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Spatiotemporal patterns of gross ecosystem product across China's cropland ecosystems over the past two decades

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As the largest artificial ecosystem on Earth, croplands not only secure the basic living materials for people but also provide ecological service values for human society. For croplands, ecosystem services have proven to be of great value and are closely linked to human activities and climate change. However, spatiotemporal patterns of cropland ecosystem services and their drivers still need to be further assessed quantitatively. In this study, we provided a comprehensive evaluation of ecosystem services across China's cropland ecosystems over the past two decades using gross ecosystem product (GEP) as a single metric of the monetary evaluation of final ecosystem services. The values of material services, regulating services, and cultural services were calculated to summarize the GEP value of cropland ecosystems in China. Our results showed that the multiyear mean value of GEP was 4.35×10^7 million CNY. The value of regulating services reached 3.86×10^7 million CNY, followed by material services of 4.76×10^6 million CNY and cultural services of 1.16×10^5 million CNY. GEP value was different among provinces, leading to a heterogeneous spatial pattern associated with population and cultivated area. Moreover, we analyzed the trends in the GEP value at the provincial and national scales. The results showed that the GEP value of China's cropland ecosystems has increased over the period. The values of the material, regulating, and cultural services have increased at a rate of $(0.35 \pm 0.01) \times 10^6$ million CNY a^{-1}, $(1.12 \pm 0.10) \times 10^6$ million CNY a^{-1}, and $(0.002 \pm 0.0002) \times 10^6$ million CNY a^{-1}, respectively ($P < 0.05$). The majority of provinces had an increasing trend in GEP, yet some developed provinces, e.g., Beijing and Shanghai, showed a decreasing trend. Furthermore, we evaluated the impacts of social-economic and natural factors on changes in GEP. We found that rising prices for agricultural products and services boosted an increase in GEP. Meanwhile, the spatiotemporal patterns of GEP were also associated with the adjustments of planting area in each province. Overall, our findings highlight the importance of assessing spatiotemporal patterns of cropland ecosystem services for decision-makers.

KEYWORDS

gross ecosystem product, ecosystem service, cropland, driving factor, spatial distribution

Introduction

China's economy has maintained a rapid growth rate over the past two decades (World Bank, 2020), yet the ensuing environmental problems are becoming one of the most serious threats to ecological sustainability and security (Intergovernmental Panel on Climate Change (IPCC), 2018; Feng et al., 2021). The balance between social and natural values plays an essential role in achieving sustainable development for every country (Polasky et al., 2019; Jiang et al., 2021). Economic development will inevitably cause changes in the internal structure of natural capital (Li et al., 2021). In recent years, the Chinese government has recognized the importance of addressing the goal of sustainable development by protecting and restoring ecosystems (Naustdalslid, 2014), as President Xi Jinping's theory that "lucid waters and lush mountains are invaluable assets." More paths such as the development of ecological civilization are needed to harmonize the apparent contradiction between economic development and environmental protection (Ma and Wei, 2021; Ma et al., 2021). The Seventeenth Congress of the Communist Party of China pointed out the construction of an ecological civilization with Chinese characteristics. In the cropland ecosystem, it has faced the problems of soil erosion and land degradation by natural forces and human pollution such as excessive application of chemical fertilizers and burning of straw. One of the aims of ecological civilization is to solve these issues for realizing the sustainable development of agriculture (Fan, 2011; Zhang, 2012).

As the world's largest artificial ecosystem, the agro-ecosystem covers nearly 40% of the global terrestrial area (Food Agriculture Organization of the United Nations, 2020). As a country with a large population, China has to consider the relationships between food production, environmental degradation, and economic development in cropland ecosystems (van Vliet et al., 2017; Zheng et al., 2019). Resolving the conflict between social-economic development and the conservation of highly productive farmland is significant and has an impact on food security (Lambin and Meyfroidt, 2011). Numerous policies for cropland conservation have been implemented all over the world, such as the Farmland Protection Program (USA) and the Basic Law of Agriculture (Japan). Since the late 1990s, China has adopted a series of policies to protect croplands in order to ensure national food security (Yang and Li, 2000; Skinner et al., 2001). The cropland area is essential to ensure food security in China. In recent years, China's food production has been increasing, but it is still facing the challenge of multiple difficulties in stabilizing the quantity, improving the quality, and preserving the ecology of cropland (Ministry of Agriculture Rural Affairs, 2021). To ensure food security, the actual cropland area in the country is maintained at 129 million hectares under the red line policy of 120 million hectares, which is about 12.7% of the national territory and ranks fourth in the world (Food Agriculture Organization of the United Nations, 2020). Therefore, valuing natural capital in China's cropland ecosystems is of importance for decision-makers, especially under the current national strategy (Song and Pijanowski, 2014; Jiang et al., 2016).

Ecosystem services mean the direct and indirect contributions of ecosystems to human society, representing part of the total economic value of the planet, including material services, regulating services, and cultural services (Costanza et al., 1997; Ouyang et al., 2016). The term "ecosystem services" is always used to assess natural resources and potential ecological benefits for human beings to survive and develop (Xu et al., 2021). For cropland ecosystems, the most important functions for human wellbeing and sustainable development are material product supply, climate regulation, soil retention, air purification, and carbon sequestration (Rodriguez-Entrena et al., 2014; Divinsky et al., 2017; Granado-Diaz et al., 2020). The values of these ecosystem services in croplands are enormous and often underappreciated (Power, 2010). Cropland ecosystems are facing the dual challenge of increasing food production while continuing to provide much-needed environmental goods and services (Cao et al., 2020). China's massive croplands make its ecosystems even more important for maintaining ecological balance, improving the environment, and protecting the basic conditions for human survival (Diaz et al., 2018; Losacco et al., 2021). Considering China's greater dependence on grain production, there will be a greater need for decision-makers to clarify changes in the provision and delivery of cropland ecosystem services to ensure self-sufficient agriculture production and sustainable cropland management (Fan et al., 2012).

