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Coupling Coordination Degree between Regional Economic System and Gross Ecosystem Product in China

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Abstract

Gross Ecosystem Product (GEP) is an important way to assess the status of ecosystems and clarify the coupling and coordination between ecosystems and economic systems, and it can be used as a scientific basis for achieving synergistic development of economic society and ecological civilization. In this paper, using China as the study area, based on land use data, normalized difference vegetation index, and statistical data, we applied mathematical modeling methods to account for GEP in China from 2000 to 2020 and analyzed the spatial and temporal variation characteristics of GEP over a long time series. Based on the economic statistics, a regional economic evaluation index system was established to measure the economic development status. The interaction mechanism and coupled coordination dynamics between economic development and the ecological environment were explored through coupled coordination degree model. The results showed that the spatial distribution of GEP varies widely in China, and the total value of GEP in China is 4.61 trillion and 7.12 trillion yuan in 2000 and 2020, respectively, which is 2.06 and 0.36 times of Gross Domestic Product (GDP) in 2000 and 2020, respectively, and the increase of GDP far exceeds the increase of GEP. The value provided by regulating services accounts for the largest share of the three major ecosystem services. The coupled coordination relationship between ecological environment and economic development remained basically consistent, showing low coordination in the northwest and high coordination in the southeast. Besides, the area with the lowest coupling coordination was in 2005. The spatial distribution pattern of the Green Gold Index (GGI) in China is generally consistent from 2000 to 2020, and the value in southeastern and northeastern regions is lower than that in northwestern and central China. The area of GGI>1 showed a lesser trend from 2000 to 2020, while the area of GGI=1 increases significantly. The fluctuation changes of each province in 2005 are relatively large. The analysis of GEP accounting and its coupling and coordination degree with the economic system has practical guidance to promote the realization of the value of ecological products in the region.

Keywords: Gross Ecosystem Product; Green Gold Index; Coupling Coordination; China

Introduction

A series of ecological and environmental problems have raised widespread concern about the reduction in the supply of key ecosystem services, which seriously threatens the sustainable development of human society and the economy [1-3]. With the rapid economic development, ecological and environmental problems such as soil erosion, desertification, and land degradation are increasing, causing the degradation of ecosystem services, and seriously threatening the sustainable development of human beings [4]. Human society and the ecological environment on which it depends constitute an economic-social-natural complex ecosystem. For the economic subsystem, Gross Domestic Product (GDP) is used as the main indicator to measure the total value of final goods and services produced and provided by a country or region in a certain period; for the social subsystem, the United Nations has established the GDP to evaluate the average life expectancy, education level and living standard of a country or region. The United Nations has established the Human Development Index to evaluate the average life expectancy, education level, and living standard of a country or region; however, for the natural subsystem, there is no accounting index to assess the support and welfare provided by natural ecosystems for human survival and development. Many countries around the world are seeking accounting indicators that go beyond GDP to reflect the contribution of natural ecosystems to human well-being. Ecosystem service functions have become a global research hotspot, and exploring ecosystem services and their valuation methods is the main research content, but the GEP has never been explicitly presented as an independent accounting indicator.

In recent years, the assessment of ecosystem service functions has made great progress, and more and more types of ecosystem service functions have been recognized, and the evaluation methods of ecosystem service functions have been developed and matured, laying the foundation for the accounting of GEP [5]. Scholars at home and abroad have carried out a lot of research work in the field of GEP, and now some scholars have constructed corresponding indicator systems for different regional characteristics, accounting for GEP global [6], national [7-8], and provincial [9-11] levels; some scholars have also conducted research in cities and municipalities such as urban clusters [12-15], county [16-17], township and village levels, and other administrative units at different scales and regional scales. Some scholars have studied the feasibility and necessity of applying GEP to ecological compensation performance assessment [18] as well as specific case studies on the application of GEP to ecological conservation performance [19-20], making useful explorations for the incorporation of GEP into conservation performance assessment and decision making. Lin et al (2022) used GEP for the evaluation method of ecological product value realization rate. Yang et al. (2019) did a study based on spatial analysis targeting the use of GEP accounting results as a reference for determining the theoretical ecological compensation standard for each district and county in Yunnan province. Lu et al. (2019) applied the GEP to urban planning and architectural design for analysis and established a theoretical framework for the application. Other scholars reveal the coupled and coordinated relationship between gross ecosystem production value and economic growth [9,15] and the coupled and coordinated analysis of the socio-economic and ecological environment [23]. In 2020, the team of researcher Ouyang Zhiyun from the Center for Ecological Environment Research, Chinese Academy of Sciences introduced the concept, accounting framework, indicator system, and technical method of GEP for the first time in the international arena, and carried out the case study of Qinghai Province as the study found that nearly 80% of the ecosystem goods and services generated in Qinghai Province benefited other provinces outside of Qinghai Province, and thus proposed the establishment of a "water fund" and other policy recommendations to coordinate regional development and explore ways to make suppliers of ecological goods and services benefit and consumers of ecological goods and services pay.

Currently, GEP accounting faces a series of problems, such as the lack of uniformity in accounting indicators and accounting standards, which leads to the reproducibility and applicability of the accounting results [24]. Many studies focus on quantitative accounting without analyzing the spatial and temporal characteristics of the long time series. There are more studies on the coupled and coordinated analysis of economic growth and energy consumption, environmental stress, and carbon emissions [25-28], while ecosystem and economy are the two systems most closely related to human and socio-economic development, and comprehensive analysis of social and ecosystem elements can help us better understand the coupling between human activities and the natural environment [23,28]. However, few studies have integrated ecosystem service value with socioeconomic development, which could provide another important perspective for ecosystem conservation. To meet the dual requirements of human economic activities and ecological protection, achieve a sustainable state of economic development and ecological balance, and realize the integrated development of "landscape, water, forest, field, lake, and grass", this paper attempts to explore the method of accounting for the total value of ecosystems in China (Figure 1) from the perspective of human-earth coupling, with ecological protection as the bottom line and human well-being as the goal. In this paper, we refer to the framework of accounting for GEP proposed by Ouyang et al. (2013). We construct the GEP using a methodology like that used to calculate the GDP. The GEP is a measure of the total monetary value of ecosystem-related goods and services (hereafter referred to as 'ecosystem services') in each region over an accounting period. Ecosystem services can be categorized as material services, regulating services (nature's contribution to carbon sequestration, flood mitigation, soil conservation, dust storm prevention, etc.), and non-material services. In this paper, we try to explore the spatial and temporal changes in China's GEP accounting methods and their spatial and temporal changes and explore the coupling and coordination between economic expansion and ecological changes.

