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Accounting of value of ecosystem services in the desert: an example of the Kubuqi Desert ecosystem

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Ecological products and ecosystem services are essential for human survival and development. Gross Ecosystem Product (GEP) is a method to combine the value of ecosystem services and can reflect the status of ecosystem and ecological conservation and restoration performance. The conservation and restoration of desert ecosystems play an important role in expanding global cultivated land, ensuring food security, and improving human wellbeing. However, ecosystem services and the value of GEP in deserts have been neglected. Taking the Kubuqi Desert ecosystem as an example, this study evaluated the pattens, GEP value, and its change in the Kubuqi Desert ecosystem from 2000 to 2020. Our study found that 1) over the past 20 years, the areas of wetlands, forests, grasslands, and shrubs in the Kubuqi desert ecosystem had increased by 100.65%, 6.05%, 2.24%, and 2.03%, respectively, while that of desert had decreased by 10.62%; 2) the GEP of Kubuqi in 2020 was 55.48 billion CNY, among which its sandstorm prevention value was the highest (39.39%); 3) The value of ecosystem services in the Kubuqi desert ecosystem were all increased over the 20-year period and the largest increase came from sandstorm prevention (increased by 195.09%). This study emphasizes how GEP accounting can promote desert conservation and restoration, quantifies the contribution of desert ecosystems to human wellbeing, and provides future GEP accounting suggestions for desert ecosystems. This study can provide scientific information on the conservation and restoration of global desert ecosystems.

KEYWORDS

desert, ecosystem services, gross ecosystem product, Kubuqi Desert ecosystem, ecosystem patterns

1 Introduction

Desert ecosystems are an important part of terrestrial ecosystems, accounting for approximately one-third of the land area, covering tropical, subtropical, temperate, and polar regions, and having an amazingly high biodiversity, including some of the world's most endangered species and (Safriel and Adeel, 2005) supporting nearly 2.5 billion people worldwide (Burrell et al., 2020). In addition, desert and other dryland ecosystems currently hold nearly one-third of the global terrestrial carbon reserves, and there is further potential for carbon sequestration through improved land management (Trumper et al., 2008). In addition, desert genetic biodiversity is key to improving agricultural productivity in drylands (Darkoh, 2003). However, desertification is intensifying in many parts of the world, affecting the livelihoods of 1.3 billion people worldwide (Van der Esch et al., 2017). Therefore, desert conservation and restoration are important for human survival and development. Transforming deserts into cultivated land is conducive to ensuring global food security and food demand. Restoration of deserts can provide more space for human survival and development and ensure human wellbeing in the future. Although deserts are of great significance for global ecological conservation and restoration, desert ecosystems have not been widely focused on, and the conservation and restoration of desert ecosystems have not received much attention from scholars and the public. Evaluating the value of ecosystem services of desert ecosystems can be a way to quantify how important a desert ecosystem is and attract more attention to desert ecosystem conservation and restoration.

Ecosystem services refer to the benefits that humans obtain directly or indirectly from ecological processes (Costanza et al., 1998; Daily, 2017). And Gross Ecosystem Product (GEP) provides a methodology to quantify the benefits of desert ecosystems to human beings (Ouyang et al., 2020). Against the complex background of a continuously increasing population and increasing demand for food, it is of great significance to carry out desert GEP accounting: It not only helps to improve people's understanding of the relationship between desert ecosystems and human wellbeing, but also helps to quantitatively evaluate the results of improving the quality and efficiency of desert ecosystems. Thus, it provides a scientific basis for decision makers to conserve and restore desert ecosystem more effectively, and allow for the sustainable development of desert ecosystems. The desert ecosystem does not only include deserts, but also grasslands, forest lands, wetlands, and cultivated lands, which can provide a variety of ecosystem services. However, little earlier research has focused on valuing desert ecosystem services. Constanza valued the global ecosystem services in 1997 but did not value desert ecosystems (Costanza et al., 1997). In 1999, Ouyang et al. (Ouyang et al., 1999a). estimated the value of China's terrestrial ecosystem services which included the value of desert ecosystem. Based on this, the value of desert ecosystem services has been revealed and scholars have begun to put the value of desert ecosystems into account in desert-related areas (such as oasis deserts) (Sawut et al., 2013; Taylor et al., 2017; Wei et al., 2018; Jordaan et al., 2021). GEP is the sum of the monetary value of final ecosystem services, including values of provisioning ecosystem goods services, values of regulating ecosystem services, and values of cultural ecosystem services. China is using GEP to guide investments in ecosystem conservation and restoration. At present, there are numerous projects that have been carried out in China to explore GEP accounting across provinces, cities, and counties, and as a policy metric it is being tested in pilot programs by numerous local governments (Dong et al., 2019; Jin et al., 2019; Ouyang et al., 2020; Zou et al., 2020), but there are few evaluation studies on the GEP value of desert ecosystems.