There is a growing interest in the assessment and valuation of ecosystem services (Carpenter et al., 2006; Jackson et al., 2016; Gomez-Baggethun et al., 2019). The approaches from the perspective of social-ecological systems are used to analyze, assess, and quantify ecosystem services (Torres et al., 2021). For instance, the Millennium Ecosystem Assessment introduced a wide-disseminated framework for managing ecosystem services, showing the possibility of using economic valuation to value natural capital in ecosystems (Millennium Ecosystem Assessment., 2005). Previous studies used the economic valuation methods to better understand how ecosystems provide value to people and how to protect that value (Ranganathan, 2011). On this basis, more studies applied ecological-economic models to estimate the value of ecosystem services from forests, wetlands, and croplands at local and national levels (Dong et al., 2007; Guo et al., 2008; Nelson et al., 2009; Goldstein et al., 2012; Li et al., 2015; Ouyang et al., 2020). However, these approaches that translate ecosystems' contributions to the economy into monetary terms could be inconsistent, leading to their results that may not be comparable with each other.

To achieve a uniform measurement of ecosystem services, Ouyang et al. (2020) developed gross ecosystem product (GEP)

to summarize the value of the contributions of nature to economic activity in a single monetary metric. Analogous to gross domestic product (GDP), GEP uses market prices and surrogates to calculate the value of ecosystem services and then aggregate them into a measure of the ecosystems to human society. Their results demonstrated that it is feasible to produce an estimate of GEP with currently available data and methods, and GEP can provide decision-makers with a clear understanding of the monetary value of ecosystem services (Wang et al., 2019a; Liang et al., 2021). In recent years, the ministry of ecology and environment of the People's Republic of China has published the technical guideline on gross ecosystem product which allowed to assess China's GEP with finite data and methods (Chinese Academy of Environmental Planning Research Center for Eco-Environmental Sciences, 2020).

The GEP has been assessed in various studies, but it is still difficult to compare the results, especially in agriculture. On the one hand, there is a shortage of unified assessment methods. On the other hand, the range of estimation and indicators is not consistent. Relevant studies show that the assessment of GEP mostly focuses on ecosystems such as forests and wetlands, and there are few specific studies on croplands, let alone a nationwide assessment of cropland ecosystem services and differentiation of human and natural impacts. In this study, we conducted a comprehensive analysis using GEP as a metric of the monetary evaluation of the final ecosystem services to assess the stock of the ecosystem and the flow of value in China's cropland ecosystems and their drivers from 2001 to 2019. The GEP of material services, regulating services, and cultural services was calculated to account for food production, water retention, soil retention, carbon sequestration, air purification, climate control, biodiversity, and agricultural tourism. The biophysical quantities were estimated using the statistical survey method, precipitation storage method, RUSLE model, carbon sequestration mechanism model, pollutant purification model, and evapotranspiration model following the recommended approaches by the Technical Guideline on Gross Ecosystem Product. The market value method, travel cost method, shadow project method, replacement cost method, and conservation value method were used to calculate the monetary value. Moreover, we analyzed spatial and temporal patterns of GEP across China's cropland ecosystems over the past two decades. Furthermore, we further set up seven experimental scenarios and used the linear least square regression method with an *F*-test to evaluate the effects of natural factors (including precipitation, high-temperature days, and evapotranspiration) and social-economic factors (including acreage and prices) on inter-annual changes in GEP. The aims of our study are as follows: (1) to evaluate the spatial pattern of GEP across China's cropland ecosystems; (2) to analyze the temporal pattern of GEP in China at the provincial scale during 2001–2019; and (3) to assess the impacts of natural factors and social-economic factors on GEP variation between years.

Materials and methods

Data

In our research, there were mainly three types of data, namely, crop data, meteorological data, and geographic information, obtained from the government departments, the industry standards, and the literature. Data from the government departments included the planting areas, prices, DEM, and climate factors. They were selected mainly from the National Bureau of Statistics, the Ministry of Agriculture and Rural Affairs, the Shuttle Radar Topography Mission, the Chinese National Metrological Information Center, and so on (Supplementary Figure 1 and Supplementary Tables 1, 2). To better assess the GEP in China's cropland, two industry standards containing the Technical Guideline on Gross Ecosystem Product and Guidelines for measurement and estimation of soil erosion in production and construction projects (SL 773-2018) were used. Moreover, other data, such as parameters, were collected from reviewing the literature (Supplementary Table 3). More detailed data descriptions are provided in the Supplementary material.

The technical framework of China's cropland ecosystem assessment

Ecological assessment systems of China's GEP in cropland have considered the individual characteristics, structure, and ecological services. The accounting index of GEP was divided into three major services and six smaller classes. We chose the ecological services described above because previous studies have shown their importance to cropland ecosystems, and we had available data and methods to evaluate their value according to the Technical Guideline on Gross Ecosystem Product (Yuan et al., 2011; Li et al., 2016; Tzilivakis et al., 2019; Cai et al., 2020). Material services, regulating services, and cultural services are accounted for in Eq. (1). Furthermore, water retention, soil retention, carbon sequestration, air purification, climate control, and biodiversity are accounted for in Eq. (2), relative to data availability:

$$\mathbf{GEP = EPV + ERV + ECV} \tag{1}$$

$$\mathbf{ERV = WR + SR + CS + AP + CC + BI} \tag{2}$$

where GEP is the value of the cropland gross ecosystem product; EPV is the value of cropland ecosystem products; ERV is the value of regulating services; ECV is the value of cultural services; WR, SR, CS, AP, CC, and BI represent the value of water retention, soil retention, carbon sequestration, air purification,

TABLE 1 Description of the evaluation methods of different types of ecosystem services.

