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Original Research

Exploring the complex trade-offs and synergies of global ecosystem services

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A B S T R A C T

The trade-off and synergy relationship of ecosystem services is an important topic in the current assessment. The value of each service provided by the ecosystem is substantially affected by human activities, and conversely, its changes will also affect the relevant human decisions. Due to varying trade-offs among ecosystem services and synergies between them that can either increase or decrease, it is difficult to optimize multiple ecosystem services simultaneously, making it a huge challenge for ecosystem management. This study firstly develops a global Gross Ecosystem Product (GEP) accounting framework. It uses remote sensing data with a spatial resolution of 1 km to estimate the ecosystem services of forests, wetlands, grasslands, deserts, and farmlands in 179 major countries in 2018. The results show that the range of global GEP values is USD 112−197 trillion, with an average value of USD 155 trillion (the constant price), and the ratio of GEP to gross domestic product (GDP) is 1.85. The trade-offs and the synergies among different ecosystem services in each continent and income group have been further explored. We found a correspondence between the income levels and the synergy among ecosystem services within each nation. Among specific ecosystem services, there are strong synergies between oxygen release, climate regulation, and carbon sequestration services. A trade-off relationship has been observed between flood regulation and other services, such as water conservation and soil retention services in low-income countries. The results will help clarify the roles and the feedback mechanisms between different stakeholders and provide a scientific basis for optimizing ecosystem management and implementing ecological compensation schemes to enhance human well-being.

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1. Introduction

Ecosystems, encompassing diverse landscapes, such as forests, agricultural lands, and wetlands, offer a plethora of benefits to human society. They are essential sources of timber, medicinal resources, food, and raw materials for industry and agriculture. Moreover, ecosystems are pivotal in climate regulation, water retention, wind and sand mitigation, and biodiversity conservation [1]. These benefits have become fundamental prerequisites for our survival and societal progression [2]. In the wake of the global assessment conducted by the United Nations (UN) Millennium Ecosystem Assessment (MA) project [3,4], the identification, quantification, and conservation of ecosystem services have emerged as dominant themes in academic discourse [5]. Numerous scholars have significantly advanced the field of ecosystem service

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valuation. Daily, for instance, was instrumental in providing a comprehensive and systematic definition of ecosystem services [6–8]. Concurrently, Costanza [9–12] spearheaded the comprehensive assessment of the global value of ecosystem services, revealing that their total value in 1994 was approximately USD 33 trillion. Subsequently, Ouyang et al. [13,14] introduced the Gross Ecosystem Product (GEP) indicator, quantifying the final ecosystem services to human society. Jiang [15] and Ma [16–18] were the first to evaluate GEP for different countries globally and provinces within China. Notably, the United Nations Statistical Commission has incorporated the GEP into the latest international standard, System of Environmental-Economic Accounting-Ecosystem Accounting (SEEA-EA), endorsing it as a metric for monitoring progress toward the UN Sustainable Development Goals (SDGs) 2030 [19]. Now, factors such as rapid population growth and global warming are straining the ecosystems' capacity to meet the current demands of human society. The urgency for scientific decisions and actions to protect and restore ecosystems at a global scale is imperative [20].

Exploring trade-offs and synergies between ecosystem services at both global and regional scales has emerged as a critical field in recent years [21,22]. The term “trade-off”, derived from economics, implies that an increase in one service often leads to a decrease in other services [23–27]. The concept is always represented by a win-lose relation [28–30]. Recognizing these trade-offs, particularly at spatial and temporal scales, is crucial, as overlooking them could significantly inhibit the benefits of ecological restoration or other engineering construction. The construction of dams serves as a pertinent example of such trade-offs. While dams are critical engineering structures for flood prevention, disaster reduction, irrigation, and electricity generation, they may also bring potential drawbacks, including alterations in downstream flow, reduction in submerged areas, and changes in river species [31]. Moreover, research shows that while large-scale ecological projects have augmented vegetation coverage in North and Northeast China, effectively mitigating the risk of soil degradation and erosion, they have also led to substantial consumption of water resources and a decrease in surface runoff within watersheds [32]. Synergy pertains to scenarios where external disturbances simultaneously enhance (win-win) or diminish (lose-lose) two or more ecosystem services. Synergistic relationships are typically more conspicuous than trade-off relationships. Huang [29] revealed synergistic relationships between water production and net primary productivity (NPP) and between water production and livestock supply in Xizang. Furthermore, the manifestation of trade-offs/synergies will be inconsistent if the spatial scale changes [29,33]. When transitioning from the autonomous region scale to the county scale, the relationship between water production and NPP shifts from synergy to trade-off. It is noted that some trade-offs are inherent, originating from underlying biophysical processes, while others can be moderated to a certain degree through management, for example, diversifying the regulatory, supportive, and cultural services provided by a single landscape through strategic decisions. Therefore, comprehensive understanding and balancing of these trade-offs and synergies among ecosystem services are crucial for formulating effective ecosystem policies and managing or restoring ecosystems.

