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# Research and application of GEP: China's experience in natural capital accounting

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In 2013, for raising the awareness of policymakers and researchers on the economic value of ecosystem services, GEP (Gross Ecosystem Product) was proposed by Chinese scholars. As a new attempt at ecosystem services evaluation, GEP has been widely accepted in China and is often used to reveal the effectiveness of regional ecological protection and the relationship between humans and nature. However, there is currently a lack of a systematic review of GEP research. In this study, we found that: 1) GEP can reflect the overall situation of ecological environment and service quality, and help decision-makers and managers formulate and implement sustainable development strategies and ecological protection policies. 2) The contradiction between the depletion of global ecosystem capital and the development of people's livelihood continues to intensify. About 68.7% of developing countries are facing a "low-low development (low GEP and low GDP)" model. 3) We have constructed the path model of the GEP working system and the path model of ecological protection compensation mechanism in China. The GEP accounting system of "from point to area, from top to bottom", the parallel evaluation strategy of GDP and GEP and the comprehensive ecological compensation system of "vertical and horizontal combination" implemented can be popularized to countries all over the world.

KEYWORDS

**gross ecosystem product (GEP), ecosystem services, natural capital, sustainable development, China**

## 1 Introduction

The global ecosystem is huge, complex, and diverse. While maintaining global biodiversity, it supports about 7.6 billion people and provides services vital to human wellbeing, health, livelihood, and survival (Costanza et al., 1997; Millennium Ecosystem Assessment Panel, 2005; Nelson et al., 2009; TEEB Foundations, 2010; Maes et al., 2016). However, under the background of extensive global climate change and the continuous impact of human activities (Chen et al., 2021; Cobb et al., 2021; Ellis et al., 2021; Grant et al., 2021; Ouyang et al., 2021; Yang et al., 2021), the global ecosystem degradation has intensified, and 60% of ecosystems are degraded, more than 30% of natural freshwater disappears, and the forest is reduced by 10 million ha each year (Havsen et al., 2013; Andrew and Erin, 2019). The global ecosystem is still facing the weakening of ecosystem services and the depletion of natural resources in the future, which seriously threatens the survival of mankind.

How to increase humanity's extensive attention to the importance and sustainability of global ecosystems? At present, the common method in the scientific community is to calculate the value of ecosystem services, that is, to evaluate the benefits of the ecosystem in the form of

monetization. Assessing global ecosystem services can help people grasp the overall status of ecosystem operations, and reflect the quality of ecological environmental services, and understand the relationship between ecosystems and human wellbeing. Furthermore to help decision-makers implement more scientific and reasonable sustainable development strategies and ecological protection policies (de Groot et al., 2012; Costanza et al., 2014; Ouyang et al., 2016).

Ouyang et al. believe that GEP, as an indicator of ecosystem contribution to the economy, can provide a basis for carrying out the research on the realistic mechanism of ecological products and transforming the value of ecological products into economic benefits (Ouyang et al., 2016; Ouyang et al., 2021; Yang et al., 2021). The Chinese government has recognized the importance of protecting and restoring ecosystem assets. GEP accounting is being widely carried out to achieve comprehensive sustainable development. At present, GEP has been incorporated into the decision-making of coordinated development of ecology and economy, eco-environmental compensation mechanism and government eco-environmental performance evaluation (Ouyang and Jin, 2017).

Although the research on GEP has become one of the research hotspots in the academic circle, there is still a lack of systematic induction and sorting of GEP's theory, method, mechanism, impact, application and other aspects. Therefore, this study will systematically describe the development and application of GEP in the form of cases, aiming to provide China's experience for the sustainable development of global ecology and economy.

Based on this, we 1) introduce the background and development trend of GEP accounting, 2)summarize the completed and ongoing GEP accounting cases in China, 3) and try to explain the necessity of global GEP accounting, 4) finally, we attempt to build the working system path model of GEP accounting and ecological protection compensation mechanism path model with Chinese characteristics.

# 2 Materials

## 2.1 Ecosystem change data

The main ecosystem change data sourced from the World Bank (WB) (https://data.worldbank.org/accessed 1 October 2021) and the Food and Agriculture Organization of the United Nations (FAO) (https://www.fao.org/accessed 10 October 2021).

## 2.2 GEP literature retrieval data

We researched articles published between 2000 and 2020, which were collected using selective keywords under "TOPIC" in the database of ISI Web of Science Core Collection. We searched the keywords (ecosystem service, GEP accounting). As needed, we selected 100 articles for detailed review, and finally selected 50 of them to review the cases of global ecosystem GEP accounting. The research area of these articles includes different countries in the world, with regional representation, and the research content includes the main terrestrial ecosystems. At the same time, the selected papers also have high citation rate and influence. In order to make the data and cases more representative and typical, the literatures selected by us mainly consider three aspects: first, the journals with an impact factor greater than 5; second, the regional distribution of the study; third, the country where the author is located.

## 2.3 GDP data

GDP data sourced from the World Bank (WB) (https://data.worldbank.org/accessed1October 2021), the Food and Agriculture Organization of the United Nations (FAO) (https://www.fao.org/accessed 10 October 2021) and United Nations Statistics Division (UNSD) (https://unstats.un.org/accessed 1 October 2021).

## 2.4 Remote sensing data of China

Sourced from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn/accessed on 1 May 2021). It is a remote sensing of China's land use status in 2015 (Landsat 8), which is 1 km grid data generated through vector data rasterization on the basis of 1:100,000 scale remote sensing monitoring data of land use status. According to the research needs, the land use types are divided into cultivated land, forest land, grassland, water area, urban land and bare land.

## 2.5 Global ecosystem change data

The main ecosystem change data sourced from the World Bank (WB) (https://data.worldbank.org/accessed 1 October 2021) and the Food and Agriculture Organization of the United Nations (FAO) (https://www.fao. org/accessed 10 October 2021). Other data: basic global geographic data sourced from the Natural Earth (http://www.naturalearthdata.com/accessed 25 October 2021).

# 3 Results

## 3.1 GEP accounting—a new accounting method of ecosystem service value

Based on the research on ecosystem services. In 2013, Ouyang and Zhu first proposed the concept of the gross ecosystem product (GEP) (Jiang et al., 2021), which is defined as the sum of the final product and service value provided by the ecosystem for human wellbeing and social development in a specific time, mainly including the ecosystem material product value, regulation service value and cultural service value (Ouyang et al., 2021). Ouyang et al. believed that the gross domestic product (GDP) did not fully reflect the contribution of nature to economic activities and human wellbeing, so they developed a measurement standard for the GEP, and at the same time constructed an indicator system and accounting method (Ouyang et al., 2021).

Through GEP accounting, we can better understand the ecological relationship between regions and understand the value of ecological product supply services and ecological regulation services of each ecosystem. At the same time, GEP accounting can better promote the virtuous cycle of ecosystem protection, restoration and management (Chen et al., 2009; Ouyang et al., 2021), (Figure 2C), (Figure 3A).

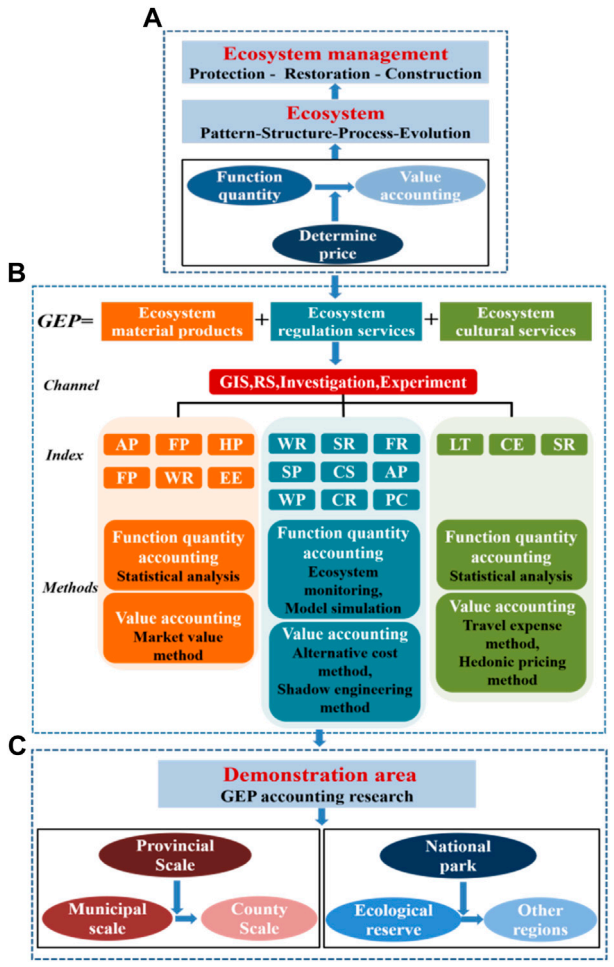


FIGURE 1
Based on the GEP accounting theory and method proposed by (Ouyang et al., 2021), we constructed a framework schematic diagram of the GEP accounting. Note: shows the idea of calculating the gross value of ecosystem production. **(A–C)** shows the data channels (Pan et al., 2004; Zhu et al., 2007; Ouyang et al., 2015), indicators (Ouyang et al., 2021), methods of GEP accounting (OECD, 1996; Xu et al., 2003; Dong et al., 2017; Ouyang et al., 2020). Accounting indicators include: AP: Agriculture products, FP: Forestry products, HP: Husbandry products, FP: Fishery products, WR: Water resource, EE: Ecological energy; WR: Water retention, SR: Soil retention, FR: Flood regulation, SP: Sandstorm prevention, CS: Carbon sequestration, AP: Air purification, WP: Water purification, CR: Climate regulation, PC: Pest control; LT: Leisure tourism, CE: Cultural education, SR: Scientific research. shows the demonstration application of GEP accounting in different ecological functional areas and at the provincial, municipal and county levels.

