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Contribution of different types of terrestrial protected areas to carbon sequestration services in China: 1980–2020

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Exploring the contribution of protected areas to carbon sequestration services is meaningful to enhance the role of protected areas in climate change mitigation globally. However, less attention has been paid to the contribution of different types of protected areas to carbon sequestration services as well as their changes, which is not conducive to provide more effective solutions in the context of future climate change. Here, we identified the status and changes of carbon sequestration in different types of terrestrial protected areas in China and calculated the amount of carbon sequestration in different ecosystems in terrestrial protected areas and in different climatic zones. Our results indicated that carbon sequestration of China's terrestrial protected areas had shown a significant increasing trend over the past 40 years (1980–2020) (R^2=0.862, p<0.05). Among the different types of terrestrial protected areas in China, nature reserves had the greatest carbon sequestration, accounting for 64–66% of the carbon sequestration in China's terrestrial protected areas from 1980 to 2020. Although the carbon sequestration per unit area of forest parks was the highest among all types of protected areas, the proportion of carbon sequestration of forest parks tended to decrease significantly over the past 40 years. Carbon sequestration of protected areas in the humid zone had been mainly contributed by forest ecosystems, while grassland and desert ecosystems in terrestrial protected areas in regions with low rainfall (e.g., semi-arid and arid) had made more contribution to carbon sequestration services. Our study showed that China's terrestrial protected areas had played an important role in carbon sequestration over the past 40 years, but there are still some gaps compared to the global level, and the planning and establishment of protected areas need to be further strengthened in the future.

KEYWORDS
carbon sequestration, climatic zones, forest parks, nature reserves, terrestrial ecosystems

1. Introduction

Protected areas are a cornerstone for the conservation of biodiversity, which also play important roles in regulating climate and maintaining or enhancing the supply of ecosystem services (Gaston et al., 2008; Protected Planet Report 2018, 2018). As illustrated in the Protected Planet Report 2016 (2016), the benefits provided by protected areas are critical to address environmental and social challenges. For example, protected areas contribute to storing and sequestering carbon to mitigate climate change, and offer opportunities to address human health and wellbeing issues (Lopoukhine et al., 2012). Therefore, in the context of global climate change, studying the carbon sequestration services of protected areas and their changes, and clarifying the contribution of protected areas in mitigating climate change, had attracted widespread attention.

In terms of carbon sequestration services in protected areas, relevant studies have shown that globally terrestrial protected areas, with the total area of 15.5 million km^2, can sequester 0.5 Pg C annually, which is about one fifth of the carbon sequestered by all land ecosystems annually (Melillo et al., 2016). For different ecosystems, forests sequester the most carbon among all types of terrestrial ecosystems, consequently there are relatively more research around carbon sequestration in forest ecosystems within protected areas. For example, the average forest carbon stock and sink per unit area are relatively higher within national parks than those on the overall national territory in Italy (Marchetti et al., 2012). Brazil's Legal Amazonia region had 718 protected areas covering 2.2 million km^2 in 2014, representing 43% of the region's area and 57.0% its carbon stock in vegetation (Nogueira et al., 2018). Therefore, protected areas need to be used as key places for national and regional responses to climate change by protecting carbon-rich habitats and ensuring sustainable management of land to maintain and store carbon (MacKinnon et al., 2011). It was further suggested that the combination of protected areas and climate change mitigation areas, such as climate stabilization areas, can contribute to store vast reserves of carbon and other greenhouse gases and prevent large-scale land cover change (Dinerstein et al., 2019).

Recent studies have also explored changes in carbon sequestration services within protected areas and found that protected areas play a positive role in mitigating carbon loss. In humid tropical forests, protected areas lost about half as much carbon as the same area of unprotected forest from 2000 to 2005 (Scharlemann et al., 2010). Similar studies have shown that tropical protected areas overall reduced deforestation carbon emissions by around 29% from 2000 to 2012, where the largest contribution was from the tropical Americas, followed by Asia and Africa (Bebber and Butt, 2018). In contrast, some protected areas had been experiencing a significant reduction in their carbon sequestration services due to a combination of climate change and anthropogenic disturbances. The first scientific assessment of the amount of greenhouse gases emitted and absorbed by forests in World Heritage sites has found that at least 10 important sites have become net sources of carbon in the last 20 years due to human activities and climate change pressures (Osipova et al., 2020). A large number and size of protected areas and buffer zones in Uganda exhibited carbon losses for the period 2000–2012 (Gizachew et al., 2018). However, less attention has been paid to the contribution of different types of protected areas to carbon sequestration services as well as their changes, which is not conducive to further explore which areas and types of protected areas are needed to provide more effective solutions for sustaining ecosystem services in the context of future climate change.