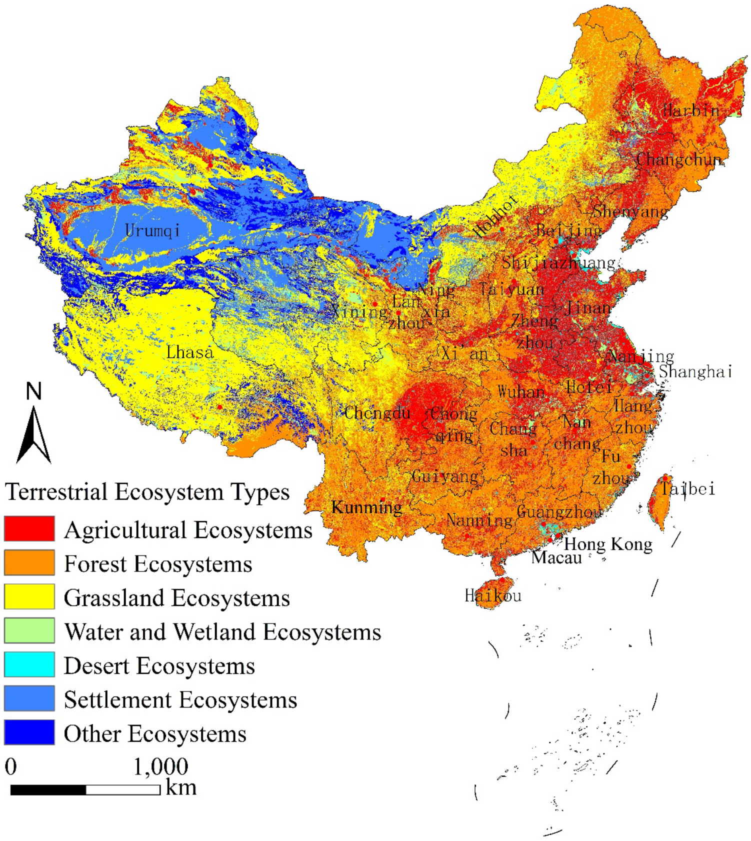

Figure 1: The terrestrial ecosystem types of the study area.

Data sources and processing

The data used in this paper mainly include: (1) Land use data were downloaded from the Resource and Environment Science Data Center of the Chinese Academy of Sciences (https://www.resdc.cn/), the time range contains 5 phases of images in 2000, 2005, 2010, 2015 and 2020, all with a resolution of 30m; (2)Topographic data DEM were downloaded from the Geospatial Data Cloud (http://www.gscloud.cn/); (3) Meteorological data were downloaded from the China Meteorological Science Data Sharing Service (https://data.cma.cn/), and the time range included temperature and precipitation data in 2000, 2010, and 2020; (4) Soil data were downloaded from the Cold and Arid Regions Science Data Center (http://bdc.casnw.net/), based on the World Soil Database (HES-

D) for the Chinese soil dataset with a resolution of 1km; (5) Vegetation net primary productivity (NPP) data from the United States Geological Survey (USGS) website (https://www.usgs.gov/) for MOD17A3 data from MODIS with a resolution of 500m; (6) The data on the economic indicators involved are obtained from the China County Statistical Yearbook (2000-2020). Finally, the data used were uniformly resampled to 1000 m, the data format was gird, and the data were based on the Krassovsky ellipsoid with the Albers projection.

Methodology

In this paper, based on the GEP accounting system proposed by Ouyang, Z. et al. (2020), and combined with the ecological background characteristics of the study area, the indicators used to account for GEP in the region were selected, including eight sub--indicators in three categories of services: provisioning services, regulating services and cultural services, based on the national remote sensing classification data of terrestrial ecosystem types, and concerning the ecological service value equivalent factor method of Xie et al.(2015). Based on remote sensing (RS) technology and geographic information science (GIS) technology, the spatial and temporal variation of GEP from 2000 to 2020 and the assessment of GEP among different ecosystems were calculated, and the variation of high and low-value zones of ecological value in the study area was analyzed by calculating the Green Gold Index (GGI) and using the coupled coordination degree model (CCDM), the coupled coordination relationship between GEP and economic development was analyzed to resolve the relationship between economic expansion and ecological changes in China from 2000 to 2020. The technical roadmap is shown in Figure 2.

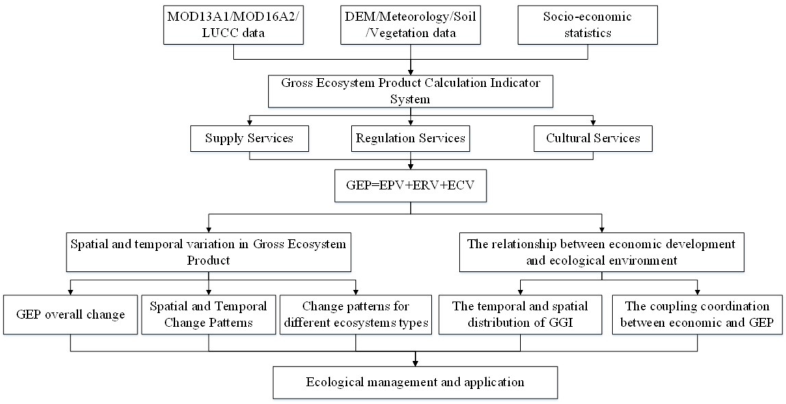

Figure 2: Technical framework of the research

Ecosystem Service Value Calculation

The value of ecosystem services was calculated based on national remote sensing classification data of terrestrial ecosystem types, concerning the ecological service value equivalent factor method such as Xie et al.(2015), to estimate the value of ecosystem supply services (product supply(a1), raw material supply(a2), water supply(a3)), regulating services (gas regulation(b1), climate regulation(b2), purification services(b3), hydrological regulation(b4)), and cultural ecosystem services (ecotourism, aesthetic value(c1)), calculated as follows[6,30]:

$$EPV = \sum_{\mathrm{i=1}}^{\mathrm{n}} EP_i \times P_i \qquad 1$$

$$ERV = \sum_{j=1}^{m} ER_j \times P_j \qquad 2$$

$$ECV = \sum_{k=1}^{l} EC_k \times P_k \qquad 3$$

Where EPV is the value of supply services, ERV is the value of ecosystem regulation services, and ECV is the value of ecological and cultural services. EP_i is the volume of ecosystem products of category i, and P_i is the price of ecosystem products of category i; ER_j is the volume of ecosystem regulation services of category j, and P_j is the price of ecosystem regulation services of category j; ECk is the amount of cultural service function of ecosystem type k, and P_k is the price of the cultural service function of ecosystem type k.

