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Spatial Trade-Offs and Synergies between Ecosystem Services in Guangdong Province, China

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Abstract: The trade-offs between ecosystem services directly affect the quality of the ecological environment and the survival and development of human society, which is of great concern to academia, governments, and non-governmental organizations. Guangdong Province is a strong economic performer in China; hence, we selected it to explore the trade-off and synergy differences between different ecosystem services, and to investigate the mechanisms of their influence in economically developed regions with a large population density. Our results showed three main points: (1) The ecosystem services in Guangdong Province showed clear spatial heterogeneity. In addition, northern Guangdong has high levels of water retention, with a value of 5804.73 $\times$ 10^4 m^3/km^2 and high values for carbon sequestration and soil retention. Western Guangdong is a functional area for food production, and the Pearl River Delta is an economically developed region with low levels of ecosystem services. (2) Overall, in Guangdong Province, three pairs of ecosystem services, namely water retention–soil retention, carbon sequestration–water retention, and carbon sequestration–soil retention, showed a strong positive correlation and good synergistic relationships. The other three pairs of relationships show strong trade-off effects. (3) The relationships between similar ecosystem services show completely different characteristics in different regions. Carbon sequestration and water retention, carbon sequestration and biodiversity conservation, water retention and biodiversity conservation, and soil retention and biodiversity conservation were mainly manifested in high–high synergies, particularly in northern Guangdong; carbon sequestration and soil retention and water retention and soil retention, primarily manifested synergies; carbon sequestration and food production, water retention and food production, and soil retention and food production mainly manifested as trade-off relationships.

Keywords: ecosystem services; trade-off; synergy; spatial relation

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1. Introduction

Ecosystem services are the environmental conditions and the effects of ecosystem formation and maintenance on human survival and development [1]. However, ecosystem services do not exist or develop independently. Complex reciprocal relationships exist among various services within an ecosystem and among several ecosystems [2]. These interactions mainly manifest as trade-offs between waning and waxing or synergies for mutual gains. Diverse and complex ecological environments provide various services for human well-being, and the impact of human activities is often at the expense of certain service levels [3]. In economically developed areas, the contradiction between intense human activities and the ecological environment is more prominent, complicating the trade-off and synergistic relationships between ecosystem services. The trade-offs between different services and the factors influencing them must be analyzed because they affect the level of ecosystem services and the stability and development of the whole ecosystem [4,5]. Therefore, Guangdong Province, being a province with strong economic performance in China, was selected as the research area; this area is also highly significant to the study of spatial trade-offs, synergistic relationships, and the mechanisms influencing regional ecosystem services.

Trade-offs in ecosystem services are mainly generated by human demand preferences. When people consume certain ecosystem services, they will have an impact on other ecosystem services, intentionally or unintentionally, leading to trade-offs and synergies between ecosystem services [6,7]. A scientific understanding of the functional characteristics, manifestations, driving mechanisms, and scale effects of ecosystem service trade-offs/synergies is of great significance for improving human well-being and achieving a "win-win" situation between human society and the ecosystem [8]. A comprehensive understanding of the relationships between ecosystem services includes multiple dimensions, such as trade-offs, synergies, and compatibilities [9]. A trade-off is a negative relationship in which ecosystem services are restricted by other functions, such as ebb and flow, including supporting and regulating functions [10,11]. A synergy is a positive relationship, and several ecosystem services show symbiosis, enhancing or weakening together, such as support and cultural functions, and regulatory and cultural functions [12]. Compatibility shows no significant relationship between ecosystem services [13]. In reality, in order to improve a certain ecosystem service, we often inevitably affect trade-offs and synergies with other services [14]. Scholars have conducted extensive research on the interaction between ecosystem services and concluded that trade-offs and synergies between ecosystem services are universal [15,16]. Ecosystem services are influenced by various factors such as land use and cover change, human needs, parameter selection, regional differences, and imbalances [17]. Different regions show significant differences [18,19]. To achieve the harmonious development of humans and nature in an urban system, we have integrated ecological elements into urban planning [20,21]. The correlation between ecosystem services and urban green infrastructure/urban sprawl currently play an important role in spatial planning [22]; however, studies on these aspects are still limited.

Ecosystem services are mainly divided into four types: provisioning (food, water, wood, and fuel), regulating (climate, flood, and disease regulation; water purification), cultural (aesthetic, spiritual, educational, and recreational), and support services that are necessary to maintain other types of services (nutrient cycling, soil formation) [23,24]. These services provide personal security, security from disasters, access to resources, food, shelter, adequate livelihoods, health, good social relations—i.e., social cohesion. For different areas (urban, rural, or wild), the types of ecosystem services concerned are different. Research often focuses on the key service types in the region. The main evaluation methods for ecosystem services are index evaluation, value evaluation, and model simulation (including models UFORE, SolVES, BUGS, ARIES, InVest, EPM, InFOREST, Envision, and EcoMetrix). These methods are widely used globally [25]. Common research methods for identifying ecosystem service trade-offs/synergies include correlation analysis, principal component analysis, root mean square deviation, and bivariate spatial autocorrelation [26,27]. At present, many models have been developed to identify the interrelationships between ecosystem services, such as InVEST, ARIES, ESValue, EcoAIM, EcoMetrix, NAIS, and SolVES [28,29]. Scholars have reported differences in the quantity of regional ecosystem services recorded using different measurement methods and the nature and intensity of ecosystem service relationships. For example, the SolVES model requires social questionnaire survey data, and the questionnaire quality directly affects the evaluation results. The UFORE, SolVES, and BUGS models have limitations regarding the spatial scale of the study area. Remote sensing data are applicable to the evaluation of ecosystem services at different spatial scales, but their accuracy is difficult to guarantee. Therefore, selecting the appropriate method for evaluating the relationships between regional ecosystem services is important to ensure accurate results.

Most developing countries in an important period of economic development often pay attention to promoting economic benefits while ignoring ecological benefits. Therefore, the ultimate goal of ecosystem service research should be to maximize the comprehensive benefits of the human–earth system, ease the trade-offs between different ecosystem services, and improve human welfare [30,31]. As an important developing country, China is currently in a crucial transition period from high-speed to high-quality economic development. Therefore, urban economic development should be coordinated with environmental protection. Guangdong, a relatively developed province in China, was selected as the research area in this study. This study clarifies the main types of ecosystem services and their spatial differentiation characteristics. The study focuses on analyzing the trade-offs and synergies among different ecosystem services and the differences in their degrees of influence, as well as comparing and analyzing their spatial patterns. Then, the influence mechanisms of trade-offs and synergies between ecosystem services were analyzed and areas for improvement were determined. The findings of this study are of great significance for the improvement of regional eco-environmental carrying capacity, protection, and management, the creation of solutions for sustainable development goals, and the coordination between economic development and ecological protection.

2. Study Area and Methods

2.1. Study Area

Guangdong Province is located in the southernmost part of mainland China, with a land area of 179,800 km^2. It is located between 20°13′ N–25°31′ N and 109°39′ E–117°19′ E and faces the South China Sea in the south. Guangdong Province has jurisdiction over 21 prefecture-level cities (including two sub-provincial cities), which are divided into four regions: the Pearl River Delta, Eastern Guangdong, Western Guangdong, and northern Guangdong. The Pearl River Delta includes the cities of Guangzhou, Shenzhen, Foshan, Dongguan, Zhongshan, Zhuhai, Jiangmen, Zhaoqing and Huizhou; Eastern Guangdong includes Shantou, Chaozhou, Jieyang, and Shanwei; Western Guangdong includes Zhanjiang, Maoming, Yangjiang, and Yunfu; and northern Guangdong includes Shaoguan, Qingyuan, Meizhou, and Heyuan (Figure 1).