China has been advocating Natural Climate Solutions to enhance the carbon sequestration of ecosystems by conserving, restoring, and improving management of forests, croplands, grasslands, and wetlands (Lu et al., 2022). Therefore, enhancing the carbon sink capacity of terrestrial ecosystems is one of the important ways to achieve China's goals of "Carbon peak in 2030 and carbon neutralization in 2060" (Yu et al., 2022). China's terrestrial ecosystems had contributed 10–31% of the global land carbon sink with approximately 6.5% of the world's land area (Piao et al., 2022). In recent years, researchers have also found that strictly regulated nature reserves provided greater benefits in terms of carbon stock and carbon sequestration in China (Liu et al., 2017). For example, the carbon sequestration within nature reserves in Qinling increased significantly higher than outside of nature reserves from 2010 to 2015 (Cao, 2021). Therefore, exploring the contribution of different types of protected areas in China in terms of carbon sequestration services and how they have changed in different regions and ecosystems, will be useful to promote the effective management of carbon sequestration services in protected areas.

Thus, this study explored the carbon sequestration services of terrestrial ecosystems within each terrestrial protected area in China from 1980 to 2020. The main purposes of this study were: (1) to clarify the status of carbon sequestration in different types of terrestrial protected areas; (2) to identify the amount of carbon sequestration in different ecosystems in terrestrial protected areas and in different climatic zones; and (3) to explore which climatic zones and ecosystems play an important role in carbon sequestration of China's terrestrial protected areas. We also proposed relevant ecosystem management recommendations on the ecological carbon sink contribution of protected areas, with the aim to contribute to achieve the goals of carbon peaking and carbon neutrality of China as well as the world.

2. Materials and methods

2.1. Calculation of carbon sequestration of terrestrial ecosystems in China

In our study, we used the InVEST Version 3.8.4 Carbon Storage and Sequestration model to estimate carbon sequestration of terrestrial ecosystems in China from 1980 to 2020. Carbon sequestration calculations for large regions are often calculated using the carbon model of the InVEST combined with a spatial correction (Abera et al., 2021). The Carbon model is based on land cover to estimate total carbon sequestration in each period by dividing the ecosystem into four carbon pools: aboveground living biomass, belowground living biomass, soil, and dead organic matter (Zaks, 2019). The land cover data of China with a resolution of 30 m × 30 m were derived from the Resource and Environment Data Cloud Platform,[1] with the year of 1980, 1990, 1995, 2000, 2005, 2010, 2015, and 2020.

Then, carbon sequestration was converted to a net annual value based on interannual differences, corrected by the Net Primary Production (NPP) spatial correction factor for each period. Finally, we obtained the total carbon sequestration by combining with soil data and root depth (Fu, 2022). The calculation formula is:

$$\mathrm{C_{total}} = \mathrm{C_{above}} + \mathrm{C_{below}} + \mathrm{C_{soil}} + \mathrm{C_{dead}} \tag{1}$$

$$C_T = \left(C_{T,total} \times F_{T,npp} - C_{T-n,total} \times F_{T-n,npp}\right) / n \tag{2}$$

$$C_{es} = \left(C_T + NPP_T\right) / 2 \tag{3}$$

1 http://www.resdc.cn

"C_{total}" is the total carbon sequestration based on the four carbon pools. "C_{above}" is the carbon sequestration of aboveground living biomass, "C_{below}" is the carbon sequestration of belowground living biomass, "C_{soil}" is the carbon sequestration in soil, "C_{dead}" is the carbon sequestration of dead organic matter.

"C_T" is the carbon sequestration in year T. "T" is time, "n" is the time interval F_{npp}, is the spatial correction factor based on NPP. The spatial correction factor was based on the mean value of the national terrestrial ecosystem, using the subordinate fuzzy method, and the NPP for the same period is converted to a mean value of 1, taking the value range of [0,2] for F_{npp}

"C_{es}" is the final carbon sequestration in year T.