Previous studies provided technical methods and ideas for desert ecosystem assessment and made the value of desert ecosystem services widely recognized. However, at present, there is a research gap in GEP value assessment of desert ecosystems focusing on the spatial-temporal scale, and the current situation and change trend of desert ecosystem patterns and GEP value are not clear. It is difficult for decision makers to measure the effect of desert conservation and restoration decisively, which is not conducive to the sustainable promotion of desert conservation and restoration. Therefore, this study takes the Kubuqi Desert ecosystem in Inner Mongolia as an example to analyze its ecosystem pattens and changes and evaluate its GEP value and its change from 2000 to 2020. Desertification is a serious global ecological problem. Kubuqi Desert ecosystem conservation and restoration practices are widely known and provide a pathway for desert ecosystem management. Assessing the GEP value and quantifying the ecosystem services of the Kubuqi Desert ecosystem is of great significance for promoting global desert ecological protection and restoration.

2 Methodology and data

2.1 Study area

The Kubuqi Desert ecosystem is the seventh largest desert in China (Wang et al., 2020). It is mostly located on the Hangjin Banner, in Ordos City, in the Inner Mongolia Autonomous Region, and borders Bayannur City in the north across the Yellow River. The highest point of the Kubuqi area is about 1,588.00 m above sea level (Figure 1) and covers a total area of 18,620.60 km^2. The Kubuqi Desert ecosystem is not only a desert, but also includes grassland, forest land, wetland, and cultivated land ecosystem. With its vast grassland and variable natural environmental conditions, the Kubuqi Desert ecosystem is one of the most typical and representative areas of arid and semi-arid regions of China. With a medium temperate and an arid and semi-arid continental monsoon climate, this windy and sandy region is characterized by dryness, lack of rain, and high evaporation.

2.2 Data acquisition

The 30 m resolution land cover data came from the National ecosystem survey and assessment of China projects from 2000 to 2010, and from 2015 to 2020 by the Chinese Academy of Sciences and Ministry of Ecology and Environment (https://www.ecosystem.csdb.cn/). The average annual rainfall, surface runoff, and evapotranspiration data came from the database of the Chinese Academy of Sciences and has been used in other studies of ecosystem service dynamics in the country (https://www.ecosystem.csdb.cn/index.jsp). The ecosystem classification, biophysical quantity, and the accounting parameters, monetary value, and price parameters of the Kubuqi desert ecosystem are mainly obtained from references (Xiao et al., 2016; Lu, 2018a). And the GEP value of the Kubuqi desert ecosystem was adjusted to a 2020-based value by using the consumer price index, which can be obtained through the National Bureau of statistics of China.

2.3 Indicator system for Kubuqi Desert ecosystem GEP accounting

Desert ecosystems are an important part of terrestrial ecosystems. The ecosystem services in desert ecosystems, especially the regulating ecosystem services, such as sandstorm control, carbon sequestration, oxygen release, water retention, and soil retention, are important elements to both the desert ecosystem and human wellbeing.