Gross Ecosystem Product Calculation

The accounting of GEP is based on the assessment of ecosystem service functions and their eco-economic value with GDP accounting, i.e., the analysis and evaluation of the economic value of the final goods and services provided by ecosystems for human survival and well-being. The sum of the value of ecosystem products, regulating services, and cultural services is the GEP, with the value of ecosystem products being a direct use value and the value of regulating services and cultural services being an indirect use value. Since support functions such as biodiversity only support product provisioning and ecological regulation functions, but do not directly contribute to human well-being, and the role of these functions is already reflected in product functions and regulation functions, the accounting of support services is not included in the accounting of GEP. In this paper, we refer to the framework of accounting for GEP proposed by Ouyang et al. (2013).

The GEP in China is calculated as follows：

$$GEP = EPV + ERV + ECV \qquad 4$$

Where GEP is the gross ecosystem product, EPV is the value of ecosystem products, ERV is the value of ecosystem regulation services, and ECV is the value of ecological and cultural services.

Regional Economic Development Index Calculation

There are many studies on economic development level, mainly including single indicator method (GDP per capita) and comprehensive indicator method [31-34]. To reflect the level of regional economic development comprehensively, in this paper, we refer to the specific calculation method of Han et al.(2020) and selects GDP per capita and local fiscal revenue per capita to reflect the scale of regional economic development, selects the per capita social fixed asset investment, and the per capita total retail sales of social consumer goods to reflect the quality of regional economic development; and the proportion of secondary and tertiary industries to reflect the structure of regional economic development (Table 1).

Table 1: Evaluation index system and its weight of economic development

Index	Unit	Weights
Per capita GDP	Yuan/person	0.16
Local fiscal revenue per capita	Yuan/person	0.2
Per capita social fixed asset investment,	Yuan/person	0.2
The per capita total retail sales of social consumer goods	Yuan/person	0.24
The proportion of secondary industry	%	0.07
The proportion of tertiary industries	%	0.13

Coupling Coordination Degree Calculation

In this paper, the CCDM was applied to study the interactive coupling between the gross ecosystem product and economic growth [35]. The CCDM is used to measure the degree of interaction and coupling level between two or more systems [36-37]. The CCDM in physics can well characterize the tendency of two (or more) systems to move from disorder to order through various interactions and coordination degrees that determine the order and structure of the system as it reaches a critical region [37-38]. We used the concept and model of capacity coupling in physics to calculate the coupling degree between GEP and GDP using Equation (6), to measure the coupling coordination degree using Equations (7) and (8), and to characterize the type of GEP and GDP coordination. The calculation equations are as follows [39]:

$$C = \sqrt{(U_1 \times U_2)/((U_1 + U_2)/2)^2} \quad 5$$

$$T = \alpha \times U_1 + \beta \times U_2 \quad 6$$

$$CD = \sqrt{C \times T} \quad 7$$

Where C refers to the coupling degree between GEP and GDP, T represents the comprehensive evaluation index, and CD denotes the coupling coordination degree. U1 and U2 refer to the natural environmental conditions and socio-economic development indexes, respectively. The two subsystems are equally important to the evaluation of the degree of coordination between GEP and GDP, thus they are given the same weight, that is, $\alpha = \beta = 0.5$ [36]. Referring to previous research [40-41], we divide the CD into three levels: high balanced, basically balanced, and serious unbalanced (Table 2).

Table 2: The standard of the coupling coordination degree

Label	Level	Degree
1	0.6 < CD < 1	High balanced
2	0.4 < CD < 0.6	Basically balanced
3	0 < CD < 0.4	Serious unbalanced

Green Gold Index Calculation

This paper cites the research results of Han et al. (2020) and introduces a relative development model to measure whether the current status of the region's ecosystem is ahead or behind the overall level of economic development by introducing the Green Gold Index (GGI), the calculation formula is as follows:

$$GGI = GEP/GDP \quad 8$$

The GGI was used to measure the level of potential regional productivity in converting natural resources into valuable assets [42-50]. Considering that the spatial heterogeneity of regional ecosystems can lead to large differences in accounting parameters, localized and specific parameters should be used in accounting to improve the appropriateness and effectiveness of policy management. The GGI was divided into three cases; if GEP < GDP, i.e., GGI < 1, it is usually a region with rapid economic development, while GEP > GDP, i.e., GGI > 1, it is a region with high ecological resource endowment; if GEP = GDP, i.e., GGI = 1, the region provides a balance between ecological environment and economic development, and not only achieves GDP growth but also promotes the growth of GEP.

Results

Gross Ecosystem Product and the Change Patterns

Overall Change of GEP

The total value of GEP in China is 4.61 trillion and 7.12 trillion yuan in 2000-2020, respectively, which is 2.06 and 0.36 times the GDP in the same years, and the increase in GDP far exceeds the increase in GEP. The value provided by regulating services is the largest among the three ecosystem services (Table 3), with 4.11 trillion and 4.62 trillion from 2000 to 2020, accounting for 89.1% and 64.9% of the total value of GEP in that year, respectively; climate regulation is the service type with the largest share of GEP in regulating services in 2000 and 2020, with 2.07 trillion and 2.63 trillion, accounting for 45.02% and 36.89% of the total value of GEP, respectively; and water quality is the service type with the largest share of GEP in 2000 and 2020. From 2000 to 2020, the proportion of regulating services to total GEP value decreases from 89.08% to 64.86%, the proportion of supply services to total GEP value increased from 9.60% to 20.83%, and the proportion of cultural services to total GEP value increases from 1.83% to 3.5%. of the total value of GEP increased from 1.83% to 14.31%; the change in the percentage of the three main services shows that the economic development of the study area has a notable impact on the function of the services provided by the ecosystem of the area, with the rate of change of supply services and cultural services exceeding 100%. Under the condition that the market prices of all types of services are elevated, the value of water connotation declines, which is related to the decrease in precipitation, the increase in evapotranspiration, and the change in land use, leading to a decrease in the service function of water connotation in this study area.

