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The Relationship Between Carbon Emissions and Ecosystem Services in Guangdong Province, China: The Perspective of Ecological Function Zones

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Abstract: Ecosystem carbon sinks can offset part of the carbon emissions from human activities, playing a significant role in the carbon neutrality process. Clarifying the relationship between carbon emissions and ecosystem services is crucial for achieving the dual goals of carbon neutrality and ecological environmental protection. Effective ecosystem management is a prerequisite for controlling carbon emissions, as well as for ecosystem conservation and restoration, making a significant contribution to emission reduction and the enhancement of ecosystem services. Therefore, this study takes Guangdong Province as an example, starting with ecological functional zones—units that can enhance the effectiveness of ecosystem management—combining multi-source data and localized methods to develop annual carbon emissions (CEs) and ecosystem service value (ESV) data from 2000 to 2020, and reveals the spatiotemporal relationships between CEs and the ESV. The results showed the following from 2000 to 2020: (1) The net CEs increased from 203.73 to 482.80 million tons, representing an increase of 279.07 million tons, or 136.98%. The metropolitan residential security zone (MRSZ) was the dominant carbon source area, accounting for more than 60% of the total net CEs. (2) The total ESV gradually decreased from CNY 596.95 to 504.56 billion, representing a decline of CNY 92.39 billion, or 15.48%. The WCZ had the highest ESV, accounting for more than 50% of the total in all periods. (3) Temporally, the net CEs were negatively correlated with the total ESV in the study area, especially in the MRSZ, while a positive correlation was observed in the agricultural products provision zone (APZ). Spatially, the main clusters were Low–Low and High–Low clusters, primarily distributed in the APZ and MRSZ. This study explores and reveals the spatiotemporal relationship between CEs and the ESV, providing valuable references for related research in Guangdong Province and other regional comparative studies.

Keywords: carbon emissions; carbon absorption; ecosystem services; ecological functional zones

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1. Introduction

Carbon emissions from human activities have resulted in global warming, with emissions since industrialization significantly exceeding historical levels [1–3]. Currently, global temperatures are 1.1 °C higher than pre-industrial levels, with approximately 1.07 °C of this increase attributed to human activities; this human-induced warming is projected to reach 1.5 °C by 2030–2035 [4–6]. Ecosystems such as forests, grasslands, and wetlands play a crucial role as carbon sinks in mitigating carbon emissions and climate warming. On one hand, ecosystems exhibit a degree of adaptability to carbon emissions; as carbon dioxide concentrations rise, the carbon sink capacity of vegetation may strengthen, helping to offset a portion of human emissions and delay warming while reducing mitigation costs [7,8]. On the other hand, scientific ecosystem management and conservation measures, such as nature-based solutions, can enhance carbon sequestration and emissions reduction, thereby increasing the net carbon sink capacity of ecosystems [9–11]. A significant correlation between carbon emissions and ecosystems exists [12]; research by the Nature Conservancy suggests that nature-based solutions could contribute approximately 30% of the emission reduction potential necessary to achieve the goals of the Paris Agreement, with more than a 66% likelihood of keeping global warming below 2 °C [13].

However, climate extremes resulting from human activities pose a significant threat to the sustainability of ecosystems, further impacting the services that humans derive from them [14,15]. Global warming has triggered changes in phenology and species distribution, resulting in issues such as biological invasions, biodiversity loss, and an increased frequency of ecological disasters. Research indicates that 47% of localized extinctions among 976 studied species are linked to climate warming [16]. In Asia, approximately 70% of studied species are projected to be negatively impacted by climate change, with around 30% facing a high risk of extinction [17]. These changes disrupt ecosystems' structure and function, weakening their stability and resilience and leading to increased fragility and degradation. Furthermore, ecosystem degradation reduces the capacity of ecosystems to provide essential services. Studies suggest that climate change is causing a global redistribution of terrestrial ecosystems, with an estimated 9% loss in ecosystem services by 2100, which will severely diminish the benefits humans receive from ecosystems and pose direct threats to regional and global ecological security [18,19]. Meanwhile, increasing carbon emissions driven by rising human demands and temperatures exacerbate the ongoing degradation of ecosystem services, creating a vicious cycle of intensified human activity, persistent climate change, and ecosystem degradation, thereby posing significant challenges for both human society and ecosystems in adapting to climate change [20,21]. Therefore, quantifying and identifying the spatiotemporal trends of carbon emissions, while clarifying their relationship with ecosystem services, are essential for the synergistic development of emissions reduction and ecosystem service enhancement, thereby supporting sustainable ecosystem development and ensuring continued human benefits, ultimately contributing to carbon neutrality goals.

Well-managed ecosystems play a crucial role in helping human societies mitigate and adapt to current climate disasters and future climate change by providing a range of ecosystem services [22–24]. Ecological functional zones (EFZs), which are delineated based on characteristics such as ecosystem features, service patterns, and the spatial heterogeneity of natural conditions, are units that can enhance the effectiveness of ecosystem management. Implementing governance and management practices within these zones strengthens the overall capacity for ecosystem governance, management, and service delivery [25,26]. Guangdong Province serves as a vital ecological barrier in southern China, maintaining a vegetation coverage of over 0.7 from 2000 to 2020 [27–29]. It is a significant provider of ecosystem services, including water conservation, biodiversity, and the provision of agricultural and forestry products, playing an important role in sustaining human production and livelihoods in the region [30–32]. At the same time, Guangdong is China′s leading industrial province, with carbon emissions in 2019 accounting for approximately 5.32% of the national total, making it one of the top five provinces for carbon emissions in China. In recent years, Guangdong has actively responded to the national "carbon neutrality" goals by promoting energy conservation and carbon reduction in the industrial sector, as well as establishing carbon sink forests [33]. While numerous studies on carbon emissions and ecosystem services in Guangdong Province have emerged [34,35], there is a notable lack of research on the relationship between carbon emissions and ecosystem services from the perspective of ecological functional zones.