Guangdong Province is located in the tropical and subtropical regions, with the Tropic of Cancer running through its central part. It is located on the north coast of the South China Sea, is heat rich, has abundant rainfall, a wide variety of animals and plants, and good natural conditions. Guangdong Province is rich in forest resources, with a forest area of 107,925.33 km^2 as of 2019, accounting for 60.05% of the total area of major land types in the province, including arbor, bamboo, and shrub forests. Guangdong Province has complex and diverse landforms, with hills, platforms, and basins developing between the mountains. The soil types are diverse, and the zonal distribution is obvious. Zonal soil types are red, latosolic red, and lateritic soils from north to south and include a small amount of yellow soil and yellow brown soil. Non-zonal soil types include paddy, tidal, mountain meadow, lime, and purple soils. The province belongs to the East Asian monsoon region, and has middle subtropical, southern subtropical, and tropical climates from north to south. It is also one of the provinces with the most abundant light, heat, and water in China. The average sunshine duration of the whole province is 1745.8 h. The average annual temperature is 22.3 °C. The average annual precipitation ranges from 1300 to 2500 mm. The spatial distribution of rainfall shows a high trend in the south and low in the north. Guangdong Province is rich in water resources, with a total water resource amount of 2068.2 × 10^8 m^3 in 2019. There are numerous rivers, mainly in the Pearl River Basin, the Hanjiang River basin that only flows into the sea, and the rivers along the east and west coasts. There are 60 branches and tributaries at all levels with a catchment area of more than 1000 km^2.

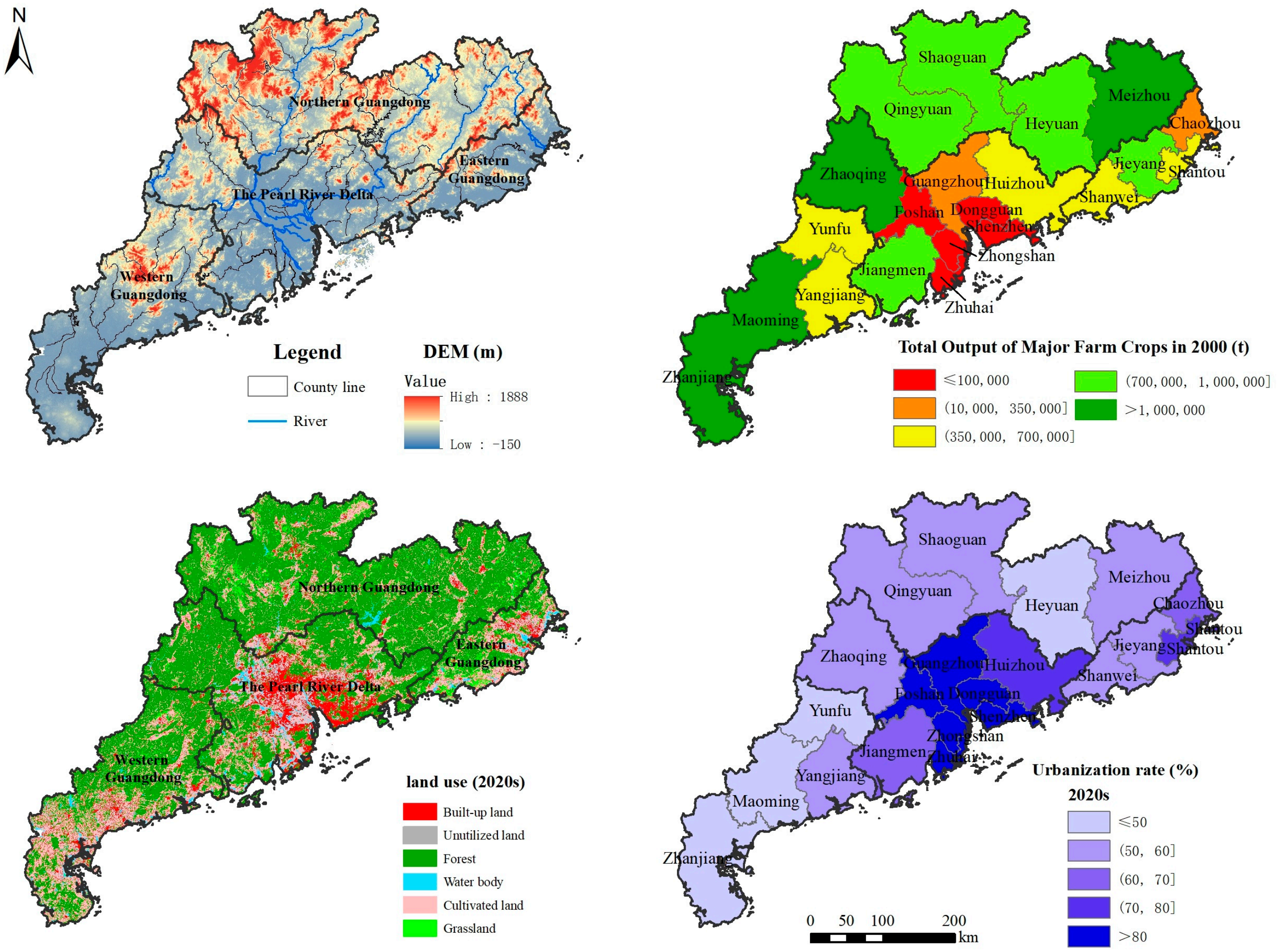

Figure 1. Location of the study area.

Guangdong is China's most populous province, with a population of 126 million in 2020. The population density is 702.77 people /km^2, and the urbanization rate is 74.15%, but regional differences are large (Table 1). Furthermore, since 1989, Guangdong's gross domestic product (GDP) has continuously ranked first in China, and it has become the province with the largest economy in the country, accounting for 1/8 of the country's total economic aggregate. In 2020, Guangdong's GDP reached 11,076.09 billion yuan, while the Pearl River Delta core region's GDP accounted for 80.83% of that of the whole province.

Table 1. Basic socioeconomic characteristics of Guangdong Province in 2020.

Region	Area/10^3 × km^2	Population/Million	Population Density People/km^2	Urbanization Rate/%	Gross Domestic Product/100 Million Yuan
Pearl River Delta	54.91	78.24	14.25	87.24	89,523.93
Eastern Guangdong	15.49	16.32	10.54	60.6	7053.51
Western Guangdong	32.67	15.77	4.83	46.15	7739.97
Northern Guangdong	76.74	15.92	2.07	51.62	6443.54
Guangdong Province	179.81	126.25	7.02	74.15	110,760.9

2.2. Methodology

2.2.1. Measurement of Ecosystem Services

Considering the natural background and socioeconomic conditions of Guangdong Province and referring to the "Territorial Spatial Planning of Guangdong Province" and other relevant planning and policy documents, five kinds of ecosystem services were selected for analysis: carbon sequestration, water retention, soil retention, food production, and biodiversity conservation.