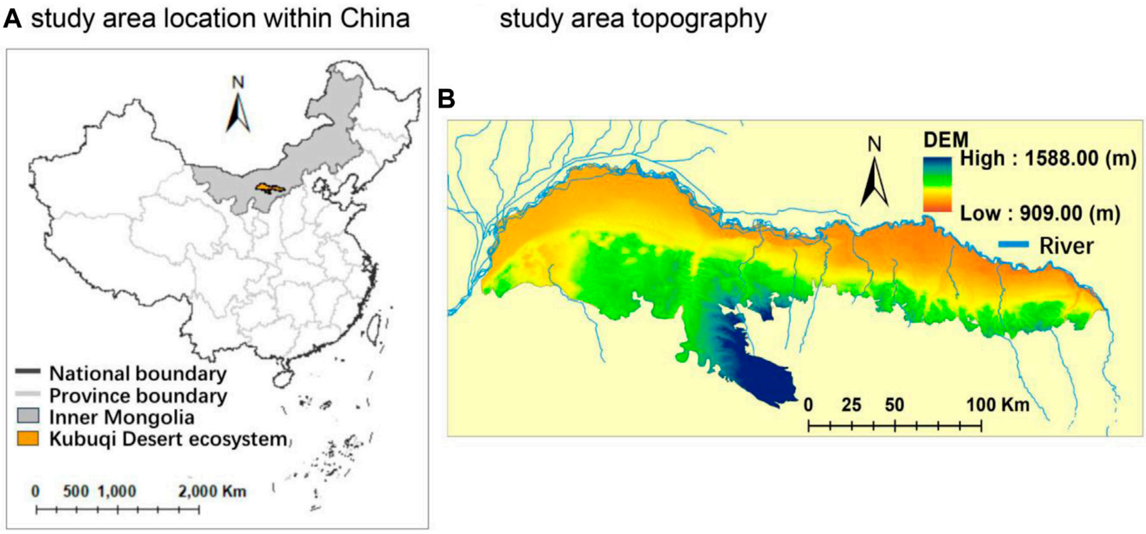

FIGURE 1
The location of Kubuqi. **(A)** Study area location within China; **(B)** Study area topography.

TABLE 1 Kubuqi Desert ecosystem GEP Accounting Indicators and Methods.

Service	Accounting subject	Biophysical quantity indicator	Biophysical quantity accounting method	Monetary value indicator	Monetary value accounting method
Provisioning ecosystem goods services	Agricultural products	Output of agricultural products	Statistical survey	Value of agricultural products	Market value
	Forestry products	Output of forest products		Value of forestry products	
	Animal husbandry products	Output of animal husbandry products		Animal husbandry products	
Regulating ecosystem services	Sandstorm prevention	Sandstorm prevented	Revised Wind Erosion Equation (RWEQ)	Sandstorm prevention value	Recovery cost
	Water retention	Water retained	Water Balance Equation	Water retention value	Shadow engineering
	Soil retention	Soil retained	Revised Universal Soil Loss Equation (RUSLE)	Value of reduction of siltation	Replacement cost method
				Value of reduction of non-point source pollution	
	Carbon sequestration	Carbon dioxide fixed	Carbon sequestration rate method	Carbon sequestration value	Replacement cost method
	Oxygen release	Oxygen released	Model of oxygen release mechanism	Oxygen release value	Replacement cost method

Sandstorm prevention is one of the most important functions in desert areas, which can improve climate environment, reduce wind erosion, and stop the expansion of quicksand. Sandstorm prevention in the Kubuqi Desert ecosystem plays a pivotal role in reducing the siltation of the Yellow River and sandstorms in China's capital city, Beijing. Water is the limiting factor for desert ecosystems to function and maintain ecological balance. Since sound water retention function often means better distribution of forest ecosystems., the change in water retention reflects the ecological management effectiveness of the Kubuqi Desert ecosystem. In addition, soil retention also works through reducing topsoil loss, protecting soil fertility, mitigating sedimentation disaster, and reducing sandstorms, which is an indispensable indicator to evaluate the ecosystem services of the Kubuqi Desert ecosystem. Also, the oxygen released by plant respiration, as well as the positive effect of desert vegetation in reducing the concentration of carbon dioxide in the atmosphere through photosynthesis, slowing down greenhouse gas production, cannot be ignored. Considering the fact that China has a large population and inadequate arable land, the desert ecosystem, with its vast area, has become the focus of development in China, especially in West China, and its function of providing material products is an important indicator to measure the value of the desert ecosystem. Therefore, focusing on the conservation and restoration effects of the Kubuqi Desert ecosystem, the indicator system for accounting the GEP of the Kubuqi Desert ecosystem covers the