While trade-off relationships can be attributed to shared drivers between different services and their interactions [34,35], a comprehensive understanding of the influencing factors behind ecosystem service trade-offs/synergies is a prerequisite for effective management. Current research primarily focuses on identifying the spatiotemporal characteristics of trade-off/synergy, with relatively insufficient attention given to the mechanisms behind it. The influencing factors could be categorized into environmental, ecological, and socio-economic factors. Feng [36] demonstrated that the proportion of forests and grasslands was the primary factor influencing the trade-off between carbon sequestration and water production services in the Loess Plateau. Among various natural environment drivers, rainfall may exacerbate these trade-offs, while forest reduction and grassland expansion can mitigate these trade-offs. Gross domestic product (GDP) and income level are significant socio-economic factors. A study led by Warchold from the Potsdam Institute for Climate Impact Research examined the changes in SDGs trade-offs/synergies among countries with different income levels. This research utilized the classification standards issued by the World Bank (high-income, upper-middle-income, lower-middle-income, and low-income). Among all 17 goals, synergies outweighed trade-offs, providing a positive foundation for implementing the SDGs 2030 Agenda. However, the study also highlighted that the SDGs' trade-offs/synergies can vary by income levels and regional groups [37]. MA also provides evidence of trade-offs and synergies at different income levels. It indicates that fisheries serve as a major source of animal protein for nearly one billion people. Among the 30 countries primarily relying on fish as a protein source, 26 are developing nations [3]. Increased fishery production frequently results in a decline in other ecosystem services. To accurately comprehend these dynamics and identify where and how trade-offs and synergies may arise and evolve, this paper quantifies the trade-offs and synergies among different ecosystem services across different spatial distribution and income level groups. The trade-offs/synergies relationship for each continent enables purposeful mitigation of the competitive effects between ecosystem services while strengthening the synergistic enhancements [22,23,38]. Additionally, this analysis offers technical support for optimizing global ecosystem service management policies [39].

2. Methods and data sources

2.1. Technical framework

Fig. 1 provides a technical framework for exploring trade-offs and synergies of ecosystem services in 179 countries.

2.2. Calculating methods

This research focused on the year 2018 and covered 179 major countries and regions worldwide. The research only included terrestrial ecosystems, such as forests, wetlands, grasslands, deserts, farmlands, and urban ecosystems. The value of the global marine ecosystem was not considered.

2.2.1. GEP accounting method

The accounting framework for the global GEP and the detailed calculating methods were comprehensively constructed based on relevant guidelines such as “Technical Guidelines of Gross Ecosystem Product Accounting of Terrestrial Ecosystem”, “Accounting Specifications for Gross Ecosystem Product”, MA, and SEEA-EA.

Biophysical quantity assessment was carried out in three categories: provisioning services, regulating services, and cultural services provided by the ecosystem, such as food output, timber output, and soil maintenance quantity. The output of mainly ecosystem products could be obtained through the existing economic accounting system, and the physical quantity of some other ecosystem regulating services could be estimated by combining mathematical models with data from some open source. Then, the monetary value assessment required determining the prices of various ecosystem products and services, such as the price per unit