GEP is the sum of the value of ecosystem products, regulation services, and cultural services (Ouyang et al., 2021) (Figure 1). Generally, ecosystem material product value is called direct use value, while regulation service value and cultural service value are called indirect use value. According to the method of ecosystem service function evaluation, GEP can be calculated from two perspectives: ecological function and ecological economic value. The quantity of ecological function can be expressed by the quantity of ecological products and ecological services, such as grain yield, carbon sequestration, number of tourists, etc. its advantage is intuitive. However, due to different units of measurement, it is difficult to sum the output of different ecological products and services. It is difficult to obtain the GEP of a region and a country in a period of time only by ecological function indicators. Therefore, it is necessary to use prices to convert the output of different ecosystem products and services into currency, and finally get GEP (Ouyang et al., 2021).

## 3.2 GEP accounting in China

### 3.2.1 The imbalance between China's ecological capital protection and regional development is still prominent

In the field of coordination between environment and human development, China has made a lot of efforts and made great progress, with highly innovative and far-reaching policies, in terms of goals, scale, and duration (Daily et al., 2013). Since 1992, the construction of ecological civilization in China has entered the stage of sustainable development. From environmental protection to sustainable development, China has made important progress in building an ecological civilization. From 1997 to 2017, a series of ecological construction projects were carried out continuously (Liu et al., 2008; Li et al., 2011; Wu et al., 2019; Zhang et al., 2020), the area of forest, grassland and wetland ecosystem was effectively increased, and the area of the bare land ecosystem was significantly reduced (Figure 2). Overall, China has huge ecosystem reserves and GEP development potential (Figure 2).

However, with the development of economy and the acceleration of urbanization, the ecological environment in many regions of China has deteriorated (Ouyang et al., 2016), and still faces the problem of imbalance between ecological protection and regional development. The 18th National Congress of the Communist Party of China formulated the five-pronged strategies for building socialism with Chinese characteristics, that is, to promote coordinated progress in economic, political, cultural, social, and ecological areas, which put forward higher requirements for ecological construction and people's livelihood development in the new era. Each initiative has a dual goal, that is, to achieve harmony development between human and nature by ensuring key natural capital and reducing poverty (Li et al., 2011).

Ouyang et al. believed that the gross domestic product (GDP) did not fully reflect the contribution of nature to economic activities and human wellbeing, so they developed a measurement standard for the GEP (Ouyang et al., 2021). GEP represents the GDP development potential of a region in a sense. The region with higher GEP represents a good ecological environment and production capacity (Ouyang et al., 2021). From Figure 3 the regions with high GEP in China are mainly concentrated in the northwest and southwest regions where the level of economic development is relatively low, while the regions with high GDP are mainly concentrated in the developed southeast coastal areas. Therefore, it is urgent to apply scientific methods to effectively improve socio-economic development and people's wellbeing in underdeveloped areas.

### 3.2.2 The Chinese government strongly supports local governments to explore and implement GEP accounting

In recent years, the Chinese government strongly supports local governments to explore and implement GEP accounting (Table 1),

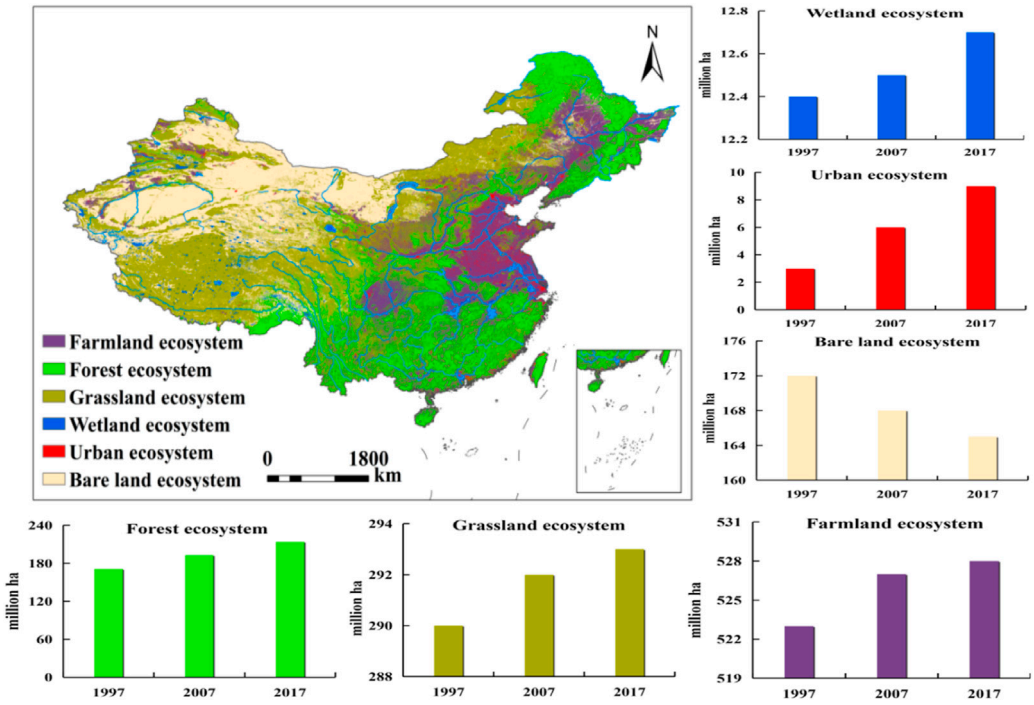


FIGURE 2
Distribution and changes of main ecosystem types in China. Note: the main ecosystem change data sourced from the World Bank (WB) (https://data.worldbank.org/ accessed 1 October 2021) and the Food and Agriculture Organization of the United Nations (FAO) (https://www.fao. org/accessed 10 October 2021). LUCC data sourced from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn/ accessed on 1 May 2021).

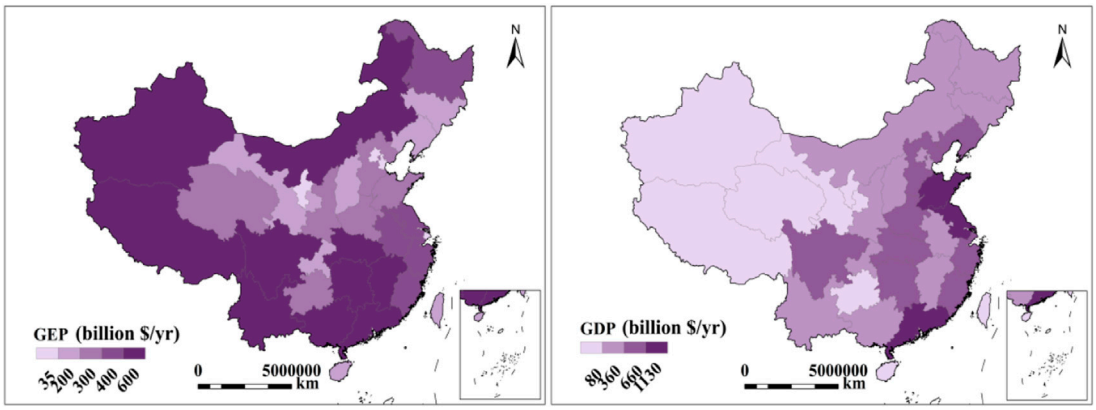


FIGURE 3
China's GEP and GDP in 2015. Note: GDP data sourced from the World Bank (WB) (https://data. worldbank.org/accessed 1 October 2021) and United Nations Statistics Division (UNSD) (https://unstats.un.org/ accessed 1 October 2021).

and carry out research on the practical mechanism of ecological products, convert the value of ecological products into economic benefits, and reveal the contribution of ecosystems to social development and human wellbeing. China has also made outstanding achievements in consolidating the scientific foundation supporting public policy. This is illustrated by the ongoing nationwide GEP accounting. At the national level, the main protected ecosystem services include water retention, flood regulation, carbon sequestration, climate regulation, sandstorm prevention, soil retention, etc (Zhang et al., 2000; Li et al., 2005; MEP, 2008; Daily et al., 2013).

(http://www.mnr.gov.cn/. http://www.guizhou.gov.cn/. http://www.qinghai.gov.cn/http://www.nmg.gov.cn/. http://www.xizang.gov.cn/. http://www.sichuan.gov.cn/. http://www.jiangsu.gov.cn/. http://www.yunnan.gov.cn/. http://www.zhejiang.gov.cn/. http://www.jilin.gov.cn/. http://www.guangdong.gov.cn/. http://www.

