SPATIOTEMPORAL DISTRIBUTION OF THE ECOLOGICAL REGULATING PRODUCTS VALUE OF TYPICAL AGRICULTURAL AND FOREST ECOSYSTEMS: A CASE STUDY IN THE BEIJIANG RIVER BASIN, GUANGDONG PROVINCE, CHINA

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Abstract. This research evaluated the value of seven ecological regulating products, including CO_2 Fixation, O_2 Release, Air Purification, Water Retention, Climate Regulation, Soil Maintenance, and Biodiversity Conservation, offered by typical agricultural and forest ecosystems of the cultivated land, horticultural land, forestland, and grassland in the Beijiang River Basin (BRB), Guangdong Province, Southern China, from 2009 to 2023. The total value of ecological regulating products showed a fluctuating increase, rising from US$ 44.96 billion in 2009 to US$ 46.15 billion in 2023 (+2.6%). Among the four ecosystems, forestland contributed the largest proportion, accounting for 88.21% of the total value in 2009 and 91.16% in 2023. The top three counties (county-level cities) in terms of the total value were Yingde, Huaiji and Yangshan, with annual average value of US$ 4.91 billion, US$ 3.32 billion and US$ 3.0 billion, respectively, over the study period. In contrast, the lowest annual average value was US$ 0.24 billion in Sanshui, just one-twentieth of the highest value recorded in Yingde. Regarding the per-unit-area value of ecological regulating products, apart from Sanshui, Huadu, and Qingcheng, the figures across the remaining twenty-two counties (county-level cities and districts) were relatively similar, all exceeding US$ 7800 ha^{-1}. However, Sanshui had the lowest per-unit-area value, equivalent to only 28.7% of the highest value of US$ 10,094.1 ha^{-1} in Guangning. Multivariate regression analysis revealed a strong positive correlation between the GDP of the primary industry and the value of ecological regulating products. Our findings provide valuable decision-making support for scientific assessment and implementation of the realization of ecological products value, as well as for advancing environmental protection efforts in the BRB.
Keywords: *ecological product, value realization, sustainable development, correlation analysis, The Beijiang River Basin*

Introduction

Ecological product, generally understood as goods and services derived directly from nature or refined through human intervention (Jin and Lu, 2021; Zhu et al., 2024), refers to the tangible materials and intangible benefits generated by natural ecological systems (Wainger et al., 2018; Vallecillo et al., 2019; Song and Du, 2024). The similar concepts include eco-labeled goods, eco-design products, eco-friendly products, green-labeled goods, and non-polluting products (Chen et al., 2024; Song et al., 2025). The concept of "ecological product" originated in China with distinctive national characteristics and has since been integrated into the internationally recognized framework of ecosystem services (Song, 2018; Jin and Lu, 2021). Scholars have defined "ecosystem services" as the ecological features, functions, and processes that directly or indirectly enhance human well-being, adding value and competitiveness to ecological assets and ecosystems (Daily, 1997; Costanza et al., 2017). This field has attracted growing interest and effort through international initiatives (Liu et al., 2025), such as the United Nations *"Millennium Ecosystem Assessment"* (MEA, 2005), the European Union's project of *"The Economics of Ecosystems and Biodiversity (TEEB)"* (Bishop et al., 2010), and the United Nations *"The System of Environmental-Economic Accounting (SEEA) and Experimental Ecosystem Accounting (EEA)"* (United Nations, 2014). It has also garnered increasing attention from scientists focused on assessment and ecological protection in recent years (Burkhard et al., 2012; Connor et al., 2015; Wolff et al., 2015; Haines-Young and Potschin, 2018). At the same time, researchers worldwide have conducted extensive studies on quantifying ecosystem services, evaluating their value, and designing payment mechanisms for these services (Costanza et al., 1997; Ligate et al., 2018; Mamat et al., 2018; Li et al., 2025; Sayre et al., 2025; Sun et al., 2025). This body of work has established a foundation for environmental decision-making by linking policy choices to human benefits (Arkema et al., 2017; Baro et al., 2017; Ye et al., 2018; Dang et al., 2021; Ye et al., 2021).

The interaction mechanisms between human well-being and ecosystem services represent a frontier area, exemplified by initiatives such as the International Program on Ecosystem Services and Poverty Reduction (Suich et al., 2015; Delgado and Marin, 2016; Bryan et al., 2018; Gao et al., 2024). In China, the concept of "ecological products" was first formally introduced in the National Planning for Main Functional Areas issued by the State Council in 2010 (Zhang, 2020; Wu et al., 2021). These products are considered essential for public welfare and the sustenance of human survival and development (Mulligan et al., 2020; Du et al., 2024). Successively, the reports of the 19th and 20th National Congress of the Communist Party of China called to "provide more high-quality ecological products to meet the people's growing needs for a beautiful ecological environment" and to "establish a mechanism for realizing the value of ecological products and improve the compensation system for ecological protection". Consequently, the supply and value realization of ecological products have become a focal point in both theoretical research and practical exploration within the field of natural resources, and attracted significant scholarly attention in China (Guo et al., 2024). In April 2021, the Chinese Government issued *"the Opinions on Establishing and Improving the Mechanism for Realizing the Value of Ecological Products"*, which outlines clear requirements for the principles and mechanisms of this process (Wang et al., 2023a; Hui et al., 2024). This policy is regarded as a Chinese initiative to pioneer a new path for green economic growth, a concrete embodiment of the ecological civilization philosophy, and a practical application of the concept of "clean water and green mountains are gold and silver mountains" (also known as the "Two Mountains") (Bai et al., 2022; Han et al.,

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2024). The national mechanism for realizing the value of ecological products is seen as a vital for correcting environmental externalities and protecting ecosystem functions and integrity in China (Gao et al., 2020; Zhang et al., 2023a, 2024). To effectively advance this goal, central authorities including the Central Committee of the Communist Party of China, the State Council, the National Development and Reform Commission and the Ministry of Natural Resources have approved multiple pilot regions for the implementing ecological product value realization mechanisms (see *Table 1*). Guided by those national strategies, governments at all levels have issued relevant policy documents. According to incomplete statistics, 17 provinces, 50 prefecture-level cities, and over 160 counties and districts in China have released their own guidelines on establishing and improving the value realization mechanism for ecological products (Wang et al., 2023b).

Table 1. *Pilot projects related to the value realization mechanism of ecological products*

Pilot type	Pilot area and time	Pilot number	Issued department
Pilot of National Ecological Civilization Zones	Fujian (2016), Jiangxi (2017), Guizhou (2017), Hainan (2019)	4	National Development and Reform Commission of the PRC
Pilot of National Provincial-level Marketization of Ecological Products	Zhejiang, Jiangxi, Guizhou, Qinghai, Fujian, and Hainan in 2016	6	National Development and Reform Commission of the PRC
Pilot City of National Ecological Products Value Realization	Lishui City in Zhejiang province (2019), Fuzhou City in Jiangxi province (2019)	2	National Development and Reform Commission of the PRC
Pilot of National Ecological Product Value Realization Mechanism	2 rounds issued cumulatively since 2024: the first round of 10 (2024), the second round of 25 (2025)	35	National Development and Reform Commission of the PRC
Typical Cases of Ecological Products Value Realization	6 batches issued cumulatively since 2020: the first batch of 11 (2020), the second batch of 10 (2021), the third batch of 11 (2022); the fourth batch of 11 (2023); the fifth batch of 10 (2024); the sixth batch of 11 (2026)	64	Ministry of Natural Resources of the PRC
National Ecological Civilization Construction Demonstration Cities and Counties (Districts)	8 batches issued cumulatively since 2017: the first batch of 46 (2017), the second batch of 45 (2018), the third batch of 84 (2019), the fourth batch of 87 (2020), the fifth batch of 100 (2021), the sixth batch of 106 (2022), and the seventh batch of 104 (2023), and the eighth batch of 105 (2025)	677	Ministry of Ecology and Environment of the PRC
National "Clear Water and Green Mountains are the Gold and Silver Mountain" Practice Innovation base	8 batches issued cumulatively since 2017: the first batch of 13 (2017), the second batch of 16 (2018), the third batch of 23 (2019), the fourth batch of 35 (2020), the fifth batch of 49 (2021), the sixth batch of 51 (2022), the seventh batch of 53 (2023); and the eighth batch of 91 (2025)	331	Ministry of Ecology and Environment of the PRC
Pilot of National Mechanism for Realizing the Ecological Products Value in the Field of Natural Resources	Chongqing, Nanping, Dongying, Jiangyin, Zoucheng, Nanyang, Lingbo, Guangzhou, Shenzhen, Suzhou (2021)	10	Ministry of Natural Resources of the PRC
Pilot of National Value Accounting of the Forest Resources	Inner Mongolia, Fujian, Henan, Hainan, and Qinghai (2022)	5	National Forestry and Grassland Bureau, National Bureau of Statistics of the PRC
Cases of Beautiful River and Lake	4 batches issued cumulatively since 2022: the first batch of 18 (2022), the second batch of 38 (2023), the third batch of 39 (2024), the fourth batch of 47 (2025)	142	Ministry of Ecology and Environment of the PRC