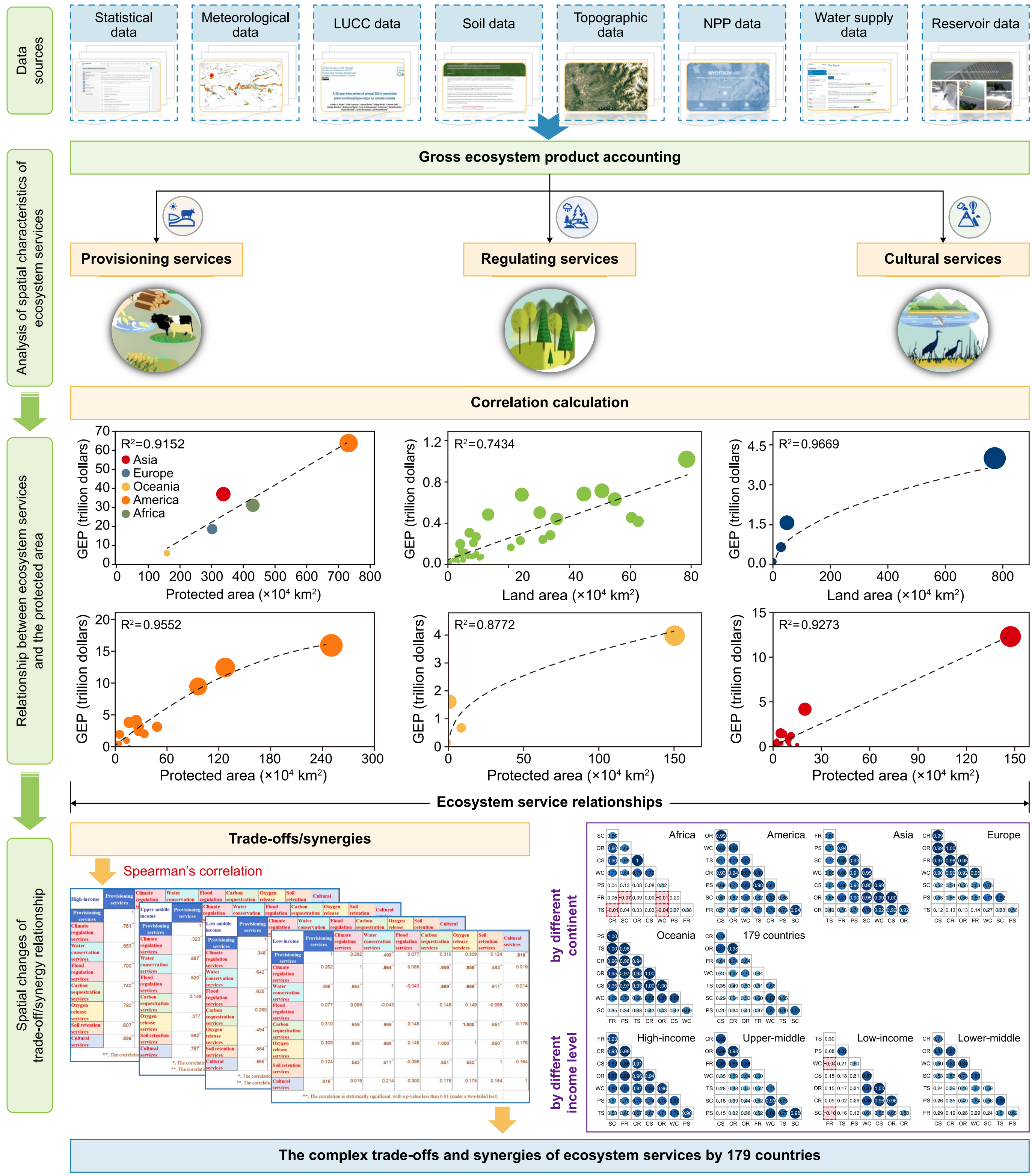

Fig. 1. The technical framework diagram of the research.

of timber, water resources, and soil conservation. Pricing methods included alternative market technology methods and simulated market technology methods. Alternative market technology used "shadow price" and consumer surplus to express the price and economic value of ecosystem service functions. Simulated market technology estimated the value of different ecosystem services by integrating all consumers' willingness to pay through surveys, questionnaires, bidding, etc. This paper used the market value method to estimate the value of ecosystem provisioning services, the replacement cost method to estimate the value of ecosystem regulating services, and the travel cost method to estimate the value of ecosystem cultural services. The specific accounting indicators and related methods are shown in Table 1.

2.2.2. Spatial correlations method

Many methodologies were available to appraise trade-offs and synergies [40]. This study primarily analyzed the trade-offs/ synergistic relationships between pairwise ecosystem services within a single year. To this end, the spatial correlations method was selected for direct calculation. The Spearman correlation coefficient [41] and the Pearson correlation coefficient [42] were utilized, employing SPSS software for analysis. Then, we measured the synergistic effect by examining the competing relationship or synergistic effect among these different indicators. The Spearman correlation coefficient (r_s) calculation formula and Pearson correlation coefficient (r_p) were used to determine whether two ecosystem services were positively or negatively correlated and to run the significance test, with a significance level of α at 0.05 (or 0.01). It was noted that a positive correlation between two ecosystem services implied a synergistic effect, while a negative correlation suggested a competitive relationship.