**TABLE 1 GEP accounting in China**

| | Time | Policy document | Content |
|---|---|---|---|
| Central government | 2016 | "Evaluation and assessment methods for ecological civilization construction objectives" | Building a unified evaluation system for ecological civilization construction |
| | 2019 | "Opinions on supporting Shenzhen to build a leading demonstration zone of socialism with Chinese characteristics" | Explore urban GEP accounting system |
| | 2021 | "Opinions on establishing and improving the value realization mechanism of ecological products" | In 2025, the GEP accounting framework will be initially formed, and in 2035, the GEP mechanism will be fully established |
| | 2021 | "Planning for ecological protection and high-quality development of the Yellow River Basin" | Strongly support local governments to explore and carry out GEP accounting |
| | Province | GEP pilot area | Content |
| Local government | Guizhou | Chishui, Jinping, Danzhai, Honghuagang, Jiangkou, Qianxi, Zhenfeng, Liping, Qinglong | Counties with the most GEP pilots |
| | Qinghai | Tianjun, Qilian | Carry out GEP in ecological functional area |
| | Inner Mongolia | Xing'an League, Arshan, Ordos | Take the lead in GEP accounting with the International Union for Conservation of Nature |
| | Tibet | Linzhi, Motuo, Shuanghu | Carry out GEP in ecological functional area |
| | Sichuan | Ganzi, Xishui | Take the lead in carrying out GEP accounting in national key ecological functional areas |
| | Jiangsu | Xuzhou, Gaochun | The first "district level" GEP accounting system |
| | Yunnan | Pu'er, Eshan, Pingbian | GEP accounting of the first green economy experimental demonstration zone in China |
| | Zhejiang | Lishui, Deqing, Qingtian, Jingning | China's first village GEP accounting report |
| | Jilin | Tonghua | International Union for Conservation of Nature and Chinese Academy of Sciences cooperation pilot area |
| | Guangdong | Shenzhen,Yantian | China's first urban ecosystem GEP accounting system |
| | Jiangxi | Fuzhou | Construction of urban GEP accounting system |
| | Fujian | Fuzhou | Construction of urban GEP accounting system |
| Ecological functional area | Hainan | Hainan Tropical Rain Forest National Park | China's first national park to release GEP accounting results |

Note:Websites for major inquiries.

jiangxi.gov.cn/. http://www.fujian.gov.cn/. http://www.hainan.gov.cn/ ) (accessed 15 October 2021).

From the current research, China's GEP is characterized by large reserve and development potential, but there are significant regional differences. In 2015, China's GEP was about 10 trillion $ (Figure 3). Among them, ecosystem material product value (EPV) accounts for about 18% of the national GEP value (Figure 4A), and the areas with EPV of more than 80 billion $ are mainly concentrated in the East and South of China (especially plain areas, such as Northeast Plain, North China Plain, Middle and Lower Reaches of the Yangtze River Plain, Pearl River delta Plain and Chengdu Plain). Due to limited natural conditions, EPV in most areas of Northwest China is low.

Ecosystem regulation service value (ERV) accounts for about 74% of the national GEP value (Figure 4B). On the whole, the Northwest is higher than the Southeast, such as water retention (Figure 4B-a), water purification (Figure 4B-c), climate regulation (Figure 4B-e) and sandstorm prevention (Figure 4B-g). It shows that Northwest China is the main ecosystem service functional area in China, with good ecological environment and production capacity (Ouyang et al., 2021). Ecological environment is the basis and condition of economic development, which means that Northwest China will have huge GDP development potential. How to convert the value of ecological products into economic benefits is an urgent problem for the future development of Northwest China.

From the distribution of ecosystem cultural service value (ECV) (Figure 4C), compared with EPV and ERV, ECV provides the lowest value, accounting for only about 8% of the national GEP value, and the ECV of Western underdeveloped areas is the lowest. ECV mainly depends on the development and utilization of natural landscape, and the limiting factor is the level of economic development. Therefore, it can be explained that the level of economic development has a significant impact on ECV. In many ecosystem services studies, ECV is often ignored (Seppelt et al., 2012). However, accounting for ECV allows us to have a more comprehensive grasp of the ecosystem, so that the government can consider not only the natural value of the ecosystem, but also its potential social and cultural value when making decisions (Laband, 2013). For example, when the government makes ecological compensation for the forest ecosystem in a certain area, it must not only protect the integrity of the forest ecosystem, but also pay attention to the protection of the habitat and religious traditions of the aborigines, and compensate them as a whole.

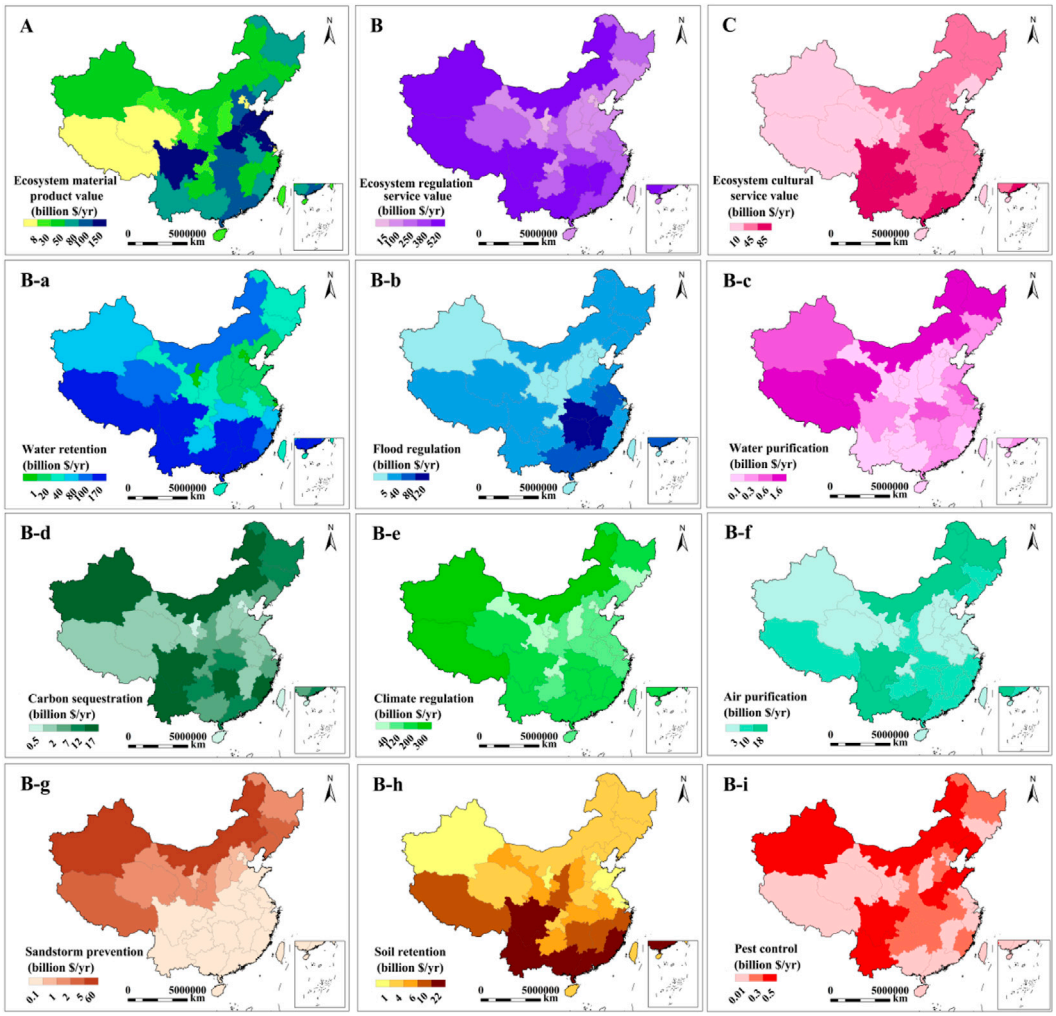


FIGURE 4
GEP accounting in China (Ecosystem material product value, Regulation service value and Cultural service value). Note: **(A)**: Ecosystem material product value (EPV). **(B)**: Regulation service value (ERV), **(B-a)**: Water retention, **(B-b)**: Flood regulation, B-c: Water purification, **(B-d)**: Carbon sequestration, **(B-e)**: Climate regulation, **(B-f)**: Air purification, **(B-g)**: Sandstorm prevention, **(B-h)**: Soil retention, **(B-i)**: Pest control. **(C)**: Cultural service value (ECV). Main references (Feng et al., 2013; Xiao et al., 2014; Xie et al., 2015; Pema et al., 2017; Wang et al., 2017; Pan et al., 2018; Dong et al., 2019; Jin et al., 2019; Song et al., 2019; Zou et al., 2019; Ding et al., 2020; Han et al., 2020; Lei et al., 2020; Qian et al., 2020; Wen et al., 2020; You et al., 2020; Deng et al., 2021; Ouyang et al., 2021; Ouyang et al., 2021; Sun et al., 2021; Wei et al., 2021; Wanget al., 2021; Yin et al., 2021; Zhang et al., 2021).