Type	Description	Methods		Indexes used for evaluation	
		Biophysical	**Monetary**	**Biophysical**	**Monetary**
EPV	Products that humans can obtain from croplands	Statistical survey method	Market value method	Agricultural products	The output value of agricultural products
ECV	Provision of spiritual sensations and artistic experiences	Statistical survey method	Travel cost method	Number of tourists and level of consumption	Tourism income
WR	Interception and storage precipitation, enhancement of soil infiltration, and accumulation	Precipitation storage method	Shadow project method	Precipitation storage	Costs of constructing water storage and conservation facilities
SR	Protection of soil and reduction of water erosion	RUSLE model	Replacement cost method	Estimated average soil loss	Costs of reservoir dredging project and pollution treatment
CS	Absorption of CO_2 from the atmosphere to synthesize organic biomass and fix carbon in plants or soil	Carbon sequestration mechanism model	Market value method	Soil, fertilizer, and straw carbon sequestration	Trading prices in the Chinese major carbon market during 2018-2019
AP	Absorption and purifier air pollutants	Pollutant purification model	Replacement cost method	Absorption of sulfur dioxide, nitrogen oxides, particulates	Costs of purifying air pollutants according to the Environmental Protection Tax Law
CC	Reducing air temperature and increasing humidity	Evapotranspiration model	Replacement cost method	The total energy consumed by evapotranspiration	The electricity consumption price required for human adjustment of corresponding temperature and humidity
BI	Providing habitats for species	Statistical survey method	Conservation value method	Area of the nature reserve	Costs per unit area of the nature reserve

climate control, and biodiversity, respectively. All the variables were defined in Table 1.

The technical framework for the GEP of cropland contained two steps. First, the biophysical value of products and services was calculated by obtaining the output and quantity in China's cropland. To calculate the GEP, the biophysical value is measured followed by the monetary value. Second, we collected different prices to assess the monetary value. More detailed assessment methods are provided in Table 1 and Supplementary material.

Estimation of different influences of natural and social-economic factors on ecosystem services value

Experimental scenario design

To reveal the relationship between climate change, human activities, and GEP, we set up separate scenarios where the normal scenario allowed all the variables to change with time, and in the other scenarios, we kept one of all the variables at the 2001 level while allowing the other variables to change over time. These experimental scenarios considered both natural and social-economic influences on the biophysical and monetary value and also referred to the literature on driving factors of ecosystem services (Schroter et al., 2005; Haberl et al., 2007; Wang et al., 2016). To be specific, S_0, S_P, S_H, S_E, S_N, S_A, S_C, and S_S represent the scenarios of normal, no variation in precipitation, high-temperature days, evapotranspiration, all three natural factors, planting area, product prices, and two social-economic factors, respectively. Owing to some prices set by the government nationwide, therefore, we chose other drivers to compare in order to represent variation between provinces.

Analysis methods

The trends in material services, regulating services, cultural services, GEP, and all the scenarios in China's croplands were estimated using the linear least square regression method with an F-test. Moreover, we analyzed the correlation between the trend of GEP and natural factors (including precipitation, high-temperature days, and evapotranspiration) and social-economic factors (including planting area and prices) over the whole study area. To be specific, the dominant factor is chosen by selecting the maximum difference between the trend of S_0 and the trend of S_i (i is the kind of scenario).
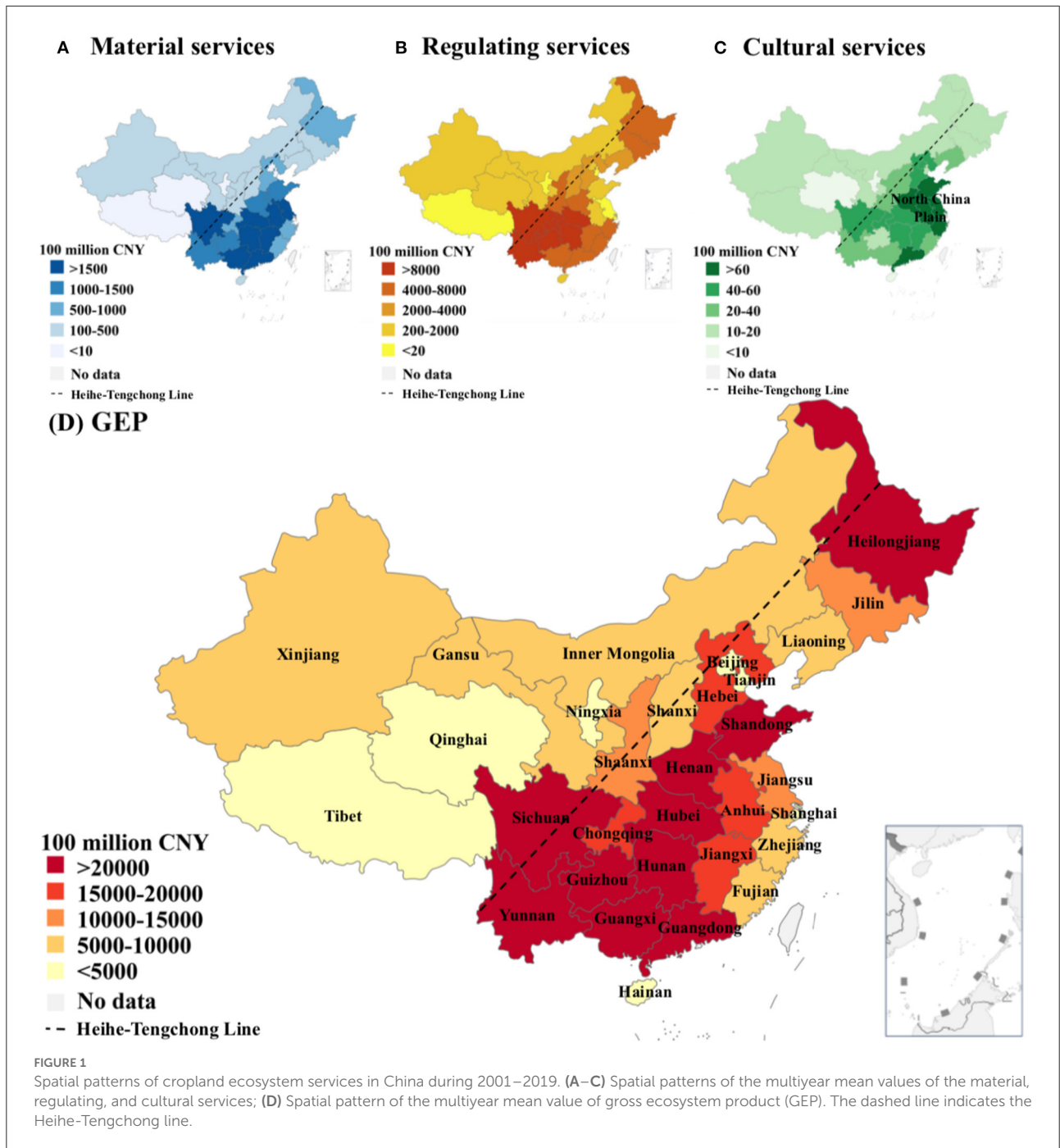
Results