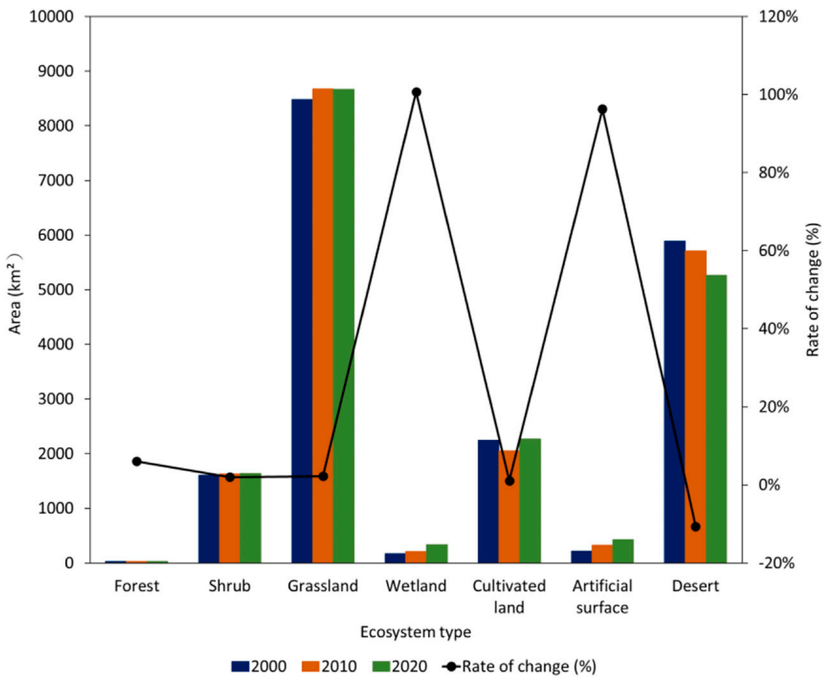

FIGURE 2
Area and rate of change rate in the Kubuqi Desert ecosystem.

values of provisioning ecosystem goods and values of regulating ecosystem services. The values of provisioning ecosystem goods services include values of agricultural products, forestry products, livestock products, etc., the values of regulating ecosystem services include values of sandstorm control, water retention, soil retention, carbon sequestration, and oxygen release (Table 1).

We assessed the biophysical quantities and monetary value of ecosystem services in the Kubuqi Desert ecosystem using a variety of data and models. Socio-economic data, hydrological data, and meteorological monitoring data came from publicly available, official statistical sources maintained by the associated provincial and national government departments. Data on the biophysical and economic factors, such as prices and inflation, and parameters of ecosystem services, were also taken from official data sources as well as the relevant literature. The evaluation methods are shown in Table 1. The accounting method mainly refers to *the Accounting Theory and Method of Gross Ecosystem Product (GEP)* (Ouyang et al., 2021) (Table 1; Supplementary Text S1).

3 Results

3.1 Ecosystem patterns and change

The Kubuqi Desert ecosystem covers a total area of 18,620.60 km^2. Forest, shrub, grassland, wetland, farmland, artificial surface, and desert constitutes Kubuqi Desert ecosystems. Its grassland ecosystem, with an area of 8,669.21 km^2, or 46.56% of the desert, accounts for the largest part of the entire Kubuqi Desert ecosystem, including 24.03% warm typical grassland, 21.22% warm desert grassland, and 1.31% warm meadow grassland. The next largest parts are desert (5,261.03 km^2) and farmland (2,268.19 km^2) ecosystems. These three types of ecosystems account for 86.99% of the Kubuqi Desert ecosystem's total area (Figure 2; Table 2).

The grassland ecosystem is mainly distributed in southern areas of the Kubuqi Desert ecosystem. And the desert is distributed in the medium area of the Kubuqi Desert ecosystem. Cultivated land us distributed to the east of the Kubuqi Desert ecosystem, with sporadic distribution of artificial surfaces in farmland ecosystems (Figure 3).

Between 2000 and 2020, the ecosystem of Kubuqi Desert remained stable: its grassland was accounting for the largest part and was followed by desert. The area of natural ecosystems, including wetlands, forests, shrubs, and grassland, was gradually increasing and the area of desert steadily decreasing. Over the 20 years, the areas of wetlands, forests, grasslands, and shrubs had increased by 100.65%, 6.05%, 2.24%, and 2.03%, respectively, while that of desert had decreased by 10.62%.

3.2 GEP values and changes

In 2020, the GEP of the Kubuqi Desert ecosystem was 55.48 billion yuan (CNY), among which its sandstorm prevention value was the highest, amounting to 21.85 billion CNY, and accounting for 39.39% of the GEP of Kubuqi Desert ecosystem. Water retention contributed the next highest value, totaling 21.38 billion CNY or 38.56% of the GEP. The other components of its GEP included values of provisioning ecosystem goods (12.00%), carbon sequestration value (6.24%), oxygen release value (3.67%), and soil retention value (0.13%).

The Kubuqi Desert ecosystem's GEP value increased from 30.80 billion CNY in 2000 to 55.48 billion CNY in 2020 (Table 3). After accounting for inflation and comparing values based on inflation-

TABLE 2 Area and proportion of ecosystems in the Kubuqi Desert ecosystem.