Table 3: Gross ecosystem product changes in China from 2000 to 2020

	2000		**2010**		2020	
Indicators	GEP/100 million	Proportion/%	GEP/100 million	Proportion/%	GEP/100 million	Proportion/%
a1	4844.29	8.31	3787.2	7.18	5194.41	7.52
a2	2852.98	4.89	2273.09	4.31	4082.89	5.91
a3	2071.25	3.55	2043.11	3.87	1228.71	1.78
b1	6419.4	11.01	5199.04	9.85	10415.6	15.07
b2	10216	17.52	8762.58	16.6	22431.2	32.46
b3	4215.26	7.23	3622.69	6.86	6724.85	9.73
b4	25614.9	43.92	25269.8	47.88	15276.4	22.11
c1	2093.04	3.59	1816.88	3.44	3752.54	5.43

a1:Product Supply; a2:Supply of raw materials; a3:Water supply; b1:Gas regulation; b2:Climate regulation; b3:Purification services; b4:Hydrological regulation; c1: Aesthetic value

Spatial and Temporal Patterns of GEP

The spatial variation of GEP in China is large (Figure 3). The GEP of four provinces, namely Tibet, Sichuan, Guangdong, and Yunnan, is relatively close to each other, ranging from 4.7 to 3.5 trillion. 8 provinces, namely Guangxi, Hunan, Qinghai, Hubei, Jiangxi, Fujian, Xinjiang, and Zhejiang have GEP between 2 and 3.5 trillion; 10 provinces, namely Jiangsu, Shandong, Anhui, Henan, Guizhou, Liaoning, Jilin, Hebei, Gansu and Shaanxi, have GEP between 1 and 2 trillion; and 7 provinces, namely Chongqing, Shanxi, Hainan, Beijing, Shanghai, Tianjin, and Ningxia, have GEP below 1 trillion. Among the provinces with high total GEP values, the total ecological value provided by wetlands and forests and the ecological value per unit area are relatively high. Wetland ecosystems in Inner Mongolia, Heilongjiang, Tibet, and Guangdong provide the highest ecological value, accounting for 66%, 76%, 52%, and 45% of the total ecological value, respectively. Forest ecosystems in Sichuan provide the highest ecological value, accounting for 37% of their total ecological value. In terms of ecological value per unit area, the five provinces with the highest total GEP values all have the highest ecological value per unit area of wetlands. The ecological values per unit area of wetlands in Inner Mongolia, Heilongjiang, Tibet, Sichuan, and Guangdong were 0.72, 0.98, 0.27, 1.31, and 205 million yuan/km2, respectively, and the ecological value per unit area of wetlands in Guangdong was the largest.

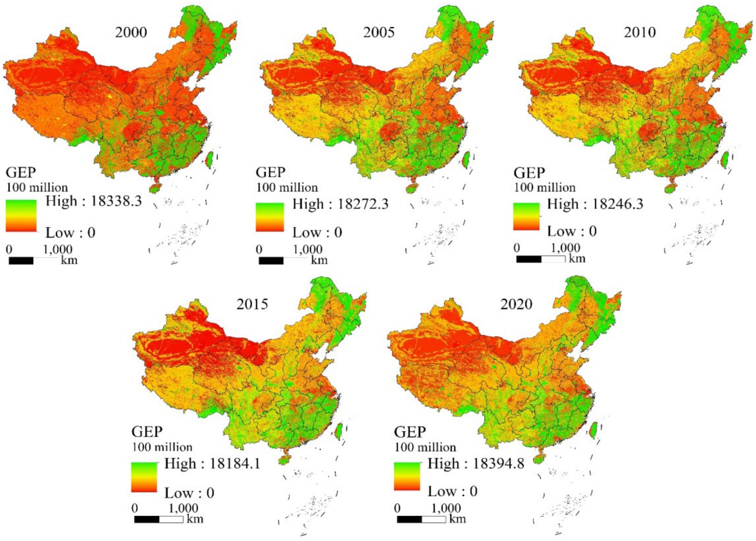

Figure 3: Spatial pattern of GEP in China from 2000 to 2020.

Change Patterns of GEP for Different Ecosystems Types

The area can reflect the number of different ecosystems and the net primary productivity reflects the quality of different ecosystems, and these two indicators are important indicators for the physical quantity accounting of GEP [42]. Take the year 2015 as an example, the total area of grassland in China was 2,647,700 km2, accounting for 28% of the total area accounting for ecosystems; the total area of forest was 2,249,500 km2, accounting for 23.8%; the area of agricultural land was 1,788,400 km2, accounting for 18.9%; the total area of wetland was 414,400 km2, accounting for 4.4%; the area of the urban area was 255,500 km2, accounting for 2.7%; the area of the desert was 2,095,900 km2, accounting for 22.2%. The total area of wetlands is 414,400 km2, accounting for 4.4%; the area of towns is 255,500 km2, accounting for 2.7%; the area of deserts is 2,095,900 km2, accounting for 22.2%. Among them, the ecological service value of wetland ecosystem is the largest, 28.08 trillion, accounting for 42.4%; followed by forest ecosystem, 19.89 trillion-yuan, accounting for 30.0%; grassland ecosystem, 10.66 trillion, accounting for 16.1%; farmland and urban ecosystem services are 6.11 trillion and 0.39 trillion respectively, accounting for 9.2% and 0.6%; desert ecosystem provides the smallest ecological service, 0.6 percent. The services provided by desert ecosystems were the smallest, with 0.36 trillion, accounting for 0.55% of the total. (Table 4). In terms of the value of different ecological services provided by all ecosystems, in 2015, the value of product supply services provided by all ecosystems was 13.12 trillion, accounting for 18%; the value of regulating services was 53.14 trillion, accounting for 73.0%; and the value of cultural services was 6.55 trillion, accounting for 9%. Among the regulating services, climate regulation is the largest, with 31.72 trillion, followed by water flow regulation, with 10.76 trillion, and carbon sequestration and oxygen release services, with 5.91 trillion.