## 3.3 Necessity of global GEP accounting

### 3.3.1 The contribution of natural ecosystems to the social economy needs to be revealed

According to WB and FAO data (Figure 5), the global forest ecosystem area is 4.36 billion ha, mainly distributed in Europe, South America, Africa and North America (Figure 6A), the grassland ecosystem area is 1.83 billion ha, mainly distributed in Asia and North America (Figure 6B), the wetland ecosystem area is 380 million ha, and North America is the most widely distributed (Figure 6C), the area of glacial permafrost ecosystem is 1.43 billion ha (Figure 6D). However, the degradation of global ecosystems is increasing (World Bank, 2019; UNFAO, 2021). About 60% of the global ecosystems are degraded, more than 30% of the natural freshwater disappears, the forest is reduced by 10 million ha per year (United Nations Food and Agriculture Organization, 2021), the vegetation growth in 59% of the global regions is weakened (Yuan et al., 2019), and the mass loss of ice sheets and mountain glaciers is accelerating (Golledge et al., 2019) (Figure 5). Although the global economy has developed rapidly, with the increase of human demand for energy and water resources, global construction, agriculture and animal husbandry are also expanding (Solomon et al., 2019), which may aggravate the increasing pressure on the stock of limited ecosystem assets and ecosystem services provided (Su et al., 2012; He et al., 2014; Ouyang et al., 2021). Under the background of extensive global climate change and the continuous impact of human activities (IPCC AR6, 2021), the global ecosystem is still facing the weakening of ecosystem service function and the depletion of natural resources in the future, which seriously threatens human survival.

In the past decade, the concept of ecosystem as an important capital has been popularized rapidly. It is gradually reflected in the fields of agriculture, water conservancy, energy, health, fishery and forestry, as well as the framework and decision-making of many

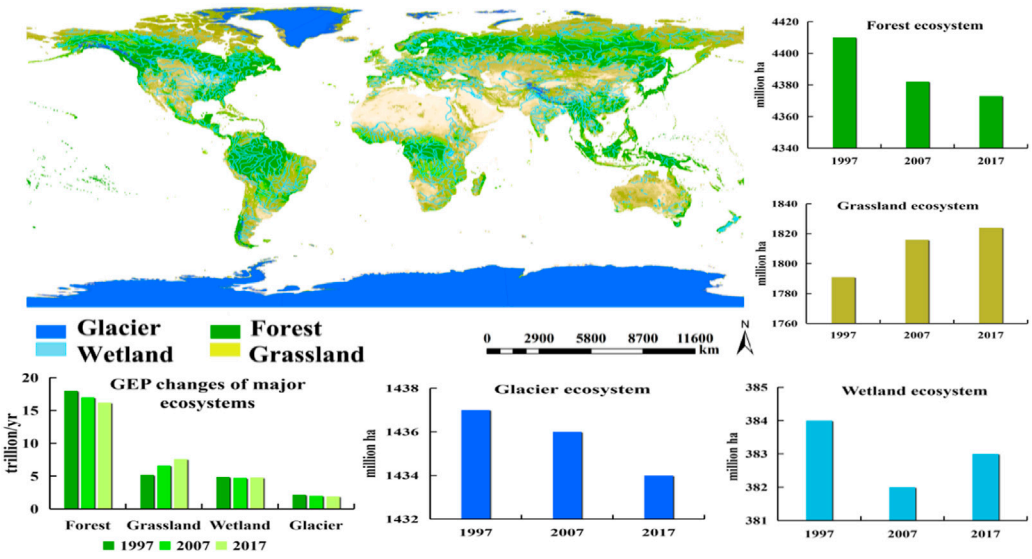


FIGURE 5
Main global ecosystem types and changes. Note: the main ecosystem change data sourced from the World Bank (WB) (https://data.worldbank.org/ accessed 1 October 2021) and the Food and Agriculture Organization of the United Nations (FAO) (https://www.fao. org/accessed 10 October 2021).

communities, enterprises and government agencies (Daily et al., 2013). In terms of natural capital accounting, many countries have started pilot projects. In 2011, the United Kingdom organized more than 500 scientists to conduct a comprehensive ecosystem assessment. In 2012, Australia also accounted for land and ecosystems. In 2012, the United Nations approved the "core framework of environmental-economic accounting system" and further adopted the "experimental ecosystem accounting of environmental economic accounting system" in 2013. However, these studies failed to measure the contribution of natural ecosystems to the social economy (COP15, 2021).

Therefore, there is an urgent need for GEP accounting research all over the world. Through GEP accounting, we can better clarify the ecological relationship between regions and understand the physical quantity, value quantity and changes of ecosystem services. Finally, it can provide decision-makers and managers in all countries with a scientific basis for ecological protection, so as to better benefit the virtuous circle of global ecosystem protection, restoration and management. (Chen et al., 2009; Ouyang et al., 2021).

### 3.3.2 Human-nature conflicts are intensifying

According to the research results of Costanza et al., the value of global ecosystem services in 2007 was 46 trillion $/yr, of which forest ecosystem provided about 16 trillion $/yr, grassland ecosystem provided about 7.6 trillion $/yr, and wetland ecosystem provided about 4.8 trillion $/yr (Costanza et al., 1997; Costanza et al., 2014) (Figure 6A–C). According to the latest research of Jiang et al., the global terrestrial GEP in 2017 was 147 trillion $ (Jiang et al., 2021). Overall, it can be said that the value of the global ecosystem is huge. However, we found that with the degradation of forest and glacier ecosystems, the GEP of global forest and glacier ecosystems is decreasing year by year.

In addition, for example, the tropical rain forest, known as the "lung of the earth", plays an extremely important ecosystem service function, mainly distributed in the Amazon basin and the Congo River Basin. However, most of these two regions belong to poor and backward areas. Whether to develop the tropical rain forest is often related to the local people's livelihood and development. According to the FAO report in 2021, the deforestation rate of tropical rain forests remained high from 2000 to 2018, especially in Africa, the expansion of cultivated land was the main cause of forest reduction, accounting for more than 75%, while nearly three-quarters of deforestation in South America was mainly caused by the expansion of husbandry (FAO, 2021). Therefore, the contradiction between global ecosystem protection and people's livelihood development is still intensifying.

At present, the increasing demand of 7.6 billion people for food, energy, and water resources will undoubtedly pose a greater challenge to the stock of ecosystem capital. The world as a whole can be divided into four development models (Figure 6G, H). The first type: "High-High model" i.e. high GEP and high GDP, mainly in the United States, China, etc., accounting for about 0.02%. The second type: the "High-Low model" i.e. high GEP and low GDP, mainly in Congo, Indonesia, Zambia, Argentina and other countries, of which less developed countries are the majority, accounting for about 18.18%. The third type: "Low-High model" i.e. low GEP and high GDP, mainly in developed countries such as Japan, Germany, Britain, Italy, France, etc., accounting for about 13.1%. The fourth type: "Low-Low model" i.e. low GEP and low GDP, mainly in underdeveloped countries in Africa, Central Asia, West Asia, South Asia and Southeast Asia, accounting for about 68.7%. We found that Africa, South America, South Asia and Southeast Asia in Asia are mostly underdeveloped areas, and the widespread poverty problem is still serious. However, the GEP level of these areas is generally higher than the GDP level (Figure 6G, H), which means that have a good ecological environment and production capacity for ecological products. As the world's main ecological asset reserve area, ecological protection has also been raised to a higher level. However, how to coordinate the contradiction between ecosystem capital protection and people's livelihood development in these regions is a problem that the world needs to face and solve. Based on this, we will focus on China's development experience to promote global ecological and economic sustainable development.

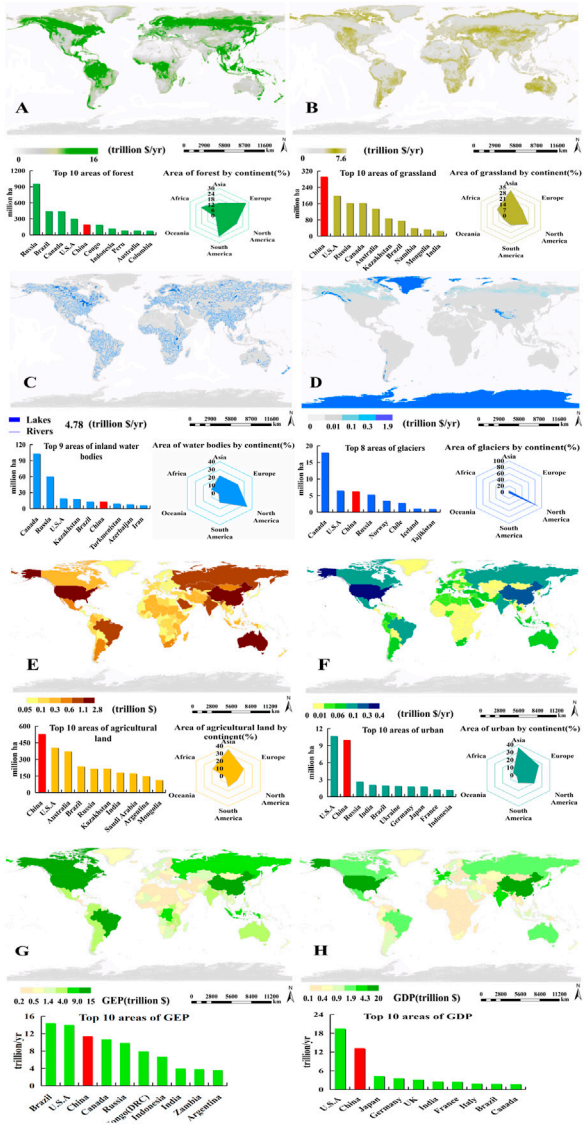


FIGURE 6
Distribution of GEP and GDP of major global ecosystems. Note: **(A–F)** represents the distribution of forest, grassland, wetland, glacier, farmland and urban ecosystems on all continents and major countries. **(G)** shows the main distribution of global GEP and **(H)** shows the main distribution of global GDP. The global GEP accounting evaluation mainly refers to the relevant research literature on ecosystem service value (Costanza et al., 1997; de Groot et al., 2012; Costanza et al., 2014; Alamgir et al., 2016; Kuittinen et al., 2016; Kubiszewski et al., 2017; Kim et al., 2018; Chaudhary et al., 2019; Pham et al., 2019; Perrings et al., 2020; Hernandez-Blanco et al., 2021; Jiang et al., 2021; Liu et al., 2021; Pertierra et al., 2021; Piaggio and Siikamäki, 2021; Taye et al., 2021). Global GDP data sourced from the WB (https://data.worldbank.org/ accessed 1 October 2021) and the FAO (https://www.fao.org/ accessed 10 October 2021).