(1) The calculation formula of Spearman correlation coefficient r_s:

$$r_s = \frac{\sum_{i=1}^{n}(A_i - \overline{A})(B_i - \overline{B})}{\sqrt{\left[\sum_{i=1}^{n}(A_i - \overline{A})^2\right]\left[\sum_{i=1}^{n}(B_i - \overline{B})^2\right]}} \tag{1}$$

(2) The calculation formula of Pearson correlation coefficient r_p:

$$r_p = \frac{n\sum_{i=1}^{n}A_i \times B_i - \sum_{i=1}^{n}A_i \times \sum_{i=1}^{n}B_i}{\sqrt{n\sum_{i=1}^{n}{A_i}^2 - \left(\sum_{i=1}^{n}A_i\right)^2}\sqrt{n\sum_{i=1}^{n}{B_i}^2 - \left(\sum_{i=1}^{n}B_i\right)^2}} \tag{2}$$

In equations (1) and (2), A and B denote the ranks of each pair of ecosystem services, while n represents the number of countries. A positive correlation coefficient for two ecosystem services that passed the significance test at the 0.05 (or 0.01) level implies a significant synergistic relationship between these two ecosystem services. Conversely, a negative correlation coefficient that passed the significance test indicates a trade-off relationship between these two ecosystem services.

Furthermore, this paper further examined the relationship between GEP indicators and various natural-social factors (including land area, protected area, population density, GDP, etc.) based on the grouping criteria of the continents of each country and the per capita national income issued by the World Bank. The results are presented in Section 3.3.

2.3. Data sources

This paper used the World Bank's World Development Indicators (WDI) database [43] to obtain group data on the protected areas, population, GDP, and per capita national income in 2018. The basic data used to calculate the provisioning and cultural services also come from the WDI database. Among them, the basic data about agricultural, forestry, and fishery products were obtained from WDI statistics on the annual added value of agriculture, forestry, and fishery in different countries and regions. The basic data about the cultural service was obtained from WDI statistics on tourism revenue worldwide. In addition, the data used to calculate the value of water resources was obtained from the World Water Outlook database [44]. Data used in the accounting of ecosystem climate regulation, carbon sequestration, oxygen release, and water storage included 2018 global vegetation NPP, 2018 global evaporation data (ET), and 2018 Global Land Use Data (LUCC). NPP and ET data came from the MODIS land standard products provided by the NASA Land Process Distributed Data Archive Center, which were MOD17A2 and MOD16A2 [45,46], respectively, while LUCC data came from the global land cover data of the European Space Agency [47].

The World Bank divided global economies into four groups based on per capita national income [48]: high-income countries (per capita > 12,535 US dollars (USD)), upper-middle-income countries (USD 4046 ≤ per capita ≤ USD 12,535), lower-middle-income countries (USD 1036 ≤ per capita < USD 4046), and low-

Table 1
The indicators and accounting methods of global GEP

No.	Service type	Specific products or services	Physical quantity	Physical measure	Monetary value	Monetary measure
1	Provisioning services	Biomass provisioning	Output	Survey	Output value	Market value
2	Provisioning services	Water supply	Water usage	Survey	Water value	Market value
3	Regulating services	Water conservation	Water storage	Water balance method	Water value	Replacement cost
4	Regulating services	Flood regulation	Water area of the reservoir	Survey	Value of flood regulation	Replacement cost
5	Regulating services	Soil retention	Soil quantity	The Revised Universal Soil Loss Equation (RUSLE)	Value of reduced sedimentation	Replacement cost
	Regulating services	Soil retention	Soil quantity	The Revised Universal Soil Loss Equation (RUSLE)	Value of reduced non-point source pollution	Replacement cost
6	Regulating services	Carbon sequestration	Carbon dioxide quantity	Carbon sequestration mechanism	Value of carbon sequestration	Replacement cost
7	Regulating services	Oxygen release	Oxygen quantity	Oxygen release mechanism	Value of oxygen release	Replacement cost
8	Regulating services	Climate regulation	Energy consumed through vegetation transpiration	Transpiration mechanism	Value of temperature and humidity regulation by vegetation transpiration	Replacement cost
	Regulating services	Climate regulation	Energy consumed through water evaporation	Transpiration mechanism	Value of temperature and humidity regulation by water evaporation	Replacement cost
9	Cultural services	Tourism-related services	Total number of visits	Survey	Value of tourism	Travel cost

income countries (per capita < USD 1036). The criterion would be used in subsequent trade-offs and synergies analyses among ecosystem services under different income levels.

