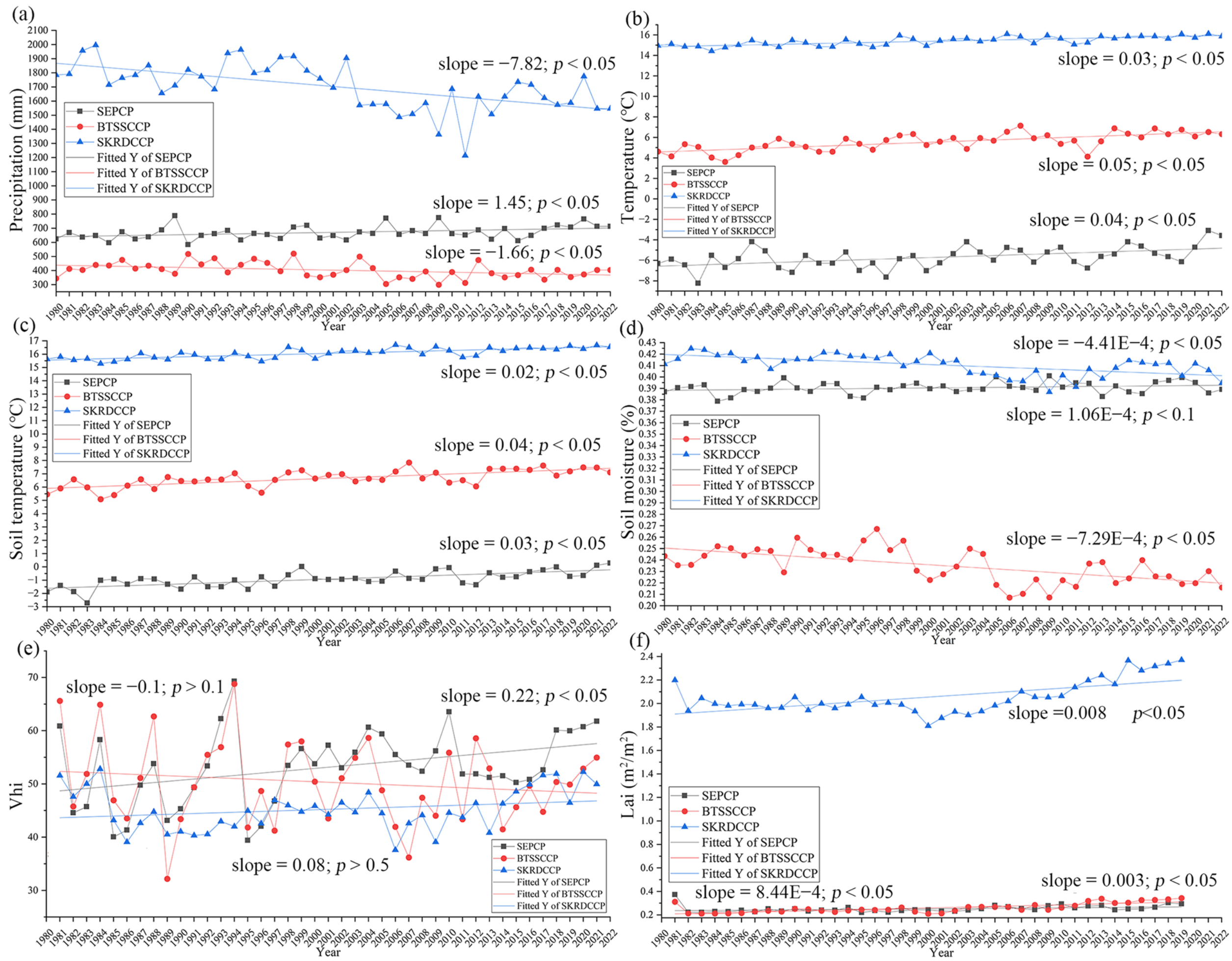


Fig. 4 The interannual changes in environmental conditions in three ecological engineering implementation areas over the past 40 years. **a** Precipitation. **b** Temperature. **c** Soil temperature. **d** Soil moisture content. **e** Vegetation health index. **f** Leaf area index

differences were concentrated mainly in the southern region of China. The CSE of the SEPCP and the BTSSCCP were relatively reliable.

3.3 Differences in the impacts of the three ecological engineering projects on carbon sinks

To more objectively assess the impact and difference of different ecological engineering projects on carbon sinks, this study compared the background values of Asia and the world to obtain statistics on the amount of carbon sink enhancement by human activities (Table 4). Based on the comprehensive results of the eight models, compared with the carbon sink change in Asia (–2.27 g C m^{-2} yr^{-1}), the SEPCP and the BTSSCCP improved carbon sink by 1.26 g C m^{-2} yr^{-1} and –1.82 g C m^{-2} yr^{-1}, respectively. The SKRDCCP was much lower than that in Asia, with a level of –19.76 g C m^{-2} yr^{-1}. This shows that the implementation of the SEPCP has significantly improved the carbon sink, while the BTSSCCP may alleviate the reduction in the carbon sink of the terrestrial ecosystem. In contrast, the SKRDCCP may exacerbate the reduction in carbon sinks. We found that globally, considering human activities, the NEP obtained based on long–term historical level simulations showed an improvement of 0.23 g C m^{-2} yr^{-1}.