# 4 Discussion

## 4.1 Fully establish a GEP accounting mechanism

For quantitative accounting of GEP. Firstly, the overall status of ecosystem operation can be grasped through GEP variables and trends. Secondly, GEP can be used to evaluate the implementation effectiveness of ecological protection and ecological construction projects, so as to maintain and improve regional ecosystem and enhance regional sustainable development capacity. Thirdly, GEP accounting can clarify the important role of products and services provided by ecosystems in economic and social development. Fourth, GEP accounting helps to understand the ecological relationship between ecosystem service providers and beneficiaries, and provides a basis for strengthening ecological protection and scientific and reasonable decision-making. Finally, through GEP accounting, ecosystem and human well-being can be linked to evaluate the contribution of ecosystem to human well-being (Ouyang et al., 2021). At present, China is actively carrying out GEP accounting pilot projects, establishing a three-level pilot demonstration system at the provincial, municipal and county levels, including 13 provinces and 32 cities and counties such as Qinghai, Tibet and Guizhou, and actively improving the GEP accounting framework and methods (Jin et al., 2019; Han et al., 2020; Yin et al., 2021). By means of remote sensing big data, digital ecological environment monitoring network and artificial intelligence, and gradually promote the automation of GEP accounting, and finally build an ecological product spatial information data resource database integrating “space, sky and earth” (Figure 7).

This “point to surface, top-down” GEP accounting method can more efficiently and comprehensively grasp the status, trends and problems of ecosystem changes and people’s livelihood development in different areas of the country. Therefore, the whole world, especially developing countries, should support local governments to actively explore and carry out quantitative accounting of the value of ecological products.

## 4.2 Comprehensive ecological compensation system of “vertical and horizontal combination”

At present, the Chinese government has set clear goals. By 2025, the ecological protection compensation system suitable for economic and social development will be basically complete(Ouyang and Jin, 2017; General Office of the State Council, PRC, 2021). China has implemented a “Vertical and Horizontal Combination” mechanism for ecological protection compensation, in which the Vertical Compensation means that the central government pays ecological compensation to functional ecological zones. The Horizontal Compensation means that the local government will set up a mechanism to compensate the upstream and downstream ecosystems for ecological protection, and carry out a cross-regional approach.

China implemented the Vertical Compensation (Figure 8A). According to the financial situation of the central government, gradually increase the scale of transfer payments for ecological functional areas, and continue to increase ecological protection compensation for key ecological functional areas, such as the Qinghai Tibet Plateau (Jiang et al., 2020; Ouyang et al., 2021), Water source conservation areas (bib_li_et_al_2015Li et al., 2015), National parks (Zheng et al., 2019), Ecologically fragile poverty alleviation areas (Yunnan Guizhou karst area) (Hu et al., 2020), the Loess Plateau areas (Liu et al., 2008; Feng et al., 2013; Delang, 2019; Zhang et al., 2020) and Northwest agro pastoral ecotone areas (Liu

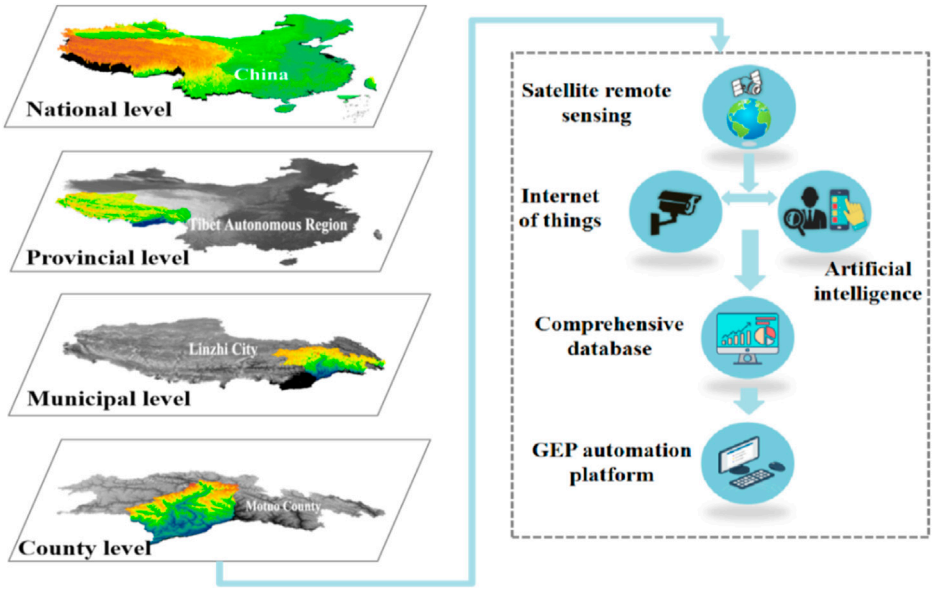


FIGURE 7
China GEP work system path model. National level: mainly carry out overall planning, policy guidance and transfer payment; Provincial level: mainly carry out capital investment, ecological value evaluation and financial reward and subsidy; Municipal level: mainly engaged in financial credit, government procurement and market development; County level: mainly engaged in infrastructure construction and ecological product development. Through the exploration of the pilot demonstration system at the provincial, municipal and county levels, and using scientific and technological means, promote the establishment of GEP accounting automation platform and ecological product spatial information data resource database.

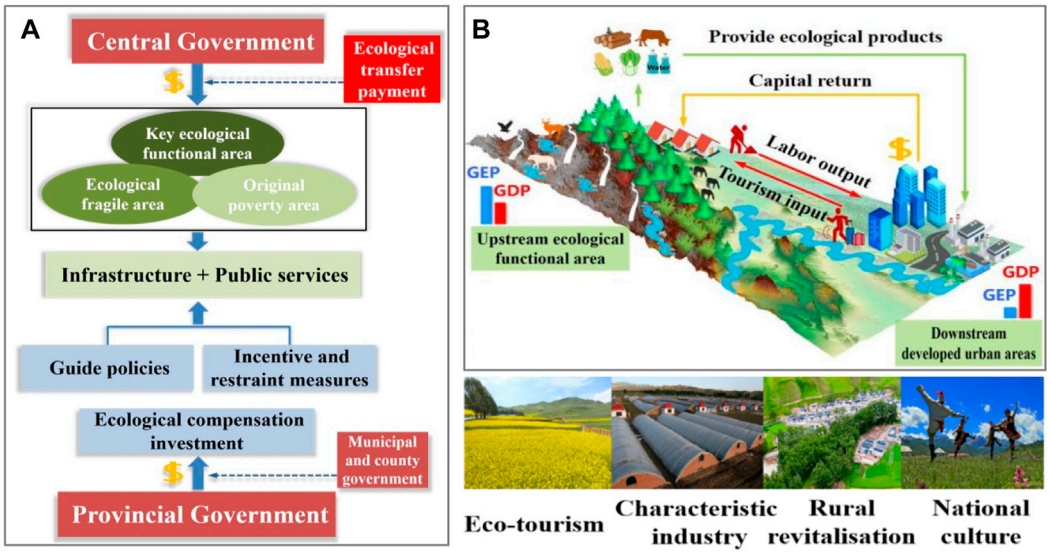


FIGURE 8
Path model of ecological protection compensation mechanism with Chinese characteristics. Note: A represents the vertical ecological protection compensation path model, i.e. the central government increases the scale of ecological transfer payments to ecological function areas, while local governments increase the investment of ecological protection compensation funds and formulate guiding policies and incentive and restraint measures for ecological protection compensation.This model is mostly based on direct financial compensation. B represents the cross regional horizontal ecological protection compensation mechanism path model. The ecological function area exports ecological products (fresh water, food, etc.) and labor force to developed areas, so as to obtain capital return and finally realize the coordinated development of various regions. The photo comes from the official website of Tianzhu County, China (http://www. Gstian zhu.gov.cn/accessed 29 October 2021).

et al., 2021). At the same time, governments at the provincial, municipal, county and town levels are encouraged to increase investment in ecological protection compensation funds and formulate guiding policies and incentive measures for ecological protection compensation, for example, compensation shall be given to areas that absorb more ecological immigrants, and the population in

ecological functional areas with high pressure on resources and environment shall be gradually transferred outward.