In light of this, this study focused on Guangdong Province and adopted an ecological functional zone perspective. Utilizing a localized carbon emission valuation methodology, combined with multi-source spatiotemporal data and a spatialization method, the study developed an annual spatiotemporal carbon emission dataset and analyzed the spatiotemporal characteristics of carbon emissions across different ecological functional zones. By employing the ecosystem service value as a representation of ecosystem services, the study explored the spatiotemporal relationship between carbon emissions and ecosystem services in various ecological functional zones, aiming to provide insights for emission reduction and the enhancement of ecosystem services. The study had the following objectives: (1) to quantify and identify the spatiotemporal evolution characteristics of carbon emissions in each ecological functional zone over the past 20 years; (2) to assess the value of ecosystem services and reveal their dynamic changes; and (3) to uncover the spatiotemporal relationship between carbon emissions and the value of ecosystem services, analyzing the impact of carbon emissions on ecosystem services.

2. Materials and Methods

2.1. Study Area

Guangdong Province is situated in southern China, with a total land area of 179,800 km^2, bordered by Fujian to the east, Jiangxi and Guangxi to the west, Hunan to the north, Hong Kong and Macao to the south, and Hainan Province to the southwest. The terrain varies from high in the north to low in the south, featuring a diverse range of landforms, including plains and plateaus in the south and mountains and hills in the north. The Nanling Mountains in the north and the southern coastal zone play a crucial role in China's ecological security strategy, known as the "two screens and three belts". The province's ecological environment is relatively fragile, susceptible to soil erosion caused by typhoons and heavy rains in hilly areas. The forest structure is simplistic, rendering the ecosystem fragile and vulnerable [36]. Guangdong Province is classified into different ecological function zones under "National Ecological Functional Zoning" [32], including the water conservation zone (WCZ), soil conservation zone (SCZ), agricultural products provision zone (APZ), forest product provision zone (FPZ), and metropolitan residential security zone (MRSZ) (Figure 1).

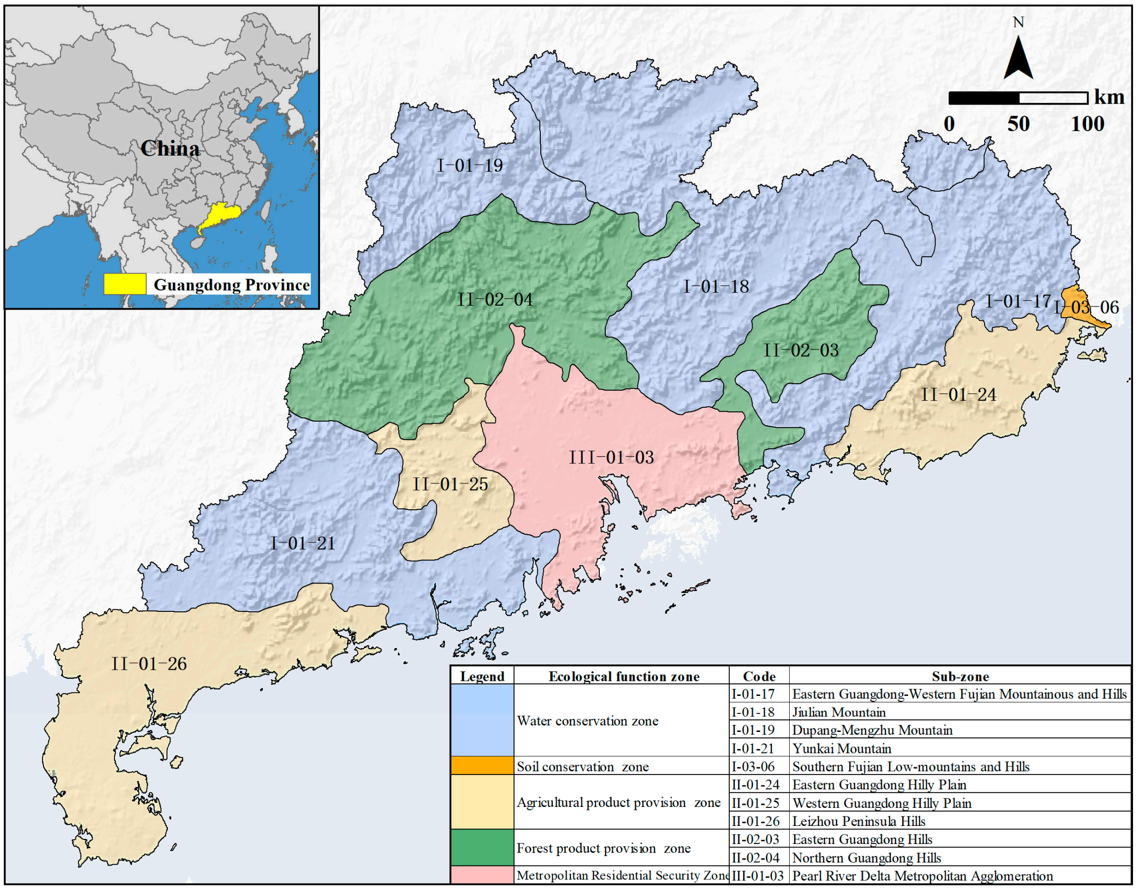


Figure 1. Study area.

2.2. Data Sources

The data used included:

(1) Land use data. The data from 2000 to 2019 were sourced from the China Annual Land Cover Dataset (CLCD) spanning from 1985 to 2019. This dataset is based on 335,709 land satellite images from Google Earth Engine. It was downloaded from Zenodo (https://zenodo.org/record/4417810, accessed on 10 January 2024) and has a spatial resolution of 30 m [37]. Data for the year 2020 were obtained from the Chinese Academy of Sciences Resource and Environmental Science Data Center (http://www.resdc.cn/, accessed on 10 January 2024), derived from LANDSAT TM/ETM+ remote sensing imagery and generated through the human–computer interactive interpretation of land use change remote sensing information, with a spatial resolution of 30 m [38,39]. This study classified the land use types from both datasets into arable land, forest land, grassland, water areas, construction land, and idle land.

(2) Nighttime light data. The dataset comprised DMPS/OLS annual products with a spatial resolution of 1 km for the period 2000–2013 and VIIRS/DNB annual products with a spatial resolution of 500 m for the years 2014–2020. All data were sourced from NOAA's National Geophysical Data Center (NGDC) (https://ngdc.noaa.gov/eog/dmsp/downloadV4composites.html, accessed on 12 January 2024).To match the land use data granularity, this study resampled the data to 30 m [40].