3. Results

3.1. The structural composition and spatial distribution

The global GEP calculated at constant prices was approximately USD 155 trillion in 2018, 1.85 times the global GDP for the same year. The unit area GEP was USD 1.07 million km^{-2}, and the per capita GEP was USD 20,300 per person, a 4.81% and 2.89% increase compared with 2017, respectively [15]. However, this growth rate was slightly lower than the average annual growth rate of the global ecosystem service value from 1994 to 2011, calculated in 2014 [11]. Those differences could be attributed to the different accounting indicators, scopes, and price factors.

The global terrestrial ecosystem's regulating service value was about USD 140 trillion, accounting for 90.31%, followed by the material product supply service value of the global terrestrial ecosystem, accounting for 5.36%, and the cultural service value, accounting for 4.33%. In 2017, the value of these three service functions accounted for 89.84%, 5.70%, and 4.46%, respectively.

The total GEP, per capita GEP, and GEP per unit area vary significantly across different regions. The total GEP is mainly distributed in the Americas, Asia, and Africa, as shown in Fig. S1. Developing countries have a total GEP of about 3.45 times higher than developed countries. However, their per capita GEP is only 54.61% of developed countries' GDP. The top 15 countries account for 65% of the total global GEP, and the five countries with the highest total GEP are Brazil, the United States, China, Russia, and Canada, with the combined GEP of these five countries accounting for 37.68%, slightly lower than the 40.90% in 2017.

3.2. Synergistic relationship between ecosystem services and other factors

Fig. 2 reveals a significant positive correlation between the total amount of ecosystem services and protected area sizes in five continents, with some variations among countries within the same continent. In the Americas and Oceania, the growth rate of ecosystem services gradually slows down and approaches a threshold as protected areas increase. This suggests that an increase in the protected areas will also increase the total value of ecosystem services within a certain range. However, further expansion of these areas eventually limits the available space for human economic and social activities, leading to a stabilization of this value. In Africa, the correlation between the total amount of ecosystem services and protected areas is comparatively weaker. This can be attributed to Africa's economic development model, which heavily relies on exporting primary raw materials. Additionally, while a positive correlation exists between the total amount of ecosystem services and land area, it is weaker than that with protected areas. Social factors like population density may also affect these correlations. There is a negative correlation between population density and ecosystem services intensity. High population densities are more likely to adversely impact the value of ecosystem services due to increased human activity.

3.3. Synergies/trade-offs among different ecosystem services

Based on the results of countries with different income levels in the world in 2018, there is a significant correlation among ecosystem services across each group ($p < 0.01$), as shown in Fig. 3. It is noted that the oxygen release service, climate regulation service, and carbon sequestration service have a strong synergy ($r > 0.75$) in all groups due to the photosynthesis of the ecosystem. Plants absorb carbon dioxide and release oxygen through photosynthesis while fixing carbon to mitigate global warming. Additionally, plants can regulate temperature and humidity through transpiration. Suppose any of the services in oxygen release, carbon fixation, and climate regulation are not effectively managed. In that case, the value of the other two services will also be affected, resulting in a functional relationship of "one prospers and one loses all." The cultural service provides spiritual enjoyment for human society, while the provisioning service provides the material basis for survival, improving the quality of life and social welfare. The provisioning and spiritual value provided by the ecosystem at the global level also show strong synergy.

A comparison of the synergy among GEP indicators in the countries with different income levels shows that in high-income and upper-middle-income countries, there are more than ten pairs of ecosystem services with strong synergy ($r > 0.75$), and the number of ecosystem services with strong synergy reaches 20 in high-income countries, accounting for more than 70%. However, no more than ten pairs of ecosystem services show strong synergies in lower-middle-income and low-income countries. In 2018, the majority of global ecosystem services exhibited synergistic relationships. However, a trade-off was observed between flood regulation and other services, such as water conservation and soil retention in low-income countries. This reflects the increase in the value of flood regulation and storage services in these regions, which would adversely impact their water conservation and soil retention capabilities. Furthermore, considering the results for each continent, the synergy between ecosystem regulation services is more pronounced in American and European countries. However, in African countries, trade-offs are observed between soil retention and flood regulation services, climate regulation and cultural services, water conservation and flood regulation services, and water conservation and cultural services. Upon analyzing GDP levels, it becomes apparent that in developing countries, trade-offs are observed between flood regulation and soil retention services, as well as between flood regulation and water conservation services. In general, a correlation exists between the income levels and the synergy among ecosystem services within each nation. The ultimate goal of human activity is to maximize the benefits of ecosystem services in synergy through a "win-win" model.