China has increased the Horizontal Compensation (Figure 8B). First of all, the central government encourages local governments to build cross provincial and cross basin horizontal ecological protection compensation mechanisms, and carry out cross regional joint prevention and governance. Secondly, further promote the benign interaction between beneficiary areas and ecological protection areas through counterpart cooperation, industrial transfer, talent training, joint construction of parks, purchase of ecological products and services, etc. In addition, in order to maximize the benefits of ecological protection and people's livelihood development, China promotes the sharing of interests between ecological benefit areas and protected areas by implementing a comprehensive ecological compensation combining vertical and horizontal. At the same time, encourage local governments to actively carry out ecotourism, develop characteristic industries, explore national culture and implement rural revitalization, and actively explore the path of transforming the value of ecological products into economic benefits, and finally realize the coordinated development of ecology and people's livelihood.

Based on this, we believe that China's "vertical and horizontal combination" comprehensive ecological compensation system can be promoted to countries all over the world, especially for countries and regions with "high GEP and low GDP". We hope that this ecological compensation system can promote common development and promote the vision of a community of shared future for mankind.

## 4.3 Realize the "dual accounting, dual operation, dual promotion" of GDP and GEP

Over the years, GDP has been widely used in the evaluation of macroeconomic operation (Jiang et al., 2021; Ouyang et al., 2021). With the development of economy and society, simply using GDP to evaluate economic development can not meet the actual needs. GEP accounting makes up for the deficiency that GDP fails to measure the consumption of natural resources and the destruction of ecological environment. With scientific statistical methods, people can clearly and intuitively realize that "lucid waters and lush mountains are invaluable assets" by looking at the data. Therefore, human development activities can determine the production based on "resources and environment", and then promote the establishment of the realization mechanism of the value of ecological products according to local conditions (Comprehensive program for reform of the ecological progress system, 2015).

Parallel evaluation of GEP and GDP is an important means to promote the coordinated development of economic construction and ecological protection (Jiang et al., 2021). At present, according to the level of economic development, China is divided into Southeast coastal developed areas and Central and Western underdeveloped areas. Among them, the main development model of the southeast coastal developed areas is "Low-High model", i.e. low GEP and high GDP, and the main development model of the central and western underdeveloped areas is "High-Low model", i.e. high GEP and low GDP. Therefore, the Chinese government has adopted different development paths and strategies for different regions. For regions with low GEP and high GDP, the State encourages to continue to maintain and steadily promote the current ecosystem protection and socio-economic development, promote the high-quality development of cities, further realize the coordinated development of economy and eco-environmental protection, and achieve a win-win situation. For areas with high GEP and low GDP, the state encourages to further strengthen the protection and increase the value of natural ecosystems on the basis of maintaining the protection of the existing natural ecosystems, while exploring the implementation of industrial upgrades and transformations to achieve sustainable development.

At the same time, we should still have a correct understanding of GEP and the status and role of GEP accounting should not be overemphasized. GDP accounting still occupies the core position in the national accounting system. GEP accounting only provides a new perspective to understand the functions and status of natural systems, especially ecosystems, and provides a new method to supplement and correct GDP accounting. In the future, we still need to increase the exploration of the parallel evaluation mechanism of GEP and GDP to realize "double accounting, double operation and double improvement" of GDP and GEP.

## 4.4 Research gap and future research challenges

In recent decades, great progress has been made in the research of global ecosystem changes, ecosystem services, human well-being and development. In this review, we comprehensively reviewed the global ecosystem change, and the methods and cases of GEP accounting, and we try to introduce China's experience in GEP to reconcile some contradictions between ecological protection and people's livelihood development around the world. The limitations of this study are mainly in two aspects. First, the selection of research cases, which did not cover all countries in the world, only selected typical research cases. Second, data acquisition is mainly based on remote sensing data, literature data and relevant data published by international organizations. There is still a lack of monitoring, experiment and research data. Therefore, we will carry out monitoring, experiment and research in different regions in the future. At the same time, we also consider the challenges that the Chinese experience of GEP poses to the global application process. We believe that the system, policy, economy, population, industry and other factors of different countries will bring great challenges to the development of GEP, so more in-depth research is still needed.

# 5 Conclusion

Our main conclusions are as follows: 1) Climate change and population growth make the stock of global ecosystem capital and services capacity face increasing pressure. In the future, the weakening of ecosystem services and the depletion of natural resources will continue to threaten human survival. Therefore, the scientific community needs to increase cross-national and interdisciplinary research exchanges and share achievements. At the same time, it needs to increase the research on the practical application and transformation of achievements. In addition, countries also need to further strengthen cooperation to jointly respond to the challenges of global change. 2) Using GEP accounting to evaluate the ecosystem can help people grasp the overall status of the ecosystem operation, reflect the quality of ecological environmental services, understand the relationship between the ecosystem and human well-being, and help decision-makers and managers formulate and implement more scientific and reasonable sustainable development strategies

and ecological protection policies. However, there is relatively little research on GEP at present, and the system construction, methods and means and achievement transformation of GEP accounting are still in the exploratory stage. Therefore, more research is needed, especially in practical application. 3) The Chinese government strongly supports local governments in exploring GEP accounting, carrying out research on the practical mechanism of ecological products, transforming the value of ecological products into economic benefits, and revealing the contribution of ecosystems to economic and social development and human wellbeing. In the future, we still need to use scientific and technological means to promote the establishment of GEP accounting automation platform and ecological product spatial information data resource database. 4) About 68.7% of the world's developing countries with "low and low model" (low GEP and low GDP), especially those in Africa, Central Asia, West Asia, South Asia and Southeast Asia, continue to intensify the contradiction between ecosystem capital protection and people's livelihood development. 5) We have constructed the path model of GEP working system and the path model of ecological protection compensation mechanism with Chinese characteristics. We believe that GEP accounting system of "from point to area, from top to bottom", the parallel evaluation strategy of GDP and GEP and the comprehensive ecological compensation system of "vertical and horizontal combination" implemented in China can be popularized to countries all over the world, and reduce the contradiction between global ecological protection and people's livelihood development.

## 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 authors.

## Author contributions

Conceptualization, HY; methodology, HY and BX; software, HY; validation, XG and WM; formal analysis, HY; investigation, HY; resources, Yangand BX; data curation, HY; writing-original draft preparation, HY; writing-review and editing, XG and WM; visualization, HY; supervision, XG; project administration, XG; funding acquisition, XG. All authors have readand agreed to the published version of the manuscript.

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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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## References

Alamgir, M., Turton, S., Macgregor, C., and Per, P. (2016). Assessing regulating and provisioning ecosystem services in a contrasting tropical forest landscape. *Ecol. Indic.* 64, 319–334. doi:10.1016/j.ecolind.2016.01.016

Andrew, J., and Erin, A. (2019). Amazon deforestation drives malaria transmission, and malaria burden reduces forest clearing. *PNAS* 116 (44), 22212–22218. doi:10.1073/pnas.1905315116

Chaudhary, S., McGregor, A., Houston, D., and Chettri, N. (2019). Spiritual enrichment or ecological protection?: A multi-scale analysis of cultural ecosystem services at the mai pokhari, a ramsar site of Nepal. *Ecosyst. Serv.* 39, 100972. doi:10.1016/j.ecoser.2019.100972

Chen, N., Li, H., and Wang, L. (2009). Reviews on ecosystem services: Connotation, valuation and GIS-based mapping. *Ecol. Environ. Sci.* 18 (5), 1987–1994. (In Chinese).

Chen, Y., Feng, X., Tian, H., Wu, X., Gao, Z., Feng, Y., et al. (2021). Accelerated increase in vegetation carbon sequestration in China after 2010: A turning point resulting from climate and human interaction. *Glob. Change Biol.* 27, 5848–5864. doi:10.1111/gcb.15854

Cobb, K., Diongue-Niang, A., Edwards, P., Emori, S., Faria, S., Hawkins, E., Hope, P., Huybrechts, P., Meinshausen, M., Mustafa, S., et al.IPCC AR6 (2021). *Climate change 2021: The physical science basis*. Cambridge, UK: Cambridge University Press.

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., et al. (1997). The value of the world's ecosystem services and natural capital. *Nature* 387, 253–260. doi:10.1038/387253a0

Costanza, R., Groot, R., Sutton, P., van der Ploeg, S., Anderson, S., Kubiszewski, I., et al. (2014). Changes in the global value of ecosystem services. *Glob. Environ. Change* 26, 152–158. doi:10.1016/j.gloenvcha.2014.04.002

Daily, G., Ouyang, Z., Zheng, H., Li, S., Wang, Y., Feldman, M., et al. (2013). Securing natural capital and human well- being: Innovation and impact in China. *Acta Ecol. Sin.* 33 (3), 669–676. doi:10.5846/stxb201212311905

de Groot, R., Brander, L., van der Ploeg, S., Costanza, R., Bernard, F., Braat, L., et al. (2012). Global estimates of the value of ecosystems and their services in monetary units. *Ecosyst. Serv.* 1, 50–61. doi:10.1016/j.ecoser.2012.07.005

Delang, C. O. (2019). The second phase of the grain for green program: Adapting the largest reforestation program in the world to the new conditions in rural China. *Environ. Manage.* 64, 303–312. doi:10.1007/s00267-019-01185-4

Deng, J., Chang, L., Zhang, Y., Zhou, W., Qi, L., Zhou, L., et al. (2021). Accounting of gross ecosystem product of Fuzhou City, China. *Chin. J. Appl. Ecol.*, 1–12. (in Chinese). doi:10.13287/j.1001-9332.202111.018

Ding, M., Pei, F., Hu, Y., Dong, S., Zhang, Z., and Liu, Z. (2020). Spatial and temporal changes of ecosystem service value in Jiangsu Province based on LUCC. *Acta Ecol. Sin.* 40 (19), 6801–6811. (in Chinese). doi:10.5846/stxb202003050413

Dong, T., Zhang, L., Xiao, Y., Zheng, H., Huang, B., and Ouyang, Z. (2019). Assessment of ecological assets and gross ecosystem product value in Ordos City. *Acta Ecol. Sin.* 39 (9), 3062–3074. (in Chinese). doi:10.5846/stxb201805291183

Dong, T., Zheng, H., Xiao, Y., and Ouyang, Z. (2017). Comparison of ZTCM and TCIA methods for evaluating the use value of tourism resources:Taking Beijing Olympic Forest Park as an exampl. *Chin. J. Appl. Ecol.* 28 (8), 2605–2610. (In Chinese).