Type	2000		2010		2020	
	Area (km^2)	Proportion (%)	Area (km^2)	Proportion (%)	Area (km^2)	Proportion (%)
Forest	26.46	0.14	27.23	0.15	28.06	0.15
Shrub	1,602.00	8.60	1,624.71	8.73	1,634.55	8.78
Grassland	8,479.64	45.54	8,675.83	46.59	8,669.21	46.56
Wetland	165.56	0.89	205.31	1.10	332.19	1.78
Cultivated land	2,243.38	12.05	2051.63	11.02	2,268.19	12.18
Artificial surface	217.74	1.17	325.21	1.75	427.38	2.30
Desert	5,885.82	31.61	5,710.67	30.67	5,261.03	28.25
Total	18,620.60	100	18,620.60	100	18,620.60	100

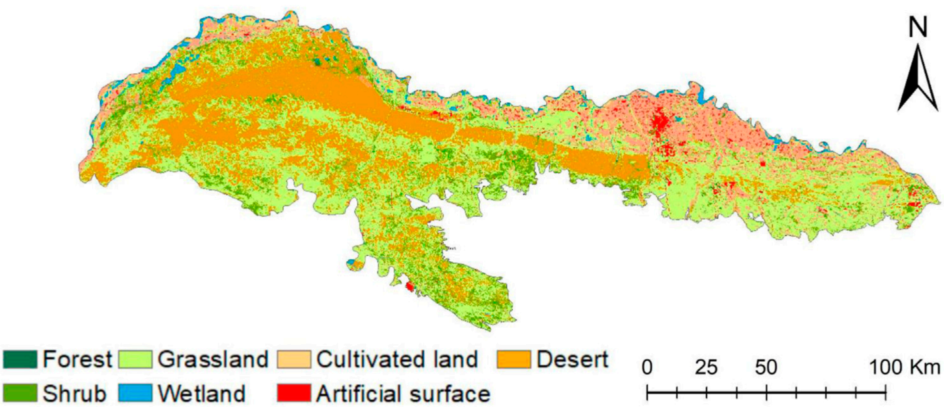

FIGURE 3
Spatial distribution of ecosystem types in the Kubuqi Desert ecosystem in 2020.

TABLE 3 GEP of the Kubuqi Desert ecosystem in 2020, 2010, and 2000.

Category	Subject	GEP (100 million yuan)		
		2000	2010	2020
Provisioning ecosystem goods services	Agriculture	14.95	33.67	33.35
	Forestry	1.14	2.81	1.76
	Animal Husbandry	9.96	29.68	31.48
Regulating ecosystem services	Sandstorm prevention	74.05	131.15	218.52
	Water retention	177.69	179.38	213.82
	Soil retention	0.56	0.6	0.73
	Carbon sequestration	18.65	23.04	34.62
	Oxygen release	10.97	13.56	20.37
Total		307.97	413.89	554.75

adjusted prices, the actual growth rate over the 20 years was 80.12%. Twenty years later, the provisioning ecosystem goods service value of the Kubuqi Desert ecosystem had increased to 6.66 billion CNY, accounting for 12.00% of that year's GEP, an increase of 155.49%. Secondly, the value of regulating services increased from 28.19 billion CNY to 48.81 billion CNY, an increase of 136.70% after adjusting for inflation.