2.2. Calculation of carbon sequestration in terrestrial protected areas in China

Since the establishment of the first nature reserve, Dinghushan Nature Reserve, in 1956, China has established more than 11,800 protected areas of various types at all levels. According to statistics, before the institutional reform of the State Council in 2018, China had established many types of protected areas including nature reserves, forest parks, geological parks, wetland parks, marine parks, and so on. This study mainly focused on China's terrestrial protected areas, including nature reserves, forest parks, geological parks, desert parks, wetland parks, and mine parks, with a total number of 8,133 protected areas. The data of protected areas were obtained from the State Ministry of Ecology and Environment, Provincial Department of Ecology and Environment, Provincial Department of Forestry and Grassland, and management bureaus of protected areas. We used ArcGIS Pro 3.0 to calculate carbon sequestration within each terrestrial protected area. The vector layer of protected areas was overlaid with the raster layers of carbon sequestration of terrestrial ecosystems of each year, and the "ZonalStatisticsAsTable" tool of spatial analysis in ArcGIS Pro 3.0 was used to calculate the carbon sequestration within each terrestrial protected area of each year, respectively. And then we calculated carbon sequestration in each type of terrestrial protected areas from 1980 to 2020. Finally, a linear trend analysis was carried out using Origin 2021 for each type of terrestrial protected areas to determine carbon sequestration and its proportion.

2.3. Calculation of carbon sequestration in different terrestrial ecosystems and climatic zones of terrestrial protected areas in China

To further clarify the spatial differences in the carbon sequestration capacity of terrestrial protected areas in China from 1980 to 2020, we calculated carbon sequestration in different terrestrial ecosystems and climatic zones. According to the remote sensing monitoring data of land cover and the agricultural zoning data of China, we used 3 ecosystem types (forest ecosystem, grassland ecosystem, and desert ecosystem) and 4 climate zones (humid zone, semi-humid zone, semi-arid zone and arid zone) to make further analyses. The carbon sequestered by terrestrial protected areas in each type of ecosystem and in each climatic zone were extracted by mask analysis tools in ArcGIS Pro 3.0.

3. Results

3.1. Carbon sequestration of China's terrestrial protected areas

Carbon sequestration of terrestrial protected areas in China over the past 40 years and its changes were investigated. The results showed that carbon sequestration of China's terrestrial protected areas was the lowest in 1980, with 298.52 Tg. While the carbon sequestration of China's terrestrial protected areas was the highest in 2020, with 334.87 Tg, which is 13.7% of the total carbon sequestration in China's terrestrial ecosystems. Over the past 40 years (1980–2020), carbon sequestration of China's terrestrial protected areas has shown a significant increasing trend ($R^2 = 0.862$, $p < 0.05$) (Figure 1A).

From different periods, carbon sequestration of China's terrestrial protected areas was in a rapid growth from 1980 to 2000. Although the carbon sequestration of China's terrestrial protected areas in 2005 decreased by 3.15 Tg compared to 2,000, it shows another rapid increasing trend from 2,005 to 2,020. However, the proportion of carbon sequestered by terrestrial protected areas in China's terrestrial ecosystems has remained relatively stable at 14–16%, with the highest proportion of carbon sequestered in 1980 at 14.06% and the lowest at 13.70% in 2020 (Figure 1B).

3.2. Carbon sequestration of different types of terrestrial protected areas in China

The carbon sequestration of 6 types of terrestrial protected areas in China was calculated separately. The results showed that the most proportion of carbon sequestration was nature reserves, accounting for 64–66% of the carbon sequestration in China's terrestrial protected areas from 1980 to 2020. The proportion of carbon sequestration of nature reserves showed a significant increasing trend over the past 40 years ($p < 0.05$) (Figure 2A). In 1980, the carbon sequestration of nature reserves was 192.40 Tg, and it was 221.11 Tg in 2020, with an increase of 28.71 Tg over the past 40 years. In contrast, the proportion of carbon sequestered by forest parks was 25.71% in 1980, decreasing to 24.33% by 2020. And the proportion of carbon sequestered by forest parks tended to decrease significantly ($p < 0.05$) over the past 40 years (Figure 2B). The proportion of carbon sequestered by geoparks decreased from 6.96 to 6.7% over the past 40 years, also showing a significant decrease trend ($p < 0.05$) (Figure 2C). The proportion of carbon sequestered by wetland parks, desert parks, and mine parks did not exceed 3% to the total carbon sequestered by China's terrestrial protected areas (Figures 2D–F).