Ellis, E., Gauthier, N., Goldewijk, K., Bird, R., Boivin, N., Díaz, S., et al. (2021). People have shaped most of terrestrial nature for at least 12,000 years. *PNAS* 11817, e2023483118. doi:10.1073/pnas.2023483118

Feng, X., Fu, B., Lu, N., Zeng, Y., and Wu, B. (2013). How ecological restoration alters ecosystem services: An analysis of carbon sequestration in China's Loess Plateau. *Sci. Rep.* 3, 2846. doi:10.1038/srep02846

Golledge, N., Keller, E., Gomez, N., Naughten, K., Bernales, J., Trusel, L., et al. (2019). Global environmental consequences of twenty-first-century ice-sheetmelt. *Nature* 566, 65–72. doi:10.1038/s41586-019-0889-9

Grant, L., Vanderkelen, I., Gudmundsson, L., Tan, Z., Perroud, M., Stepanenko, V. M., et al. (2021). Attribution of global lake systems change to anthropogenic forcing. *Nat. Geosci.* 14, 849–854. doi:10.1038/s41561-021-00833-x

Han, Z., Zhao, Y., Yan, X., and Zhong, J. (2020). Coupling coordination mechanism and spatial-temporal relationship between gross ecosystem product and regional economy:A case study of dalian. *Econ. Geogr.* 40 (10), 1–10. doi:10.15957/j.cnki.jjdl.2020.10.001

Havsen, M., Potapovr, P., Moore, R., Hancher, M., Turubanova, S., Tyukavina, A., et al. (2013). High-resolution global maps of 21st-century forest cover change. *Science* 324, 850–853. doi:10.1126/science.1244693

He, C., Liu, Z., Tian, J., and Ma, Q. (2014). Urban expansion dynamics and natural habitat loss in China: A multiscale landscape perspective. *Glob. Change Biol.* 20 (9), 2886–2902. doi:10.1111/gcb.12553

Hernandez-Blanco, M., Costanza, R., and Cifuentes-Jara, M. (2021). Economic valuation of the ecosystem services provided by the mangroves of the Gulf of Nicoya using a hybrid methodology. *Ecosyst. Serv.* 49, 101258. doi:10.1016/j.ecoser.2021.101258

Hu, Z., Wang, S., Bai, X., Luo, G., Li, Q., Wu, L., et al. (2020). Changes in ecosystem service values in karst areas of China. *Agric. Ecosyst. Environ.* 301, 107026. doi:10.1016/j.agee.2020.107026

Jiang, H., Wu, W., Wang, J., Yang, W., Gao, Y., Duan, Y., et al. (2021). Mapping global value of terrestrial ecosystem services by countries. *Ecosyst. Serv.* 5, 101361. doi:10.1016/j.ecoser.2021.101361

Jiang, W., Lü, Y., Liu, Y., and Gao, W. (2020). Ecosystem service value of the Qinghai-Tibet Plateau significantly increased during 25 years. *Ecosyst. Serv.* 44, 101146. doi:10.1016/j.ecoser.2020.101146

Jin, L., Liu, J., and Kong, D. (2019). Evaluation of the incorporation of gross ecosystem product into performance appraisals for ecological compensationActa. *Ecol. Sin.* 39 (1), 24–36. (in Chinese).

Kim, Y., Latifah, S., Afifi, M., Mulligan, M., Burke, S., Fisher, L., et al. (2018). Managing forests for global and local ecosystem services: A case study of carbon, water and livelihoods from eastern Indonesia. *Ecosyst. Serv.* 31, 153–168. doi:10.1016/j.ecoser.2018.03.018

Kubiszewski, I., Costanza, R., Anderson, S., and Sutton, P. (2017). The future value of ecosystem services: Global scenarios and national implications. *Ecosyst. Serv.* 26, 289–301. doi:10.1016/j.ecoser.2017.05.004

Kuittinen, M., Moinel, C., and Adalgeirsdottir, K. (2016). Carbon sequestration through urban ecosystem services: A case study from Finland. *Sci. Total Environ.* 563-564, 623–632. doi:10.1016/j.scitotenv.2016.03.168

Laband, D. (2013). The neglected stepchildren of forest-based ecosystem services: Cultural, spiritual, and aesthetic values. *For. POLICY Econ.* 35 (-), 39–44. doi:10.1016/j.forpol.2013.06.006

Lei, J., Chen, Z., Chen, X., Li, Y., and Wu, T. (2020). Spatio-temporal changes of land use and ecosystem services value in Hainan Island from 1980 to 2018. *Acta Ecol. Sin.* 40 (14), 4760–4773. (in Chinese). doi:10.5846/stxb201907261580

Li, C., Zheng, H., Li, S., Chen, X., Li, J., Zeng, W., et al. (2015). Impacts of conservation and human development policy across stakeholders and scales. *PNAS* 24, 7396–7401. doi:10.1073/pnas.1406486112

Li, F., Wang, R., Paulussen, J., and Liu, X. (2005). Comprehensive concept planning of urban greening based on ecological principles: A case study in beijing, China. *Landsc. Urban Plan.* 72, 325–336. doi:10.1016/j.landurbplan.2004.04.002

Li, J., Feldman, M. W., Li, S., and Daily, G. C. (2011). Rural household income and inequality under the sloping land conversion program in Western China. *PNAS* 108, 7721–7726. doi:10.1073/pnas.1101018108

Liu, J., Li, S., Ouyang, Z., Tam, C., and Chen, X. (2008). Ecological and socioeconomic effects of China's policies for ecosystem services. *PNAS105* 105 (28), 9477–9482. doi:10.1073/pnas.0706436105

Liu, M., Jia, Y., Zhao, J., Shen, Y., Pei, H., Zhang, H., et al. (2021). Revegetation projects significantly improved ecosystem service values in the agro-pastoral ecotone of northern China in recent 20 years. *Sci. Total Environ.* 788, 147756. doi:10.1016/j.scitotenv.2021.147756

Maes, J., Liquete, C., Teller, A., Erhard, M., Paracchini, M., Barredo, J., et al. (2016). An indicator framework for assessing ecosystem services in support of the EU Biodiversity Strategy to 2020. *Ecosyst. Serv.* 17, 14–23. doi:10.1016/j.ecoser.2015.10.023

MEP (Ministry of Environmental Protection of China) (2008). *CAS (Chinese Academy of Sciences)*. Beijing, China: National Ecosystem service Zoning in China.

Millenium Ecosystem Assessment Panel (MA) (2005). *Millenium Ecosystem Assessment Series*. Washington, DC: Island Press.Ecosystems and human well-being: Synthesis

Nelson, E., Mendoza, G., Rogetz, J., Polasky, S., Tallis, H., Cameron, R. D., et al. (2009). Modeling multiple ecosystem services, biodiversity conservation, commodity production, and tradeoffs at landscape scales. *Front. Ecol. Environ.* 7 (1), 4–11. doi:10.1890/080023

OECD (1996). *The economic appraisal of environmental protects and policies:A practical guide*. Paris: OECD.

Ouyang, Z., Hua, Z., Yang, X., Polasky, S., Daily, G., Xu, W., et al. (2016). Improvements in ecosystem services from investments in natural capital. *Science* 352 (6292), 1455–1459. doi:10.1126/science.aaf2295

Ouyang, Z., and Jin, L. (2017). *Developing gross ecosystem product and ecological asset accounting for eco-compensation*. Beijing: Science Press.

Ouyang, Z., Song, C., Zheng, H., Polasky, S., Xiao, Y., Bateman, I., et al. (2020). Using gross ecosystem product (GEP) to value nature in decision making. *Proc. Natl. Acad. Sci. U. S. A.* 117 (25), 14593–14601. doi:10.1073/pnas.1911439117

Ouyang, Z., Xiao, Y., Zhu, C., Zheng, H., Zou, Z., Song, C., et al. (2021). *Theory and method of gross ecosystem product (GEP) accounting*. Beijing: Science Press.

Ouyang, Z., Zhang, L., Wu, B., Li, X., Xu, W., Xiao, Y., et al. (2015). An ecosystem classification system based on remote sensor information in China. *Acta Ecol. Sin.* 35 (2), 219–226. (In Chinese).