Ecological products can be categorized into three main groups: material supply products, regulating service products, and cultural service products (de Groot et al., 2002). Material supply products primarily encompass tangible ecological resources such as medicinal herbs, timber, and food (Crenna et al., 2018). Regulating service products refer to functions

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including carbon fixation, oxygen release, air purification, water retention, climate regulation, soil maintenance, etc. (Niu et al., 2012), while cultural service products involve benefits derived from ecotourism and aesthetic experiences. Previous studies have indicated that assessing the value of ecological products is vital for recognizing their worth (Farber et al., 2002; Liu and Mou, 2020; Geng and Zhang, 2023). In China, research on the value of ecological products has focused primarily on aspects such as conceptual definition and classification (Ben et al., 2024), accounting indicators and methods (Wang et al., 2021; Guo et al., 2022; Zhu et al., 2023), operational mechanisms and pathways for value realization (Cui et al., 2019; Yu et al., 2022), conversion efficiency (Wang et al., 2022a), and human well-being (Xu et al., 2019; Wu et al., 2022; Li et al., 2023; Zhang et al., 2023b). Research subjects range from the national scale (Ma et al., 2020; Shen et al., 2023), to provincial scales-such as Jiangxi (Xie et al., 2022), Shandong (Wang et al., 2023b), Fujian (Hu et al., 2023), Zhejiang (Wang et al., 2022a), Hainan (Zhou et al., 2022), Hubei (Guan et al., 2022), Guangxi (Wang et al., 2022b), as well as metropolitan areas (Liang et al., 2021; Zhou et al., 2020), city scales (Yang et al., 2023; Zhao et al., 2023), river basins (Han et al., 2024; Zhu et al., 2024b), and specific ecosystems such as croplands (Zhang et al., 2022), forestlands (Xie et al., 2024), and so on. Regarding accounting methods, three main approaches are currently employed for assessing the value of ecological products (Howarth and Farber, 2002; Jin and Lu, 2021; Zhu et al., 2024a): the Equivalent Factor Approach proposed by Xie et al. (2003), the functional value approach, which utilizes various monitoring data and techniques such as market valuation, replacement cost, and travel cost methods, and the "energy-based" approach, which is grounded in the solar energy captured by ecosystems.

Ecosystems vary in quantity and quality across regions, leading to differences in the ecological products they provide. Agricultural and forest ecosystems, which mainly include the cultivated land and grassland covering 24%-38% of the earth's land area, are among the world's most important ecosystems (Ye et al., 2016). They deliver a wide range of economic, ecological, and social benefits (Jiang et al., 2022; Romanova et al., 2022) and contribute to addressing several United Nations Sustainable Development Goals (SDGs), such as Zero Hunger, Climate Action, and Life on Land (Hu et al., 2015; Bryan et al., 2018; Martin et al., 2020). Since the convening of the 18th National Congress of the Communist Party of China in 2012, China has continued to advance the ecological civilization construction, guided by the ecological civilization philosophy and the concept of the "Two Mountains". This has encouraged local governments to integrate resource and environmental management into the protection of ecological products value (Song and Du, 2024). Currently, pathways for realizing the value of material supply products and cultural-tourism products are relatively well-established. However, how to realize the value of ecological regulating products remains a key challenge in both theoretical research and practical implementation (Gao et al., 2020).

The Beijiang River Basin (BRB), located within the National Key Ecological Function Zone (specifically, the Nanling Mountains Forest and Biodiversity Ecological Function Zone), is the second-largest tributary in the Pearl River Basin (Zhao et al., 2024). As a crucial ecological barrier of Guangdong province, the BRB is rich in green resources characterized by a subtropical evergreen broadleaf forest system. It also serves as the largest gene bank of biological species in Guangdong Province and holds significant potential for the valorization of ecological resources. So, in this study, we quantified the changes in agricultural and forest ecosystems within the BRB using land-use survey data from Guangdong Province spanning 2009 to 2023. We then assessed the impact of these

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agricultural and forest ecosystems change on the value of ecological regulating products. Furthermore, using SPSS 26.0, we analyzed the correlation between the value of ecological regulating products and several economic indicators: gross domestic product (GDP), GDP per capita, and the GDP of the primary, secondary, and tertiary industries. Spatial autocorrelation of the ecological regulating products value was examined using ArcGIS10.2. The results aim to provide insights and technical references for the spatial implementation and zoning of ecological regulation product value realization. Additionally, this study intends to offer decision-making support for promoting the high-quality development aligning with the "Two Mountains" theory in China.

Materials and methods

Study area

Geographical location

The Beijiang River (23°05'~25°31'N, 112°32'~114°41'E) is the second-largest water system of the Pearl River in Southern China. It originates from Damaokeng in Xinfeng County, Jiangxi Province, and enters Guangdong Province via Dayu County. Flowing from north to south, it traverses Shaoguan City and Qingyuan City to Foshan City, converges with the Xijiang River at Sixianjiao in Sanshui District, and finally enters the river network of the Pearl River Delta. The mainstream of the Beijiang River is 468 km long, of which 458 km lies within Guangdong Province, with a total catchment area of 46,710 km^2 (42,930 km^2 within Guangdong Province). Based on data availability and accuracy, this study area of the Beijiang River Basin (BRB) covers twenty-five counties (county-level cities and districts) belonging to six prefecture-level cities within Guangdong Province, including Zhenjiang District, Wujiang District, Qujiang District, Lechang City, Nanxiong City, Renhua County, Shixing County, Wengyuan County, Xinfeng County, and Ruyuan County in Shaoguan City; Qingcheng District, Qingxin District, Yingde City, Lianzhou City, and Fogang County, Yangshan County, Lianshan County, and Liannan County in Qingyuan City; Sihui City, Guangning County and Huaiji County in Zhaoqing City, Conghua District and Huadu District in Guangzhou City, Sanshui District in Foshan City, and Lianping County in Heyuan City (see *Fig. 1*). The region experiences a humid subtropical monsoon climate, with a multi-year (1956-2000) annual average rainfall of 1785 mm. Its total average water resources amount to 47.76 billion m^3, with a utilizable volume of 14.43 billion m^3 (http://slt.gd.gov.cn/ysgk_new/lygk/bjly/). The BRB is rich in natural resources, including abundant solar, thermal, and rainfall resources, and possesses significant potential for agricultural and forest development for large areas of cultivated land and forestland (Zhang et al., 2025). Notably, Shaoguan City and Qingyuan City within the BRB are among the key agricultural areas in Guangdong Province.

Socio-economic status

The total land area of the BRB in Guangdong Province is 43,240 km^2, with 3695.4 km^2 cultivated land in 2023. Since the start of China's reform and opening-up, the economy of the BRB has developed rapidly, accompanied by the continuous optimization of its industrial structure. The gross domestic product (GDP) of the region increased from US$ 85.56 billion in 2015 to US$ 128.57 billion in 2023 (values adjusted for inflation to 2020 dollars; Statistics Bureau of Guangdong Province, 2024). By 2023, the proportion

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of the GDP of the primary industry had risen to 11.3% and that of the tertiary industry to 45.0%, while GDP of the secondary industry had decreased to 43.7%.