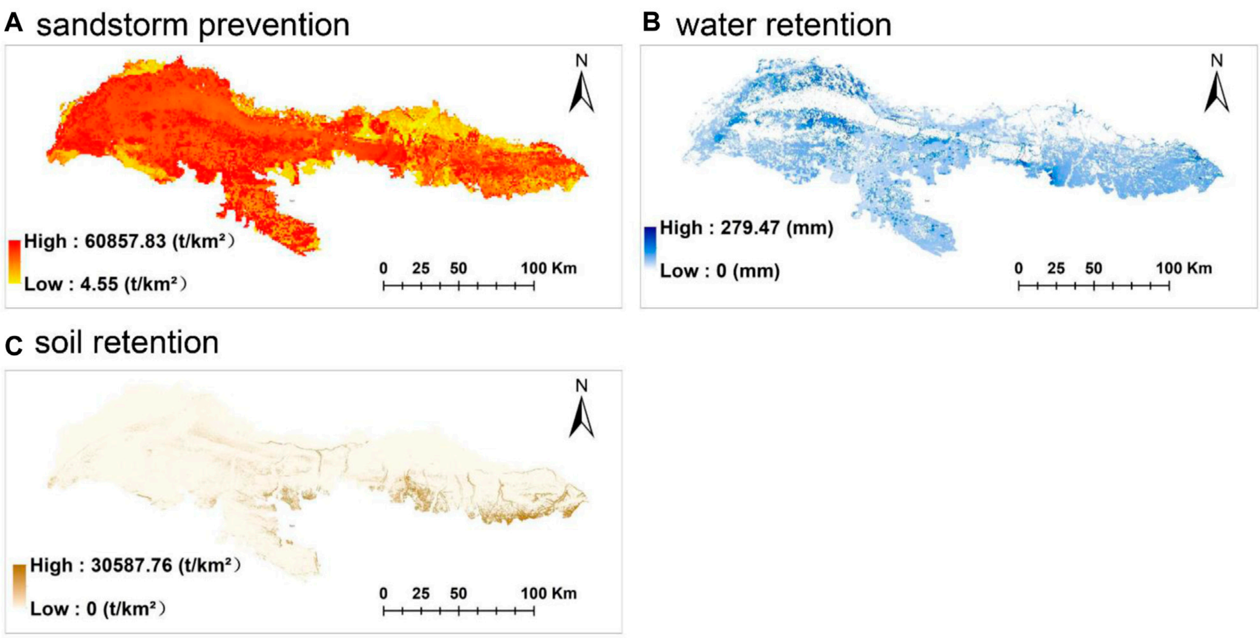

FIGURE 4
Spatial distribution of sandstorm prevention, water retention, and soil retention in the Kubuqi Desert ecosystem in 2020. **(A)** The biophysical quantity of sandstorm prevention service; **(B)** The biophysical quantity of water retention service; **(C)** The biophysical quantity of soil retention service.

3.3 Change of regulating services' biophysical quantity and monetary value

As the main component of Kubuqi Desert ecosystem GEP, we conducted a more detailed analysis of regulating ecosystems services. Sandstorm prevention, water retention, soil retention, carbon sequestration, and oxygen release constituted the regulating services of Kubuqi Desert ecosystem GEP accounting.

From the perspective of biophysical quantity, in 2020, the sandstorm prevention service retained a total of 681,677,000 tons of sand in Kubuqi. The water retention service retained a 804.53 million m^3 volume of water in Kubuqi. In addition, 3.60 million tons CO_2 were fixed and 2.62 million tons of O_2 released in Kubuqi. And 13.46 million tons of soil in the Kubuqi Desert ecosystem have been retained. From the perspective of monetary value, the value of regulating services was 48.81 billion CNY and the sandstorm prevention accounted for the largest share at 39.39% (21.85 billion CNY). This was followed by the value of water retention and carbon sequestration, accounting for 21.38 billion CNY and 3.46 billion CNY, respectively. And the value of oxygen release and soil retention was 2.04 billion CNY and 0.07 billion CNY, respectively. From the perspective of spatial distribution (Figure 4), almost all areas in Kubuqi Desert ecosystem, especially eastern, provided sandstorm prevention services in 2020. The northwest of the Kubuqi Desert ecosystem was the main contribution area of water retention services while the southeast edge of the Kubuqi Desert ecosystem was the main contribution area of soil retention services. According to our calculations, the spatial pattern and changes in the value of regulating services bear significant spatial relation to changes in the pattern and quality of the region's natural ecosystems.

The value of these five types of regulating services all increased over the 20-year period. The largest increase came from sandstorm prevention (increased by 195.09%), followed by carbon sequestration and oxygen release (both increased by 85.61%).

4 Discussion

4.1 Driven forces of GEP values and changes in the Kubuqi Desert ecosystem

Changes in GEP are related to changes in the area of ecosystems. Over the 20 years, the area of forest, grassland, shrub, and wetland in the Kubuqi Desert ecosystem were increased while desert area was decreased. This change in area of ecosystems is driven by conservation and restoration policies, government and public participation in desert conservation and restoration, and technological innovation.

A number of major ecological protection construction projects in China were implemented around the year 2000. Among them, China's "three north" shelterbelt project, Beijing-Tianjin sandstorm source control project, natural forest protection, conversion of farmland to forest and grassland, and other large national ecological construction projects played a role in the conservation and restoration of the Kubuqi Desert ecosystem (Zhang et al., 2016; Niu et al., 2023).

Public participation in Kubuqi Desert ecosystem conservation and restoration has been encouraged by favorable policies. In 2000, the Ordos government established a number of policies to support the conservation and restoration of deserts. (e.g., ecological migration, grazing prohibition, and ecological infrastructure construction). This has stimulated the whole society to participate in desert ecological governance by attracting stakeholders other than the government. A series of preferential policies and measures were also adopted to encourage and guide the public (enterprises, farmers, and herdsmen) in participating in the prevention and control of desertification through contractual agreements, shareholdings, leasing, and investments in human capital (Han et al., 2015; Yan and Feng, 2020).