Pan, F., Wang, H., and Wang, L. (2018). Spatial differentiation of flood regulation service of lakes and reservoirs in hubei province. *Resour. Environ. Yangtze Basin* 27 (08), 1891–1900. (in Chinese). doi:10.11870/cjlyzyyhj201808025

Pan, Y., Shi, P., and Zhu, W. (2004). Measurement of ecological capital of Chinese terrestrial ecosystem based on remote sensing. *Sci. China* 34 (4), 374–384. (in Chinese).

Pema, D., Xiao, Y., Ouyang, Z., and Wang, L. (2017). Gross ecosystem product accounting for the garzê Tibetan autonomous prefecture. *Acta Ecol. Sin.* 37 (19), 6302–6312. (in Chinese). doi:10.5846/stxb201607011362

Perrings, C., Naeem, S., Ahrestani, F., Bunker, D., Burkill, P., Canziani, G., et al. (2020). Ecosystem services for 2020. *Science* 330 (6002), 323–324. doi:10.1126/science.1196431

Pertierra, L., Martin, F., Hughes, K., Avila, C., Caceres, J., De Filippo, D., et al. (2021). Ecosystem services in Antarctica: Global assessment of the current state, future challenges and managing opportunities. *Ecosyst. Serv.* 49, 101299. doi:10.1016/j.ecoser.2021.101299

Pham, H., Torresan, S., Critto, A., and Marcomini, A. (2019). Alteration of freshwater ecosystem services under global change - a review focusing on the Po River basin (Italy) and the Red River basin (Vietnam). *Sci. Total Environ.* 652, 1347–1365. doi:10.1016/j.scitotenv.2018.10.303

Piaggio, M., and Siikamäki, J. (2021). The value of forest water purification ecosystem services in Costa Rica. *Sci. Total Environ.* 789, 147952. doi:10.1016/j.scitotenv.2021.147952

Qian, D., Cao, G., Du, Y., Guo, X., and Guo Xiaowei, 郭. (2020). Spatio-temporal dynamics of ecosystem service value in the southern slope of Qilian Mountain from 2000 to 2015. *Acta Ecol. Sin.* 40 (4), 1392–1404. (in Chinese). doi:10.5846/stxb201811292598

Seppelt, R., Fath, B., Burkhard, B., Fisher, J., Regamey, A., Lautenbach, S ., et al. (2012). Form follows function? Proposing a blueprint for ecosystem service assessments based on reviews and case studie. *Ecol. Indic.* 21 (3), 145–154. doi:10.1016/j.ecolind.2011.09.003

Solomon, N., Segnon, A. C., and Birhane, E. (2019). Ecosystem service values changes in response to land-use/land-cover dynamics in dry afromontane forest in northern Ethiopia. *Int. J. Env. Res. Pub. He.* 16 (23), 4653. doi:10.3390/ijerph16234653

Song, C., Xiao, Y., Bo, W., Xiao, Y., Zou, Z., and Ouyang, Z. (2019). The ecological asset accounting method study: A case study of Qinghai province. *Acta Ecol. Sin.* 39 (1), 9–23. (in Chinese). doi:10.5846/stxb201810172243

Su, S., Xiao, R., Jiang, Z., and Zhang, Y. (2012). Characterizing landscape pattern and ecosystem service value changes for urbanization impacts at an eco-regional scale. *Appl. Geogr.* 34, 295–305. doi:10.1016/j.apgeog.2011.12.001

Sun, M., Niu, W., Zhang, B., Geng, Q., and Yu, Q. (2021). Spatial-temporal evolution pattern and response of ecosystem service value under land use change in the yellow River Basin: A case study of shaanxi-gansu-ningxia region, northwest China. *Chin. J. Appl. Ecol.*, 1–11. (in Chinese). doi:10.13287/j.1001-9332.202111.016

Taye, F., Folkersen, M., Fleming, C., Buckwell, A., Mackey, B., Diwakar, K., et al. (2021). The economic values of global forest ecosystem services: A meta-analysis. *Ecol. Econ.* 189, 107145. doi:10.1016/j.ecolecon.2021.107145

TEEB Foundations (2010). *The economics of ecosystems and biodiversity: Ecological and economic foundations*. London and Washington: Earthscan.

United Nations Food and Agriculture Organization (FAO) (2021). Global remote sensing survey. Available at: http://www.fao.org/home/en (Accessed November 6, 2021).

Wang, L., Xiao, Y., Ouyang, Z., Wei, Q., Bo, W., Zhang, J., et al. (2017). Gross ecosystem product accounting in the national key ecological function area. *China Popul. Resour. Environ.* 27 (3), 46–154. (in Chinese).

Wei, Q., Xi, Z., Su, H., Miao, Y., and Cao, Y. (2021). Spatial differentiation of supporting service value of coastal wetland ecosystem in the Caofeidian District of Tangshan in Hebei Province. *Sci. Geogr. Sin.* 41 (5), 890–899. (in Chinese). doi:10.13249/j.cnki.sgs.2021.05.017

Wen, L., Song, J., Zhang, H., Zhang, X., Wang, F., Ha, S., et al. (2020). Dynamics of ecosystem service value in Ulan buh Desert from 1990 to 2018. *J. Arid Land Resour. Environ.* 34 (12), 57–64. (in Chinese). doi:10.13448/j.cnki.Jalre.2020.328

World Bank(WB) (2019). GDP statistics. Available at: https://data.worldbank.org/indicator/NY.GDP.MKTP.KD (Accessed October 1, 2021).

Wu, X., Wang, S., Fu, B., Feng, X., and Chen, Y. (2019). Socio-ecological changes on the Loess Plateau of China after grain to green program. *Sci. Total Environ.* 678, 565–573. doi:10.1016/j.scitotenv.2019.05.022

Xiao, Q., Xiao, Y., Ouyang, Z., Xu, W., Xiang, S., and Li, Y. (2014). Value assessment of the function of the forest ecosystem services in Chongqing. *Acta Ecol. Sin.* 34 (1), 216–223. (in Chinese). doi:10.5846/stxb201306261782

Xie, G., Zhang, C., Zhang, C., Xiao, Y., and Lu, C. (2015). Value of China's ecosystem services. *Resour. Sci.* 37 (9), 1740–1746. (in Chinese).

Xu, Z., Zhang, Z., Long, A., Cheng, D., Gong, Z., Su, Z., et al. (2003). Comparison and application of different contingent valuation methods in measuring total economic value of restoring Ejina Banner's ecosystem services. *Acta Ecol. Sin.* 9, 1841–1850. (In Chinese).

Yang, H., Gou, X., and Yin, D. (2021). Response of biodiversity, ecosystems, and ecosystem services to climate change in China: A review. *Ecologies* 2, 313–331. doi:10.3390/ecologies2040018

Yin, Y., Xi, F., Wang, J., Bing, L., and Du, L. (2021). Application of ecosystem value in policy system design: A case study of fuzhou city, China. *Chin. J. Appl. Ecol.* 11, 3815–3823. doi:10.13287/j.1001-9332.202111.00610.13287/j.1001-9332.202111.006

You, X., He, D., Xiao, Y., Bo, W., Song, C., and Ouyang, Z. (2020). Assessment of eco-assets in a county area: A case of pingbian county. *Acta Ecol. Sin.* 40 (15), 5220–5229. (in Chinese). doi:10.5846/stxb201903050407

Yuan, W., Zheng, Y., Piao, S., Ciais, P., Lombardozzi, D., Wang, Y., et al. (2019). Increased atmospheric vapor pressure deficit reduces global vegetation growth. *Sci. Adv.* 5, eaax1396. doi:10.1126/sciadv.aax1396

Zhang, J., Guo, L., Song, C., and Xu, W. (2021). Assessment of ecological in Qinghai -Tibet Plateau: A case of study of shannan city. *Acta Ecol. Sin.* (23), 1–8.

Zhang, P., Shao, G., Zhao, G., Le Master, D., Parker, G., Dunning, J., Jr, et al. (2000). China's forest policy for the 21st Century. *Science* 288, 2135–2136. doi:10.1126/science.288.5474.2135

Zhang, Q., Wang, Y., Tao, S., Bilsborrow, R., Qiu, T., Liu, C., et al. (2020). Divergent socioeconomic-ecological outcomes of China's conversion of cropland to forest program in the subtropical mountainous area and the semi-arid Loess Plateau. *Ecosys Tem. Serv.* 45, 101167. doi:10.1016/j.ecoser.2020.101167

Zheng, H., Wang, L., Peng, W., Zhang, C., Li, C., Robinsone, B., et al. (2019). Realizing the values of natural capital for inclusive, sustainable development: Informing China's new ecological development strategy. *PNAS* 116 (17), 8623–8628. doi:10.1073/pnas.1819501116

Zhu, W., Zhang, J., Pan, Y., Yang, X., and Jia, B. (2007). Measurement and dynamic analysis of ecological capital of terrestrial ecosystem in China. *Chin. J. Appl. Ecol.* 18 (3), 586–594. (in Chinese).

Zou, Z., Xiao, Y., Ouyang, Z., Song, C., and Wang, K. (2019). Evaluation of the effectiveness of ecological protection in qiandongnan miao-dong autonomous prefecture. *Acta Ecol. Sin.* 39 (4), 1407–1415. (in Chinese). doi:10.5846/stxb201809272096