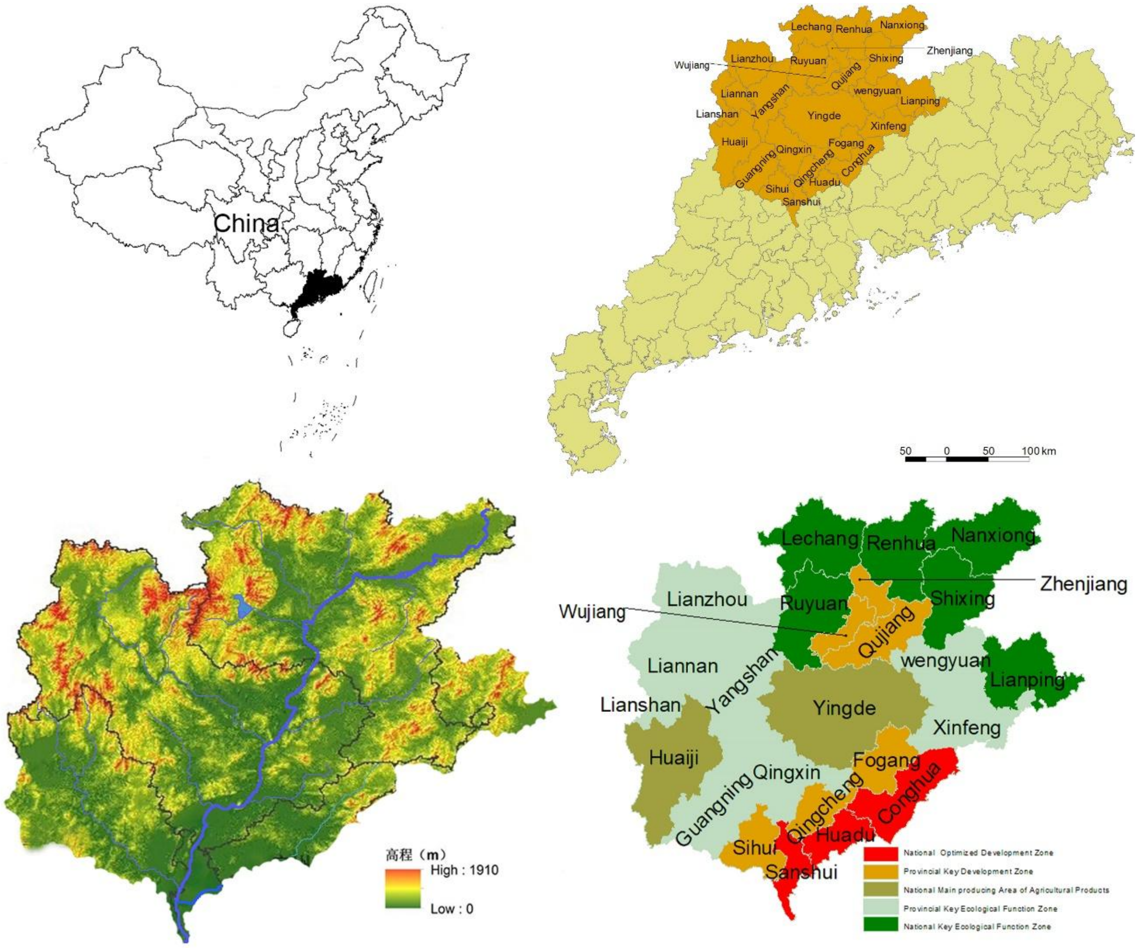

Figure 1. *Location map of the Beijiang River Basin, southern China*

Data collection

In this study, we selected cultivated land, horticultural land, forestland, and grassland areas to assess the value of ecological regulating products offered by the typical agricultural and forest ecosystems in the BRB from 2009 to 2023. The land-use data were obtained from annual land- use change surveys conducted in Guangdong Province (https://nr.gd.gov.cn/gkmlpt/index). Socioeconomic data for the BRB were primarily sourced from the provincial-level publications such as the Guangdong Statistical Yearbook and the Guangdong Rural Statistical Yearbook, as well as from statistical bulletins and official websites of the respective counties. Most meteorological data were collected from the China National Meteorological Science Data Center (http://data.cma.cn/).

Research methods

Selection of ecological products

Building on the Common International Classification for Ecosystem Services (CICES) version 5.1 (Haines-Young and Potschin, 2018) and China's national

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accounting specifications for the gross ecosystem product (National Development and Reform Commission & National Bureau of Statistics, 2022a), and considering data availability, this study selected the following ecological regulating products for assessment: Carbon (CO_2) Fixation, Oxygen (O_2) Release, Air Purification (including SO_2, NO_x and DUST removal), Water Retention, Climate Regulation, Soil Maintenance, and Biodiversity Conservation.

Dynamic degree of agricultural and forest ecosystem

We primarily employed the single land-use dynamic degree to analyze the change rate of each agricultural and forest ecosystem type in the study area.

$$D = \frac{A_b - A_a}{A_a} \times \frac{1}{T} \times 100\% \quad \text{(Eq.1)}$$

where:
D—dynamic degree of the agricultural and forest ecosystem (%);
A_a, A_b—area of the agricultural and forest ecosystems at the beginning and the end of the study period (ha), respectively;
T—the length of the study period in years.

Calculation models of the ecological regulating products value

In this study, the value of ecological regulating products was converted to U.S. dollars per year (US$·yr^{-1}) using the average 2020 exchange rate of 1US$ = 6.8976 RMB (https://www.exchange-rates.org/zh/exchange-rate-history/usd-cny-2020).

Carbon Fixation value

The value of Carbon Fixation was calculated using the following formula:

$$V_{CO_2} = \sum_{k=1}^{4} S_{k,t} \times Q_{c,k} \times P_{CO_2} \quad \text{(Eq.2)}$$

where:
V_{CO_2}—value of CO_2 fixation by agricultural and forest ecosystems (US$·yr^{-1});
$S_{k,t}$—area of agricultural and forest ecosystem type k in time period t (ha);
$Q_{c,k}$—CO_2 fixation capacity of agricultural and forest ecosystem type k (t·ha^{-1}·yr^{-1}). It is 5.6 t·ha^{-1}·yr^{-1} for cultivated land, 4.675 t·ha^{-1}·yr^{-1} for horticultural land, 7.25 t ha^{-1}·yr^{-1} for forestland, and 201 t·ha^{-1}·yr^{-1} for grassland (Zhu et al., 2024a);
P_{CO_2}—cost of CO_2 fixation (US$·t^{-1}). This study adopted a carbon price of 137 US$·t^{-1} for the year 2020, based on Swedish carbon pricing data (World Bank, 2022).

Oxygen Release value

The value of Oxygen Release was calculated based on the biological growth of ecosystems, using the following formula:

$$V_{O_2} = \sum_{k=1}^{4} S_{k,t} \times Q_{o,k} \times P_{O_2} \quad \text{(Eq.3)}$$

where:
V_{O_2}—value of O_2 released by agricultural and forest ecosystems (US$·yr^{-1});
$S_{k,t}$—area of agricultural and forest ecosystem type k in time period t (ha);

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$Q_{o,k}$—O_2 release capacity of agricultural and forest ecosystem type *k* (t·ha^{-1}·yr^{-1}). It is 15 t·ha^{-1}·yr^{-1} for cultivated land, 12.425 t·ha^{-1}·yr^{-1} for horticultural land, 19.35 t·ha^{-1}·yr^{-1} for forestland, and 5.5 t·ha^{-1}·yr^{-1} for grassland (Zhu et al., 2024a);
P_{O_2}—cost of industrial oxygen production (US$·t^{-1}). This study adopted a price of US$ 144.98 ·t^{-1}, based on the State Forestry Administration's Monitoring Report on the Ecological Benefits of the Retired Forest Project (Zhong et al., 2021).