Based on the assessment of the change in the carbon sink after considering the effect of ecological engineering, this study also assessed the improvement effect of three ecological engineering and human activities on the carbon sink using 2004 as the base period (Table 5). The SEPCP had the best effect on improving the carbon sink of the terrestrial ecosystem, which was approximately 14% higher than the level in 2004. However, the carbon sink difference between the regions with and without ecological engineering in the BTSSCCP decreased by approximately 5.41% compared with 2004. Although it decreased, the value slightly increased by 0.16% compared with the value of –5.57% for Asia, indicating that

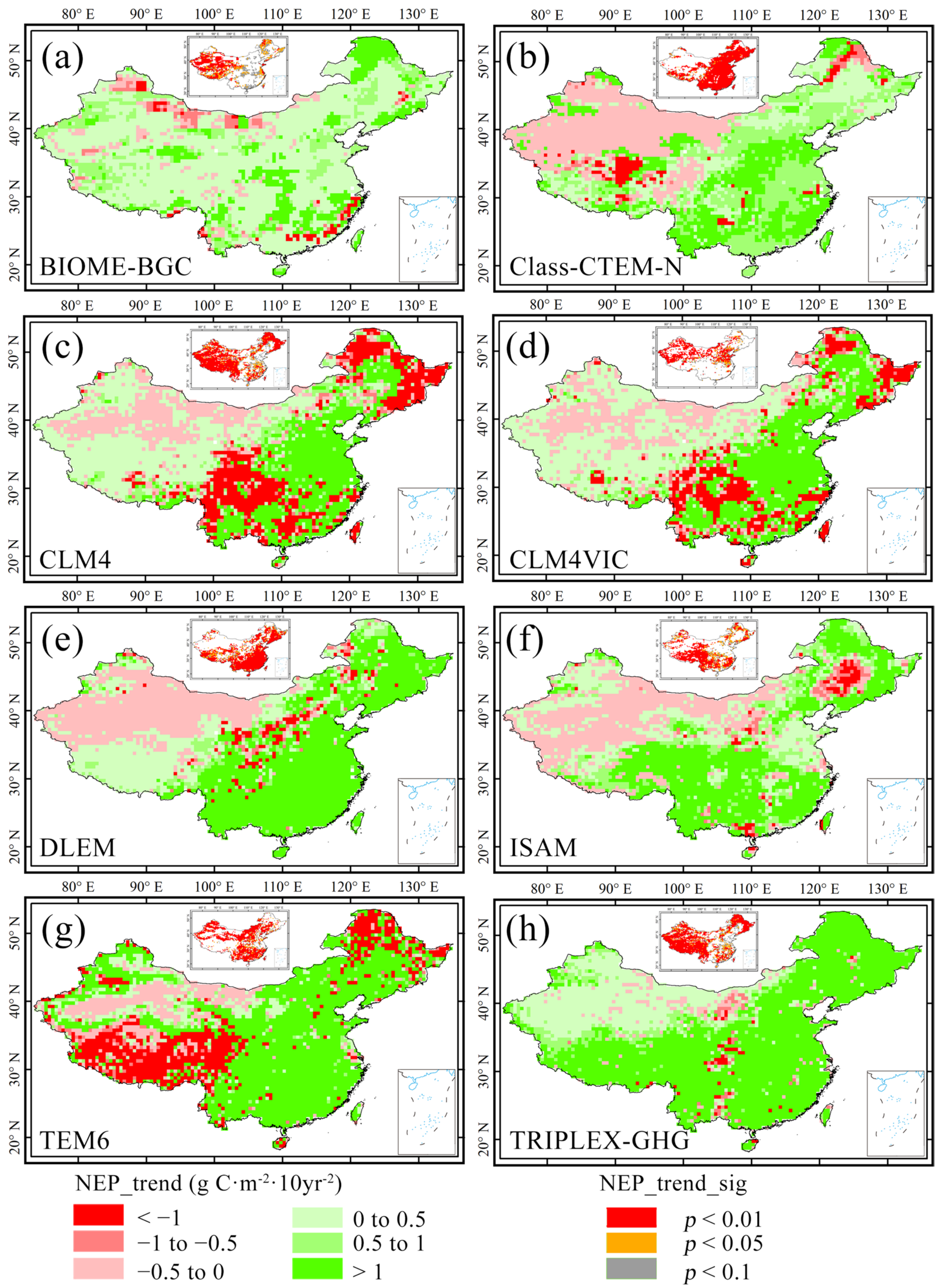


Fig. 5 The annual change trend of the carbon sink in China's terrestrial ecosystem estimated by 8 terrestrial biosphere models. The small figures represent the significance level of NEP changes, with red indicating $p<0.01$, orange indicating $p<0.05$, gray indicating $p<0.1$, and white indicating $p>0.1$