(3) Net ecosystem productivity (NEP) data. The data were derived from the global daily NEP simulation data product spanning from 1981 to 2019, downloaded from the National Ecosystem Science Data Center (http://nesdc.org.cn/, accessed on 14 January 2024) with a spatial resolution of 8 km. The NEP characterizes the flux of carbon exchange between terrestrial ecosystems and the atmosphere under undisturbed conditions, and it can be used to represent the carbon source–sink status of terrestrial ecosystems [41]. This data product was generated by simulating mechanistic ecological models, such as the BEPS model, driven by vegetation parameters (such as the leaf area index, clumping index, and land cover), remote sensing data, meteorological data, and the atmospheric CO_2 concentration [11]. In this study, through data computation and resampling, annual NEP data for the study area from 2000 to 2020 with a spatial resolution of 30 m were obtained.

(4) Statistical data. The data included information used for carbon emission accounting and revised ecosystem service values from 2000 to 2020. The main sources were the China Energy Statistical Yearbook, China Agricultural Statistical Yearbook, China Agricultural Products Price Survey Yearbook, Guangdong Statistical Yearbook, and Guangdong Rural Statistical Yearbook, the municipal statistical yearbooks of various cities in Guangdong Province, Environmental Status Bulletins, Solid Waste Pollution Prevention Information Announcements, and Environmental Statistical Yearbooks, with the data downloaded from CNKI (https://data.cnki.net/yearBook?type=type&code=A, accessed on 15 January 2024).

2.3. Research Design

This study combined remote sensing and multi-source statistical data to assess carbon emissions and ecosystem service values, while exploring the spatiotemporal relationship between carbon emissions and ecosystem services. First, by integrating land use data, energy statistics, NEP data, and localized carbon emission accounting methods, the study evaluated carbon emissions and spatialized the carbon emission data using nighttime light data, thereby analyzing the annual spatiotemporal trends in carbon emissions.

Second, ecosystem services were represented by the ecosystem service value. By integrating land use data with revised ecosystem service value coefficients, the study assessed the ecosystem services value and used the coefficient of variation to evaluate the spatial differences in the ecosystem service value across different ecological functional zones.

Last, based on Pearson correlation coefficients and bivariate Moran's I, the study explored the temporal and spatial relationships between carbon emissions and the ecosystem service value. The specific process is illustrated in Figure 2.

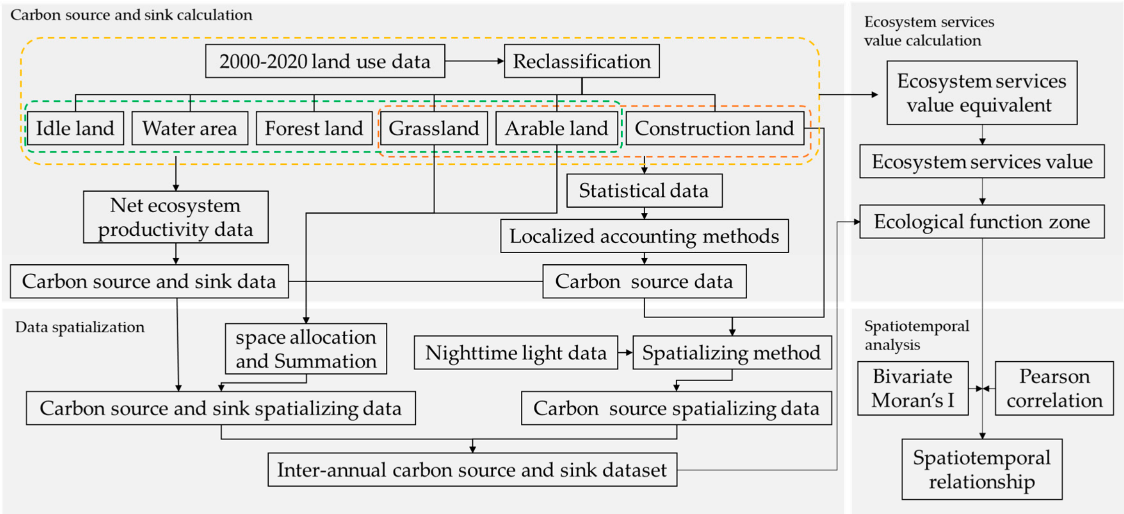


Figure 2. Illustration of the research design. Source: drawn by the author.

2.4. Methodology

2.4.1. The Assessment of Carbon Emissions

The assessment of carbon emission data was primarily based on land use data, NEP data, and energy consumption data. The carbon emissions and absorption for different land types were calculated individually: construction land mainly acts as a carbon source, and its carbon emissions were calculated based on energy consumption data using the methodology outlined in the Guidelines for the Compilation of Greenhouse Gas Inventories at the City, County, and District Levels of Guangdong Province [42]. The guidelines categorize carbon emission activities into five main processes: energy activities, industrial processes, agricultural processes, land use change and forestry, and waste treatment. Construction land involves three main processes: energy activities, industrial processes, and waste treatment. The specific calculation formula is as follows:

$$CE = A * EF \tag{1}$$

where CE is the carbon emissions, unit: kg; A is the energy consumption, unit: TJ; and EF is the emission factor, unit: kg/TJ. Specific accounting items and emission factors were referenced from the above-mentioned guideline.

Arable land and grassland primarily exhibit carbon absorption and emissions resulting from the carbon sink function and respiration of vegetation, as well as carbon emissions from human agricultural activities. The carbon absorption and emissions of vegetation were calculated based on NEP data.

The carbon emissions from human agricultural activities were calculated using the formulas for agricultural processes outlined in the Guidelines for the Compilation of Greenhouse Gas Inventories at the City, County, and District Levels of Guangdong Province. For arable land, the primary source of carbon emissions is paddy field emissions, while for grassland, the main sources are enteric fermentation and the management of manure from livestock.