4. Discussions

4.1. Comparative analysis

In 2018, the GEP and GDP rankings of countries exhibited significant differences. Notably, for most countries, their total GEP was substantially higher than their total GDP. Countries generally ranked high in both GEP and GDP, but African and other underdeveloped nations had higher rankings in GEP compared to GDP. The increasement of the global GEP in 2018, relative to 2017 [15], may potentially obscure the fact that certain nations experienced a decline. Specifically, the GEP of 69 countries declined in 2018, while the rest showed an increasing trend. However, only 84 countries or regions, including China, demonstrated concurrent growth in both GEP and GDP. Among the top ten countries in terms of GEP, only China, Congo (Kinshasa), Indonesia, and Australia manifested growth in both metrics. Focusing on China, its global ranking in total GEP value in 2018 was third. However, its per capita GEP and per unit area GEP rankings were 134th and 101th, respectively. Despite an increase of five places in per capita GEP compared to 2017, reaching USD 8800 per person (at current price), it remained significantly below the global average. This ranking was even lower

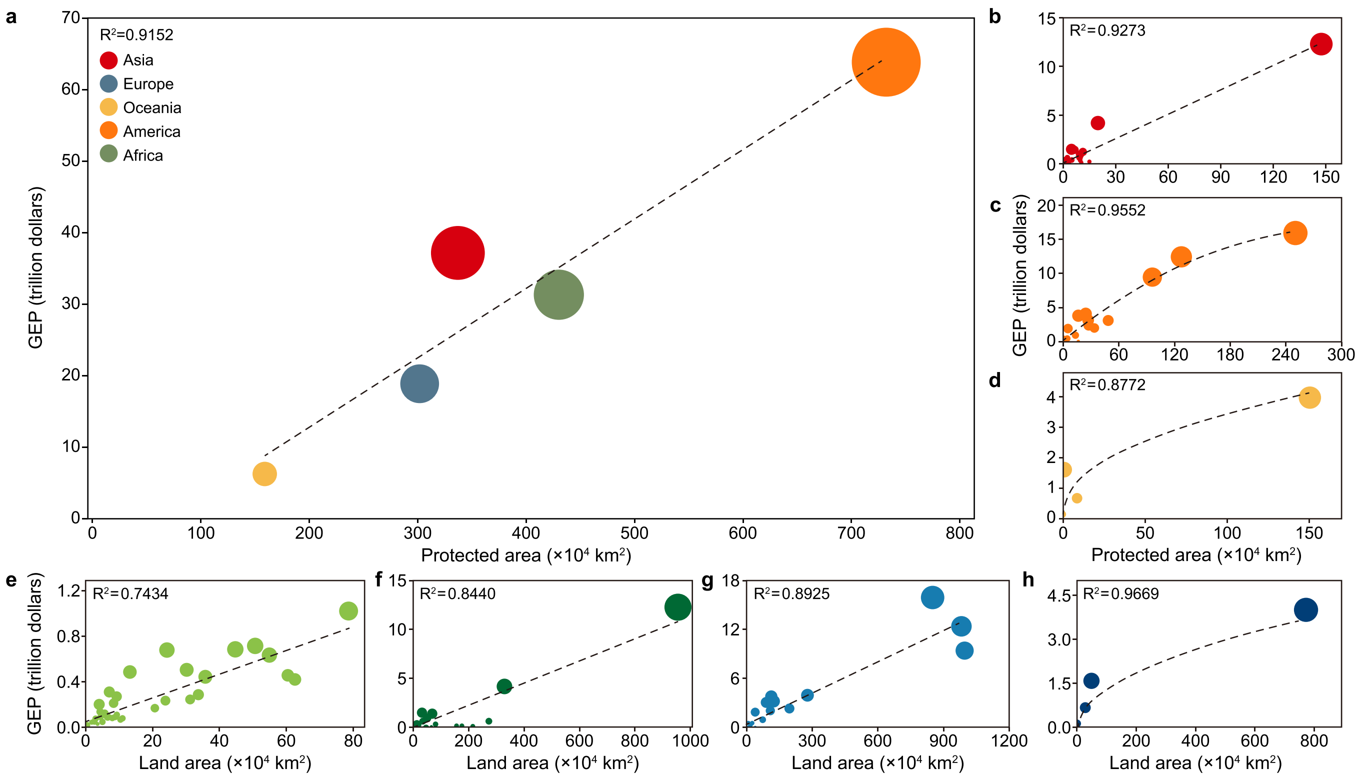

Fig. 2. The relationship between the total amount of ecosystem services and the land area. **a**–**d**, Protected area: Continental scale (**a**); Asia (**b**); America (**c**); and Oceania (**d**). **e**–**h**, Land area: Europe (**e**); Asia (**f**); America (**g**); and Oceania (**h**). The circle size represents the total amount of GEP in each continent. The larger the GEP amount, the larger the size of the circle.

than the per capita GDP of USD 9900 per person (65th globally). On the other hand, China's GEP per unit area was USD 1,288,200 km^{-2} (at current price), slightly above the global average.