This study used ecosystem services data from the Chinese Academy of Sciences Ecological Environmental Research Center (http://www.sciencedb.cn/dataSet/handle/458, accessed on 31 December 2018). The dataset is based on remote sensing feature classification data. The management modes of land features, community structure, and ecological process differences were analyzed using MODIS satellite data Q13A1 [32,33]. Temperature and precipitation data were provided by the China Meteorological Data Sharing Network (https://data.cma.cn/data/detail/dataCode/A.0012.0001.html, accessed on 5 January 2017) and topographic data, from the United States' GEOM satellite. Ecosystem services in China in 2010 were simulated based on ecological process simulation methods, such as the CASA light energy utilization rate model, the universal soil loss equation, the water balance equation, the wind model, and by summarizing the literature and ground monitoring data to determine model parameters. A spatial dataset with a resolution of 250 m was created.

Carbon sequestration was measured mainly based on net primary productivity (NPP), which is represented by the product of photosynthetic active radiation absorbed by plants and actual light utilization (ε). Water retention was calculated using the water balance equation. Soil retention was simulated using the general soil loss equation. In the specific calculation, existing measured soil erosion data was used to verify the model simulation results and modify the parameters. Food production data provided county ecosystems with food output, such as grain, aquatic products, meat, forest fruit products, uniformly converted into energy. Also, rather than using the total number of species, the measure of biodiversity conservation used in this study represented the total number of indicator species with a recorded distribution in each county, primarily nationally protected plants and animals of special significance, or species with threatened or endangered status. The biodiversity conservation values in Guangdong Province were the average values for all districts and counties, and the values of the four regions were the average values of all districts and counties in the region.

2.2.2. Evaluation of Ecosystem Service Trade-Offs and Synergies

The Pearson correlation coefficient method was used to evaluate ecosystem service trade-offs and synergies. If the correlation coefficient was positive, the synergies between the two services were mutually promoted. Conversely, a negative correlation coefficient indicated a trade-off between the two services. Otherwise, the two functions were independent of each other [24].

In terms of the spatial dimension, a bivariate local spatial autocorrelation model was used to quantitatively measure the spatial distribution pattern and correlation characteristics of ecosystem service trade-offs and synergies in Guangdong Province. Cluster diagrams between the pairs of ecosystem services in the study area were obtained through bivariate local Moran's I spatial analysis using GeoDa (v1.20) software. In this study, a queen spatial adjacency matrix was constructed to measure the statistics of the local indicator of spatial association between two services. Specifically, "high-high" (HH) indicated that the two services with a high score clustered significantly in this region, "low-low" (LL) indicated that the two services with a low score clustered significantly in this region, "high-low" (HL) indicated that the first function scores were high and that the other function scores were low, and "low-high" (LH) indicated the opposite of HL. "Not significant" indicated that the two functions were independent within the regional space. HH and LL were regarded as synergies, whereas HL and LH were regarded as trade-offs. The values of local Moran's I were processed without dimensionality and ranged from 0 to 1.

2.2.3. Degree of Influence of Ecosystem Service Trade-Offs and Synergies

To classify the degree of ecosystem service trade-offs and synergies, a specific method was applied. First, the natural breakpoint method was used to divide the five ecosystem services into three levels: low, medium, and high, numbered 1, 2, and 3, respectively (Table 2).

Table 2. Classification levels of ecosystem service capacity.

Server Type	Low (1)	Medium (2)	High (3)
Carbon sequestration (t/km^2)	[0, 65]	(65, 204)	>204
Water retention (10^4 m/km^2)	[0, 32]	(32, 81)	>81
Biodiversity conservation (numbers)	[0, 78]	(78, 92)	>92
Food production (10^8 $kcal/km^2$)	[0, 4]	(4, 9)	>9
Soil retention (10^4 t/km^2)	[0, 9]	(9, 28)	>28

The five types of service standardization and classification of raster data were superimposed using ArcGIS 10.2 data:

$$\text{CODE} = \text{C} \times 10{,}000 + \text{W} \times 1000 + \text{B} \times 100 + \text{F} \times 10 + \text{S} \tag{1}$$

In Equation (1), C, W, B, F, and S represent carbon sequestration, water retention, biodiversity conservation, food production, and soil retention, respectively. CODE is a five-digit code, and each code sequence is a combination of 1, 2, and 3, representing the degree of influence of the ecosystem services [34].

Subsequently, criteria for classifying trade-offs and synergies were developed (Table 2). Trade-offs were classified as strong or weak. A strong trade-off was a state with one high service supply capacity, and all others were medium or low. Service capacity combinations in a strong trade-off may be 1 high 4 low, 1 high 1 medium 3 low, 1 high 2 medium 2 low, etc. A weak trade-off referred to a state with two, three, or four types of high service capacities, while all other services had medium or low capacities. Service capacity combinations in a weak trade-off may be 2 high 3 low, 2 high 1 medium 2 low, 2 high 2 medium 1 low, etc. Synergies were also classified as high or low. In high synergies, all services were high; this being the most coordinated state and the ultimate goal of ecosystem management. High-synergy combinations include 5 high, 4 high 1 medium, 3 high 2 medium, etc. A low synergy meant that all five types of service capacities were at a low level, which is the least ideal state. Low-synergy combinations included 1 medium 4 low, 2 medium 3 low, and 3 medium 2 low.

3. Results

3.1. Spatial Differentiation of Ecosystem Services in Guangdong Province

To ensure that different ecosystem services were comparable (Table 3), ecosystem service values were processed without dimensionality, and all values ranged from 0 to 1 (Table 4). Among the five ecosystem services in Guangdong Province, water retention was the strongest (0.71). Soil retention and carbon sequestration had values of 0.54 and 0.51, respectively. Biodiversity conservation (0.48) and food production (0.33) were ranked fourth and fifth, respectively, among the ecosystem services.

Specifically, the spatial distribution of the different ecosystem services was as follows:

(1) The overall carbon sequestration level in Guangdong Province was 50.06 t/km^2, and its spatial distribution was higher in the north than in the south. The overall carbon sequestration level in the Pearl River Delta region (47.58 t/km^2) was higher than that in Western Guangdong (39.79 t/km^2) and Eastern Guangdong (40.77 t/km^2). However, there was a contiguous low-value area in the Pearl River estuary (Figure 2). The contiguous low-value area on the west bank of the Pearl River estuary was larger than that on the east bank.

The cities of Dongguan, Zhongshan, and Foshan had the lowest carbon sequestration levels in Pearl River Delta, with 13.89 t/km^2, 17.61 t/km^2, and 19.06 t/km^2, respectively. The carbon sequestration level in Zhaoqing City in the Pearl River Delta was the highest of the entire province with 66.24 t/km^2. The carbon sequestration level of Western Guangdong was the lowest among the four regions in the province, especially in the Leizhou Peninsula, the southernmost part of mainland China, with only 13.35 t/km^2 for the 21 cities in the province. The carbon sequestration level in Shantou City in Eastern Guangdong was also noticeably low with 18.59 t/km^2, lower than that of the surrounding cities. Northern Guangdong showed a remarkably high carbon sequestration, and the four cities in the region had values greater than 55 t/km^2. The maximum carbon sequestration value of the entire province (1164 t/km^2) was also distributed in Heyuan City in northern Guangdong Province.

Table 3. Values of ecosystem services in Guangdong Province in China in 2010.