Forest land, water areas, and idle land primarily exhibit carbon absorption resulting from their own carbon sink function and respiration, which was calculated based on NEP data. The difference between carbon emissions and carbon absorption represents the net carbon emissions.

2.4.2. The Spatialization of Carbon Emissions

Using land use data and nighttime light data to spatialize carbon absorption and emissions, this analysis was conducted for each land use type as follows.

For construction land, carbon absorption was not considered. Previous studies have established a linear relationship between nighttime light data and urban carbon emissions [43]. Therefore, carbon emission data were spatialized by fitting a linear relationship between nighttime light data and carbon emissions. The total carbon emissions calculated for each city within the study area were allocated spatially to obtain the carbon emission data for construction land.

For grassland and arable land, the annual number of grassland and arable land grids in each city was first counted. These data, combined with earlier calculations of carbon emissions from agricultural activities, allowed for the computation of carbon emissions per grid for arable land cultivation and grassland livestock management in each city. The calculated emissions were then assigned to the corresponding annual grassland and arable land grid data. Finally, the difference between the NEP values and the per-grid emission data for the arable land and grassland was calculated to derive the spatiotemporal distribution data of the annual net carbon emissions for these land types. The specific calculation formula is as follows:

$$CE_{ij} = NEP_{ij} + CE_a \tag{2}$$

where CE_{ij} is the carbon emissions of grid j of the i-th land use type, unit: kg; NEP_{ij} is the NEP of grid j of the i-th land use type, unit: kg; and CE_a is the average CE per grid, unit: kg.

For forest land, water areas, and idle land, carbon absorption and emissions were directly represented using NEP spatiotemporal distribution data. The specific calculation formula is as follows:

$$CE_{ij} = NEP_{ij} \tag{3}$$

where CE_{ij} is the carbon emission of grid j of the i-th land use type, unit: kg; NEP_{ij} is the NEP of grid j of the i-th land use type, unit: kg.

The spatiotemporal carbon emission data for each land use type were aggregated annually to produce the overall spatiotemporal distribution data of the carbon emissions for the study area from 2000 to 2020. Values less than 0 indicate a carbon sink, representing the absorption of atmospheric carbon, while values greater than 0 indicate a carbon source, representing emissions into the atmosphere. A value of 0 signifies no net carbon emissions.

2.4.3. The Assessment of the Ecosystem Service Value

Based on the research findings of Costanza et al. (1997), Xie et al. (2003) conducted a survey of multiple experts in the field of ecology in China to construct an ecosystem service value equivalency table for the country (Table 1) [44–46]. Building on this framework, the economic value generated by food production per unit area of Guangdong was calculated. The specific calculation method is as follows:

$$Ea = \frac{1}{7}\sum_{i=1}^{n}\frac{m_i p_i q_i}{M} \tag{4}$$

where Ea represents the economic value generated by food production per unit area (CNY/hectare). i denotes the type of crop, p_i is the national average price of crop i in a given year (CNY/ton), q_i is the yield per unit area of crop i (tons/hectare), m_i is the planting area of crop i (hectares), and M is the total planting area of all crops (hectares).

Combining the Ea calculation results with the ecosystem service value equivalent (Table 1), the adjusted ecosystem service value coefficients (Table 2) were calculated using land use data and these adjusted ecosystem service value coefficients, and the ecosystem service values were then computed. Specifically,

$$VC_i = ESVE_i \times Ea_i \tag{5}$$

$$ESV_i = \sum_{i=1}^{n} A_i \times VC_i \quad (6)$$

$$ESV = \sum_{i=1}^{n} ESV_i \quad (7)$$

where VC_i is the ecosystem service value coefficient for the i-th land use type, CNY/hectares, $ESVE_i$ is the ecosystem service value equivalent of the i-th land use type, dimensionless, and Ea_i is the Ea of the i-th land use type. ESV_i represents the ecosystem service value of the i-th land use type, CNY, A_i denotes the area of the i-th land use type, hectares, and ESV is the total ecosystem service value, CNY.

Table 1. The ecosystem service value equivalent per hectare.

	Provisioning Services	Regulating Services	Supporting Services	Cultural Services
Arable land	0.05	2.99	0.85	0.08
Forest land	1.13	13.02	4.62	0.93
Grassland	0.77	7.79	2.92	0.59
Water area	6.46	72.09	6.96	3.31
Construction land	0.00	0.00	0.00	0.00
Idle land	0.03	0.44	0.15	0.03

Note: The ecosystem service value equivalent is a dimensionless factor. According to the definition by Xie et al. (2003), one standard unit of the ecosystem service value equivalent factor refers to the annual economic value of the natural grain yield produced by 1 hectare of farmland with the national average yield [45].

Table 2. The ecosystem service value coefficient of Guangdong Province (CNY/hectare).

	Provisioning Services	Regulating Services	Supporting Services	Cultural Services
Arable land	73.96	4905.77	1388.74	123.26
Forest land	1861.23	21,402.13	7584.63	1524.32
Grassland	1260.00	12,797.18	4798.94	969.65
Water area	10,616.84	118,478.00	11,430.36	5439.90
Construction land	0.00	0.00	0.00	0.00
Idle land	49.30	723.13	246.52	49.30

Furthermore, the coefficient of variation was used to illustrate the spatial variability of ecosystem service values in different EFZs. The coefficient of variation reflects the degree of dispersion of a set of data around its mean. A higher coefficient of variation indicates a greater disparity in ecosystem service values within the study area. The calculation formula is as follows:

$$\mathrm{CV} = \frac{1}{\mathrm{ESV}_{p0}} \sqrt{\frac{\sum_{i=1}^{n} \left(\mathrm{ESV}_{pi} - \mathrm{ESV}_{p0}\right)^2}{n}} \quad (8)$$

where n is the number of EFZs, ESV_{pi} is the per-unit area ecosystem service value of the i-th EFZ, and ESV_{p0} is the average per-unit area ecosystem service value for the entire province.