In terms of carbon sequestration per unit area of different types of protected areas, forest parks sequestrated the highest carbon per unit. From 1980 to 2020, the carbon sequestration per unit area of forest parks increased from 422.78 to 448.81 Mg/km^2, but the increasing trend was not significant ($p > 0.05$) (Figure 3B). The carbon sequestration per unit area of nature reserves is the second. From 1980 to 2020, the carbon sequestration per unit area of nature reserves increased from 167.27 to 192.23 Mg/km^2, showing a significant increasing trend over the last 40 years ($p < 0.05$) (Figure 3A). Furthermore, from 1980 to 2020, the carbon sequestration per unit area of geoparks, wetland parks, and desert parks all showed significant increasing trends ($p < 0.05$) (Figures 3C–F).

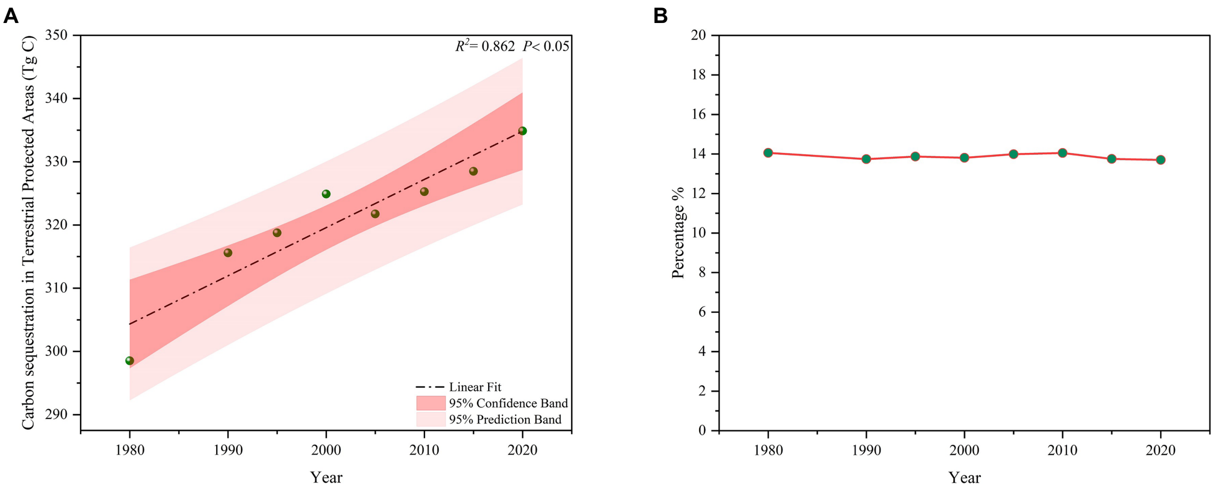

FIGURE 1
(A) Carbon sequestration of China's terrestrial protected areas from 1980 to 2020. **(B)** The proportion of carbon sequestered by terrestrial protected areas in China's terrestrial ecosystems from 1980 to 2020.

3.3. Carbon sequestration of different terrestrial ecosystems and climatic zones in terrestrial protected areas in China

Among the terrestrial protected areas in China, forest ecosystems sequestered the most carbon, with the lowest of 189.34 Tg in 1980 and the highest of 199.46 Tg in 2020. From 1980 to 2020, the proportion of carbon sequestered by forest ecosystems in China's terrestrial protected areas to the total carbon sequestration in China's terrestrial protected areas declined from 63.43 to 59.56%, showing a decrease of 3.87% in the past 40 years. Grassland ecosystems in terrestrial protected areas had the second highest carbon sequestration, ranging from 66.32 Tg in 1980 to 77.06 Tg in 2020. From 1980 to 2020, the proportion of carbon sequestered by grassland ecosystems in terrestrial protected areas increased from 22.22 to 23.01% of the total carbon sequestration in terrestrial protected areas in China, showing an increase of 0.79% in the past 40 years. As to the desert ecosystems, from 1980 to 2020, the carbon sequestration of desert ecosystems in terrestrial protected areas increased from 2.87 Tg to 4.72 Tg, showing a significant increasing trend in the past 40 years (Table 1).