4.2. Uncertainty analysis

To analyze the synergistic effects among GEP indicators in various countries worldwide, we must first consider the uncertainties that arise in GEP accounting. Different researchers may obtain varying results due to differences in accounting scope, indicators, data, and methods. Moreover, accounting results may be overestimated or underestimated due to differences in the acquisition of accounting parameter coefficients. Regarding global data required for accounting, there are limitations in animal husbandry and bioenergy-related data in the World Bank's global WDI database, which affects the calculation of the value of global ecosystem material products and services. Additionally, rainfall, runoff, and evapotranspiration data must be considered when calculating the value of water resource services. However, obtaining runoff data for all countries is difficult, so this paper uses an alternative algorithm based on rainfall intensity, which may lead to overestimated results. Regional differences in cooling and humidification services provided by ecosystems at different latitudes are fully considered in the accounting process. However, relevant parameters for water conservation services are converted according to relevant cost data, such as labor costs, in major regions of the world, which may impact the results. Furthermore, the value of soil conservation services includes reducing sedimentation, mitigating non-point source pollution, and maintaining soil fertility. However, due to the challenges in obtaining the necessary parameters for the latter two components, our analysis primarily considers the value of sedimentation reduction services. This approach leads to an underestimation of this part of the results. Lastly, the tourism revenue data of natural scenic spots in various countries are limited to international tourists arriving via airports. This method fails to account for non-airport inbound tourists, potentially leading to an undervaluation of cultural services, especially in countries with less developed air transportation systems. Global GEP accounting and synergy analysis still face many difficulties in obtaining basic data, particularly regional parameters. This would result in many uncertainties in the final analysis. Therefore, it is very important to strengthen the research support for global multi-regional parameters, monitoring, and assimilation simulation in the future.

4.3. Further implication

Human society frequently disturbs the equilibrium of ecosystem service supply and demand, making it difficult to simultaneously maximize the benefits of various ecosystem services. This imbalance results in trade-offs of varying degrees, most notably in low-income countries. Among these, African nations, which constitute over 88% of the 26 low-income countries, face the most severe flood challenges globally. Addressing flood-related issues requires a holistic approach that values not only flood regulation and storage services but also considers other ecosystem services. In other words, a myopic pursuit of flood mitigation through reservoir construction would inevitably hinder the achievement of optimal regional ecosystem management. Moreover, it is proposed that synergistic analyses among different ecosystem services be conducted at different levels and regions promptly. This would provide a scientific basis for establishing a global ecological fiscal transfer payment (EFT). Ultimately, the scale of EFT and diversity funds,