	Carbon Sequestration (t/km^2)	Water Retention (10^4 m/km^2)	Soil Retention (10^4 t/km^2)	Food Production (10^8 kcal/km^2)	Biodiversity (Numbers)
Pearl River Delta	47.58	51.20	7.76	3.05	77
Northern Guangdong	59.91	58.05	9.26	2.08	87
Eastern Guangdong	40.77	38.58	7.59	4.53	75
Western Guangdong	39.79	49.52	6.75	6.80	76
Guangdong Province	50.06	52.40	8.11	3.63	80

Table 4. Values without dimensionality of ecosystem services in Guangdong Province in China in 2010.

	Carbon Sequestration	Water Retention	Soil Retention	Food Production	Biodiversity
Pearl River Delta	0.39	0.65	0.40	0.21	0.22
Northern Guangdong	1.00	1.00	1.00	0.00	1.00
Eastern Guangdong	0.05	0.00	0.33	0.52	0.00
Western Guangdong	0.00	0.56	0.00	1.00	0.11
Guangdong Province	0.51	0.71	0.54	0.33	0.48

(2) Guangdong has a humid climate, high forest coverage, and strong water retention for ecosystem services. The average value of water retention in Guangdong was 52.40×10^4 m^3/km^2, and the spatial distribution among cities was similar to that of carbon sequestration. Northern Guangdong was also a high-value area for water retention, with a value of 58.05×10^4 m^3/km^2. Except for Meizhou, the water retention in the other three cities was higher than the average provincial level. This is followed by the Pearl River Delta and Western Guangdong regions. The high-value areas in the Pearl River Delta region were distributed in its periphery. Remarkably, among the 21 cities, Yangjiang (74.10×10^4 m^3/km^2) and Zhanjiang (18.16×10^4 m^3/km^2) had the highest and lowest water conservation values in Western Guangdong, respectively. Water conservation in Eastern Guangdong (38.58×10^4 m^3/km^2) was significantly lower than in other regions.

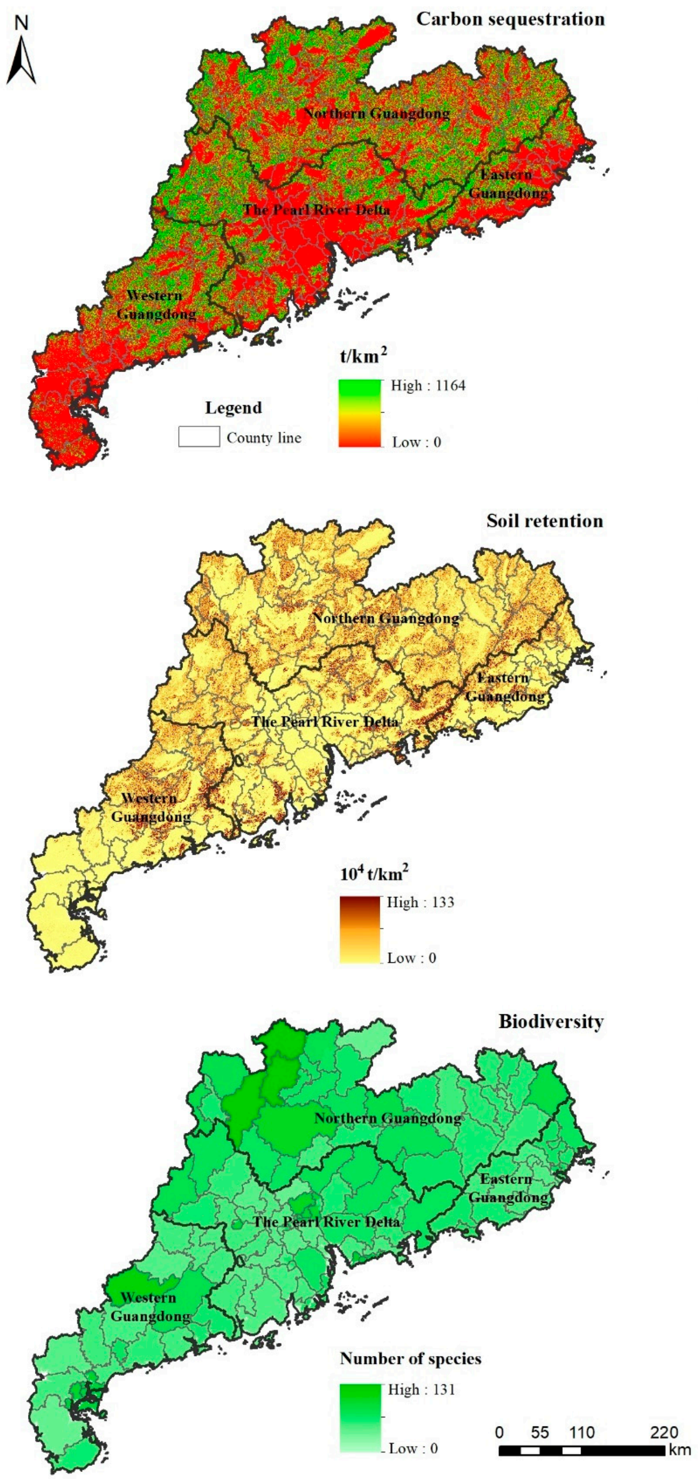

Figure 2. Spatial distribution of ecosystem services in Guangdong Province in 2010.

(3) Guangdong Province had a strong soil retention service, with an average value of 8.11×10^4 m^3/km^2. The soil retention level of northern Guangdong, which has a high forest coverage, was the highest, with a value of 9.26×10^4 m^3/km^2. Soil retention services in the Pearl River Delta and Eastern Guangdong regions were similar, with 7.76×10^4 m^3/km^2 and 7.59×104 m^3/km^2, respectively, among which Huizhou had the highest of the 21 cities with 10.96×10^4 m^3/km^2. Western Guangdong had the lowest soil retention service value with 6.75×10^4 m^3/km^2. In this region, Zhanjiang had the lowest soil retention value among the

21 cities in the Leizhou Peninsula with 0.88×10^4 m^3/km^2, while Yunfu and Yangjiang had strong soil retention with values of 10.69×10^4 m^3/km^2 and 10.09×10^4 m^3/km^2, respectively.

(4) Food production data were sourced from county data, and foods such as grain, aquatic products, meat, and fruits were uniformly converted into total food supply calories. The average value of food production in Guangdong Province was 3.63×10^8 kcal/km^2, and the main food production area was mainly concentrated in Western Guangdong, with a value of 6.80×10^8 kcal/km^2. In this region, the cities of Zhanjiang and Maoming had the highest food production values with 10.65×10^8 kcal/km^2, and 7.08×10^8 kcal/km^2, respectively. This was followed by Eastern Guangdong and the Pearl River Delta, with values of 4.53×10^8 kcal/km^2 and 3.05×10^8 kcal/km^2, respectively. In Eastern Guangdong, Shantou City had the highest food production value with 8.34×10^8 kcal/km^2, followed by Jieyang City with 5.09×10^8 kcal/km^2. The cities of Chaozhou and Shanwei did not reach provincial average levels. In the Pearl River Delta region, food production in Guangzhou and Jiangmen was relatively high, while very low in Shenzhen and Dongguan with only 0.03×10^8 kcal/km^2 and 0.08×10^8 kcal/km^2, respectively. However, the food production in northern Guangdong was the lowest with only 2.08×10^8 kcal/km^2, less than one third of that in Western Guangdong. Northern Guangdong is an important ecological barrier in Guangdong Province with extensive forest land and a low proportion of cultivated land; thus, food production is not its main ecosystem service.