2.4.4. The Analysis of the Spatiotemporal Relationship

(1) Pearson correlation

The Pearson correlation coefficient was used to analyze the temporal correlation between the net carbon emissions and ecosystem services value. The specific formula is as follows:

$$r_{xy} = \frac{\sum\limits_{i=1}^{n} (x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum\limits_{i=1}^{n} (x_i - \overline{x})^2 \sum\limits_{i=1}^{n} (y_i - \overline{y})^2}} \quad (9)$$

where r_{xy} represents the correlation between the net carbon emissions and ecosystem services value. When $r_{xy} > 0$, it indicates a positive correlation between the two variables; when $r_{xy} < 0$, it signifies a negative correlation. The larger the absolute value of r_{xy}, the stronger the correlation. When $r_{xy} = 0$, it implies no correlation between the variables. Here, x_i represents the time series data of the net carbon emissions, x represents the average value of the net carbon emissions, y_i represents the time series data of the ecosystem service values, and y represents the average value of the ecosystem service values. Additionally, a *t*-test was used for significance testing.

(2) Bivariate Moran's I

The bivariate Moran's I index was utilized to assess the spatial correlation between the net carbon emissions and ecosystem services with the following calculation formula:

$$I_{xy} = \frac{n}{\sum\sum w_{ij}} \cdot \frac{\sum\sum w_{ij}(x_i - \overline{x})(y_j - \overline{y})}{\sqrt{\sum(x_i - \overline{x})^2}\sqrt{\sum(y_j - \overline{y})^2}} \tag{10}$$

where I_{xy} represents the bivariate Moran's I index, n is the grid number of spatial units in the study area, x_i is the attribute value of variable x for neighboring region i and y_j is the attribute value of variable y for neighboring region j, and $\overline{x}$ and y are the mean attribute values of x and in the sample, respectively. w_{ij} is the spatial connectivity matrix between regions i and j.

The values of bivariate Moran's I range from -1 to 1, where $I_{xy} > 0$ indicates a positive spatial correlation between the two variables, with higher values signifying a stronger positive correlation. Conversely, $I_{xy} < 0$ indicates a negative spatial correlation, with lower values indicating a more pronounced negative correlation. $I_{xy} = 0$ signifies a spatially random distribution.

The bivariate Local Indicators of Spatial Association (LISA) cluster map can illustrate the spatial association between two variables at a certain significance level. The clustering results can be categorized into four types: High–High (H-H), Low–Low (L-L), High–Low (H-L), and Low–High (L-H). H-H clustering indicates that both variables have high values, while L-L clustering indicates that both variables have low values. H-L clustering indicates that one variable has a high value while the other has a low value, whereas L-H clustering indicates that one variable has a low value while the other has a high value. H-H and L-L clustering suggest a positive correlation between the two variables, while H-L and L-H clustering indicate a negative correlation.

3. Results

3.1. Carbon Emissions in Ecological Function Zones

3.1.1. Changes in Carbon Emissions and Absorption

From 2000 to 2020, carbon emissions consistently exceeded carbon absorption in the study area. The total carbon emissions increased from 210.78 million tons to 503.96 million tons, representing an increase of 293.17 million tons, or 139.09%. In contrast, the total carbon absorption rose from 7.05 million tons to 21.15 million tons, marking an increase of 14.10 million tons, or 200%. The WCZ functioned as the primary carbon sink, contributing over 58% of total absorption during each period. The FPZ followed with approximately 24%, while the APZ contributed 13%. Both the SCZ and MRSZ accounted for less than 5%. In contrast, the MRSZ was the leading carbon source, responsible for around 60% of total emissions across all periods. The APZ followed with emissions comprising 20–30% of the total, while the WCZ and FPZ contributed approximately 10% and 5%, respectively. The SCZ represented the smallest share, with less than 1%.

There was a general trend of increasing carbon emissions and absorption across all ecological function zones over time (Figure 3). However, the rate of the increase in carbon emissions far exceeded that of carbon absorption, leading to a continuous rise in net carbon emissions. The MRSZ experienced the largest increase in carbon emissions at 164.31 million tons, followed by the APZ at 83.19 million tons, the WCZ at 29.25 million tons, the FPZ at 16.26 million tons, and the SCZ at 0.17 million tons. In contrast, the WCZ recorded the largest increase in carbon absorption at 7.87 million tons, followed by the APZ at 1.89 million tons, the FPZ at 3.58 million tons, the SCZ at 0.06 million tons, and the MRSZ at 0.71 million tons.