Table 4: GEP of terrestrial ecosystems (100 million yuan)

Indicators	**Forests**	**Grasslands**	**Wetlands**	**Farmland**	**Urban**	**Desert**	**Ocean**	Total	Percentage (%)
a1	1376.5	30220.9	38270.6	53604.3	—	—	7701.5	131173.8	18.02
a2	346.8	1435.6	56.4	223.9	27.9	1350.7		3441.3	0.47
a3	23588.1	7003.5	1053.2	7036.2	1335.4	1042.3	—	41058.7	5.64
b1	198.5	100.7	24.8	196.8	39.3	43.8	—	603.9	0.08
b2	80280.9	34360.8	202530.5	0	0	0	—	317172.2	43.56
b3	—	—	2302.8	—	—	—	—	2302.8	0.32
b4	53870.8	18467	35246.3	—	—	—	—	107584.1	14.78
c1	—	—	—	—	—	—	—	65527.4	9

Note: The value of cultural services cannot be disaggregated into different ecosystems, only aggregated. — Indicates not suitable for assessment.

Spatiotemporal Evolution of Coupling Coordination between Economic Development and Ecological Environment

Analyzing the spatial and temporal changes in the coupling and coordination between economic development and the ecological environment in China from 2000 to 2020 (Figure 4), the coupling and coordination between the two remained basically consistent during these 20 years, showing a distribution pattern of low in the northwest and high in the southeast in space, with the northwest of China mainly dominated by serious unbalanced and high balanced areas. In terms of temporal changes(Figure 5), the type of coupling and coordination between economic development and ecological environment in these 20 years is mainly serious unbalanced, followed by high balanced, among which, the area with the lower coupling and coordination degree is the largest in 2005, 2000, 2010, 2020 area is basically the same, the area in 2015 accounts for the least, and basically unbalanced area in 2015 accounts for the largest, indicating that in 2015 the coupling coordination between China's economic development and ecological environment is better, and the ecological environment and economic development are steadily growing trend.

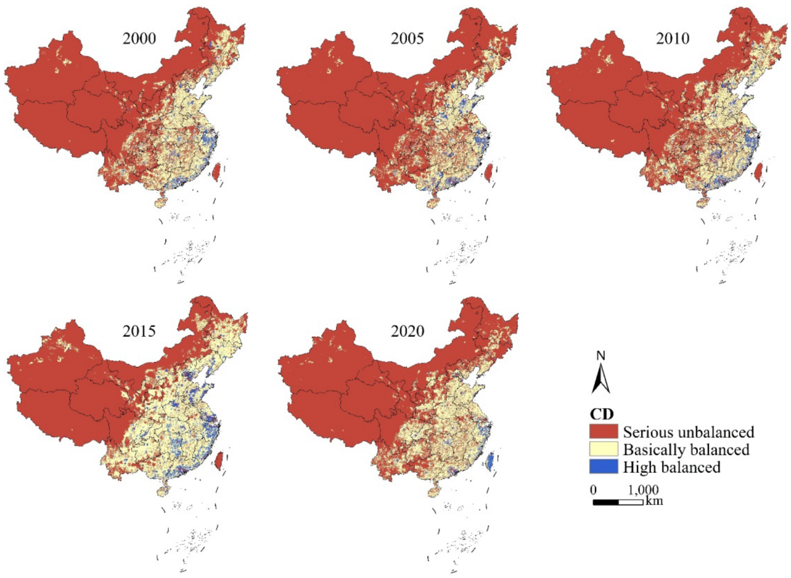

Figure 4: The spatiotemporal evolution of the coupling coordination development between economic development and the ecological environment from 2000 to 2020.

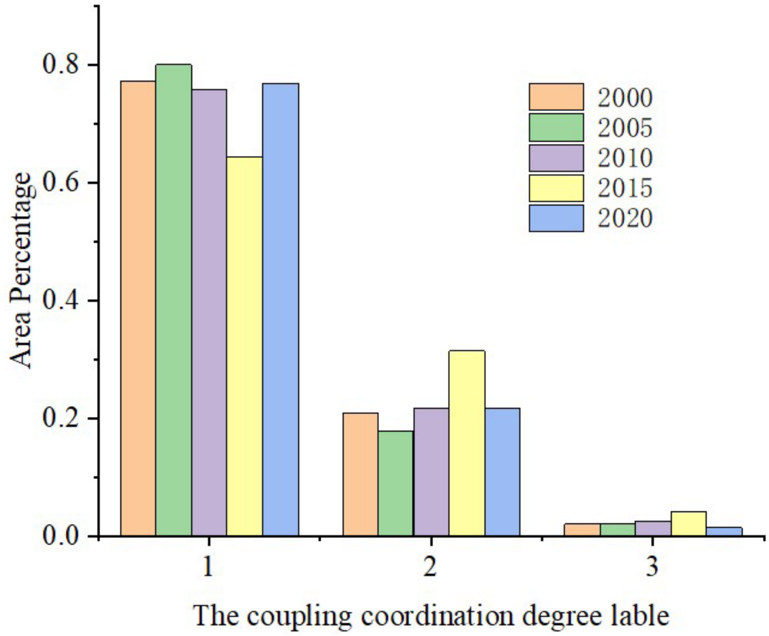

Figure 5: Percentage of the area of the type of coupling coordination between economic development and the ecological environment from 2000 to 2020.

Discussion

Relationship between the Total Economic Development and Ecological Development

Recent studies have attempted to combine ecological and traditional economic indices to form a comprehensive indicator for measuring the construction of ecological civilization. The coupled coordination model can reflect the strength of the internal relationship between GEP and economic development, but not the differences between them.