Spatial pattern of GEP across China's cropland ecosystems

To evaluate the spatial pattern of GEP across China's cropland ecosystems from 2001 to 2019, we accounted for the values of the material, regulating, and cultural services and then aggregated them into GEP at the provincial and national scales (Figure 1 and Supplementary Table 4). The multiyear mean values of material services, regulating services, and cultural services of China's cropland ecosystems were 4.76×10^6 million CNY, 3.86×10^7 million CNY, and 1.16×10^5 million CNY, respectively. The multiyear mean value of GEP was 4.35×10^7 million CNY. However, our results showed that the values of the material, regulating, and cultural services were different

among provinces, leading to a heterogeneous spatial pattern of GEP across China's cropland ecosystems. Specifically, the values of material and regulating services in the southern provinces were higher than those in the northern provinces, and the values of cultural services were high in the provinces of the North China Plain and Guangdong Province. The spatial pattern of GEP was similar to that of regulating services across China's cropland ecosystems, implying that cropland ecosystems contributed more to regulating services in the southern provinces. Moreover, we found that one-quarter of the provinces (including Sichuan, Henan, Hunan, Hubei, Yunnan, Guangdong, and Guangxi) contributed to over 50% of the total values of GEP across China's cropland ecosystems. Unlike natural ecosystems, cropland ecosystems were associated with human activities. Most of those provinces with high GEP were located on the east side of the Heihe-Tengchong line. Therefore, the spatial pattern of GEP was influenced by the population and cultivated area of each province according to the GEP accounting method.