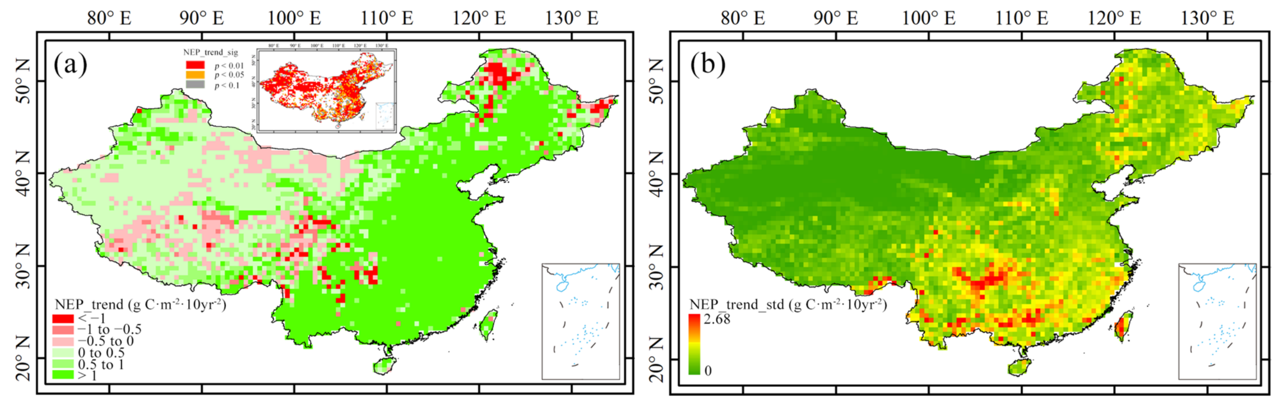


Fig. 6 Annual change trend and standard deviation of the terrestrial ecosystem carbon sink in China estimated by 8 terrestrial biosphere models. **a** NEP trend. **b** The standard deviation of the NEP trend. The small figures represent the significance level of NEP changes, with red indicating $p < 0.01$, orange indicating $p < 0.05$, gray indicating $p < 0.1$, and white indicating $p > 0.1$

the BTSSCCP is helpful in mitigating carbon sink reduction. The SKRDCCP may have had a negative effect on the increase in the carbon sink. We also found that globally, the difference between carbon sequestration after considering human activities and that estimated based on historical conditions has slightly increased compared to 2004, with a CSE improvement of approximately 0.48%.

4 Discussion

4.1 Analysis of the reasons for the impacts and differences of three ecological engineering projects on carbon sinks

Despite differences in estimated results using different methods, China is widely regarded as a carbon sink, with quantities ranging from 0.118 to 1.11 Pg C/yr (Zeng et al. 2023b), absorbing 22% of China's total anthropogenic carbon emissions (Friedlingstein et al. 2019; Piao et al. 2022a). China has contributed a huge global carbon sink, accounting for approximately 10–31% (Fang et al. 2018). In 2019, China announced the "carbon neutrality" goal (Piao et al. 2022b). Many ecological engineering projects have been implemented in China, such as afforestation, Grain for Green and grassland, rocky desertification and wind sand control (Chen et al. 2019a). They not only increase the forest area, enhance the carbon storage of the ecosystem, and prevent carbon loss of vegetation and soil but also significantly increase the carbon sink function of China's terrestrial ecosystems (Gong et al. 2021). However, different ecological engineering may have different impacts on carbon sinks, and their broader impacts on ecosystem sustainability need to be assessed (Wang et al. 2023). This study selected three ecological engineering implementation areas and evaluated their impact on carbon sinks (Fig. 9). We found that the vegetation area in the implementation areas of the two ecological engineering projects that are helpful for the carbon sink function of the ecosystem has increased since the implementation of the ecological engineering, indicating that the help of ecological engineering for carbon sink function first lies in the increase of vegetation area.