Furthermore, profits from the desertification industry are steadily contributing to the conservation and restoration of the Kubuqi Desert ecosystem. Local government effectively promoted technological innovations and market intervention in the area of conservation and restoration of the Kubuqi Desert ecosystem. The Kubuqi Desert ecosystem has abundant solar energy, which is attracting photovoltaic power generation to the area and creating profits in the process. According to Elion Group, a company known for its desert conservation and restoration projects, it achieved a profit margin of 43% in its photovoltaic power generation project in the Kubuqi Desert ecosystem from 2010 to 2020. By generating considerable profit, the investment in Kubuqi Desert ecosystem conservation and restoration is extended from a solely public welfare venture to a commercial enterprise. In this way, a solid economic foundation was built for ensuring investment in conservation and restoration in Kubuqi Desert ecosystem.

Finally, local farmers and herdsmen also participated in Kubuqi Desert ecosystem conservation and restoration. More than 1 million people have been employed for the conservation and restoration of the Kubuqi Desert ecosystem, and more than 100,000 farmers and herders have been able to escape poverty as a result. Kubuqi Desert ecosystem conservation benefits local residents, ensures sufficient numbers of participants for desertification governance, and promotes the effective conservation and restoration of Kubuqi Desert ecosystems.

In conclusion, policies, the government, and the public combined to promote the continuous implementation of the conservation and restoration of the Kubuqi Desert ecosystem and promoted the increase of the ecosystem area of the Kubuqi Desert ecosystem. From 2000 to 2020, a total of 6,000 $km^2$of desert had been treated (Xinhua News Agency, 2020), which is over one-third of the total area of the Kubuqi Desert ecosystem. The areas of forests, wetlands, grasslands, and shrubs increased, prompting an increase of 24.68 billion CNY in GEP.

4.2 GEP accounting in the Kubuqi Desert ecosystem benefits sustainable desert conservation and restoration

GEP benefits desert conservation and restoration. The desert ecosystem is characterized by its extremely fragile ecological environment and poor living conditions. Desert ecosystems have always been more neglected by decision makers in ecological construction projects compared with biodiversity and land planning, which have attracted widespread attention. Because GEP presents the contribution of different ecosystem services to human wellbeing by converting them into monetary value (GDP), it makes the Kubuqi Desert's ecosystem services easy to interpret. The economy has a significant impact on ecosystem construction globally and economic growth is a crucial indicator of the effectiveness of local and national governments. GEP provides a method to convert ecosystem services and their changes into easily and comparable monetary values. This makes it simpler for the public and private sector decision makers to understand. We can regard the desert ecosystem GEP accounting as one of the assessment indicators in addition to economic growth, which is of great significance to attract more policymakers to promote the conservation and restoration of desert ecosystems.

By translating the value of ecosystem services into a widely understood monetary value, GEP has promoted social and public interest in the sustainable development of desert ecosystems. The government, enterprises, and residents in the Kubuqi Desert ecosystem participated in the process of conserving and restoring the ecosystem. Our results showed that desert conservation and restoration effectively changed the quality and quantity of the ecosystems and the resulting value of GEP was increased by 80.12%. Moreover, investment in ecosystem assets benefits economic growth and helps locals out of poverty (discussion 4.1). The results from the Kubuqi Desert ecosystem show that investment in ecosystem assets can generate a high rate of return in the form of increased value of ecosystem services. Taking the Kubuqi Desert ecosystem as an example, the increase in GEP value indicated good potential for expanding the conservation and restoration of desert ecosystems globally.

More importantly, the economic value generated by the desert ecosystem can be used as the basis for ecological compensation. The Kubuqi Desert ecosystem is the closest sand source to Beijing and is a major sand source in Beijing, Tianjin, and Hebei provinces. The ecological conservation and restoration of the Kubuqi Desert ecosystem is not only of great significance to the improvement of the local ecological environment in Inner Mongolia, but has also significantly improved the environmental air quality problems caused by sand and dust in the downstream provinces by increasing vegetation coverage, enhancing sand-fixing capacity, and reducing the amount of sand and dust transmission in the desert. The local decision makers of Inner Mongolia can put forward ecological compensation demands to Beijing, Tianjin, and Hebei province, and the GEP value can be used as a scientific-based reference for the amount of compensation. We provide a tractable method for desert ecosystem assessment, which can be adopted globally, used as the basis for ecological compensation, and guide investments in desert ecosystem conservation and restoration.