(5) Guangdong Province has a complex ecological environment and a rich biodiversity. The biodiversity conservation value in Guangdong Province was 80 and, among the four regions, the biodiversity maintained in northern Guangdong was the highest at 86. This is to be expected as important forest areas, nature reserves, and natural parks in Guangdong are mostly distributed in northern Guangdong. In fact, Shimentai Nature Reserve, the largest contiguous forest reserve in Guangdong Province, is located in the southernmost part of the Nanling Mountains in northern Guangdong. The main objects of protection are subtropical evergreen broad-leaved forests, rare plants, and animals. There are 2242 species of higher plants and 301 wild vertebrate species in Shimentai Nature Reserve. Among them, one species of first-class nationally protected plant and 23 of second-class were included in the study. There were four species in the category first-class national protected animals and 41 under second-class protection. Among all the districts and counties, Ruyuan County (131) and Lechang County (117) in Shaoguan City and Fogang County (114) in Qingyuan City had the highest biodiversity. The lowest number of indicator species were conserved in Eastern Guangdong with 74.

3.2. Ecosystem Service Trade-Offs and Synergies, and Their Influence in Guangdong Province

The correlation between paired services among the five ecosystem services was obtained based on Pearson correlation analysis (Figure 3). Water retention–soil retention, carbon sequestration–water retention, and carbon sequestration–soil retention showed positive correlations ($r = 0.389$, $r = 0.299$, $r = 0.258$, $p < 0.05$), indicating a synergistic relationship between them. These three ecosystem services are also the main functions of forestland. The correlation coefficients between carbon sequestration–biodiversity conservation, water retention–biodiversity conservation, and soil retention–biodiversity conservation were positive and statistically significant; however, the relative coefficient values were small ($r = 0.073$, $r = 0.137$, $r = 0.116$), indicating a poor synergistic relationship. The negative correlation between food production and carbon sequestration was low ($r = -0.110$, $p < 0.05$), indicating a weak trade-off effect. There were negative correlations between food production–water retention, food production–soil retention, and food production–biodiversity conservation ($r = -0.179$, $r = -0.182$, $r = -0.304$, $p < 0.05$), indicating trade-off effects and reciprocal relationships between them.

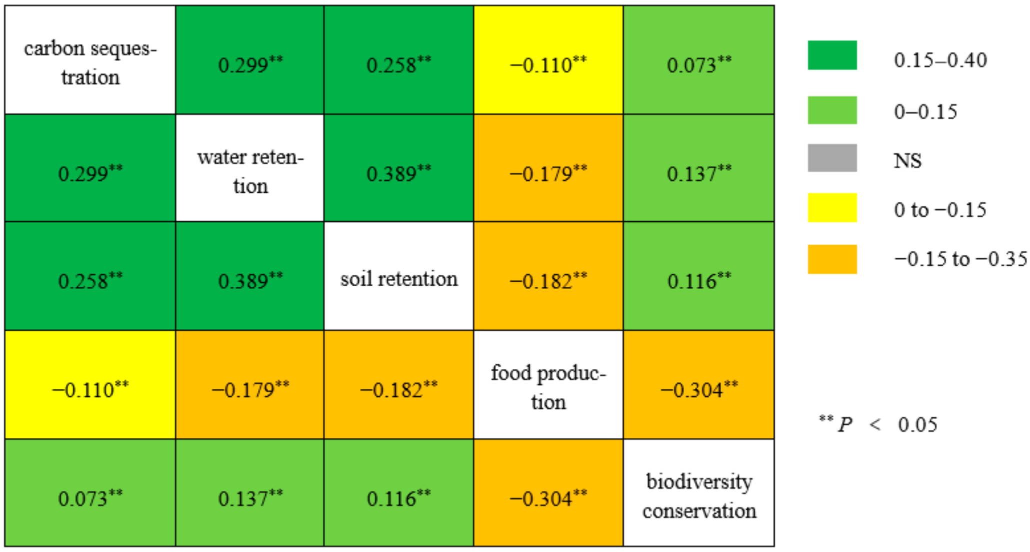

Figure 3. Pearson correlation coefficients between ecosystem service pairs.

Ecosystem services were divided into levels 1, 2, and 3 according to Table 1, and then the strengths and weaknesses of trade-offs and synergies between different services were evaluated. Also, the spatial distribution of ecosystem service trade-offs and synergies in Guangdong Province were assessed (Figure 4). This mainly showed poor synergies and strong trade-offs, accounting for 89.34% of the total area of Guangdong Province. Among them, poor synergies between different ecosystem service pairs occupied the largest area, mainly concentrated in Eastern Guangdong and most of the Pearl River Delta region. The other counties and districts in northern Guangdong showed poor synergies, except for Lechang County and Ruyuan Yao Autonomous County in Shaoguan City, and Yingde County and Yangshan County in Qingyuan City. There were also many regions with strong trade-offs between different ecosystem service pairs, mainly in Western and northern Guangdong and Guangzhou City in the Pearl River Delta region. The spatial distribution of the services with weak trade-offs was limited to Xinyi County in Maoming City in Western Guangdong, and Yingde County, Yangshan County, and Ruyuan Yao Autonomous County in Qingyuan City in northern Guangdong. Few areas with good synergies were scattered in Xinyi County in Maoming City in Western Guangdong.

From the combinations of ecosystem service trade-offs and synergies (Table 5), the trade-offs between services accounted for 44.33% of the total province area, and the strong trade-offs accounted for 34.15%, which was mainly manifested as services with levels of "1 high, 1 medium, 3 low", especially the 13,121 type (low carbon sequestration, high water retention, low biodiversity conservation, medium food production, and low soil retention), occupying an area of 4688.845 km^2. Weak trade-offs accounted for 10.18% of the whole province area, mainly showing combinations of "2 high, 1 medium, 2 low", "2 high, 2 medium, 1 low", and "2 high, 3 low", which covered an area of more than 1000 km^2. These combinations included 13,113 (low carbon sequestration, high water retention, low biodiversity conservation, low food production, high soil retention; 2367.10 km^2), 13,312 (low carbon sequestration, high water retention, high biodiversity conservation, low food production, medium soil retention; 1245.93 km^2), 13,213 (low carbon sequestration, high water retention, medium biodiversity conservation, low food production, high soil retention; 1179.34 km^2), 23,113 (medium carbon sequestration, high water retention, low biodiversity conservation, low food production, high soil retention; 1083.80 km^2), and 23,312 (medium carbon sequestration, high water retention, high biodiversity conservation, low food production, medium soil retention; 1018.74 km^2).