Analysis of the temporal and spatial distribution of GGI (Fig. 6) shows that the pattern of the spatial distribution of GGI in China from 2000 to 2020 is generally consistent, i.e., the GGI in southeastern and northeastern regions is lower than that in northwestern and central regions of China. In terms of temporal changes, the area with GGI>1 from 2000-2020 is on a lesser trend, and the area with GGI=1 increases significantly. GGI values in Shandong, Jiangsu, Anhui, and Hebei gradually converge to 1 in 2015-2020, indicating that this part of the country provides a balance between ecological environment and economic development, which not only achieves the growth of GDP but also promotes the growth of GEP. GEP is the well-being provided by the natural ecosystem enjoyed by human beings. Western regions with a relatively small population but relatively larger ecological services provided by the natural ecosystem have relatively higher GEP per capita. 15 provinces with GGI > 1 are mainly located in western regions, among which, Tibet and Qinghai, which are located on China's Qinghai-Tibet Plateau, have GGI indexes greater than 10. The GGI index of eastern provinces such as Shanghai, Tianjin, Beijing, Jiangsu, Jiangsu, and Shandong is less than 0.5. The change in GGI of China provinces in 2000-2020 (Fig. 7), the fluctuation changes of each provincial capital city in 2005 are relatively large, among which the GGI values of Shijiazhuang, Nanjing are relatively large; the GGI of Changsha and Hangzhou are the largest in 2015, and the GGI of Shanghai is the largest in 2020. Analyzing the reasons, these regions are higher ecological resource endowment, better ecological environment, and higher economic development levels, but the overall ecological environment level is higher than the economic development level.

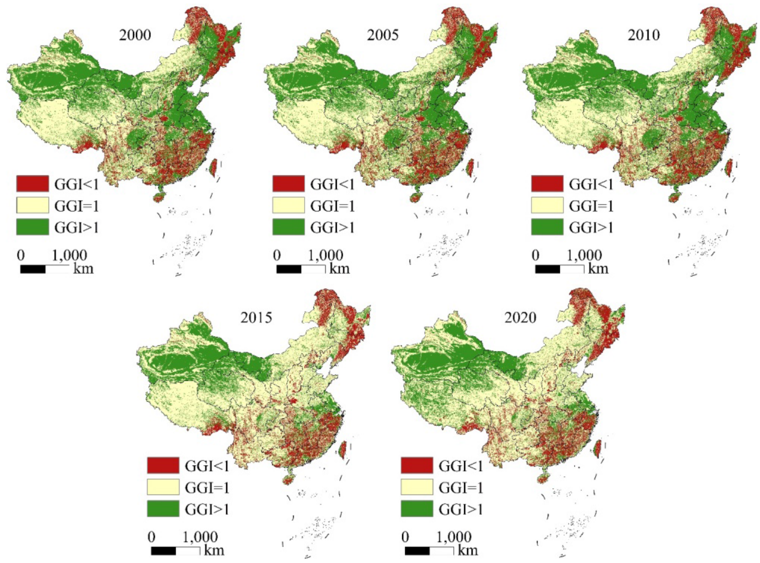

Figure 6: Spatial distribution of green gold index (GGI) in China

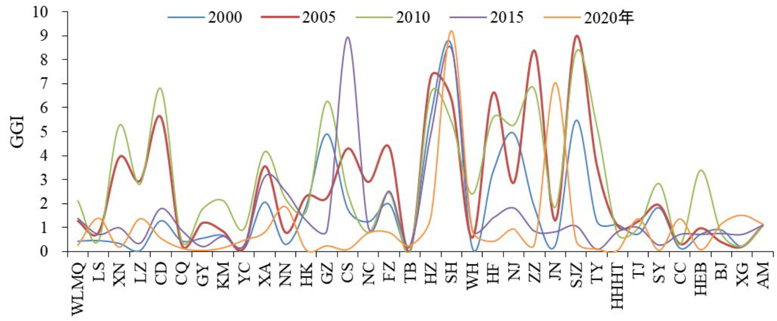

Figure 7: Change in GGI by the province in China, 2000-2020. In the figure, WLMQ: Urumqi; LS: Lhasa; XN: Xining; LZ: Lanzhou; CD: Chengdu; CQ: Chongqing; GY: Guiyang; KM: Kunming; YC: Yinchuan; XA: Xi'an ; NN: Nanning; HK: Haikou ;GZ: Guangzhou; CS: Changsha; NC: Nanchang; FZ: Fuzhou; TB: Taipei; HZ: Hangzhou; SH: Shanghai; WH: Wuhan; HF: Hefei ; NJ: Nanjing; ZZ: Zhengzhou; JN: Jinan; SJZ: Shijiazhuang; TY: ;HHHT: Hohhot; TJ: Tianjin; SY: Shenyang; CC: Changchun; HEB: Harbin; BJ: Beijing; XG: Hong Kong; AM: Macau

The GGI value in China has large spatial regional differences. For regions with relatively high GEP but relatively backward economic development, it is necessary to use GEP accounting as a reference basis for ecological compensation and ecological civilization construction assessment, explore the way to change ecological factors into production factors and ecological wealth into material wealth, improve the market supply of green products and ecological compensation, and promote the transformation of "green water and green mountains". For cities with GGI > 1, they should be encouraged to transform their ecological advantages into ecological agriculture, ecological industry, and ecological tourism, to promote the transformation of natural resources into valuable assets and achieve sustainable ecological and economic development. Cities with low GGI to further encourage the balance between GEP and GDP. A high-quality ecological environment is a prerequisite for building a globally competitive world-class urban agglomeration and is most beneficial to people's livelihood. If the ecosystem service function can be incorporated into the statistical system of the national economy in the future, it will greatly promote the motivation of less developed regions to protect ecology, and the relationship between economic development and environmental protection will be more harmonious and effective. This study can serve as an important indicator for monitoring regional sustainable development and provide valuable insights not only for newly industrialized regions in China but also for other urban areas with rapid economic growth around the world. From the perspective of GEP accounting, the ecological service value of national key ecological function areas is relatively large, but according to the requirements of the main functional zoning, these areas are restricted development zones, and their socio-economic development is severely restricted. For areas with relatively high GEP but a backward economy, we need to use the GEP accounting value as the basis to find a way to change ecological factors into production factors and ecological wealth into material wealth, to improve the market supply of green products, to fight for ecological compensation from the state, to change the assessment system of social and economic development, and to realize "green mountains and water". is the important transformation of " Green mountains and rivers " is "golden mountain and silver mountain".