Air Purification value

Air Purification in this study encompasses the removal of sulfur dioxide (SO_2), nitrogen oxides (NO_x) and DUST (particulate matter). The calculation of Air Purification value accounts for subcategories within the typical agricultural and forest ecosystem types: cultivated land was classified into paddy fields and drylands, while forestland was distinguished into arboreal forests and shrublands. The value for SO_2, NO_x and DUST Purification was then calculated as follows:

$$V_{\mathrm{SO_2}} = \sum_{k=1}^{6} S_{k,t} \times Q_{s,k} \times P_{SO_2} \quad \text{(Eq.4)}$$

$$V_{\mathrm{NO}_x} = \sum_{k=1}^{6} S_{k,t} \times Q_{n,k} \times P_{NO_x} \quad \text{(Eq.5)}$$

$$V_{dust} = \sum_{k=1}^{6} S_{k,t} \times Q_{d,k} \times P_{dust} \quad \text{(Eq.6)}$$

$$V_{air} = V_{\mathrm{SO_2}} + V_{NOx} + V_{dust} \quad \text{(Eq.7)}$$

where:
$V_{\mathrm{SO_2}}$, V_{NO_x}, V_{dust}, V_{air}—value of SO_2 purification, NO_x purification, DUST removal, and total air purification, respectively, by agricultural and forest ecosystem type *k* in time period *t* (US$·yr^{-1});
$S_{k,t}$—area of agricultural and forest ecosystem type *k* in time period *t* (ha),
$Q_{s,k}$—SO_2 absorption capacity of agricultural and forest ecosystem type *k* (t·ha^{-1}·yr^{-1}). It is 403 t·ha^{-1}·yr^{-1} for paddy field, 250 t·ha^{-1}·yr^{-1} for dryland, 327 t·ha^{-1}·yr^{-1} for horticultural land, 437 t·ha^{-1}·yr^{-1} for arboreal forest, 338 t·ha^{-1}·yr^{-1} for shrubland and 294 t·ha^{-1}·yr^{-1} for grassland,
$Q_{n,k}$—NO_x absorption capacity of agricultural and forest ecosystem type *k* (t·ha^{-1}·yr^{-1}). It is 275 t·ha^{-1}·yr^{-1} for paddy fields, 157 t·ha^{-1}·yr^{-1} for drylands, 237 t·ha^{-1}·yr^{-1} for horticultural land, 274 t·ha^{-1}·yr^{-1} for arboreal forest, 208 t·ha^{-1}·yr^{-1} for shrubland and 157 t·ha^{-1}·yr^{-1} for grassland,
$Q_{d,k}$—the capacity of DUST removal by agricultural and forest ecosystem k (t·ha^{-1}·yr^{-1}). It is 887 t·ha^{-1}·yr^{-1} for paddy fields, 841 t·ha^{-1}·yr^{-1} for drylands, 729 t·ha^{-1}·yr^{-1} for horticultural land, 1300 t·ha^{-1}·yr^{-1} for arboreal forest, 941 t·ha^{-1}·yr^{-1} for shrubland and 841 t·ha^{-1}·yr^{-1} for grassland (National Development and Reform Commission National Bureau of Statistics, 2022b),
P_{SO_2}, P_{NO_x}, P_{dust}—unit cost of SO_2 and NO_x emission control, and DUST removal in China, taken as US$ 274.73·t^{-1}, US$ 274.73·t^{-1}, and US$ 65.24·t^{-1}, respectively (Shenzhen Administration for Market Regulation, 2021).

Other moderating values

The value of Water Retention (V_{wat}), Climate Regulation (V_{cli}), Soil Maintenance (V_{soil}) and Biodiversity Conservation (V_{bio}) is calculated as follows:

$$V_{wat} = \sum_{k=1}^{4} S_{k,t} \times M_{wk,t} \quad \text{(Eq.8)}$$

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$$V_{cli} = \sum_{k=1}^{4} S_{k,t} \times M_{ck,t} \quad \text{(Eq.9)}$$

$$V_{soil} = \sum_{k=1}^{4} S_{k,t} \times M_{sk,t} \quad \text{(Eq.10)}$$

$$V_{bio} = \sum_{k=1}^{4} S_{k,t} \times M_{bk,t} \quad \text{(Eq.11)}$$

where:
$S_{k,t}$—area of agricultural and forest ecosystem type *k* in time period *t* (ha);
$M_{wk,t}$, $M_{ck,t}$, $M_{sk,t}$, and $M_{bk,t}$—per-unit-area value of Water Retention, Climate Regulation, Soil Maintenance and Biodiversity Conservation for ecosystem type *k* (US$·$ha^{-1}$·$yr^{-1}$), respectively. Following Ye et al. (2018, 2021), these per-unit-area values are listed in *Table 2*.

Table 2. *Per-unit-area ecological regulating products value for Guangdong in 2020 (Unit: US$·$ha^{-1}$)*

Ecological regulating products type	Cultivated land	Horticultural land	Forestland	Grassland
Water retention	434.32	1061.68	1668.92	611.27
Climate regulation	546.92	1065.70	1660.88	627.35
Soil maintenance	828.43	1182.32	1640.77	900.82
Biodiversity conservation	575.07	1206.45	1841.85	752.02

For the per-unit-area ecological regulating products value in *Table 2,* a reference value was first established based on the 2020 national minimum purchase price for grain crops of CNY 3.41·kg^{-1} (US$ 0.49·kg^{-1}). Following Xie et al. (2015), the proportion of food production value attributable to cropland was set at 1/7. Consequently, the ecological regulating service value per hectare for cultivated land in the BRB was calculated as US$ 402.15·ha^{-1} (i.e., 5,745 kg·ha^{-1} × US$ 0.49·kg^{-1}/7). The per-unit values supplied by different ecosystem types are listed in *Table 2*. The horticultural land category was also added, with its value coefficients for all regulating products assigned according to Ye et al. (2021).

Spatial autocorrelation analysis

In this study, Global Spatial Autocorrelation (Global Moran's I) and Local Indicators of Spatial Association (LISA) were employed to measure the spatial dependence and heterogeneity of the ecological regulating products value across the study area. Taking counties (including county-level cities and districts) in the BRB as the basic analytical units, Global Moran's I was used to assess the overall spatial correlation, while LISA was applied to identify local clusters and outliers by measuring the similarity between each unit and its neighbors (Sun et al., 2025).

$$I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n}\omega_{ij}(x_i-\bar{x})(x_j-\bar{x})}{\sum_{i=1}^{n}\sum_{j=1}^{n}\omega_{ij}\sum_{i=1}^{n}(x_i-\bar{x})^2} \quad \text{(Eq.12)}$$

$$I_i = \frac{(x_i-\bar{x})\sum_{j=1}^{n}\omega_{ij}(x_j-\bar{x})}{\sum_{i=1}^{n}(x_i-\bar{x})^2} \quad \text{(Eq.13)}$$

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where:

I—Global Moran's I statistic, ranging from −1 to 1. A value significantly greater than 0 indicates positive spatial autocorrelation (similar values cluster together), a value significantly less than 0 indicates negative spatial autocorrelation (dissimilar values are adjacent), and a value near 0 suggests a spatially random pattern;

I_i—Local Indicator of Spatial Association (LISA). $I_i > 0$ signifies positive correlation, manifesting as high-high or low-low clusters; $I_i < 0$ signifies negative local spatial correlation, manifesting as high-low or low-high outliers;

x_i and x_j—value of the ecological regulating products in spatial units i and j, respectively;

n—total number of special units (here, n = 25, corresponding to the counties, county-level cities, and districts);

$\bar{x}$—mean value of the ecological regulating products across all spatial units;

ω_{ij}—element of the spatial weight matrix, representing the spatial relationship between units i and j.

Data analysis

All data processing was conducted using Microsoft Excel. Land use areas were extracted and spatial correlation analyses were performed with ArcGIS10.2 and SPSS 26.0. Microsoft Excel was then used to organize the compiled data and calculate the value of each ecological regulating product based on the formulas defined earlier.

Results

Area changes of agricultural and forest ecosystems in the BRB

As shown in *Table 3*, the total area of the agricultural and forest ecosystems in the BRB decreased slightly by 26.6 km^2 between 2009 and 2023. Specifically, cultivated land and grassland decreased by 1729.5 km^2 and 900.8 km^2, respectively, whereas horticultural land and forestland increased by 490.3 km^2 and 2113.4 km^2, respectively. Based on the dynamic degree calculated using *Equation 1*, grassland exhibited the largest rate of change at -4.5%, followed by the horticultural land (+2.3%) and cultivated land (-2.1%). Forestland showed the smallest change at +0.4%. The notable expansion in horticultural land is primarily attributed to its higher economic return per-unit-area compared with the cultivated land and forestland, which has driven the conversion of substantial areas from both land types into horticultural land.

Changes in the value of ecological regulating products

Based on *Equations 2–11*, we calculated the total value of ecological regulating products for different agricultural and forest ecosystems (see *Table 4*) and the value of individual ecological regulating products (see *Table 5*) in the BRB from 2009 to 2023.

Changes in total value of ecological regulating products

As shown in *Table 4*, the total value of ecological regulating products in the BRB exhibited a fluctuating upward trend from 2009 to 2023. The overall increase during the study period was US$ 1.19 billion, representing a growth of 2.64% compared with the 2009 baseline. By examining different sub-periods, the total value showed a continuous decline from US$ 44.9 billion in 2009 to US$ 44.51 billion in 2018, then a sharp increase to US$

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46.39 billion occurred in 2019-(in which the third national land resource survey data were released), and followed by a gradual decline to 2023. The total value was primarily contributed by forestland, followed by cultivated land, horticultural land, and grassland. Forestland also recorded the largest absolute increase in value (US$ 2.41 billion), followed by horticultural land (US$ 0.34 billion). In contrast, the value of cultivated land and grassland decreased by US$ 1.15 billion and US$ 0.41 billion, respectively.