This study uses robust statistical models combined with multiple terrestrial biosphere models to quantify the impact of China's ecological engineering on terrestrial ecosystem carbon sink trends and their differences according to the difference between reality and non-practice assumptions. This approach has been proven to be feasible (Wang et al. 2023). This study found that the SEPCP had the most effective effect on the improvement of carbon sinks, with an average increase of 1.26 g C m^{-2} yr^{-1} compared with the NEP without the implementation of ecological engineering; this is an increase of 14.13% compared with 2004. The BTSSCCP did not significantly improve the NEP and reduced the NEP by 1.82 g C m^{-2} yr^{-1} compared to the NEP without ecological engineering. However, compared with the background standard of Asia, the NEP change in Asia was −2.27 g C m^{-2} yr^{-1}, indicating that in actual situations with human activities, the NEP in Asia has generally decreased compared to historical trends. The BTSSCCP may be helpful in alleviating the decrease in NEP. We explored the key factors influencing the differences in carbon sink function among different ecological engineering through statistical methods (Fig. 10). We found that there are differences in the key factors affecting carbon sink function among the three regions. This may be because the main limiting factor of vegetation on the QTP is water, and the SEPCP plays a considerable role in regional water conservation, alleviating the limiting

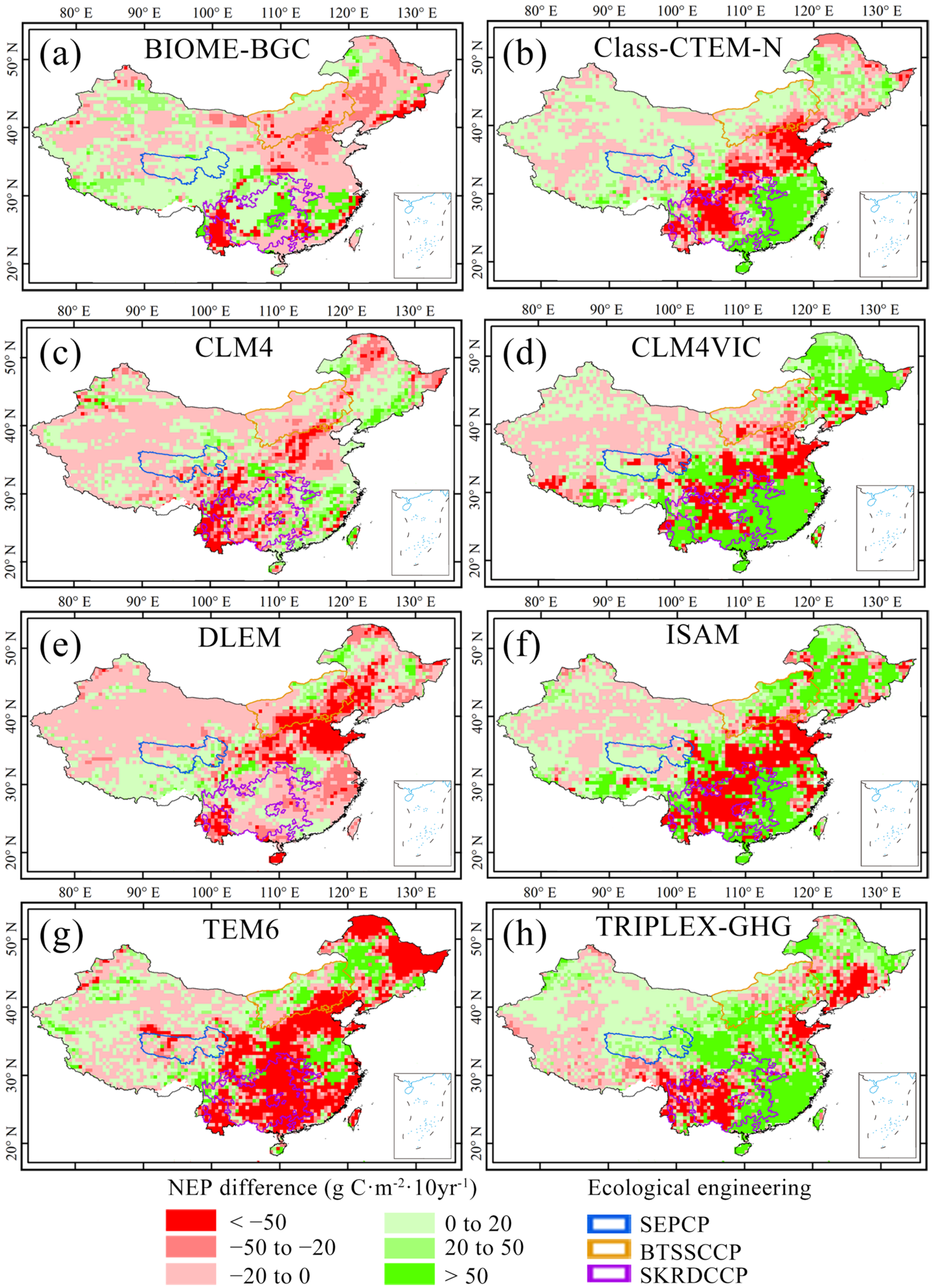


Fig. 7 The amount of carbon sink enhancement by human activities and ecological engineering estimated by 8 terrestrial biosphere models. Different color blocks represent the difference between the carbon sink considering ecological engineering and the carbon sink not considering ecological engineering