Ecological Management and Application of the Research Framework

Based on the previous spatial and temporal evolution of the coupled coordination between the gross ecosystem product and the degree of economic development and the GGI index, the spatial distribution has a certain spatial distribution pattern, and combined with China's geographic zoning data, we propose a spatial distribution map (Fig.8) for the optimization of regional GEP enhancement in China and suggest the corresponding zoning optimization. Since 2000, China has vigorously promoted the construction of ecological civilization. The performance of ecosystem conservation has gradually improved with the improvement of economic structure and quality [7]. During the study period, growth rates in the central and western regions of mainland China increased rapidly, but the performance of ecosystem conservation was not significant, and a large number ofmany people migrated to the economically developed eastern and northeastern regions. In contrast, populations from the eastern and northeastern regions of mainland China migrated to the central and western regions. Although economic growth rates are declining, the performance of ecosystem protection is outstanding.

(1) Eco-Economic Management Zone. This area is mainly located in Urumqi, Lhasa, Xining, Lanzhou, and Hohhot. The land use type of unused land accounts for a large proportion, including desert, sandy land, saline land, Gobi, and bare land, which have fewer human activities and are unsuitable for human survival and development, and are less affected by human activities, in addition, the natural native base of the area is poor and the vegetation coverage is low. As an area with a relatively fragile and sensitive ecological environment, it is necessary to strictly restrain unreasonable human activities such as dumping garbage and waste and reclaiming uplands, to strengthen the pace of promoting ecological restoration projects, to focus on protecting existing vegetation and carry out measures to cultivate new species of drought-tolerant vegetation and to insist on planting artificial wind and sand--fixing forests to prevent further expansion and spread of the area.

(2) Eco-Economic Development Zone. This area is mainly located in Beijing, Tianjin, Jinan, Hangzhou, Xiamen, and Guangzhou. The main land use types in this area are mainly arable land and construction land, with high population density and intensive and frequent human activities. For the zoning of this region, first of all, we should continue to further maintain the number of ecological restoration projects and promote the construction progress, adopt the policy of returning farmland to forests and grasses for low-yielding arable land areas to release the pressure of human activities in the upper land, and encourage the implementation of intensive production methods of agriculture and animal husbandry in the key protection areas, plant drought-resistant and heat-resistant high-yielding crops, implement the policies of no grazing, body grazing, and rotational grazing, and maintain the normal economic income of residents. normal economic income and implement appropriate subsidy policies, while actively building green ecological barriers.

(3) Eco-Economic Conservation Zone. The eco-economic conservation zone is also widely distributed, mainly in Harbin, Changchun, Taiyuan, Xi'an, Yinchuan, Chengdu, Kunming, Guiyang, etc. The land use types are mainly forest land, grassland, construction land, and cultivated land. In general, the ecological environment of the region is in good condition, with a good natural local foundation, high vegetation cover, mild climate conditions, rich natural resources in the region, and less disturbance to the environment caused by human activities. For grassland resources, corresponding closed areas should be established, and the implementation of grazing bans, body grazing, rotational grazing, and other related should be strengthened to alleviate the disturbance and damage caused by grazing behavior and maintain the reasonable, sustainable, and healthy development of grassland resources; for forest resources, all kinds of indiscriminate felling and other behaviors should be strictly controlled, continuous attention should be paid to and prevention of forest fires and attention should be paid to the conservation and maintenance of the stable

growth of the area of forest land. In addition, for the border zone between the area and other management areas, focus and attention should be strengthened to reinforce the green barrier and inhibit further extension and interference of human activities into the area.

(4) Eco-Economic Coordination Zone. The eco-economic coordination zone is mainly located in Shenyang, Shijiazhuang, Zhengzhou, Hangzhou, Hefei, Nanchang, Changsha, Chongqing, Nanning, etc. The economic development and population density of this region are relatively high. The land use type is mainly arable land and construction land. This area has high population density, rapid economic development, a high level of urbanization, superior natural conditions, and more crop production. For this zoning type, we should give full play to the dual advantages of high natural environment background foundation and a high socio-economic development level to promote green industrialization development. At the same time, we should pay attention to the reasonable deployment and development of various resources within the synergistic development zone, promote the implementation of reasonable economic development models such as green economy, ecological economy, and circular economy, and focus on creating a sustainable and benign synergistic development zone under the coordinated development model of "natural environment - social economy".

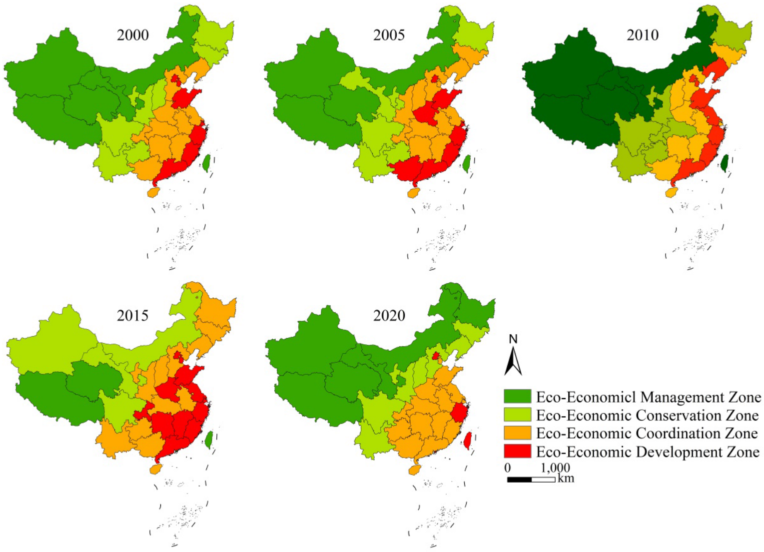

Figure 8: Spatial Distribution Map of China's Geographic Regions for the Optimization of GEP Enhancement