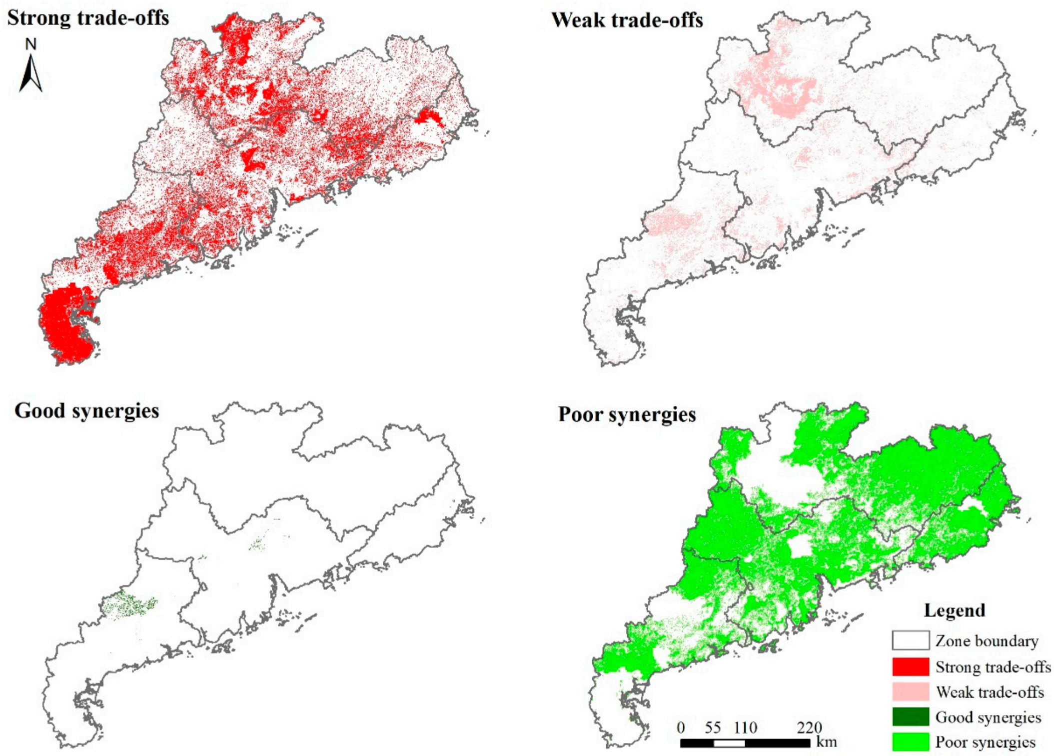

Figure 4. Spatial distribution of trade-offs (strong or weak) and synergies (good or poor) between ecosystem services.

Table 5. Classification criteria and statistics of trade-offs and synergies between the five ecosystem services.

Service Relationship	Area Ratio	Subclass	Area Ratio	Service Composition	Area Ratio
Trade-offs	44.33%	Strong trade-offs	34.15%	1 high 4 low	8.75%
				1 high 1 medium 3 low	12.71%
				1 high 2 medium 2 low	9.20%
				1 high 3 medium 1 low	3.49%
				2 high 3 low	2.38%
		Weak trade-offs	10.18	2 high 1 medium 2 low	4.32%
				2 high 2 medium 1 low	2.46%
				3 high 2 low	0.45%
				3 high 1 medium 1 low	0.54%
				4 high 1 low	0.03%
Synergies	55.67%	Good synergies	0.48%	5 high	0
				4 high 1 medium	0.01%
				3 high 2 medium	0.11%
				2 high 3 medium	0.26%
				1 high 4 medium	0.10%
				5 medium	0.01%
		Poor synergies	55.19%	1 medium 4 low	21.24%
				2 medium 3 low	12.97%
				3 medium 2 low	9.10%
				4 medium 1 low	2.53%
				5 low	9.36%

Poor synergistic relationships between different ecosystem service pairs accounted for 55.19% of the total area, mainly with the combinations “1 medium, 4 low” (21.24%) and “2 medium, 3 low” (12.97%). Here, the three specific combinations accounting for the largest area were 11,111 (low carbon sequestration, low water retention, low biodiversity conservation, low food production, low soil retention; 16,581.04 km^2), 11,112 (low carbon sequestration, low water retention, low biodiversity conservation, low food production, medium soil retention; 15,747.79 km^2), and 11,121 (low carbon sequestration, low water retention, low biodiversity conservation, medium food production, low soil retention; 11,942.03 km^2). Areas with good synergies accounted for only 0.48% of total provincial area.

3.3. Spatial Pattern Characteristics of Ecosystem Service Trade-Offs and Synergies in Guangdong Province

The spatial distribution characteristics and rules of the trade-offs and synergies between ecosystem services pairs were explored. Based on the area of Guangdong Province, fishnet (9 km) was selected and bivariate local Moran's I spatial analysis was performed based on the GeoDa (v1.20) software to obtain a cluster diagram between the ecosystem services in the study area (Figure 5) and explore the spatial distribution characteristics and rules of the tradeoff and synergistic relationships between the ecosystem services in the study area. In particular, HH synergies and LL synergies were mainly observed between carbon sequestration and water retention. HH synergies were mainly concentrated in areas rich in forest resources and were spatially manifested in Shaoguan, Qingyuan, and Heyuan cities in northern Guangdong, and Maoming and Yangjiang cities in western Guangdong. Carbon sequestration and water retention were the main ecosystem services of forest land. The Pearl River estuary coastal area with a developed economy and low forest coverage was mainly categorized as an LL synergy area. In addition, areas of cultivated land in Zhanjiang City, Shantou, and Shanwei City were categorized as LL synergistic areas.

Carbon sequestration and biodiversity conservation were mainly manifested in HH synergies, particularly in northern Guangdong and Maoming City in western Guangdong; a small number of LH trade-offs were mixed in with the HH synergy regions. The LL synergies were distributed in the coastal area, wherein HL trade-off zones and their mixed distribution was also detected.

Carbon sequestration and soil retention, and water retention and soil retention, show similar relationships, mainly for synergies. The forest land concentration areas in Maoming, Yunfu, Zhaoqing, Qingyuan, Heyuan, and Meizhou City formed continuous zonal HH synergies, whereas the cultivated land concentration areas in Zhanjiang, Shantou, and Shanwei showed LL synergies.

Carbon sequestration and food production, water retention and food production, and soil retention and food production are three pairs of services with similar relationship characteristics, and they mainly manifest as a trade-off relationship. HL trade-offs were concentrated in northern Guangdong and LH trade-offs were manifested in Zhanjiang City and Shantou City. LL synergies were mainly distributed in Zhongshan and Shenzhen City along the Pearl River estuary and in scattered areas in northern Guangdong; southeast Maoming was a contiguous HH coordination area.

The characteristics of water retention and biodiversity conservation and soil retention and biodiversity conservation were similar, mainly manifesting as synergies. Among them, HH synergies were mainly concentrated in northern Guangdong and those of water retention and biodiversity conservation were larger, whereas the LH trade-off area was also mixed in northern Guangdong.

Food production and biodiversity conservation mainly showed LH trade-off areas, which were mainly distributed in Shaoguan, Qingyuan, and Huizhou City. The distribution of HL trade-offs and LL synergies was lower, being limited to the coastal line of southern Guangdong Province.