Temporal pattern of GEP across China's cropland ecosystems
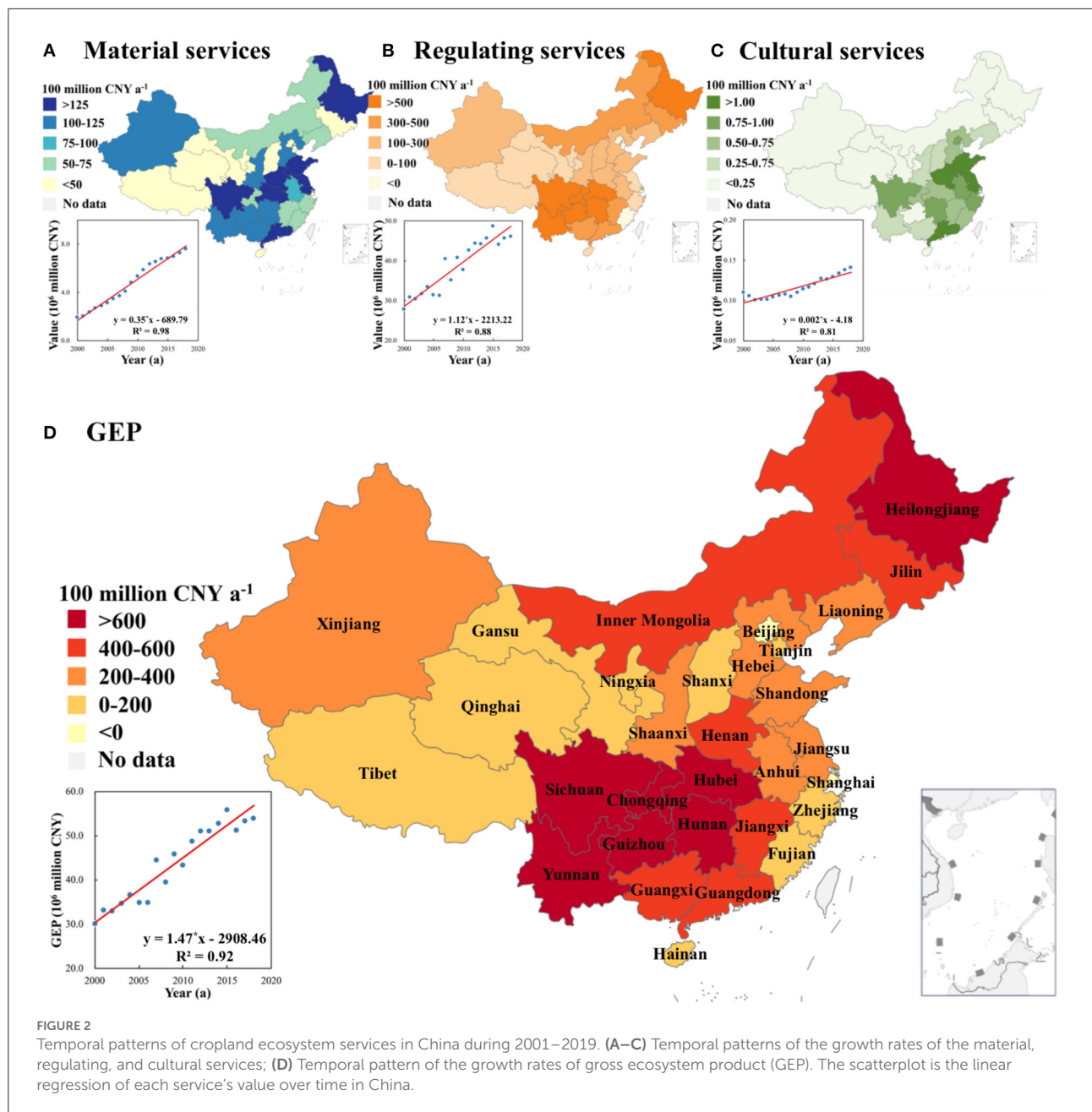
To examine the temporal pattern of GEP across China's cropland ecosystems from 2001 to 2019, we analyzed the trends in the values of the material, regulating, cultural services, and GEP at the provincial and national scales (Figure 2 and Supplementary Table 4). The values of the material, regulating, and cultural services have increased at a rate of $(0.35 \pm 0.01) \times 10^6$ million CNY a^{-1}, $(1.12 \pm 0.10) \times 10^6$ million CNY a^{-1}, and $(0.002 \pm 0.0002) \times 10^6$ million CNY a^{-1}, respectively ($P < 0.05$). Over this period, GEP associated with China's cropland ecosystems has increased at a rate of $(1.47 \pm 0.11) \times 10^6$ million CNY a^{-1} ($P < 0.05$). Our results showed that the increase in the value of regulating services accounted for the majority of the increase in GEP over the past two decades. Specifically, the values of soil retention, climate control, water retention, carbon sequestration, air purification, and biodiversity have increased at a rate of $(0.86 \pm 0.08) \times 10^6$ million CNY a^{-1}, $(0.11 \pm 0.02) \times 10^6$ million CNY a^{-1}, $(0.10 \pm 0.01) \times 10^6$ million CNY a^{-1}, $(0.04 \pm 0.003) \times 10^6$ million CNY a^{-1}, $(0.004 \pm 0.001) \times 10^6$ million CNY a^{-1}, and $(0.004 \pm 0.0004) \times 10^6$ million CNY a^{-1}, respectively ($P < 0.05$). Moreover, our results showed that the changes in the values of the material, regulating, and cultural services were different among provinces, leading to a heterogeneous temporal pattern of GEP across China's cropland ecosystems. The provinces with a high multiyear mean GEP (including Sichuan, Henan, Hunan, Hubei, Yunnan, Guangdong, and Guangxi) have a large increase in GEP due to the fast rise of the value of regulating services. However, not all provinces showed an increase in GEP, e.g.,

FIGURE 1
Spatial patterns of cropland ecosystem services in China during 2001–2019. **(A–C)** Spatial patterns of the multiyear mean values of the material, regulating, and cultural services; **(D)** Spatial pattern of the multiyear mean value of gross ecosystem product (GEP). The dashed line indicates the Heihe-Tengchong line.