As to different climatic zones, carbon sequestration of terrestrial protected areas in the humid zone was mainly contributed by forest ecosystems, which had accounted for 73–75% over the last 40 years. Carbon sequestration of protected areas in the semi-humid zone was mainly contributed by grassland ecosystems, which had accounted for 31–35% over the last 40 years. Carbon sequestration of protected areas in semi-arid protected areas was mainly contributed by grassland and desert ecosystems, which had contributed 28–32% and 22–40% over the last 40 years, respectively. Carbon sequestration of protected areas in arid zones was mainly contributed by desert ecosystems, which had increased significantly over the last 40 years, from 54.17 to 65.83% (Table 2).

4. Discussion

Exploring the contribution of protected areas to carbon sequestration services is important to enhance the role of protected areas in climate change mitigation globally. This study analyzed the amount and changes of carbon sequestration of different types of protected areas in China from 1980 to 2020 and found that carbon sequestration in China's terrestrial protected areas has shown a significant increasing trend over the past 40 years. This finding is similar to the change of carbon density index in Asia from 1994 to 2015 (Shi et al., 2020). Recent studies had revealed that the total area of protected areas in China had covered 18 percent of land area, which were relatively effective for conserving most important ecosystems and key protected wild animals and plants (Wang and Li, 2021). In response to ecosystem degradation from rapid economic development, China began investing heavily in protecting and restoring natural capital starting in 2000, which had contributed significantly to the increases in key ecosystem services such as carbon sequestration (Ouyang et al., 2016). It could be concluded that these policies and practices of protected areas in China were beneficial to enhance the carbon sequestration capacity, which is similar to the global situation (Shi et al., 2020). Even so, the terrestrial protected areas we studied covered approximately 15% of China's total land area, and the proportion of carbon sequestration in these protected areas to the total carbon sequestration in China's terrestrial ecosystems ranged from about 14 to 16%. Comparing to the carbon sequestration capacity of global terrestrial protected areas which accounted for approximately 20% of all terrestrial ecosystem (Melillo et al., 2016), there is still room for improvement in the carbon sequestration services of protected areas in China.

Among the different types of terrestrial protected areas in China, nature reserves had the greatest carbon sequestration, accounting for 64 to 66% of the total carbon sequestration in terrestrial protected areas. Furthermore, the proportion of carbon sequestration in nature reserves had shown a significant increase over the past 40 years. These findings are easily understood because nature reserves are the foundation of China's protected areas, accounting for the highest proportion of all protected areas and are the most strictly protected type of protected areas in China (Wang and Li, 2021). Studies have also shown that strictly protected areas play a positive role in protecting forest ecosystems (Feng et al., 2021) and provide greater benefits in terms of carbon stock and carbon sequestration at the national and global scale (Liu et al., 2017).