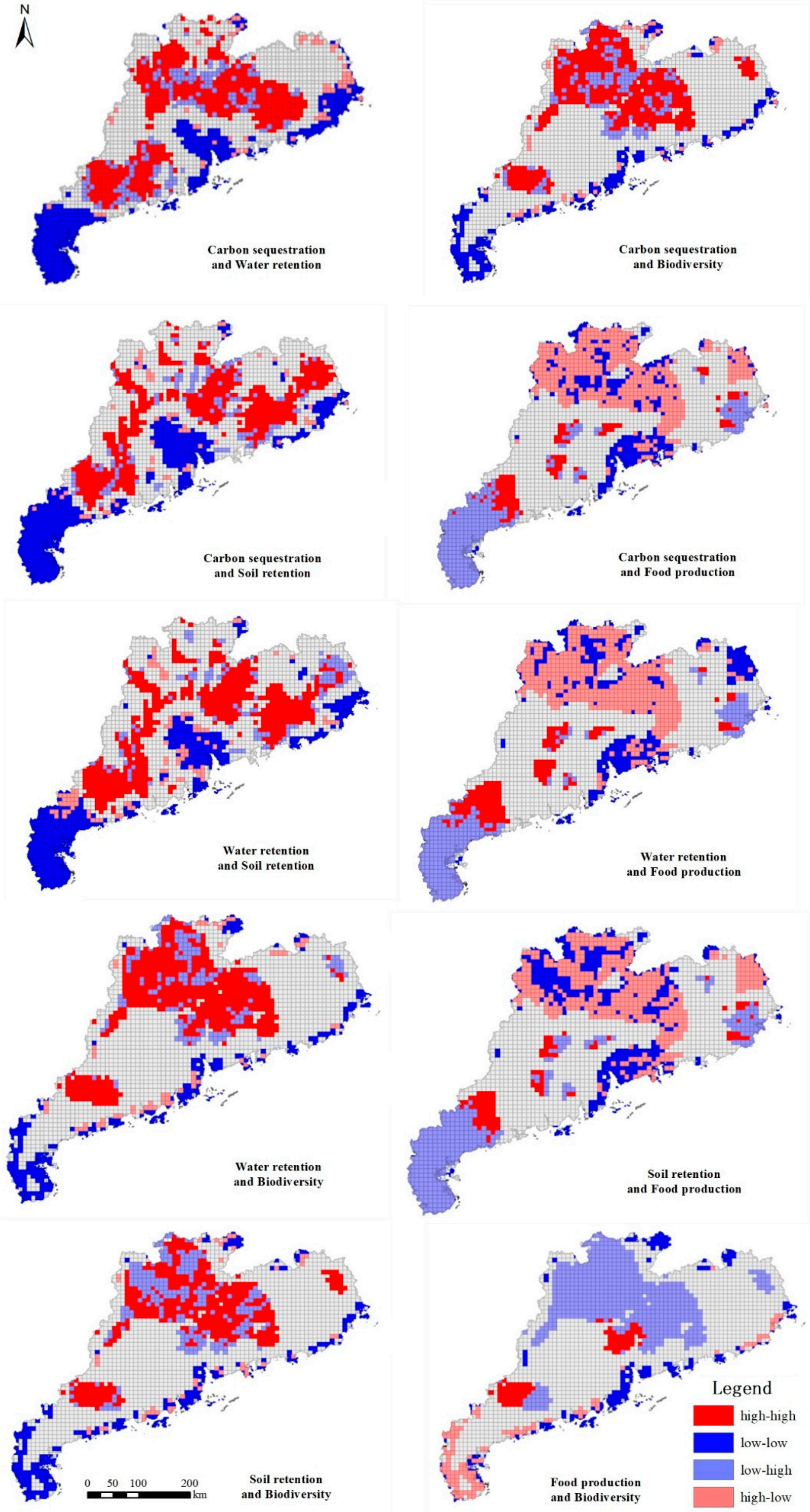

Figure 5. Spatial distribution of trade-offs and synergies between ecosystem services in Guangdong Province.

4. Discussion

4.1. Analysis of Spatial Diversity Mechanisms of Ecosystem Services

Owing to the influence of different natural and socioeconomic conditions, different ecosystem services in Guangdong Province showed clear spatial differences. Guangdong has a strong economy. In 2022, China's economic aggregate reached 121.02 trillion yuan, and Guangdong's GDP was the highest in the country (Guangdong has ranked first for 34 consecutive years), with an economic aggregate of 12.91 trillion yuan. The Pearl River Delta region accounts for ~80% of the province's economy. Economic development and a relatively high proportion of construction land are accompanied by a relatively low level of ecosystem services [35]. The main function of the northern Guangdong region is the ecological barrier of the whole province, a large area of forest reserves, so its economy is not fully active, being mainly reflected in high ecosystem services.

The carbon sequestration service in the study was measured based on NPP; therefore, the carbon sequestration level was mainly affected by the surface vegetation coverage. The Nanling Mountain area in northern Guangdong is an important ecological barrier and a core area of ecological security in Guangdong Province and in South China. The forest area in the northern Guangdong mountains accounts for approximately 55% of the entire province woodland area, and the national key ecological area accounts for 85% of the regional land area. Therefore, the carbon sequestration value in northern Guangdong was the highest among the four regions in Guangdong. The carbon sequestration level in Zhaoqing was the highest among the 21 cities because it is close to northern Guangdong and has a good ecological environment and high forest cover, accounting for 70% of the city area. Zhaoqing, Huizhou, and other peripheral areas of the Pearl River Delta are important ecological barriers to the core area of the Pearl River Delta and their ecosystem services are affected by natural and social factors such as urban spatial structure, land cover, and economic development in the process of urbanization in the Pearl River Delta [35]. The carbon sequestration level of Zhanjiang was the lowest among the 21 cities because it mainly consists of cultivated land and its main function is grain production, with a carbon sequestration capacity lower than that of forests. The forest area is small, with an atypical forest structure as more than 80% are commercial forests (including timber forests and economic fruit forests). In addition, as a coastal city, Zhanjiang often suffers from frequent landings of low-pressure tropical storms and typhoons, which have a great impact on forestry production.

Water retention is mainly reflected in forest function. The interception and infiltration of forests can slow down surface water flow intensity, increase the amount of groundwater, control soil desertification, and reduce soil and water loss by restoring vegetation and building water conservation areas [36]. The water retention of forests is manifested in many aspects including water storage, runoff regulation, forest flood reduction, drought resistance, and forest water purification. Through the interception, absorption, and infiltration of precipitation, its spatial and temporal redistribution is conducted to reduce ineffective water use and increase effective water use [37]. High-value areas with high water retention were mainly distributed in areas with high forest coverage. Therefore, northern Guangdong, an important ecological green area in Guangdong Province, had the highest water retention value. Yangjiang City, with the highest water retention, and Zhanjiang City, with the lowest water retention, are both distributed in the west of Guangdong, but their forest coverage rates are vastly different. The forest area in Yangjiang City accounts for approximately 60% of the city area, whereas the forest area in Zhanjiang City only accounts for just over 20% of the city area. Moreover, carbon sequestration and soil retention in Yangjiang City were much higher than in Zhanjiang City (soil retention was 11.5 times higher).

Soil retention is an important ecosystem service that refers to the ability of the ecosystem to regulate erosion to prevent soil loss and retain sediments [23]. Therefore, soil retention is important for preventing regional land degradation and reducing flood risk [38]. Owing to a high forest coverage rate, the soil retention services in Guangdong Province were higher than those in northern China. However, with the significant influence of human activities on rapid urbanization, the soil erosion area in Guangdong Province has been increasing since 2000. By 2019, it had increased to 1.80×10^4 km^2. Light erosion has been observed in 10.09% of the total area of Guangdong Province, accounting for more than 80% of the total erosion area. Cities with high soil retention were in areas with high forest coverage rate, while Zhanjiang City, with the lowest soil retention value, had insufficient forest resources, atypical forest structure, and weak sediment retention ability. Moreover, the coastal area in Zhanjiang City is composed of bare coastal sand, coastal salt-marred soils, and coastal salt soils.