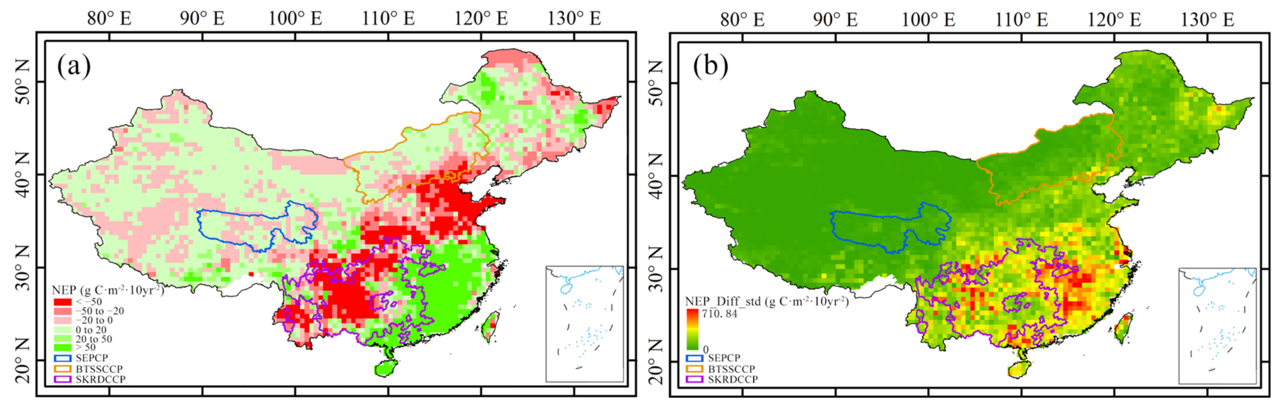


Fig. 8 The amount and standard deviation of carbon sink enhancement from human activities and ecological engineering estimated by 8 terrestrial biosphere models. **a** the difference between the carbon sink considering ecological engineering and the carbon sink not considering ecological engineering. **b** Standard deviation of carbon sink enhancement

Table 4 Comparison of CSP of ecological engineering with Asia and global value as the background standard

CSP of ecological engineering (g C/ m^2 yr)	SEPCP	BTSSCCP	SKRDCCP	Asia	Global
BIOME–BGC	3.74	−9.85	10.78	0.59	5.10
CLASS–CTEM–N	0.42	−0.39	−1.65	−0.66	−4.45
CLM4	0.48	17.33	−119.66	0.21	8.12
CLM4VIC	−11.00	−3.42	56.72	17.64	10.03
DLEM	3.25	−21.61	−8.24	11.97	−0.10
ISAM	−1.62	−4.47	−16.88	−9.87	−10.41
TEM6	−8.71	−13.79	−107.31	−34.02	−28.13
TRIPLEX–GHG	17.43	19.33	2.42	15.70	0.68
Mean	1.26	−1.82	−19.76	−2.27	0.23

Mean represents the mean of 8 models; the CSP data for Asia and the world are calculated based on 8 models

Table 5 Comparison of the CSE of ecological engineering with Asia and global value as the background standard

CSE of ecological engineering (%)	SEPCP	BTSSCCP	SKRDCCP	Asia	Global
BIOME–BGC	25.74	−18.02	11.02	1.49	10.09
CLASS–CTEM–N	4.47	−3.16	−12.45	−3.91	−7.39
CLM4	14.42	298.95	−292.79	0.55	23.99
CLM4VIC	−118.78	−17.18	105.63	62.61	40.67
DLEM	57.05	−203.56	−10.99	−56.00	−0.51
ISAM	−19.40	−87.34	−50.26	−81.26	−71.52
TEM6	\	−18.14	−61.97	−54.64	−49.27
TRIPLEX–GHG	44.95	22.83	1.14	14.14	0.53
Mean	14.13	−5.41	−22.58	−5.57	0.48

Mean represents the mean of 8 models; \ indicates that the carbon sink changes and CSP estimated by the model are both negative; the CSE data for Asia and the world are calculated based on 8 models

effect of water stress on vegetation growth on QTP (Xu et al. 2008; Li et al. 2022a). In addition, the implementation of ecological engineering has also protected forest and grassland while limiting the expansion of residential areas, which is also a positive impact of ecological engineering on carbon sequestration (Zhou et al. 2020). The factors that affect carbon sink function in the BTSSCCP region, in addition to water conditions, also include soil temperature. However, in the context of climate warming and increased precipitation, its ecological engineering is not as helpful as SEPCP in improving carbon sink function. The SKRDCCP region is relatively more complex, with good local vegetation conditions and a vegetation area of over 98%. Therefore, the impact of changes in water and heat conditions on carbon sink function is more complex.