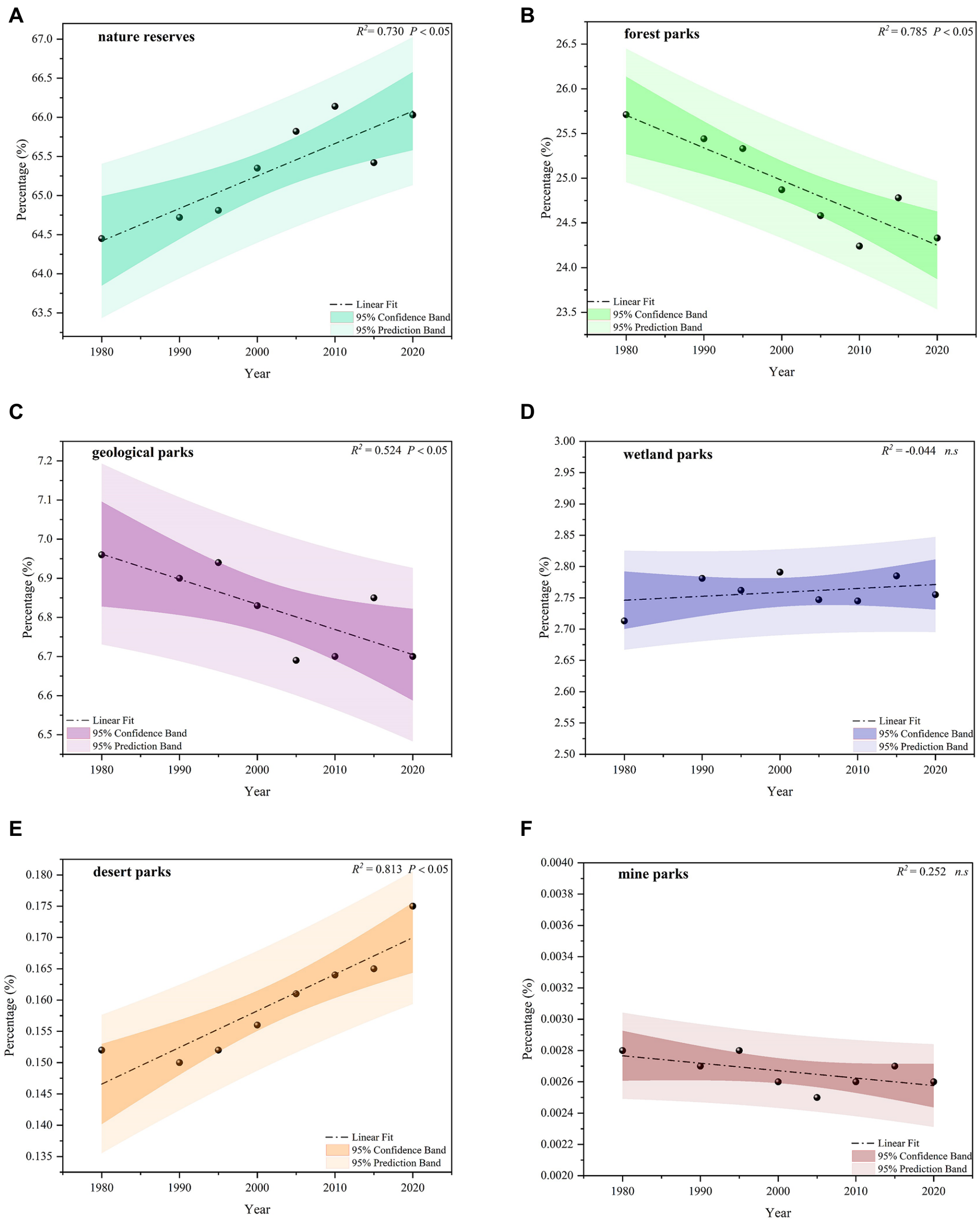

FIGURE 2
The proportion of carbon sequestration of different types of protected areas from 1980 to 2020: **(A)** nature reserves, **(B)** forest parks, **(C)** geological parks, **(D)** wetland parks, **(E)** desert parks, and **(F)** mine parks.

Our results also revealed that forest parks were the second in total carbon sequestration of China's terrestrial protected areas, accounting for 24 to 26%. Although the carbon sequestration per unit area of forest parks was the highest among all types of protected areas, the proportion of carbon sequestration of forest parks tended to decrease significantly over the past 40 years. Considering forest ecosystems were the mainstay of forest parks and played an important role in stabilizing the carbon cycle (Hu and Duan, 2020), it was not surprised that the carbon sequestration per unit area of forest parks was the highest. But the major component of the forest ecosystems in China were near-mature, mature, or over-mature forests, together accounting for 40% of the natural forest ecosystems (Pu, 2013). The net productivity in those forest ecosystems may gradually decline with the age of forests (Zhu, 2020). This also explains why the proportion of carbon sequestration in forest parks shows a significant decreasing trend. Therefore, in the future, the area of forest parks can be further expanded, and the quality of plantation forests can be enhanced by implementing forest quality precision enhancement projects and strengthening forest nurturing and management measures, thus further improving the carbon sequestration of forest parks (Li et al., 2021).