Table 3. *Area changes of agricultural and forest ecosystems in the BRB (km^2)*

Year	Cultivated land	Horticultural land	Forestland	Grassland
2009	6002.0	1494.7	35942.0	1432.0
2010	6081.3	1629.3	35868.0	1388.0
2011	6171.3	1610.0	35752.0	1367.3
2012	6184.7	1606.7	35722.0	1358.7
2013	6198.0	1599.3	35690.0	1352.0
2014	6201.3	1587.3	35665.3	1344.0
2015	6190.0	1579.3	35652.0	1337.3
2016	6172.0	1571.3	35632.0	1333.3
2017	6156.0	1562.0	35607.3	1331.3
2018	6148.1	1556.8	35594.1	1328.0
2019	4259.2	2055.9	38236.5	510.4
2020	4250.1	2050.0	38186.9	508.6
2021	4257.5	2043.3	38132.7	499.7
2022	4261.6	2009.8	38110.1	516.4
2023	4272.5	1985.0	38055.4	531.2
Area change from 2009 to 2023	-1729.5	490.3	2113.4	-900.8
Rate of change (%)	-28.8	32.8	5.9	-6.3
Dynamic degree (%)	-2.1	2.3	0.4	-4.5

The proportion of cultivated land's value of ecological regulating products to the total value decreased the most, falling from 7.95% in 2009 to 5.25% in 2023 (a reduction of 2.69%). Conversely, the proportion of forestland increased by 2.95%, from 88.21% in 2009 to 91.16% in 2023. The proportions contributed by horticultural land and grassland changed relatively little: horticultural land's proportion increased 0.67%, while grassland's protortion decreased 0.93%.

Changes in the value of individual ecological regulating product

As shown in *Table 5*, the individual value of various ecological regulating products exhibited consistent trends over the study period. The value of O_2 release was the highest, reaching to US$ 11.77 billion in 2009 and US$ 12.01 billion in 2023, accounting for over 26% of the total ecological regulating products value. This was followed, in descending order of contribution in 2023, by the value of Biodiversity Conservation (16.32%), Soil Maintenance (14.91%), Climate Regulation (14.73%), Water Retention (14.69%) and CO_2 Fixation (13.07%). In contrast, the total value from Air Purification was minimal, constituting only 0.26% of the total in 2023. Within this category, the contributions of SO_2 absorption, NOx absorption, and Dust removal were 0.11%, 0.07%, and 0.08%, respectively. *Figure 2* further illustrates that the proportional contribution of each

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individual regulating product to the total value remained relatively stable throughout the study period.

Table 4. *Changes and the ratio of the ecological regulating products value in BRB from 2009 to 2023 (×10^8 US$·yr^{-1})*

Year	Cultivated land (ratio to total /%)	Horticultural land (ratio to total /%)	Forestland (ratio to total /%)	Grassland (ratio to total /%)	Total
2009	35.72 (7.94)	11.01 (2.45)	396.63 (88.21)	6.28 (1.40)	449.64
2010	34.48 (7.69)	11.81 (2.63)	396.53 (88.41)	5.71 (1.27)	448.53
2011	34.99 (7.82)	11.67 (2.61)	395.25 (88.32)	5.63 (1.26)	447.54
2012	35.07 (7.84)	11.64 (2.60)	394.92 (88.31)	5.59 (1.25)	447.22
2013	35.15 (7.87)	11.59 (2.59)	394.56 (88.30)	5.56 (1.24)	446.86
2014	35.16 (7.87)	11.50 (2.58)	394.29 (88.31)	5.53 (1.24)	446.48
2015	35.10 (7.87)	11.45 (2.57)	394.14 (88.33)	5.50 (1.23)	446.19
2016	35.00 (7.85)	11.39 (2.55)	393.92 (88.36)	5.49 (1.23)	445.8
2017	34.91 (7.84)	11.32 (2.54)	393.65 (88.39)	5.48 (1.23)	445.36
2018	34.86 (7.83)	11.28 (2.53)	393.50 (88.41)	5.46 (1.23)	445.10
2019	24.16 (5.21)	14.90 (3.21)	422.70 (91.13)	2.10 (0.45)	463.86
2020	24.11 (5.20)	14.86 (3.21)	422.15 (91.14)	2.09 (0.45)	463.21
2021	24.15 (5.22)	14.81 (3.20)	421.55 (91.13)	2.06 (0.45)	462.57
2022	24.17 (5.23)	14.57 (3.15)	421.30 (91.16)	2.13 (0.46)	462.17
2023	24.23 (5.25)	14.39 (3.12)	420.70 (91.16)	2.19 (0.47)	461.51
2023-2009	-11.49	3.38	24.07	-4.10	11.87

Table 5. *Changes in the value of individual ecological regulating products from agricultural and forest ecosystems in the BRB (×10^8 US$·yr^{-1})*

Year	CO_2 Fixation	O_2 Release	Air Purification			Water Retention	Climate Regulation	Soil Maintenance	Biodiversity Conservation
			SO_2 Absorption	NO_x Absorption	Dust Removal				
2009	59.17	117.72	0.50	0.32	0.35	65.05	67.00	67.00	72.53
2010	59.25	117.89	0.51	0.32	0.35	65.08	65.51	67.07	72.57
2011	59.16	117.71	0.50	0.32	0.34	64.89	65.33	66.91	72.37
2012	59.13	117.64	0.50	0.32	0.34	64.84	65.28	66.86	72.31
2013	59.09	117.56	0.50	0.32	0.34	64.78	65.22	66.80	72.25
2014	59.04	117.47	0.50	0.32	0.34	64.72	65.16	66.74	72.18
2015	59.00	117.39	0.50	0.32	0.34	64.68	65.12	66.70	72.14
2016	58.95	117.28	0.50	0.32	0.34	64.63	65.07	66.64	72.08
2017	58.88	117.15	0.50	0.32	0.34	64.57	65.01	66.57	72.01
2018	58.85	117.09	0.50	0.32	0.34	64.54	64.97	66.53	71.97
2019	60.64	120.64	0.51	0.32	0.35	68.16	68.35	69.16	75.74
2020	60.55	120.47	0.51	0.32	0.35	68.06	68.25	69.06	75.63
2021	60.47	120.31	0.51	0.32	0.35	67.96	68.15	68.96	75.52
2022	60.42	120.21	0.51	0.32	0.35	67.90	68.09	68.90	75.46
2023	60.34	120.05	0.51	0.32	0.35	67.80	67.99	68.81	75.34
2023-2009	1.17	2.33	0.01	0	0	2.75	0.99	1.81	2.81

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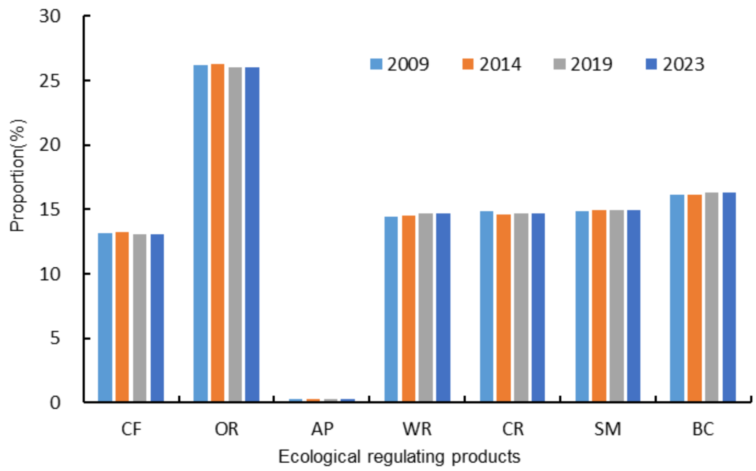

Figure 2. *Proportions of individual ecological regulating products value to the total value in the BRB. CF-CO_2 Fixation; OR- O_2 Release; AP-Air Purification; WR-Water Retention; CR-Climate Regulation; SM-Soil Maintenance; BC- Biodiversity Conservation*

Changes in the spatial and temporal distribution of ecological regulating products value

As shown in *Table 6*, the total value of ecological regulating products for each county (county-level city and district) was calculated by aggregating the values across the BRB from 2009 to 2023. The results indicated that, with the exception of Huadu, all counties experienced an overall growth in the total value of ecological regulating products during the study period, reflecting a general increase in ecological outputs from natural assets such as the cultivated land, horticultural land, forestland, and grassland. Yingde stood out with highest ecological regulating products value, exceeding US$ 5 billion in 2023, followed by Huaiji (over US$ 3.3 billion) and Yangshan (over US$ 3.2 billion). These high values highlight the abundance of natural capital, such as horticultural land and forestland in these areas, which contributes substantially to ecological regulating functions. In contrast, more urbanized and developed districts, including Sanshui, Zhenjiang and Huadu, generated relatively lower ecological regulating value due to their limited extent of natural ecosystems.