Limitations and Research Improvement in the Future

There are some limitations in our assessment of China's GEP. First, limited by the availability of statistical and spatial data, this paper only calculated GEP for five years from 2000 to 2020, and did not perform year-by-year calculations; Second, when performing GEP accounting, only a portion of ecosystem services were calculated, given the limitations of data availability and accessibility and related accounting methods; Furthermore, several selected ecosystem services were generalized in an accounting manner, this inevitably underestimates the value, so the true value is almost certainly much greater. As more research is conducted and more information becomes available, the calculations will tend to be closer to the actual values. There are also questions about accounting methods, which are heavily influenced by differences in the definition of ecosystem services, specific contexts, and the market pricing methods chosen. There is still no universally accepted accounting framework for GEP, and therefore comparability across regions and countries is greatly affected. So, one avenue for further research would be to develop a comprehensive accounting framework. Such a study would facilitate future attempts to thoroughly understand the ecological conditions and potential of a given region. The relationship between GEP and GDP is complex because it is influenced by a myriad of different factors, such as natural endowments, development priorities, technology, and economic structure. Due to the limitation of research depth and time, we only studied the coupled coordination between GEP and GDP based on their relationship and their spatial and temporal heterogeneity. In the future, we can try to account for the coupling and coordination relationship between GEP and regional economy year by year, and then we can judge the relative relationship changes between the ecological environment and socio-economic system more accurately. The development of the GEP accounting system should be a long-term process, and to meet these challenges, we should fully draw on the experience and practice of the development of the GDP accounting system and establish a perfect investigation and monitoring to fully draw the experience and practice of the development of GDP accounting system. The experience and practice of the development of the GDP accounting system, and adjusting the GEP accounting index screening principles as a possible future direction. By improving the GEP concept and accounting, it will be possible to establish a unified and comparable GEP accounting system and narrow the gap between GEP and policy-making [8]. At the same time, a comprehensive survey and monitoring system will be established to unify the accounting subjects and model methods to play an important role in the field of environmental protection.

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Conclusion

In this paper, based on the perspective of GEP accounting, the GEP accounting of the value provided by different ecosystem services in China is carried out, combining China's land use data and economic statistics, and specifically describing the changes in the value provided by ecosystems to humans in China regions from 2000 to 2020. At the same time, the coupled ecological-economic coordinated development of the past two decades was calculated based on China socio-economic data. The paper draws the following conclusions:

(1) GEP is an important indicator for assessing the contribution of ecosystems to human well-being. The total value of GEP in China in 2000 and 2020 is 4.61 trillion and 7.12 trillion, respectively, which is 2.06 and 0.36 times of GDP in the same years, and the increase in GDP far exceeds the increase of GEP. In 2000 and 2020, regulating services provide the largest share of value among the three ecosystem services, with climate regulation being the service type with the largest share and water purification being the ser-

vice type with the smallest share. The spatial variation of GEP in China is large. The GEP of four provinces, namely Tibet, Sichuan, Guangdong, and Yunnan, is relatively close to each other, ranging from 4.7 to 3.5 trillion. The provinces with GEP between 2 and 3.5 trillion include eight provinces, namely Guangxi, Hunan, Qinghai, Hubei, Jiangxi, Fujian, Xinjiang, and Zhejiang; the provinces with GEP between 1 and 2 trillion include Jiangsu, Shandong, Anhui, Henan, Guizhou, Liaoning, Jilin, Hebei, Gansu, and Shaanxi 10 provinces; 7 provinces and cities in Chongqing, Shanxi, Hainan, Beijing, Shanghai, Tianjin, and Ningxia have a GEP below 1 trillion.

(2) The coupling and coordination between ecological environment and economic development remained basically consistent during 2000-2020, showing a spatial distribution pattern of low in the northwest and high in the southeast, with the northwestern part of China mainly dominated by serious unbalanced and high balanced areas mainly distributed in the southeastern coastal areas; in terms of temporal changes, the coupling and coordination type between economic development and the ecological environment remained basically consistent. The type of coupling and coordination between economic development and ecological environment is mainly dominated by serious unbalanced, followed by high balanced, among which, the area with low coupling and coordination is the largest in 2005, and the area is basically the same in 2000, 2010 and 2020, and the area accounts for the least in 2015, while the basically unbalanced area in 2015 accounted for the largest proportion, indicating that the coupling coordination between economic development and ecological environment in China was better in 2015, and the trend of the steady growth of ecological environment and economic development, but the constraints of ecosystem on economic development were also increasing.

(3) The spatial distribution pattern of GGI in China from 2000 to 2020 is generally consistent, i.e., the GGI in southeastern and northeastern regions is lower than that in northwestern and central regions of China, and there are large regional differences. The ecological function areas, mainly Tibet and Qinghai, have relatively high GEP values, but their economic development levels are relatively backward in general. The area of GGI>1 is less in 2000-2020, and the area of GGI=1 increases significantly in 2005, the fluctuation of each provincial capital city is relatively large, among which the GGI values of Shijiazhuang and Nanjing are relatively large; the GGI of Changsha and Hangzhou is the largest in 2015, and the GGI of Shanghai is the largest in 2020, analyzing the reasons to see that these regions are higher ecological resource endowment, better ecological environment, and higher economic development level, but the overall ecological environment level is higher than the economic development level.

GEP accounting is a decision-making tool to achieve high-quality development and an important tool to guide local actions to protect and improve the ecological environment. While developing the economy, the government should develop policies to protect the forest and wetland ecosystems because of their high GEP per unit area. The degree of coupling and coordination between GEP and the economic system can be used as an evaluation indicator for the high-quality development of the regional economy and has practical guidance for promoting the realization of the value of ecological products in the region. The realization of the value of ecological products in the coordinated development of the ecological and economic system has practical guidance.

Compliance with Ethical Standards

Conflict of Interest

The authors declare no competing interests.

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Ethical Approval

The concept, writing, and publication process of this article comply with human ethical standards.

Consent to Participate

The coauthors of this article participated in the specific work and agreed to publish it.

Consent to Publish

The coauthors of this article participated in the specific work and agreed to publish it.

Authors Contributions

Wei Wei: Conceptualization, Methodology, Software.

Shengxiang Nan: Data processing, Research framework, Paper Writing.

Binbin Xie: Data processing, Paper Writing.

Chunfang Liu: Method

Junju Zhou: Data processing

Congying Liu: Writing- Reviewing and Editing.

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Competing Interests

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

Availability of Data and Materials

Data derived from a source in the public domain, at https://www.resdc.cn/.

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