In addition, our results emphasize that, although the desert is characterized as fragile, dry, and not suitable for human habitation, it can also contribute to human wellbeing. Land use and land cover (LULC) change is the most direct driver of global terrestrial ecosystems (Díaz et al., 2019) and will therefore affect the ability of ecosystems to provide the services that humans ultimately depend on (Wan et al., 2015). The conservation and restoration of desert ecosystems will significantly change LULC, which will have a positive impact on increasing the global cultivated land area, ensuring global food security, expanding space for human survival and development, and benefitting human wellbeing.

4.3 Future GEP accounting in desert ecosystems

This study evaluated the changes of GEP value in the Kubuqi Desert ecosystem from 2000 to 2020 and found that GEP had

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increased over the past 20 years. Firstly, we emphasize that accounting of GEP value can be used to guide the performance of desert conservation and restoration in future.

Secondly, the maintenance of ecological construction in deserts needs to form a stable investment. The Kubuqi Desert ecosystem has gradually diversified the sources of investment from both public welfare and business investment, thus ensuring the sustainable progress of desert conservation and restoration. However, desert ecological conservation and restoration should not only be based on territorial division, but also on the basis of GEP value and economic compensation (to benefit areas such as Beijing, Tianjin, and Hebei province). Furthermore, the value realization of desert ecological products, such as the production of forestry, agricultural, and animal husbandry goods, ecotourism, and recreation, should be promoted to encourage economic growth and ensure a stable investment for desert conservation and restoration.

Finally, since statistical data worldwide is reported by administrative regions, and the Kubuqi Desert is not an administrative region, there is a lack of statistical data to calculate accurate cultural services in Kubuqi Desert GEP accounting. However, the cultural services generated by the desert ecosystem can be accurately accounted for in the future by establishing a complete data collection and statistical mechanism, especially for the number of desert tourists and travel costs. This is conducive to quantifying the nonmaterial benefits such as spiritual feelings, knowledge acquisition, leisure and entertainment, aesthetic experience, and other nonmaterial benefits obtained by human beings through desert ecosystems. Some of the data and models used in the current GEP biophysical calculations have shortcomings, mainly due to the limitations of the relevant ecological-environment monitoring system in terms of the frequency and resolution of data collection.

5 Conclusion

This study, using the Kubuqi Desert ecosystem as an example, has contributions to natural scientists, social scientists, decision makers, and the public, who are involved in desert ecosystem services and desert conservation and restoration. First, we identified the ecosystem patterns and changes in the Kubuqi Desert ecosystem and found that the grassland ecosystem was the largest part of the Kubuqi Desert ecosystem (8,669.21 km^2, 46.56% of the Kubuqi Desert ecosystem). Over the 20 years, the areas of wetlands, forests, grasslands, and shrubs had increased, while that of the desert had decreased. Second, by calculating the GEP value of the Kubuqi Desert ecosystem, we found the GEP of the Kubuqi Desert ecosystem in 2020 was 55.48 billion CNY and had increased from 2000 to 2020 based on the constant price in 2020. This was a result of increasing the area of ecosystems such as forests, grasslands, and wetlands and reducing desertification. Third, by analyzing regulating ecosystems services, the main component of Kubuqi Desert ecosystem GEP, we found that the sandstorm prevention value was the highest, amounting to 21.85 billion CNY, and accounting for 39.39% of the GEP of Kubuqi Desert ecosystem. And from 2000 to 2020, the value of regulating services all increased, and the sandstorm prevention value showed the largest increase of 195.09%. The cultural services can be included in future accounting of the Kubuqi Desert ecosystem once the statistics dataset has been completed. Overall, this study synergistically quantified the economic and ecological sense of desert ecosystems and its conservation and restoration. This study emphasizes how GEP accounting can support the conservation and restoration of desert ecosystems, assesses the value of desert ecosystems to human wellbeing, and makes recommendations for future GEP accounting for desert ecosystems. Finally, it should be pointed out that, although the study takes the Kubuqi Desert ecosystem as an example, the methodology of desert ecosystem GEP accounting and evaluation of the performance of desert conservation and restoration has worldwide significance.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

ZO designed the research. YL, LK, CJ, XZ, and ZO performed the research. YL conducted the analysis, wrote the paper, and drew figures. YL and ZO reviewed the paper, exchanged ideas, and prepared the final version of the manuscript. 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.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2023.1247367/full#supplementary-material

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