Figure 3 illustrates the annual average value of ecological regulating products across the twenty-five counties (county-level cities and districts) in the BRB. Yingde stood out with the highest annual average value at ecological regulating products of US$ 4.91 billion, reflecting its robust natural capital base, which consistently generated substantial ecological regulating value each year. It is followed by Huaiji (US$ 3.32 billion) and Yangshan (US$ 3.0 billion). These top three regions highlighted the steady and significant contribution of agricultural and forest ecosystems to ecological output in the basin. Beyond the top three counties, eleven counties-Lianzhou, Guangning, Ruyuan, Lianping, Lechang, Renhua, Shixing, Nanxiong, Qingxin, Wengyuan, and Xinfeng-exhibited similar levels of ecological regulating value, ranging between US$ 2.0 billion and US$ 2.4 billion. In contrast, counties such as Shihui, Qingcheng, Wujiang, Huadu, Zhenjiang, and Sanshui recorded notably lower ecological regulating values, ranging from US$ 1.17 billion to US$ 1.95 billion. Among these, Sanshui registered the lowest annual average value (US$ 240 million), indicating a pronounced depletion of natural capital. Neighboring Zhenjiang also showed a relatively low value of US$ 451 million.

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Table 6. *Total value of ecological regulating products in counties (county-level cities and districts) (×10^8 US$·yr^{-1})*

Districts	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2023-2009
Huadu	5.18	5.30	5.27	5.26	5.24	5.20	5.18	5.16	5.14	5.13	5.27	5.25	5.20	5.16	5.10	-0.08
Conghua	16.80	16.77	16.74	16.71	16.68	16.64	16.63	16.61	16.57	16.56	16.96	16.94	16.90	16.85	16.81	0.01
Wujiang	5.97	5.95	5.95	5.94	5.93	5.92	5.90	5.89	5.89	5.88	6.06	6.05	6.04	6.04	6.03	0.06
Zhenjiang	4.53	4.51	4.50	4.50	4.48	4.46	4.46	4.45	4.44	4.44	4.59	4.59	4.57	4.55	4.54	0.01
Qujiang	14.76	14.75	14.73	14.73	14.72	14.71	14.70	14.71	14.70	14.68	15.05	15.02	14.98	14.96	14.93	0.17
Shixing	20.61	20.66	20.66	20.66	20.62	20.61	20.60	20.57	20.56	20.55	20.96	20.95	20.94	20.91	20.88	0.27
Renhua	21.46	21.47	21.45	21.43	21.43	21.43	21.42	21.40	21.38	21.38	21.78	21.77	21.76	21.75	21.74	0.28
Wengyuan	19.89	19.99	19.98	19.98	19.94	19.94	19.90	19.87	19.85	19.84	20.38	20.35	20.32	20.29	20.27	0.38
Ruyuan	22.40	22.41	22.37	22.37	22.37	22.34	22.34	22.34	22.33	22.32	22.52	22.51	22.48	22.47	22.46	0.06
Xinfeng	19.45	19.45	19.46	19.45	19.41	19.41	19.41	19.39	19.39	19.38	19.78	19.76	19.75	19.74	19.73	0.28
Lechang	21.69	21.70	21.57	21.57	21.56	21.56	21.56	21.55	21.56	21.55	22.73	22.72	22.69	22.70	22.68	0.99
Nanxiong	20.42	20.43	20.40	20.38	20.38	20.37	20.37	20.37	20.36	20.36	20.90	20.88	20.86	20.84	20.79	0.37
Sanshui	2.36	2.39	2.38	2.37	2.36	2.34	2.33	2.31	2.30	2.29	2.54	2.53	2.50	2.49	2.47	0.11
Guangning	23.98	23.94	23.90	23.90	23.90	23.90	23.88	23.88	23.87	23.85	24.29	24.28	24.28	24.27	24.24	0.26
Huaiji	33.14	33.11	33.02	33.00	32.99	32.98	32.95	32.94	32.92	32.91	33.77	33.74	33.72	33.68	33.64	0.5
Sihui	8.51	8.52	8.50	8.49	8.48	8.47	8.48	8.44	8.42	8.41	8.86	8.84	8.81	8.79	8.76	0.25
Lianping	21.88	22.02	21.97	21.95	21.90	21.88	21.84	21.83	21.82	21.82	22.33	22.31	22.29	22.25	22.23	0.35
Qingcheng	8.14	8.10	8.05	8.02	7.99	7.92	7.85	7.81	7.75	7.71	8.48	8.43	8.35	8.34	8.28	0.14
Qingxin	20.09	20.07	20.02	20.02	20.00	19.99	19.99	19.95	19.92	19.91	21.17	21.14	21.12	21.13	21.09	1.00
Fogang	11.60	11.57	11.57	11.56	11.55	11.55	11.54	11.53	11.49	11.47	11.91	11.89	11.84	11.83	11.81	0.21
Yangshan	28.93	28.92	28.85	28.78	28.77	28.76	28.76	28.75	28.73	28.73	32.43	32.39	32.38	32.39	32.39	3.46
Lianshan	12.17	12.20	12.16	12.16	12.16	12.16	12.16	12.16	12.16	12.16	12.34	12.34	12.33	12.32	12.32	0.15
Liannan	12.15	12.12	12.09	12.09	12.09	12.09	12.09	12.10	12.09	12.09	12.60	12.59	12.59	12.57	12.56	0.41
Yingde	48.38	48.54	48.40	48.37	48.37	48.34	48.32	48.27	48.22	48.19	50.86	50.66	50.68	50.62	50.54	2.16
Lianzhou	23.60	23.63	23.56	23.54	23.54	23.54	23.53	23.52	23.51	23.51	25.31	25.26	25.21	25.22	25.21	1.61

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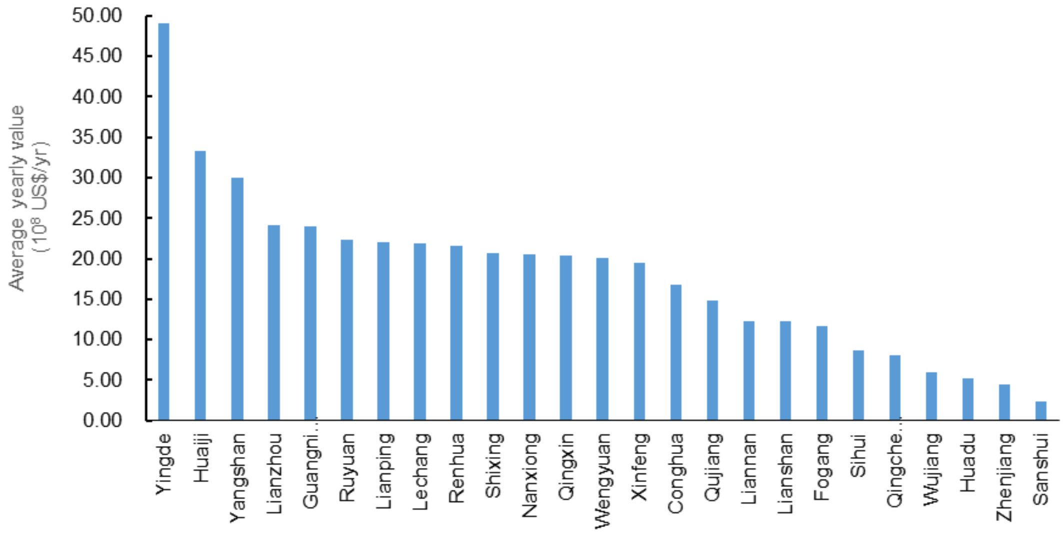

***Figure 3.** Changes in the annual average value of ecological regulating products in the BRB (calculated from Table 6)*

As shown in *Table 6*, the total ecological regulating products value in each county changed only marginally from 2009 to 2023. Consequently, the per-unit-area value, calculated by dividing the total value by the land area of each county (city, district), also remained relatively stable. *Figure 4* present the annual average per-unit-area value of ecological regulating products across the twenty-five counties (county-level cities and districts) in the BRB. The top three counties with the highest and most stable per-unit-area value over the study period were Guangning, Ruyuan and Lianshan, each exceeding US$ 10,000ha^{-1}. In total, 22 counties maintained an average per-unit-area value above US$ 7800 ha^{-1}. In contrast, Qingcheng, Huadu, and Sanshui recorded the lowest per-unit-area value at US$ 6235.6 ha^{-1}, US$ 5369.1ha^{-1}, and US$ 2896.4 ha^{-1} respectively. Notably, per-unit-area value in Huadu was the lowest, amounting to only 28.7% of the highest value of US$ 10094.1 ha^{-1} in Guangning.