The study also found that the SKRDCCP not only alleviated the decreasing trend of NEP but also increased the risk of it becoming a carbon source. This may be mainly because the SKRDCCP is aimed at rocky desertification areas with low carbon sinks, and rocky desertification control is an important and slow long–term process. Ecological engineering cannot effectively solve the problem of rocky desertification in the short term, so it cannot directly improve carbon sinks (Piao et al. 2022a). However, southwestern China has more forestland, and the carbon sink increase has been large in the long–term historical development process. In recent years, the intensity of human activities has gradually increased and become the leading factor driving vegetation change (Deng et al. 2023). Therefore, comparing the current carbon sink change with the historical average carbon sink increase may be another main reason (Yang et al. 2022).

We also help identify how ecological engineering affects carbon sink function by segmenting the changes

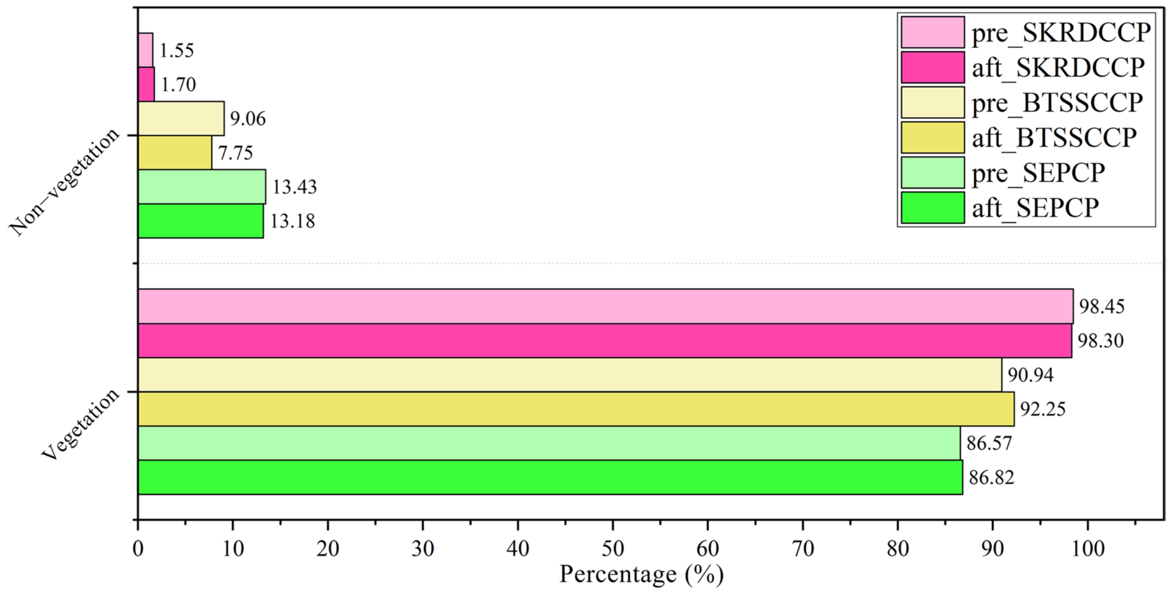


Fig. 9 Comparison of the proportion of vegetation area before and after the implementation of different ecological projects

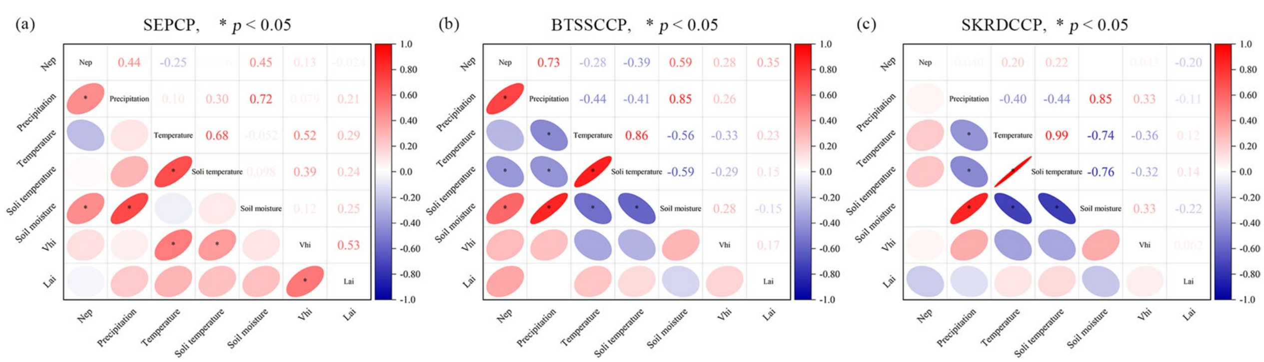


Fig. 10 The correlation between environmental factors and carbon sink function in three ecological engineering implementation areas. **a** SEPCPC. **b** BTSSCCP. **c** SKRDCCP

in water conditions in the SEPCP region (Fig. 11). Due to the influence of water conditions, the carbon sink function in the SEPCP area is mainly affected. Therefore, the changes in precipitation and soil moisture are fitted separately based on the implementation time of ecological engineering. We found that after implementing ecological engineering, there was a significant increase in precipitation and a significant decrease in soil moisture, indicating that ecological engineering can not only help improve microclimate, but also have a positive effect on water conservation, making vegetation more effective in using water to improve productivity.