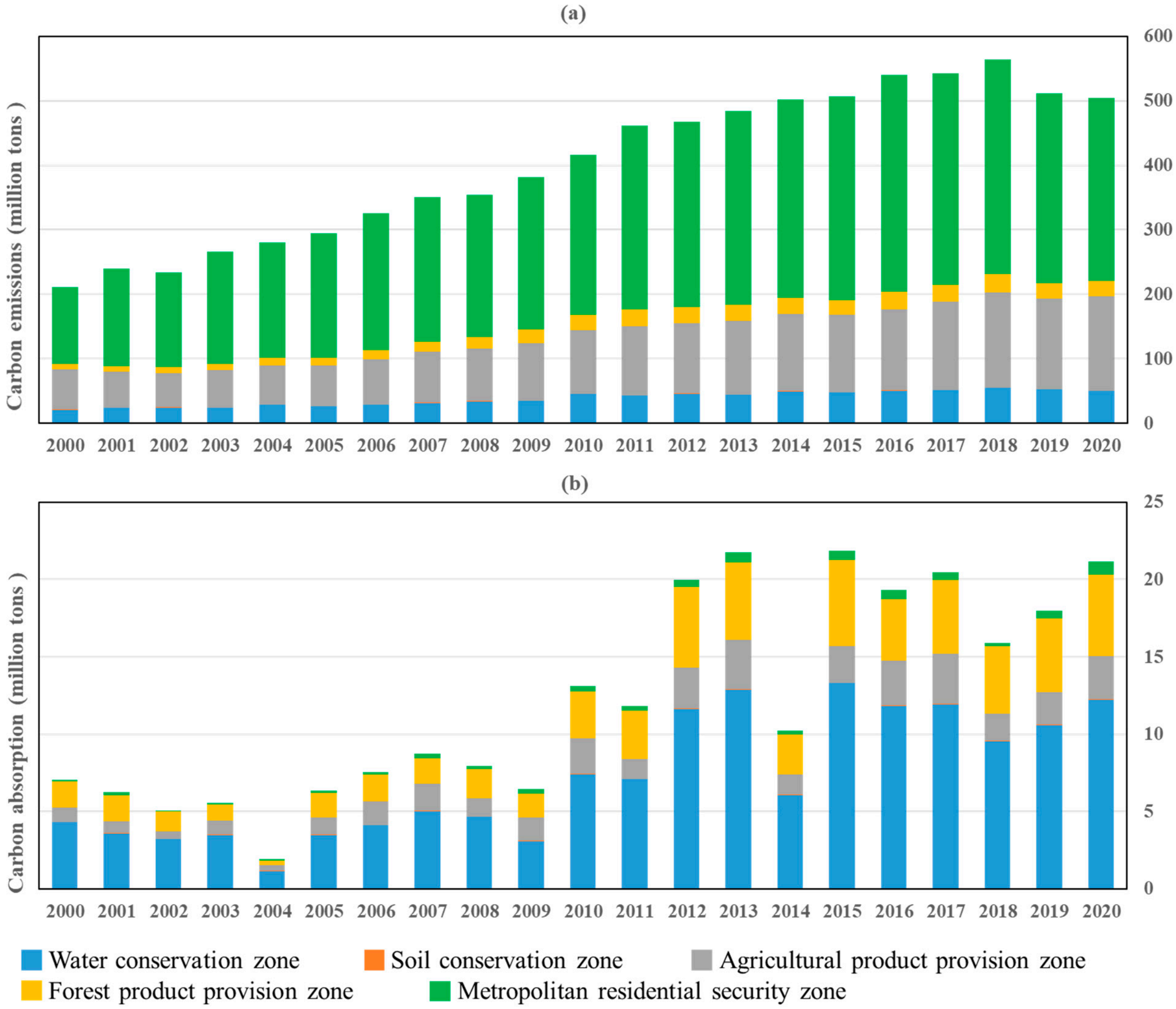
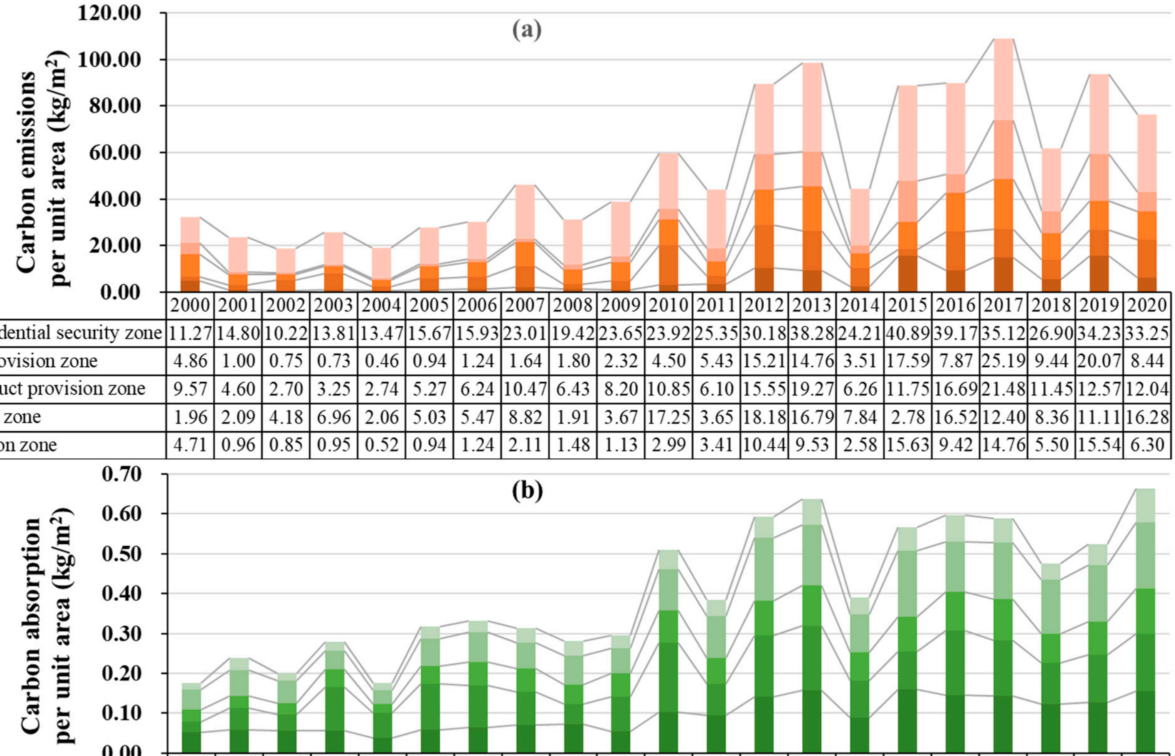


Figure 3. Carbon emissions (**a**) and carbon absorption (**b**) from 2000 to 2020 in each ecological function zone.

Ultimately, net carbon emissions increased from 203.73 million tons in 2000 to 482.80 million tons in 2020, representing an increase of 279.07 million tons, or 136.98%. The increments in the net carbon emissions for each ecological function zone were as follows: 163.61 million tons in the MRSZ, 81.30 million tons in the APZ, 21.38 million tons in the WCZ, 12.68 million tons in the FPZ, and 0.11 million tons in the SCZ.

3.1.2. Carbon Emission and Absorption Density

The MRSZ exhibited the highest carbon emission density, averaging 24.42 kg/m^2 over multiple years. The APZ, FPZ, and SCZ had multi-year averages of 9.69 kg/m^2, 7.03 kg/m^2, and 8.25 kg/m^2, respectively. In contrast, the WCZ had the lowest carbon emission density, with an average of 5.29 kg/m^2. All ecological functional zones demonstrated a gradual increase in the carbon emission density over time (Figure 4a).