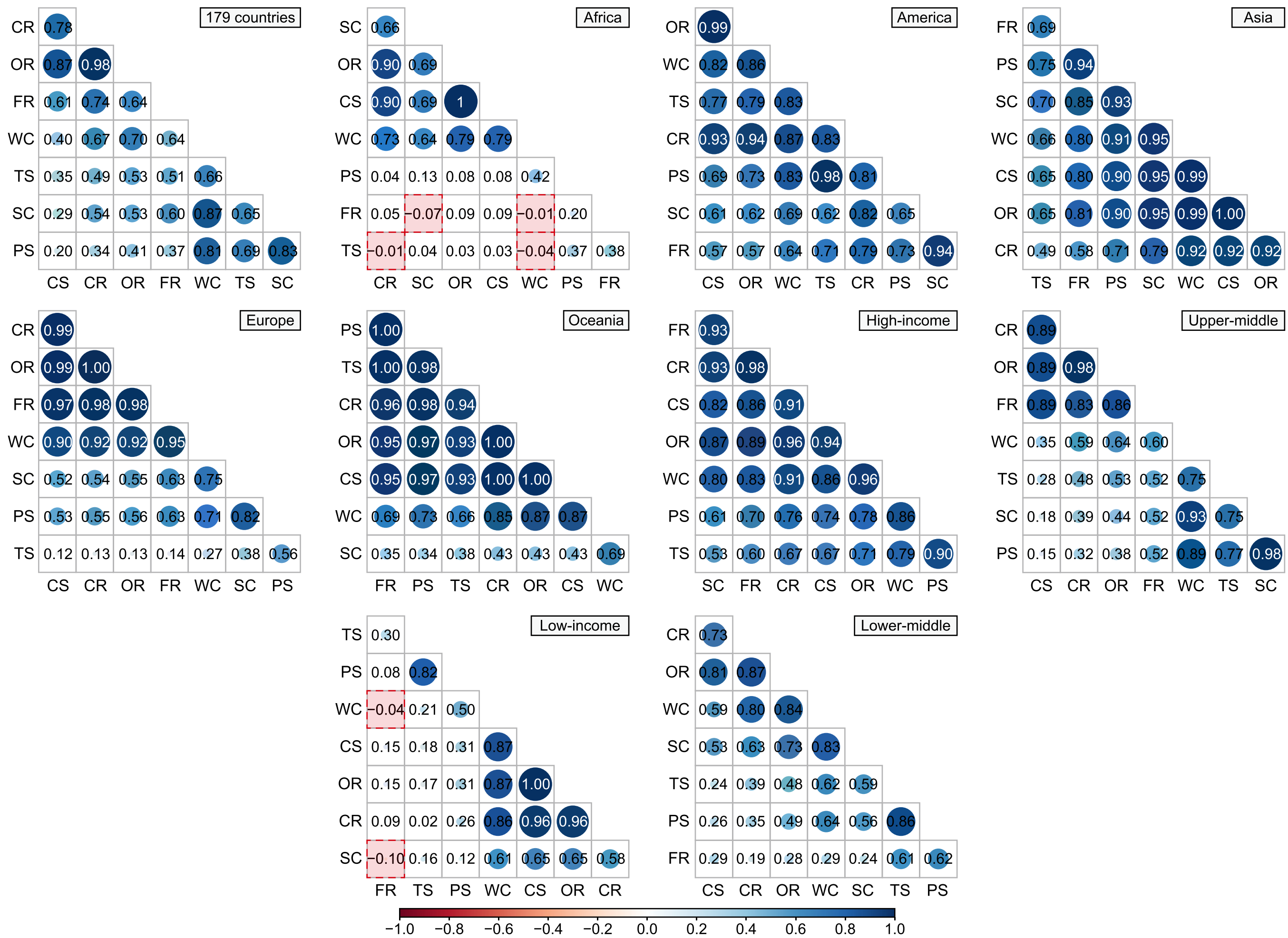

Fig. 3. The trade-off/synergistic relationship among different ecosystem services.

along with other funding channels could be expanded to offer multilateral assistance to regions with high GEP but low GDP, thereby promoting global sustainable development. Furthermore, it is essential to thoroughly examine the relationship between ecosystem services and natural social factors. Enhancing the evaluation system that integrates the social-economic-natural nexus, particularly through the dual evaluation of GDP and GEP, is crucial.

5. Conclusions

In 2018, the global GEP was approximately USD 155 trillion (the constant price), which is 1.85 times the global GDP. The growth rate of GEP was slightly higher than that of the global GDP. The value of ecosystem regulating services accounted for 90.31% of the total GEP. Significant spatial differences existed in the total GEP, per capita GEP, and GEP per unit area. The total amount of GEP was mainly distributed in the Americas, Asia, and Africa. Developing countries accounted for about 3.45 times the total GEP of developed countries, but their per capita GEP was only 54.61% of developed countries. The five countries leading in total GEP were Brazil, the United States, China, Russia, and Canada. A notable positive correlation exists between ecosystem services and the protected areas across five continents and, to a lesser extent, with land areas. However, an increase in population density can lead to a decline in the value of ecosystem services due to human activities. This study also highlights strong synergies among oxygen release regulation, climate regulation, and carbon sequestration services provided by the global ecosystem, as well as between ecosystem cultural services and provisioning services. Ineffective management of one service can affect the value of other services. Additionally, there is a correspondence between the income levels and the synergy among ecosystem services within each nation. In low-income countries, particularly in Africa, there is a trade-off relationship between flood regulation and water conservation soil retention services. Therefore, flood mitigation strategies such as reservoir construction should be carefully balanced to avoid overlooking other vital ecosystem services.

CRediT authorship contribution statement

Jinnan Wang: Conceptualization, Writing - Original Draft. **Wenjun Wu:** Writing - Original Draft, Writing - Review & Editing. **Hongqiang Jiang:** Conceptualization, Writing - Review & Editing. **Meng Yang:** Data Curation, Validation. **Yueming Gao:** Formal Analysis. **Guoxia Ma:** Methodology. **Fang Yu:** Methodology. **Weishan Yang:** Validation. **Nan Yao:** Visualization. **Jiacheng Shao:** Visualization. All authors provided critical input to the analyses and the final version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ese.2024.100391.

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