Among the five ecosystem services, food production was the weakest. Because the income of agriculture is significantly lower than that of the secondary and tertiary sectors, the main rural labor force chooses to work in cities to increase family income, and the rural labor force continues to decrease [39]. Although Guangdong Province has abundant photothermal conditions and good soil resources, which together with the poor livelihood guarantee of agricultural land and reduced rental cost of large-scale agricultural land, has led some rural returnee workers to engage in agricultural production mainly planting economic fruit forests and medicinal materials; thus, the use of non-grain agricultural land is promoted. On the other hand, the Pearl River Delta is an area with rapid urbanization and a high economic level. A large amount of cultivated land is occupied by construction land and the food production function of the ecosystem is repeatedly squeezed. According to the *Statistical Yearbook of Guangdong Province*, the grain yield per unit area of Guangdong Province increased from 517.5 t/km^2 to 574.5 t/km^2 from 2009 to 2019 (11.01% growth). However, the total grain production decreased from 131.45×10^5 t to 124.08×10^5 t (5.61% reduction), with the most significant reduction in the mountainous areas of northern Guangdong and the Pearl River Delta. The mountainous areas of northern Guangdong were identified as key national ecological areas according to topographic features and location and some cultivated lands were converted to forest. The Pearl River Delta is mainly used for economic functions. The added value of land in economically developed areas is high, and cultivated land has been occupied by construction land. The food production function in Shenzhen was the lowest because its urbanization rate is 100%, there is almost no distribution of construction land and thus, no agricultural population.

4.2. Analysis of the Mechanisms of Influence of Ecosystem Service Trade-Offs and Synergies

The proportion of trade-offs and synergies between ecosystem services in Guangdong Province was basically the same. The proportion of synergies was slightly higher (55.67%) but almost all were poor synergies; that is, the five kinds of services were at low levels, which is the least ideal state. A total of 21.24% of the province area had "1 medium, 4 low" poor synergies, whereas high synergies accounted for only 0.48% of the provincial area. Most trade-offs were strong, mainly showing low carbon sequestration, high water retention, low biodiversity conservation, medium food production, and low soil retention. The trade-off regions were mainly distributed in Maoming City, Shantou City, Huilai County of Jieyang City, and parts of the Pearl River Delta. In these areas, the forest coverage rate and carbon sequestration were low, and since carbon sequestration, soil retention, and biodiversity conservation were positively correlated, soil retention and biodiversity conservation were also low. These regions are rich in water resources, and water retention services were of high value, so a high trade-off relationship was formed.

In Guangdong Province, the pairwise ecosystem services involving carbon sequestration, water retention, and soil retention showed a significant synergistic relationship because these services are mainly determined by forest cover level. Forest was the land type with the highest level of carbon sequestration. Dense forestland promotes photosynthesis and increases vegetation carbon sequestration capacity. It is also conducive to enhancing water and soil retention. Dense branches, leaves, and large roots in forests can intercept precipitation and surface runoff, which helps maintain soil and prevent erosion. Therefore, these three types of ecosystem services had a higher concentration in forest areas. In bare areas, all three ecosystem services had low values. Also, biodiversity conservation showed poor synergy with carbon sequestration, water retention, and soil retention. The biodiversity function in lush forest areas may be strong and the total number of plant and animal species may be relatively high, but it may not have a strong relationship with nationally protected species of special significance.

The trade-offs and synergies of ecosystem services in Guangdong Province showed clear spatial differences. Paired ecosystem services may show a trade-off relationship in one region and synergistic relationships in other regions. This finding aligns with several previous studies that highlighted heterogeneity within urban ecosystems [6,40,41]. For example, for the carbon sequestration–water retention pair, the coastline of the Pearl River estuary was an LL synergy area; however, the partial region of northern Guangdong and Western Guangdong were HL or LH trade-off areas. The relationships between the same ecosystem services may show completely different characteristics in different regions because of the combined influence of different natural environments and socioeconomic characteristics [42,43]. The geomorphological conditions of Guangdong Province are complex as the region is known as “seven mountains, one water, and two fields.” It gradually declines from the northern mountains to the southern coastal areas, forming a geomorphic pattern dominated by the northern middle mountains, central low mountains and hills, and southern plains. Under different geomorphic conditions, the regional ecosystem service capacities and the trade-offs and synergies between the paired services also had significant differences. Guangdong Province is a province of China with a large economy, and its economic center is mainly distributed in the Pearl River Delta region. Human interference is strong in this region, exhibited by intense land development and the destruction of various ecological environments due to industrial development. The same is happening in other parts of the world with rapid urbanization [40,41]. This decline in ecosystem service capacity and destruction of natural vegetation inhibit the positive succession of ecosystems, reducing their regulatory service capacity. In contrast, northern Guangdong is an ecologically protected area, and its overall ecological environment is better.

Guangdong Province is rich in natural resources and has a high level of ecosystem services. However, poor synergies and strong trade-offs remain dominant among the ecosystem services. Sufficient attention should be paid to the protection of ecosystem services, and efforts should be made to practice ecological urban construction while steadily improving social and economic levels. Guangdong Province also represents an economically developed region in developing countries. In future planning, optimized allocation of land can be effectively conducted based on the analysis results of the trade-off and synergy relationship between regional ecosystem services. Adjusting the quantity and spatial structure of land use types with different ecosystem services can facilitate promotion of the synergistic relationship of ecosystem services actively and adjust the trade-off relationship, such that the harmonious coexistence between humans and nature is achieved.

4.3. Uncertainty

Ecosystem services are the goods and services provided by ecosystems to society [23,44], and include dozens of services of four kinds: providing products, regulating functions, supporting functions, and cultural services. Currently, no model can comprehensively evaluate all ecosystem services and different methods of evaluating the same ecosystem services in the same region produce different results. In this study, ecosystem services were selected for analysis according to the characteristics of the research object and the research region [45]. This study used “a spatial dataset of ecosystem services in China”, which included six important ecosystem services, namely food production, soil retention, water retention, windbreak and sand fixation, biodiversity conservation, and carbon sequestration. The tropical and subtropical monsoon climate in the study area was significant, with abundant rainfall and abundant water resources; thus, windbreak and sand fixation were not considered in the study.

In addition, it is necessary to note that these five ecosystem services were divided into three levels using a natural breakpoint method (Table 2). Therefore, since the level of ecosystem services was relative to that of the local region, it is possible that the low-value ranges in some ecosystem services were still higher than those in some ecologically fragile areas in northwest China.

5. Conclusions

(1) The ecosystem services in Guangdong Province showed clear spatial heterogeneity. Owing to a humid climate and high forest coverage, the area showed strong water retention. Northern Guangdong had high water retention and carbon sequestration, and the highest soil retention in the province. Food production services were mainly concentrated in Western Guangdong.

(2) Overall, in Guangdong Province, three pairs of ecosystem services, water retention–soil retention, carbon sequestration–water retention, carbon sequestration–soil retention, showed strong positive correlations and strong synergistic relationships. There were strong negative correlations between food production–water retention, food production–soil retention, and food production–biodiversity conservation. There was a strong trade-off between food production and water retention.

(3) The trade-offs and synergies between the ecosystem service pairs were spatially different. In northern Guangdong, forests are widely distributed; the area is a national nature reserve with a good ecological environment. It is also an area where HH synergies are mainly observed between carbon sequestration and water retention, carbon sequestration and biodiversity maintenance, water retention and biodiversity conservation, and soil retention and biodiversity conservation. The relationships between carbon sequestration and food production, water retention and food production, and soil retention and biodiversity conservation are similar and mainly show trade-off relationships; HL tradeoffs are concentrated in northern Guangdong.

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