Beijing and Shanghai. Similar to the spatial patterns of cropland ecosystem services in China, the temporal patterns showed an important role in regulating services in boosting the total GEP of cropland ecosystems in China, especially in the southern provinces. In addition, we found a rapid increase in GEP in Xinjiang and Inner Mongolia. With shifting the centers of population and economy, GEP growth may no longer be limited by the Heihe-Tengchong line.
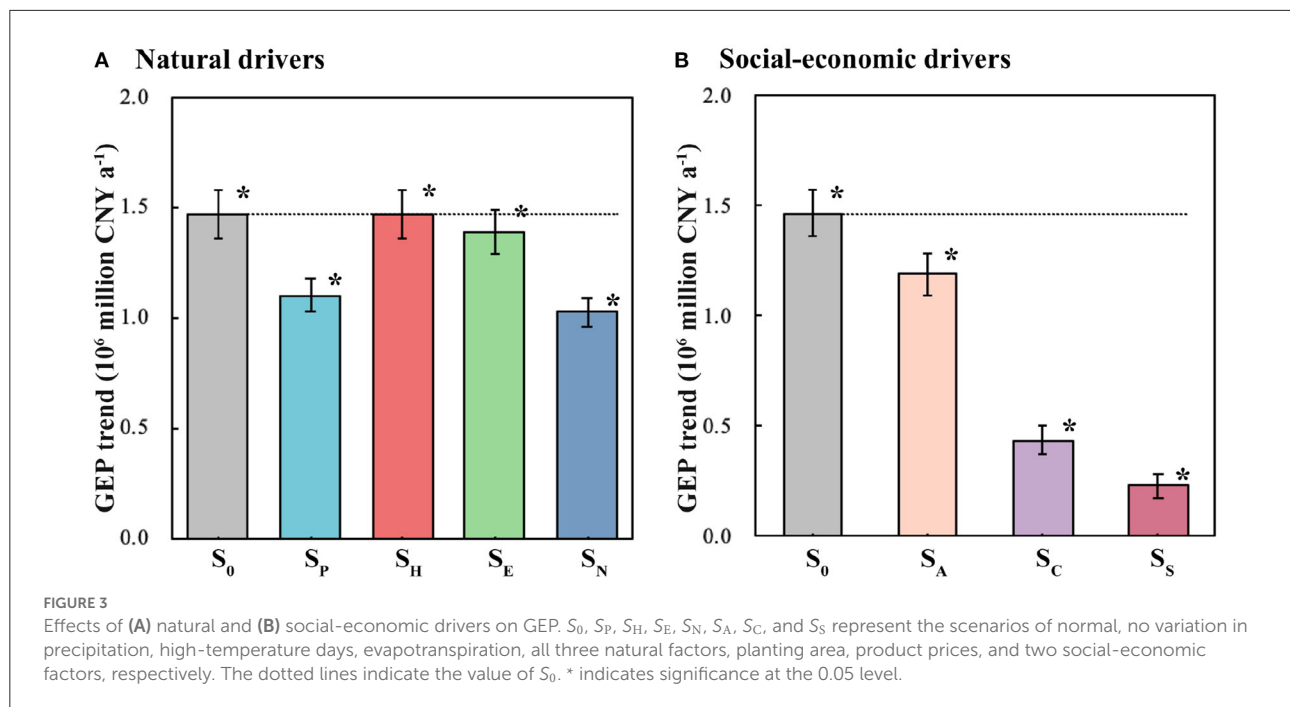
Effects of natural and social-economic drivers on GEP

In this study, we performed several types of experimental scenarios to separate the effects of natural (i.e., precipitation, high-temperature days, and evapotranspiration) and social-economic (i.e., planting area and product prices) drivers on GEP during 2001–2019 (Figure 3 and Supplementary Table 5).

FIGURE 2
Temporal patterns of cropland ecosystem services in China during 2001–2019. **(A–C)** Temporal patterns of the growth rates of the material, regulating, and cultural services; **(D)** Temporal pattern of the growth rates of gross ecosystem product (GEP). The scatterplot is the linear regression of each service's value over time in China.

The normal scenario (S_0) allowed all the variables to change with time, showing a GEP trend at a rate of $(1.47 \pm 0.11) \times 10^6$ million CNY a^{-1} ($P < 0.05$). For the other scenarios, we held one of all the variables constant at its 2001 level, while allowing the other variables to change with time. Our results showed that the natural effects of precipitation, high-temperature days, and evapotranspiration on GEP were $(1.10 \pm 0.07) \times 10^6$ million CNY a^{-1}, $(1.47 \pm 0.11) \times 10^6$ million CNY a^{-1}, and $(1.39 \pm 0.10) \times 10^6$ million CNY a^{-1}, respectively. The effect of precipitation contributed to a significant increase in GEP during 2001–2019, accounting for $(0.37 \pm 0.09) \times$

10^6 million CNY a^{-1}. The total effect of natural drivers on GEP was $(1.02 \pm 0.06) \times 10^6$ million CNY a^{-1}. Moreover, the social-economic effects of planting area and prices on GEP were $(1.19 \pm 0.09) \times 10^6$ million CNY a^{-1} and $(0.44 \pm 0.06) \times 10^6$ million CNY a^{-1}, respectively. The effect of product prices contributed to a significant increase in GEP during 2001–2019, accounting for $(1.03 \pm 0.06) \times 10^6$ million CNY a^{-1}. The total effect of social-economic drivers on GEP was $(0.23 \pm 0.05) \times 10^6$ million CNY a^{-1}. Overall, we found that social-economic factors had a greater impact on GEP than natural factors, driving the increase

FIGURE 3
Effects of **(A)** natural and **(B)** social-economic drivers on GEP. S_0, S_P, S_H, S_E, S_N, S_A, S_C, and S_S represent the scenarios of normal, no variation in precipitation, high-temperature days, evapotranspiration, all three natural factors, planting area, product prices, and two social-economic factors, respectively. The dotted lines indicate the value of S_0. * indicates significance at the 0.05 level.

in ecosystem services in China's croplands over the past two decades.

Furthermore, we evaluated the effects of natural and social-economic drivers on GEP for each province during 2001–2019 (Figure 4 and Supplementary Table 6). Considering the uniformity of prices across 31 provinces in China, we only separated the effects of the other variables (i.e., precipitation, high-temperature days, evapotranspiration, and planting area) on GEP at the provincial scale. Our results showed that the trends in GEP were dominated by the changes in planting area in 20 of the 31 provinces over the past two decades. Specifically, the increases in planting area led to the growth of GEP in most provinces, such as Hunan, Yunnan, and Guizhou. However, for the provinces with faster economic development, such as Guangdong, Fujian, Hebei, Zhejiang, Hainan, Shanghai, Tianjin, and Beijing, the decreases in planting area resulted in slow growth and even a decrease in GEP. In addition, the changes in precipitation dominated the growth of GEP by affecting 8 of the 31 provinces, including Sichuan, Hubei, Jiangxi, and so on. Meanwhile, the changes in evapotranspiration dominated the growth of GEP affecting 3 of the 31 provinces, including Guangxi, Shandong, and Tibet. As we mentioned above, the changes in GEP were more relevant to social-economic factors rather than natural factors at both the provincial and national scales. China's social-economic policies (e.g., land-use change, ecological redline policy, and macro-economic control) exhibited a significant role in cropland ecosystem services over the past two decades.