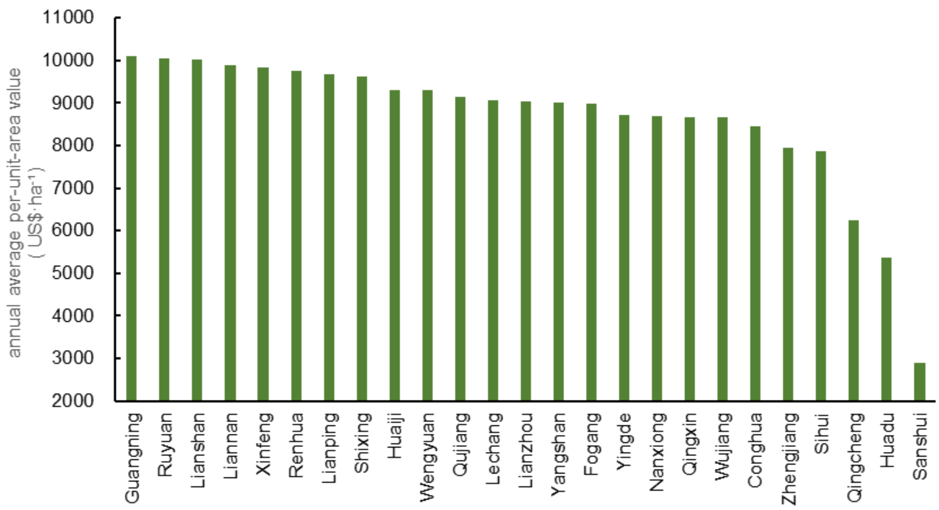

***Figure 4.** Changes in the per-unit-area value of annual average ecological regulating products from 2009 to 2023*

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To comprehensively analyze the spatial variation of ecological regulating products value in the BRB, we used ArcGIS 10.7 to map the total value and the per-unit-area value for each county. *Figure 5* illustrates the distribution of the total ecological regulating products value in the BRB in 2009 and 2023. These maps visually highlight the regional differences in economic output derived from natural assets, such as cultivated land, horticultural land, forestland, and grassland, over the 15-year study period. A comparison of the 2009 and 2023 maps shows that Yingde, Huaiji, and Yangshan consistently retained the highest total values, demonstrating the resilience and sustained productivity of their natural asset base. In contrast, significantly lower total values were observed in Sanshui, Huadu, and Sihui, which are located within or near the rapidly urbanizing Guangzhou-Foshan metropolitan area, as well as in the more urbanized districts of Qingcheng, Wujiang, and Zhenjiang.

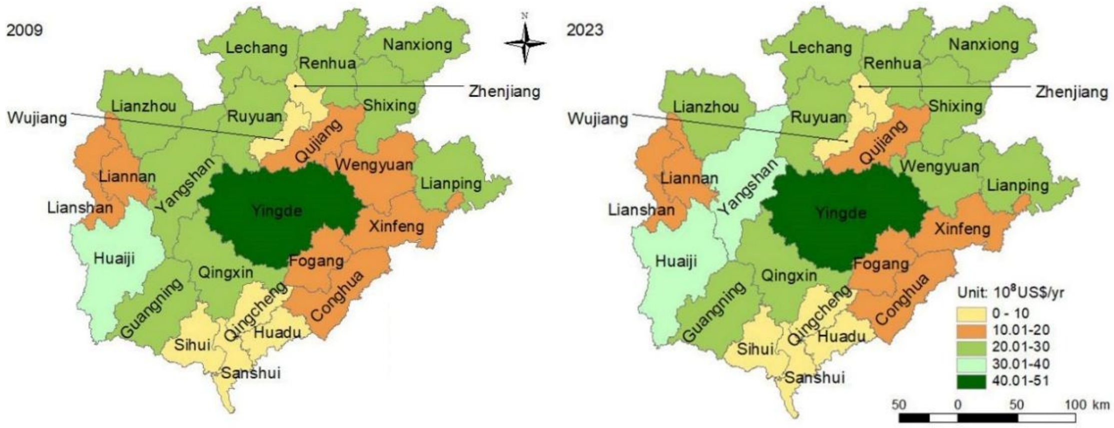

Figure 5. *Distribution of total ecological regulating products value in the BRB in 2009 and 2023*

Figure 6 presents the distribution of per-unit-area ecological regulating products value in the BRB in 2009 and 2023. The maps show that the spatial pattern of per-unit-area value remained largely stable across the study period, with notable changes observed only in Lianshan, Liannan, Yangshan, Lianzhou, Lechang, Fogang, Zhenjiang, and Sihui.

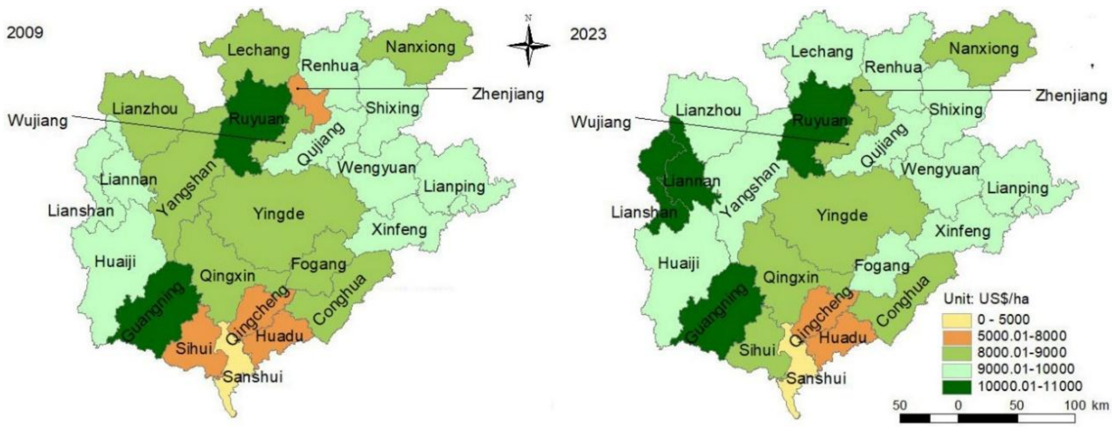

Figure 6. *Distribution of per-unit-area ecological regulating products value in the BRB for 2009 and 2023*

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Correlation analysis

Using a two-way fixed-effect model given by the *Equations 12* and *13*, we examined the relationship between the ecological regulating products value and socioeconomic indicators-including gross domestic product (GDP), GDP per capita, and the GDP of the primary, secondary, and tertiary industries-in the BRB. We originally intended to analyze the complete study interval to capture long-term trends of cumulative effects, which can provide more informative insights by revealing dynamic, continuous processes rather than static trends. However, the period before 2015 was excluded due to a lack of available data on the GDP of the primary, secondary, and tertiary industries in the BRB. Consequently, the correlation analysis was conducted only for the period from 2015 to 2023. As presented in *Table 7*, the GDP of the primary industry showed a statistically significant positive correlation with ecological regulating products value during the study period. In contrast, the other four indicators of total GDP, GDP per capita, and the GDP of the secondary and tertiary industries exhibited negative correlations with the ecological regulating products value, respectively.