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Metropolitan residential security zone	11.27	14.80	10.22	13.81	13.47	15.67	15.93	23.01	19.42	23.65	23.92	25.35	30.18	38.28	24.21	40.89	39.17	35.12	26.90	34.23	33.25
Forest product provision zone	4.86	1.00	0.75	0.73	0.46	0.94	1.24	1.64	1.80	2.32	4.50	5.43	15.21	14.76	3.51	17.59	7.87	25.19	9.44	20.07	8.44
Agricultural product provision zone	9.57	4.60	2.70	3.25	2.74	5.27	6.24	10.47	6.43	8.20	10.85	6.10	15.55	19.27	6.26	11.75	16.69	21.48	11.45	12.57	12.04
Soil conservation zone	1.96	2.09	4.18	6.96	2.06	5.03	5.47	8.82	1.91	3.67	17.25	3.65	18.18	16.79	7.84	2.78	16.52	12.40	8.36	11.11	16.28
Water conservation zone	4.71	0.96	0.85	0.95	0.52	0.94	1.24	2.11	1.48	1.13	2.99	3.41	10.44	9.53	2.58	15.63	9.42	14.76	5.50	15.54	6.30

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Metropolitan residential security zone	0.02	0.03	0.02	0.02	0.02	0.03	0.03	0.04	0.04	0.03	0.05	0.04	0.05	0.06	0.04	0.06	0.07	0.06	0.04	0.05	0.09
Forest product provision zone	0.05	0.06	0.06	0.05	0.03	0.07	0.07	0.06	0.07	0.06	0.10	0.10	0.16	0.15	0.09	0.17	0.13	0.14	0.14	0.14	0.16
Agricultural product provision zone	0.03	0.03	0.03	0.05	0.02	0.04	0.06	0.06	0.05	0.06	0.08	0.07	0.09	0.10	0.07	0.09	0.10	0.10	0.07	0.08	0.11
Soil conservation zone	0.03	0.05	0.04	0.11	0.06	0.12	0.10	0.08	0.05	0.09	0.17	0.08	0.15	0.16	0.09	0.10	0.16	0.14	0.10	0.12	0.14
Water conservation zone	0.05	0.06	0.06	0.06	0.04	0.06	0.06	0.07	0.07	0.06	0.10	0.10	0.14	0.16	0.09	0.16	0.15	0.14	0.12	0.13	0.16

Figure 4. Per-unit area carbon emissions (**a**) and carbon absorption (**b**) from 2000 to 2020 in each ecological function zone.

The carbon absorption density in the WCZ, FPZ, and SCZ was comparable, with each exhibiting a multi-year average of 0.01 kg/m^2. The APZ followed with an average of 0.07 kg/m^2, while the MRSZ had the lowest carbon absorption density, averaging 0.04 kg/m^2. Notably, all ecological functional zones demonstrated a gradual increase in the carbon absorption density over time (Figure 4b).

3.2. Ecosystem Service Value Changes in Ecological Function Zones

3.2.1. Changes in the Total Value of Ecosystem Services

In 2000, the total value of ecosystem services in Guangdong Province was CNY 596.96 billion. The values of provisioning services, regulating services, supporting services, and cultural services were CNY 28.25, 391.04, 144.88, and 32.79 billion, respectively (Figure 5). The WCZ had the highest ecosystem service value (ESV) at CNY 257.30 billion, followed by the FPZ with an ESV of CNY 202.74 billion. The APZ and MRSZ had ESVs of CNY 80.41 and 55.40 billion, respectively, while the SCZ had the lowest ESV at CNY 1.11 billion. Regulating services constituted approximately 70% of each zone's ESV, followed by supporting services at around 20%, with provisioning and cultural services each making up about 5%.

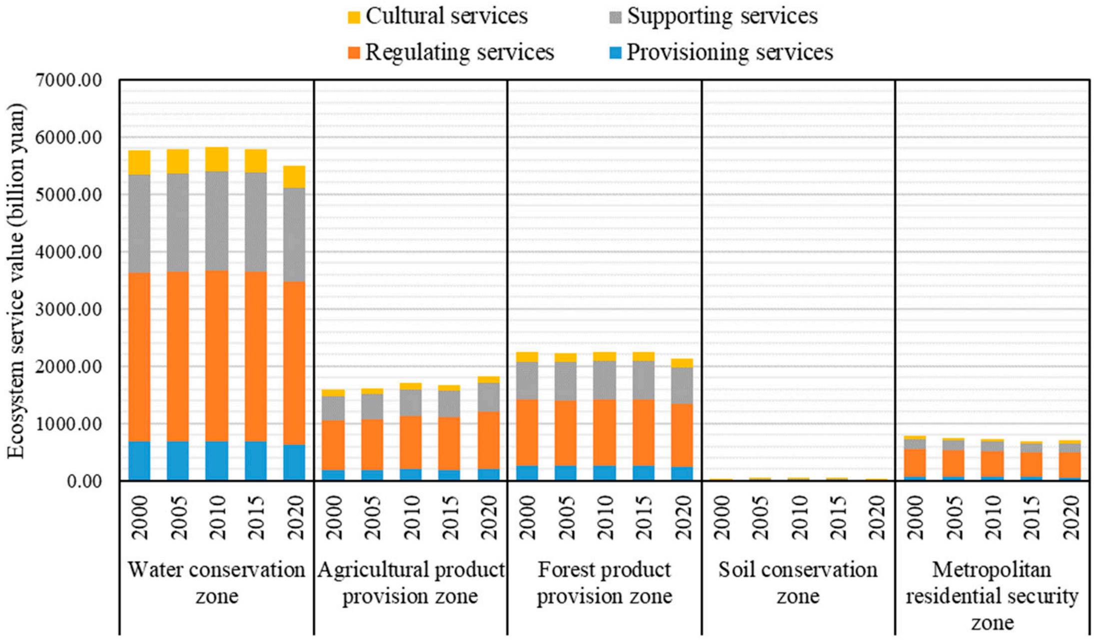


Figure 5. Ecosystem services value from 2000 to 2020 in each ecological function zone.

From 2000 to 2020, the total ESV decreased by CNY 92.39 billion, representing a decline of 15.48%. The values of regulating services, supporting services, and cultural services fell by CNY 38.08, 44.81, and 10.87 billion, respectively, while provisioning services increased by CNY 1.36 billion. The ESV declined in all EFZs except for the APZ, which experienced a notable increase of CNY 20.42 billion. The FPZ saw the largest decrease, losing CNY 105.12 billion, while the WCZ, SCZ, and MRSZ experienced smaller reductions of CNY 3.37, 0.06, and 4.27 billion, respectively.