Among different ecosystems in China's terrestrial protected areas, the largest carbon sequestration was forest ecosystems, followed by grassland ecosystems. This is also directly related to the carbon sequestration capacity of each type of ecosystem, with forest ecosystems sequestering the most carbon among all types of terrestrial ecosystems in China, accounting for 68 to 71%, while other ecosystems (wetlands, grasslands, and scrub) account for about 17 to 19% (Huang et al., 2022). Our results also showed that carbon sequestration of protected areas in the humid zone had been

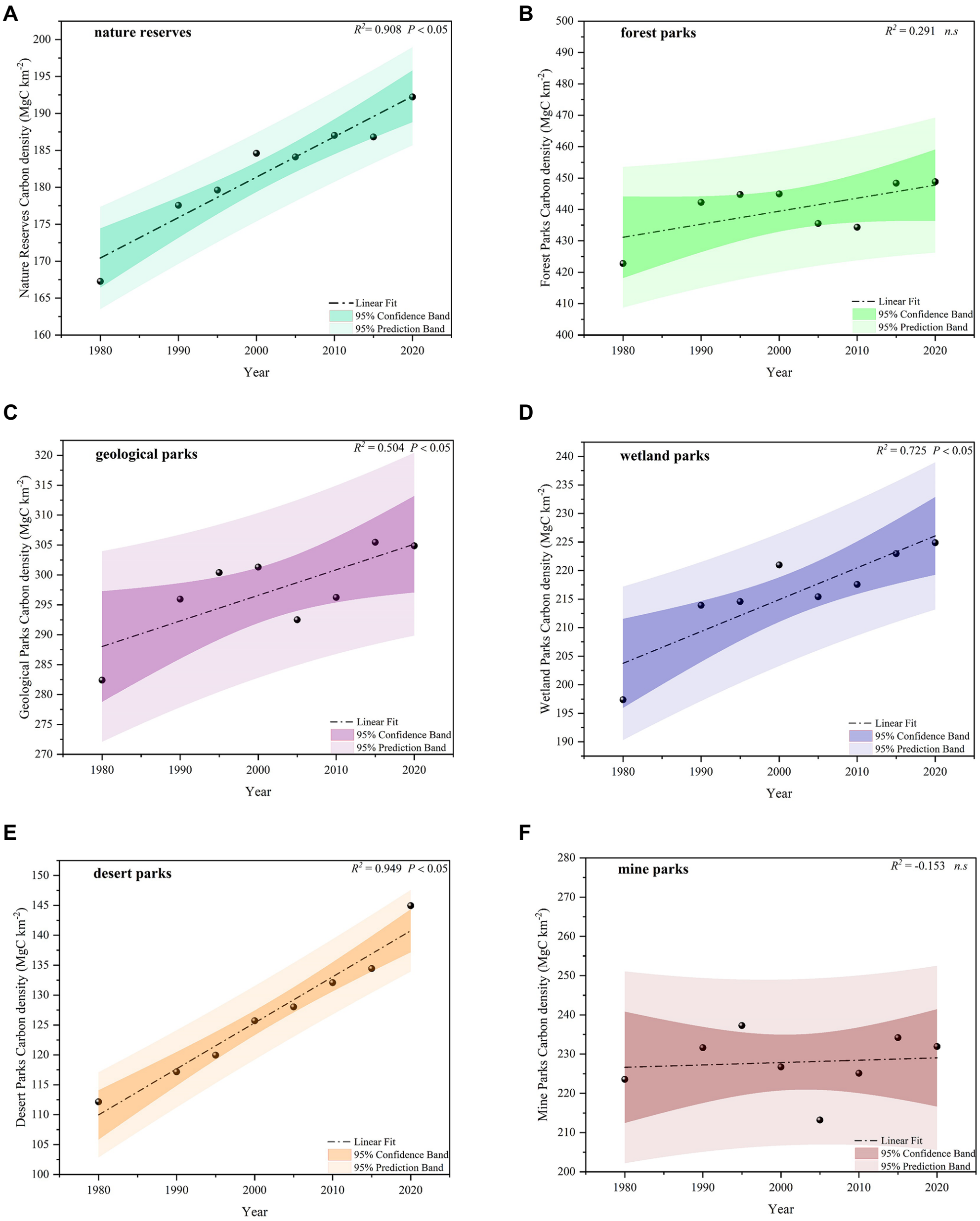

FIGURE 3
Carbon sequestration per unit area of different types of protected areas from 1980 to 2020: **(A)** nature reserves, **(B)** forest parks, **(C)** geological parks, **(D)** wetland parks, **(E)** desert parks, and **(F)** mine parks.

mainly contributed by forest ecosystems over the past 40 years. The findings are similar to the Southeast Asia's forests which play important roles in global carbon balance (Estoque et al., 2019). In addition, grassland and desert ecosystems in terrestrial protected areas in regions with low rainfall (e.g., semi-arid and arid) had made more contribution to carbon sequestration services. Particularly, desert ecosystems in terrestrial protected areas had shown a significant increase in carbon sequestration over the last 40 years. This is closely related to the fact that China has carried out a lot of work on sand and wind control and desertification control in the western region since the 1960s, which has effectively improved the ecosystem in the north-western region (Gao, 2022).