Studies have shown that ecological engineering led to a significant increase in vegetation productivity (Lu et al. 2018), and effectively alleviated the trend of carbon sink reduction in China from 1981 to 2019, which was consistent with our research results (Xu et al. 2023). We also compared the CSP differences of the three major ecological engineering projects on this basis, which is of great significance for the system management optimization scheme of terrestrial ecosystem sink increases and can effectively serve the national carbon neutral strategy.

4.2 Uncertainty

A variety of estimation methods for carbon sources and sinks in terrestrial ecosystems have been developed. Different methods have their own advantages, and their applicability varies greatly (Sarkar et al. 2022). The top–down atmospheric inversion method can estimate real–time changes in carbon sources and sinks

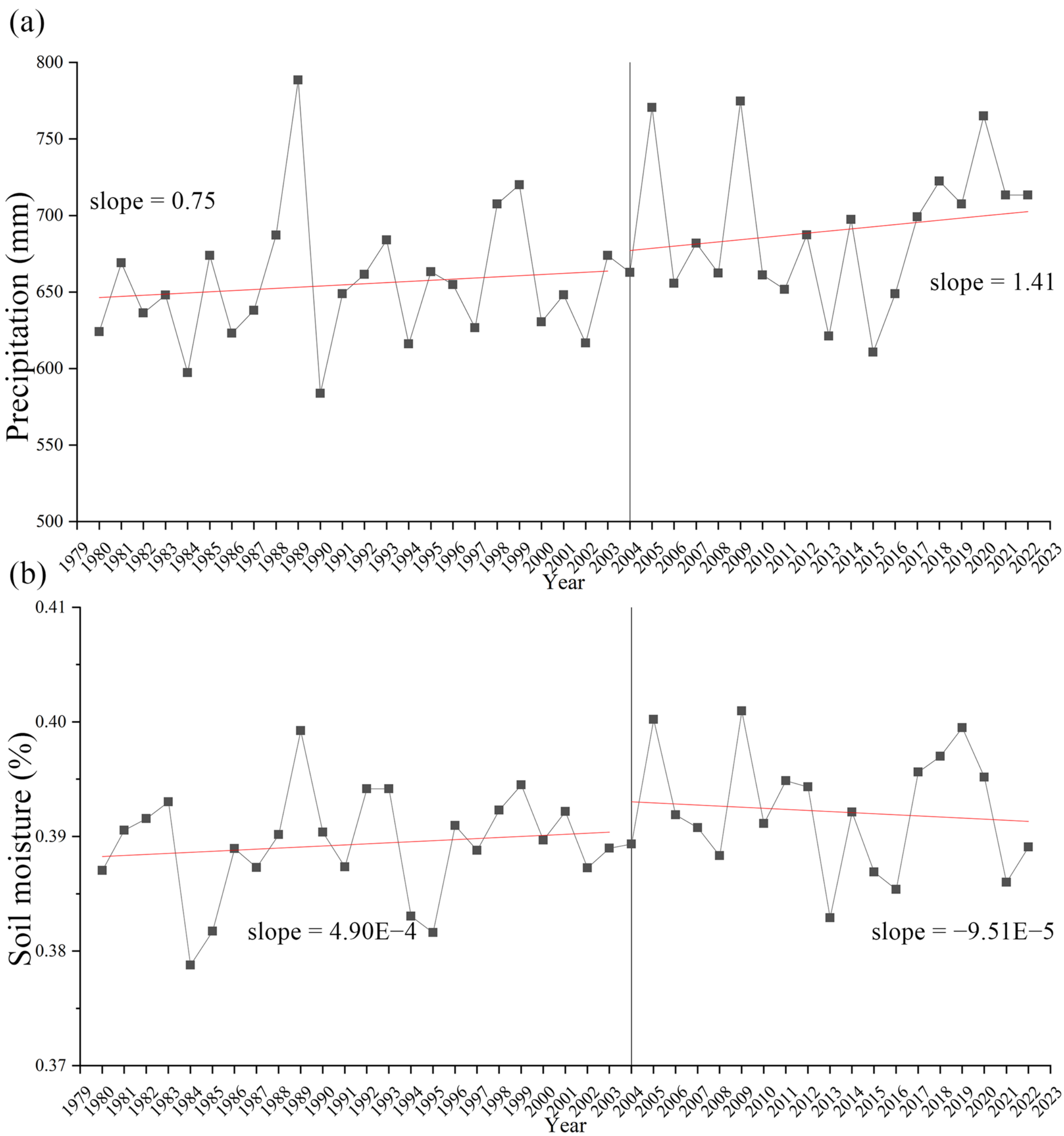


Fig. 11 Trend of changes in moisture conditions before and after SEPCP implementation. **a** Precipitation. **b** Soil moisture content