Discussion

As the foundation of social development, agriculture has consistently played an irreplaceable role in the national economy (Swinton et al., 2007; Power, 2010; Schipanski et al., 2014). The assessment of products and services within croplands helps to better understand the current state of agricultural development (Duguma et al., 2019; Balzan et al., 2020). However, many ecosystem services have indirect market-based prices in the current assessment system, and each service has different price accounting methods, making the assessment results more dependent on choices of distinct methods and consequently less comparable (Polasky et al., 2015). Therefore, a valuation was carried out for the cropland ecosystem services in China during 2001–2019 for 31 provinces (autonomous regions and municipalities) in our study, aiming to address the uncertainty of existing assessment strategies for the selection of indicators and inter-annual variables for each province. For example, Xie et al. (2015) calculated the value of the ecological services equivalent factor for rice, wheat, and maize. The factor was only defined as the value of the natural production of croplands with a national average yield of 3406.5 $CNY \cdot hm^{-2}$. After adding ecological services of croplands, the value has increased to 12919.2 $CNY \cdot hm^{-2}$ (Huang et al., 2022). Compared with previous studies, our estimated GEP is slightly larger than their findings (Chen et al., 2020; Yang et al., 2020; Jia et al., 2021). The major reason could be due to the selection of ecosystem indicators, inconsistent pricing methods for products and services, and inter-annual variations in model parameters. Some previous
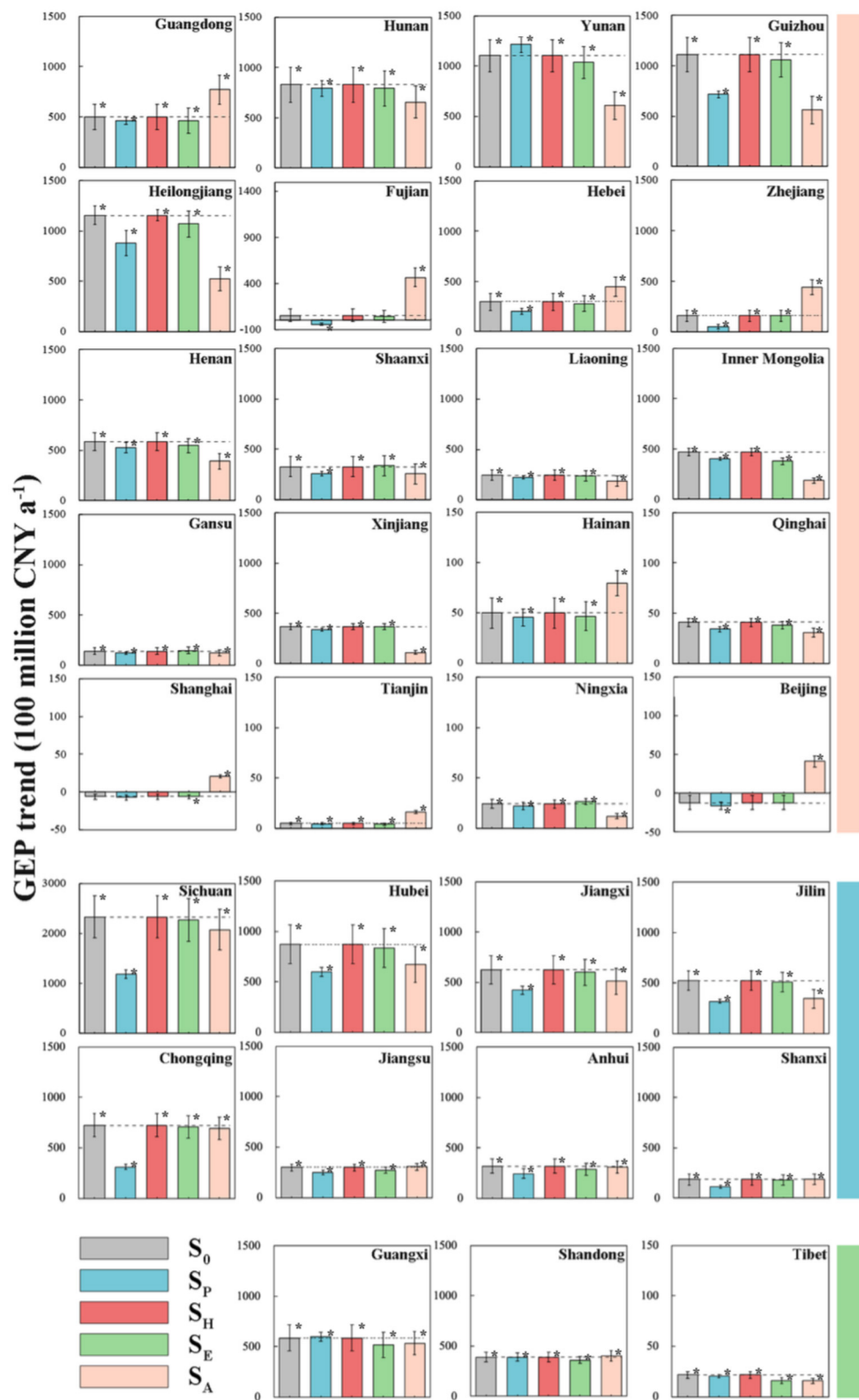
FIGURE 4
Effects of natural and social-economic drivers on GEP for 31 provinces in China. S_0, S_P, S_H, S_E, S_N, S_A, S_C, and S_S represent the scenarios of normal, no variation in precipitation, high-temperature days, evapotranspiration, all three natural factors, planting area, product prices, and two social-economic factors, respectively. The dotted lines indicate the value of S_0. * indicates significance at the 0.05 level. The colors of the rectangle on the right side indicate the dominant driver.