Strengthening the effective management of different types of protected areas is an effective means of enhancing and protecting ecosystem carbon sequestration, which can play a positive role in mitigating global warming and protecting biodiversity (Bai and Wang, 2021). Our study showed that China's terrestrial protected areas had played an important role in carbon sequestration over the past 40 years, but there are still some gaps compared to the global level, and the planning and establishment of protected areas need to be further strengthened in the future. The expansion of protected area should prioritize opportunities to protect climate refugia and ecosystems which store high levels of irrecoverable carbon (Carroll and Ray, 2021). And exploring possible cobenefits for prioritizing carbon and biodiversity hotspots can both enable the fulfillment of climate targets and facilitate biodiversity conservation (Zhu et al., 2021). Furthermore, integrating biodiversity, key ecosystem services (such as water retention, soil retention, sandstorm prevention, and carbon sequestration), and human activities would be important to balance the conservation and

TABLE 1 Carbon sequestration of different terrestrial ecosystems in terrestrial protected areas in China.

Year	Forest ecosystems		Grassland ecosystems		Desert ecosystems	
	Carbon storage (Tg C)	Percentage (%)	Carbon storage (Tg C)	Percentage (%)	Carbon storage (Tg C)	Percentage (%)
1980	189.34	63.43	66.32	22.22	2.87	0.96
1990	195.03	61.80	72.96	23.12	3.14	0.99
1995	194.99	61.17	74.40	23.34	3.65	1.15
2000	196.68	60.54	78.08	24.03	3.80	1.17
2005	191.15	59.41	79.89	24.83	4.31	1.34
2010	191.02	58.73	76.83	23.62	5.68	1.75
2015	196.16	59.72	74.44	22.66	4.94	1.50
2020	199.46	59.56	77.06	23.01	4.72	1.41

TABLE 2 Carbon sequestration of different terrestrial ecosystems and climatic zones in terrestrial protected areas in China.

Climate zones	Ecosystems	Percentage (%)							
		1980	1990	1995	2000	2005	2010	2015	2020
Wet zones	Forest	75.51	74.80	75.30	74.60	73.76	73.61	74.18	73.48
	Grassland	25.45	23.74	23.61	22.64	21.21	21.36	22.44	20.54
	Desert	2.04	1.94	1.74	1.62	1.43	0.69	0.84	0.58
Semi-humid zones	Forest	17.31	17.77	17.69	17.97	18.46	18.81	18.28	18.63
	Grassland	31.49	32.23	35.40	33.46	33.46	35.64	35.72	34.11
	Desert	9.49	10.59	6.02	10.66	9.93	4.13	4.60	4.75
Semi-arid zones	Forest	5.48	5.69	5.35	5.63	5.91	5.88	5.90	5.71
	Grassland	28.17	29.57	28.39	29.58	30.49	30.58	29.71	32.57
	Desert	34.29	35.96	22.83	38.71	39.14	29.20	27.77	28.85
Arid zones	Forest	1.70	1.74	1.66	1.80	1.86	1.70	1.64	2.19
	Grassland	14.89	14.46	12.61	14.32	14.51	12.43	12.13	12.78
	Desert	54.17	51.51	69.40	49.00	49.50	65.98	66.78	65.83

sustainable development goals (Xu et al., 2017). At the same time, in the future planning of protected areas, the ecosystem and climatic conditions should be considered to identify priority conservation areas with the aim to improve carbon sequestration capacity. And forest ecosystem in wet areas, grassland ecosystem in semi-humid areas, and desert ecosystem in semi-arid and arid areas should be provided with higher priorities in future conservation activities.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/supplementary material.

Author contributions

JT conceptualization, methodology, and writing—original draft preparation. CF and GF methodology, software, and formal analysis. LF methodology. WW supervision, writing—review, and editing. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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