(Fernandez-Martinez et al. 2019); however, its spatial resolution is low, and the number and distribution of atmospheric observation points limit its inversion accuracy (Jiang et al. 2016). The bottom−up is based on carbon flux sites or ecological sample sites (Wood 2023), which has high accuracy and can realize long−term continuous positioning observations of ecosystem carbon fluxes (Heiskanen et al. 2022). However, this method is greatly affected by topography and meteorological conditions and is characterized by insufficient sample representativeness and high cost (Piao et al. 2022a). It is a promising method to estimate the carbon sink of a large range of terrestrial ecosystems with the help of the terrestrial biosphere model (Pugh et al. 2019; Seiler et al.

2022). However, the structure of terrestrial biosphere models is complex with numerous parameters, and there are significant differences in various models (Fig. 3). Therefore, this study used multiple model integrations for comprehensive carbon sink research, which is an effective method to reduce the uncertainty of results caused by model differences (Bastos et al. 2021). Additionally, due to the numerous model parameters, different parameters affect different ecological processes, especially in cases where the research time series is long and the research area is large, and it is even more necessary to continuously optimize the model parameters (Seiler et al. 2022). Therefore, this study selected 8 models with annual updated and optimized parameters from 15 terrestrial biosphere models to minimize the uncertainty of simulation results.

Terrestrial ecosystem carbon sinks are affected not only by the ecosystem itself but also by climate, atmospheric CO_2, nitrogen deposition and other factors (Guo et al. 2021; Zeng et al. 2022; Zhou et al. 2022). Especially since the twenty-first century, the intensity of human activities has increased, and the change in carbon sinks will continue to become more complex. Therefore, it is crucial to reveal the impact of environmental variables and ecological engineering on carbon sinks (Piao et al. 2022a). In this study, eight models for the real–time updating of climate, atmospheric CO_2 concentration, nitrogen deposition and land use types were selected for carbon sink simulation, and robust statistical models were used to describe the response of carbon sinks to climate change. According to the differences between reality and nonpractice assumptions, the CSP and CSE of different ecological engineering were analyzed and quantified. Research has shown that this approach is feasible and effective, and it has been used to evaluate the environmental and socioeconomic impacts of China's "Grain for Green" and grazing ban practices (Wang et al. 2023). However, the impact of human activities on terrestrial ecosystem carbon sinks includes not only the implementation of ecological engineering but also socioeconomic behaviors such as fossil energy consumption (Bu et al. 2019). For example, in this study, ecological engineering in the Sanjiangyuan area has the most prominent positive effect in improving carbon sinks, and the discovery that other types of ecological engineering have poor CSE supports this. The intensity of human activities in the Sanjiangyuan area is low, so the CSE of ecological engineering may be more obvious (Chen et al. 2014). Although ecological engineering and man–made land use change were considered in this study, the impacts of industrial activities, population migration and other factors on terrestrial ecosystem carbon sinks have not been fully considered. These factors need to be further included in the research framework in future research.

5 Conclusion

Exploring the impact of China's ecological engineering on terrestrial ecosystem carbon sinks, quantifying the contribution of ecological engineering to the increase in carbon sinks, and determining the carbon sequestration differences among various types of ecological engineering are of great significance for global climate governance and extending the service time of ecosystem carbon sinks. The CSP of the three major ecological engineering projects and their differences were evaluated based on eight terrestrial biosphere models with real–time parameter updates and a robust statistical method based on long–term historical data. The study found the impact of human activities on terrestrial ecosystems in Asia has decreased by 2.27 g C m^{-2} yr^{-1} compared with the carbon sink estimated based on environmental factors, and the CSP and CSE of SEPCP were the best, with values of 1.26 g C m^{-2} yr^{-1} and 14.13%, respectively. Taking the overall level of Asia for comparison, the BTSSCCP is helpful in alleviating carbon sink reduction, while the SKRDCCP may exacerbate carbon sink reduction. This study clarified the potential of China's ecological engineering to increase carbon sinks, quantified the contributions of climate and human activities factors to the potential of the ecosystem to increase carbon sinks and is of great significance for the system management optimization scheme of terrestrial ecosystems to increase carbon sinks, which can effectively serve the national carbon neutral strategy.

Supplementary Information

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Additional file 1.

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Authors' contributions
Jingyu Zeng and Tao Zhou conceived and designed the study. Jingyu Zeng performed material preparation, interpreted the results and wrote the original manuscript. Tao Zhou supervised this project. E Tan, Yixin Xu and Qiaoyu Lin collected the data. Yajie Zhang, Xuemei Wu, Jingzhou Zhang, Xia Liu and Qi Zhang edited the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors have no competing interests to declare that are relevant to the content of this article.

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