studies have concluded that material services were the dominant services of cropland ecosystem, which is mainly attributed to the fact that the material produced in the previous studies contained the additional products of cropland. For example, Yin et al. (2022) considered the value of straw, which was included in the carbon sequestration of regulating services in our study. In addition, compared with previous studies, we integrated more regulating services subsets to further expand its value (Bai et al., 2010; Marinidou et al., 2019; Cai et al., 2020). Therefore, it is recommended to strengthen the standardization of essential aspects such as ecological product assessment framework, index system, methods, and key parameters in the research of GEP, so as to achieve the systematic, repeatability, and horizontal comparability of results.

In our study, we found that the values of the southern provinces were generally higher than those of the northern provinces. More than half of China's croplands were in Hebei, Shandong, Henan, Shanxi, Heilongjiang, Jilin, Liaoning, and Sichuan (Song and Deng, 2017). However, China's precipitation resources were abundant but unbalanced, leading to a spatially heterogeneous distribution of GEP (Wang et al., 2016). Moreover, the provinces with high GEP were located on the east side of the Heihe-Tengchong line, which indicates a positive correlation between agriculture, population density, and topography (Wang et al., 2019b). Our results also showed that the major reasons why GEP was increasing in most of China's provinces were the effects of variation in price, planting area, and precipitation. Similarly, the findings on population, social-economic level, and industry scale for spatial heterogeneity have been proved in other studies (Gordeev et al., 2021; Wang et al., 2021, 2022; Zeng and Wang, 2022). In China, the effects of population growth and urbanization were significant. The decrease in food supplies has made structural inflation inevitable (Durevall et al., 2013). China's government has implemented a policy of agricultural subsidies to encourage cultivation, which was aiming at maintaining planting areas and safeguarding production (Huang and Yang, 2017). However, due to economic development accelerating the process of urbanization and reducing planting area, the two provinces where GEP was decreasing were Beijing and Shanghai. Due to the responses exhibited in both areas, specific ecological protection policies should be adopted. Besides, the provinces that were influenced by precipitation were mostly distributed along the Yangtze River. The phenomenon may be caused by the significant effects of meteorological factors on the extreme precipitation of the Yangtze River (Zou et al., 2021).

At present, the assessment of GEP in croplands is still in a developing stage, there are many imperfections. The effort in this study represents a start toward accounting of GEP in croplands, but much work remains. First, data limitations lead to an inaccurate estimation of assessment. Therefore, it is important to improve the scale, resolution, and frequency of data collection to examine a comprehensive and accurate accounting. Second, the growth periods of different plants should be considered in the calculation and using meteorological data at different stages. Maybe we estimated the contribution of croplands slightly higher than it actually was by using annual data. Third, although we have considered the influence of three natural factors and two social-economic factors and set up seven different scenarios based on each ecosystem service assessment process and referring to previous literature, the drivers of cropland ecosystems are still complex and various. We need to measure more comprehensively the drivers of cropland ecosystems, such as the population density and the transfer of GEP in croplands among provinces after policy regulation. This is an issue that needs to be considered in the future.

Conclusion

This study uses GEP as a metric of the monetary evaluation of final ecosystem services to estimate the stock of the ecosystem and the flow of value in China's cropland ecosystems and their drivers from 2001 to 2019 based on crop data, meteorological data, and geographic information. The study presents the following conclusions: (1) The average of China's GEP in croplands over the past two decades was 4.35×10^7 million CNY. From the perspective of different ecosystem services, the value of regulating services reached 3.86×10^7 million CNY and accounted for 88.78% of the gross ecosystem products. This was followed by material services 4.76×10^6 million CNY and cultural services 1.16×10^5 million CNY. Specifically, the values in the southern provinces were higher than those in the northern provinces. (2) In general, the temporal pattern of GEP across China's cropland ecosystems showed a positive trend during 2001–2019. GEP associated with China's cropland ecosystems has increased at a rate of $(1.47 \pm 0.11) \times 10^6$ million CNY a^{-1} ($P < 0.05$). The values of the material, regulating, and cultural services have increased at a rate of $(0.35 \pm 0.01) \times 10^6$ million CNY a^{-1}, $(1.12 \pm 0.10) \times 10^6$ million CNY a^{-1}, and $(0.002 \pm 0.0002) \times 10^6$ million CNY a^{-1}, respectively ($P < 0.05$). Within the regulating services, the value of soil retention increased most rapidly, followed by climate control, water retention, and carbon sequestration, and the slowest was in the values of air purification and biodiversity. However, not all provinces showed an increase in GEP, e.g., Beijing and Shanghai. (3) In addition, social-economic factors have contributed more to cropland GEP than natural factors. In particular, inflation has significantly improved GEP over the past two decades. Furthermore, except for economic factors, the planting area influenced most provinces. It is expected that the results of our study will provide a novel insight for the future ecological assessments of cropland. This information will assist stakeholders in the scientific management of agriculture in China and draw greater attention to the utility of its resources.

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/s.

Author contributions

JZ collected and calculated the data and wrote the manuscript. YS helped design the structure of the manuscript and revised it. JW was involved in the study design and critically revised the manuscript. All authors have contributed to the article and approved the submitted version.

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Conflict of interest

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

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fevo.2022.959329/full#supplementary-material

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