Table 7. *Correlation between ecological regulating products value and socioeconomic development indicators in the BRB (2015-2023)*

Year	GDP of the primary industry	GDP of the secondary industry	GDP of the tertiary industry	GDP	GDP per capita
2015	0.478^{**}	-0.494^{**}	-0.427^{**}	-0.458^{**}	-0.632^{***}
2016	0.477^{**}	-0.492^{**}	-0.433^{**}	-0.458^{**}	-0.626^{***}
2017	0.492^{**}	-0.478^{**}	-0.443^{**}	-0.456^{**}	-0.631^{***}
2018	0.504^{**}	-0.477^{**}	-0.439^{**}	-0.442^{**}	-0.615^{***}
2019	0.518^{***}	-0.457^{**}	-0.412^{**}	-0.429^{**}	-0.605^{***}
2020	0.499^{*}	-0.466^{**}	-0.407^{**}	-0.426^{**}	-0.627^{***}
2021	0.517^{***}	-0.464^{**}	-0.410^{**}	-0.426^{**}	-0.616^{***}
2022	0.535^{***}	-0.464^{**}	-0.411^{**}	-0.427^{**}	-0.611^{***}
2023	0.550^{***}	-0.462^{**}	-0.411^{**}	-0.429^{**}	-0.620^{***}

***, **, and * represent significance level of parameters at $p < 0.01$, $p < 0.05$, and $p < 0.10$, respectively

The Spatial Autocorrelation (Global Moran's I) analysis indicated that the ecological regulating products value in the BRB did not exhibit statistically significant spatial autocorrelation during the study period ($p > 0.05$). The corresponding z scores were below 2.58, suggesting a greater than 10% probability that any observed spatial pattern could be due to random chance (*Table 8*). Although the Moran's I values were positive (indicating a tendency toward spatial clustering), the lack of statistical significance implies that the overall spatial distribution of values was close to random, without a clear clustered or dispersed pattern. Furthermore, *Table 8* shows that the Moran's I index for ecological regulating products value followed a pattern of initial increase from 2009 to 2018, peaking in 2014 and existing a valley value in 2019, and then increase to 2023. These temporal shifts likely reflect the changes in the spatial distribution of ecological regulating products value driven by both natural environmental dynamics and human activities.

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The random distribution pattern is further supported by the results of Local Indicators of Spatial Association (LISA) cluster analysis (see *Fig 7*). As shown in *Figure 7*, only Qingcheng, Huadu, and Sanshui exhibited a statistically significant “low-low” cluster type, indicating that these adjacent units collectively formed areas of low ecological regulating products value. The spatial associations for all other counties (including county-level cities and districts) were statistically insignificant throughout the study period.

Table 8. *Global Moran’s I index for ecological regulating products value in BRB*

Time	Moran’s I index	Expected index	Variance	z-Score	p-Value
2009	0.2637	-0.0417	0.0315	1.7213	0.0852
2010	0.2625	-0.0417	0.0314	1.7161	0.0861
2011	0.2638	-0.0417	0.0314	1.7230	0.0849
2012	0.2642	-0.0417	0.0314	1.7248	0.0846
2013	0.2638	-0.0417	0.0314	1.7232	0.0849
2014	0.2784	-0.0417	0.0320	1.7906	0.0734
2015	0.2654	-0.0417	0.0315	1.7316	0.0834
2016	0.2659	-0.0417	0.0315	1.7337	0.0830
2017	0.2663	-0.0417	0.0315	1.7355	0.0827
2018	0.2667	-0.0417	0.0315	1.7373	0.0823
2019	0.2545	-0.0417	0.0314	1.6720	0.0945
2020	0.2556	-0.0417	0.0314	1.6771	0.0935
2021	0.2562	-0.0417	0.0314	1.6804	0.0929
2022	0.2562	-0.0417	0.0314	1.6801	0.0929
2023	0.2569	-0.0417	0.0315	1.6835	0.0923

Figure 7. *LISA cluster for ecological regulating products value in the BRB*

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Discussion

Necessity for assessing ecological regulating products value of agricultural and forest ecosystems

As a critical indicator for evaluating ecosystem status and dynamics, ecosystem services provide a foundation for their effective conservation and sustainable use. Ecological products, derived from these services, are essential for human well-being, livelihoods, and long-term development. Assessing the value of ecological products is therefore fundamental for recognizing their worth and facilitating the transformation of ecological assets into economic and social benefits, often described as turning "clear water and green mountains" into "invaluable assets". Among ecological products, the regulating products are the most significant categories. These are the benefits that ecosystems provided by maintaining or improving environmental conditions for human societies, and they are characterized by spatial and temporal complexity (Sutherland et al., 2018). The value of ecological regulating products constitutes an indirect-use value that typically far exceeds direct-use value, accounting for more than 70% and sometimes nearly 90% of the total ecological products value (Hao et al., 2020). In China, valuation of ecological regulating products, which entails the rational development and utilization of natural resources and their conversion into socioeconomic value, forms a core component of Gross Ecosystem Product (GEP) accounting. Current research on valuing ecological regulating products has tended to focus on specific, localized ecosystems (e.g., shrublands, glaciers, or marine systems), often lacking broader regional correlation analysis and in-depth discussion of linkages with socioeconomic development (Hu et al., 2021). As widely distributed ecosystem types globally, agricultural and forest ecosystems provide vital, high-value regulating products such as Carbon Fixation, Air Purification, O_2 Release, Soil Maintenance, and Biodiversity Conservation, etc. However, comprehensive assessment of the value of these products within agricultural and forest ecosystems remains relatively scarce. Therefore, an accurate valuation of ecological regulating products is a prerequisite for realizing the full economic potential of agricultural and forest ecosystems.

Limitations and prospects

Although this study provides a detailed assessment of ecological regulating products value, several limitations should also be acknowledged. First, the valuation at the county level was based on continuous land-use data from 2009 to 2023 and did not account for finer spatial scales, such as sub-basins, which limits the analysis of spatial heterogeneity in the value distribution. Second, the assessment focused only on cultivated land, horticultural land, forestland, and grassland, omitting other ecosystems (e.g., rivers, reservoirs, wetlands etc.), which likely leads to an underestimation of the total ecological regulating products value in the BRB. Third, the correlation analysis was confined to economic indicators of GDP, GDP per capita, the GDP of the primary, secondary, and tertiary industries. In reality, ecological regulating products value is also influenced by meteorological factors (e.g., temperature, precipitation) and physiographic conditions (e.g., elevation, slope, etc.), which were not included here. Despite these limitations, this study offers a foundation for quantifying ecological products value in agricultural and forest ecosystems and supports further work on value realization.

For future research, we recommend a multi-scale approach such as 1-km grids or sub-basin units to better capture spatial variation in ecological products value. Assessment

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methods should also be refined by integrating established biophysical and valuation models, including the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model (Sharp et al., 2020), the Artificial Intelligence for Ecosystem Services (ARIES) model (Villa et al., 2014), and the Spatial Assessment and Optimization Tool for Regional Ecosystem Services (SAORES) model (Hu et al., 2015), etc. Additionally, analyzing the flow of ecological products value from supply to consumption, potentially using input-output model, could offer valuable insights (Song and Du, 2024). Further investigation is also needed to clarify the mechanisms and diverse drivers influencing ecological products value, including the impact of government policies designed to promote value realization.

Conclusion

This study assessed the value of ecological regulating products of agricultural and forest ecosystems in the BRB, with a focus on analyzing their spatiotemporal trends to inform sustainable development. A specific accounting framework was constructed, and the value of these products was quantified from 2009 to 2023. The findings reveal that the total ecological regulating products value across the 25 studied counties (county-level cities and districts) in the BRB increased from US$ 44.96 billion yr^{-1} in 2009 to US$ 46.15 billion yr^{-1} in 2023. Spatially, counties located in the upper and middle reaches of the basin consistently maintained higher values throughout the study period. In contrast, downstream areas, including Qingcheng, Huadu, Sanshuit, and Sihui, recorded significantly lower values, each below under US$ 1 billion yr^{-1}. Correlation analysis indicated that only the GDP of the primary industry showed a statistically significant positive relationship with ecological regulating products value across all the study years ($P < 0.10$). All other economic indicators of the total GDP, GDP per capita, and the GDP of the secondary and tertiary industries, exhibited a negative relationship ($P < 0.10$). Global Spatial Autocorrelation (Global Morans' I) analysis suggested that the spatial distribution of ecological regulation products value in the BRB was close to random. This pattern was corroborated by Local Indicators of Spatial Association (LISA) results, which identified a statistically significant "low-low" cluster only in Qingcheng, Huadu, and Sanshui, while all other county-level units showed an insignificant spatial association with their neighbors.

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