In terms of the annual average ESV per unit area, the FPZ had the highest value at 2.99 million CNY/km^2, followed by the WCZ, MRSZ, and SCZ with values of 2.99, 2.87, and 2.64 million CNY/km^2, respectively. The APZ had the lowest value at 2.32 million CNY/km^2.

3.2.2. Spatial Changes in Ecosystem Service Value

From the perspective of the coefficient of variation, the spatial differences in the ESV among the EFZs have gradually expanded (Figure 6). From 2000 to 2020, the coefficient of variation exhibited a general upward trend, indicating an increasing degree of spatial variation. Specifically, within the study area, the coefficient of variation first increased, then decreased, showing fluctuations from 2000 to 2008. Starting in 2008, it continued to rise until it experienced a slight decline in 2020.

3.3. The Relationship Between Carbon Emissions and the Ecosystem Service Value

3.3.1. Quantitative Relationship

Based on the results of the Pearson correlation coefficients, the net carbon emissions in Guangdong Province were negatively correlated with the total ecosystem service value, exhibiting a correlation coefficient of −0.4161 (p = 0.06 < 0.1). Additionally, the net carbon emissions displayed varying degrees of correlation with different ecosystem service values: they showed a positive correlation with the provisioning services value, while exhibiting negative correlations with the other three service values. However, these correlations were not statistically significant (Table 3).

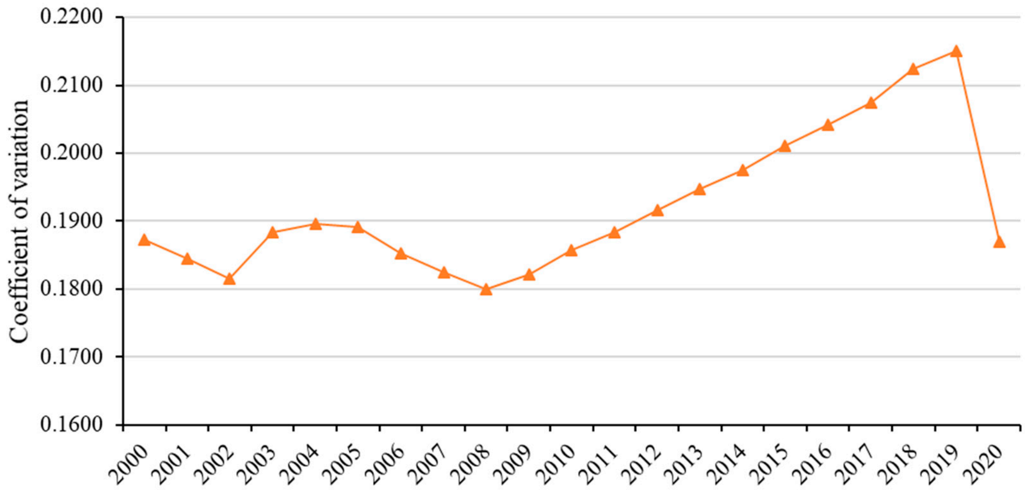


Figure 6. Coefficient of variation in ecosystem services value from 2000 to 2020.

Table 3. Pearson correlation coefficients between net carbon emissions and ecosystem service values.

	Net Carbon Emissions					
	Guangdong Province	**Water Conservation Zone**	**Agricultural Products Provision Zone**	**Forest Product Provision Zone**	**Soil Conservation Zone**	**Metropolitan Residential Security Zone**
Total ecosystem services value	−0.4161 *	0.0390	0.5297 ***	−0.3784 *	0.3376	−0.8565 ***
Provisioning services value	0.0342	0.1509	0.5955 ***	0.6245 *	0.3566	−0.8133 ***
Regulating services value	−0.4504	0.0623	0.5497 ***	−0.3741 *	0.3428	−0.8561 ***
Supporting services value	−0.3716	−0.0381	0.7244 ***	−0.3837 *	0.3142	−0.8906 ***
Cultural services value	−0.3780	0.0525	0.6534 ***	−0.3829 *	0.3387	−0.8259 ***

Note: *** and *, respectively, indicate significance at the 1% and 10% levels.

The relationship between the net carbon emissions and total ecosystem service values varied across different EFZs (Table 3).

Specifically, in the APZ, there was a significant positive correlation between the net carbon emissions and total ecosystem service value (R = 0.5297; $p < 0.01$), indicating that as the net carbon emissions increase, the total ecosystem service value also increases. Moreover, net carbon emissions in the APZ exhibited significant positive correlations with all four ecosystem services. The strongest correlation was with the supporting service value (R = 0.7244), followed by the cultural service value (R = −0.6534). The correlation coefficients for the provisioning service value and regulation service value were below 0.6.

In the MRSZ, the net carbon emissions showed a significant negative correlation with the total ecosystem service value (R = −0.8565; $p < 0.01$), suggesting that higher carbon emissions are associated with declines in ecosystem services. Moreover, net carbon emissions in the MRSZ were significantly negatively correlated with the four ecosystem service values, with the absolute correlation coefficients all exceeding 0.8.

Additionally, in the FPZ, there was a significant negative correlation between the net carbon emissions and the total ecosystem service value (R = −0.3784; $p < 0.1$). However, the relationship between the net carbon emissions and individual ecosystem service values in the FPZ was more complex. The net carbon emissions exhibited a positive correlation with the provisioning service value but negative correlations with the other three service values. Notably, the positive correlations were stronger than the negative ones.

In both the WCZ and SCZ, there was no significant correlation between the net carbon emissions and the total ecosystem service value. Among the correlations between the net carbon emissions and individual ecosystem service values, only in the WCZ was there a non-significant negative correlation with the supporting service value, while all other correlations in both zones were non-significant positive correlations.

3.3.2. Spatial Relationship

The spatial relationship between the net carbon emissions and total ecosystem service value was complex, often showing a random distribution, with consistent clustering primarily observed in the APZ and MRSZ (Figure 7).

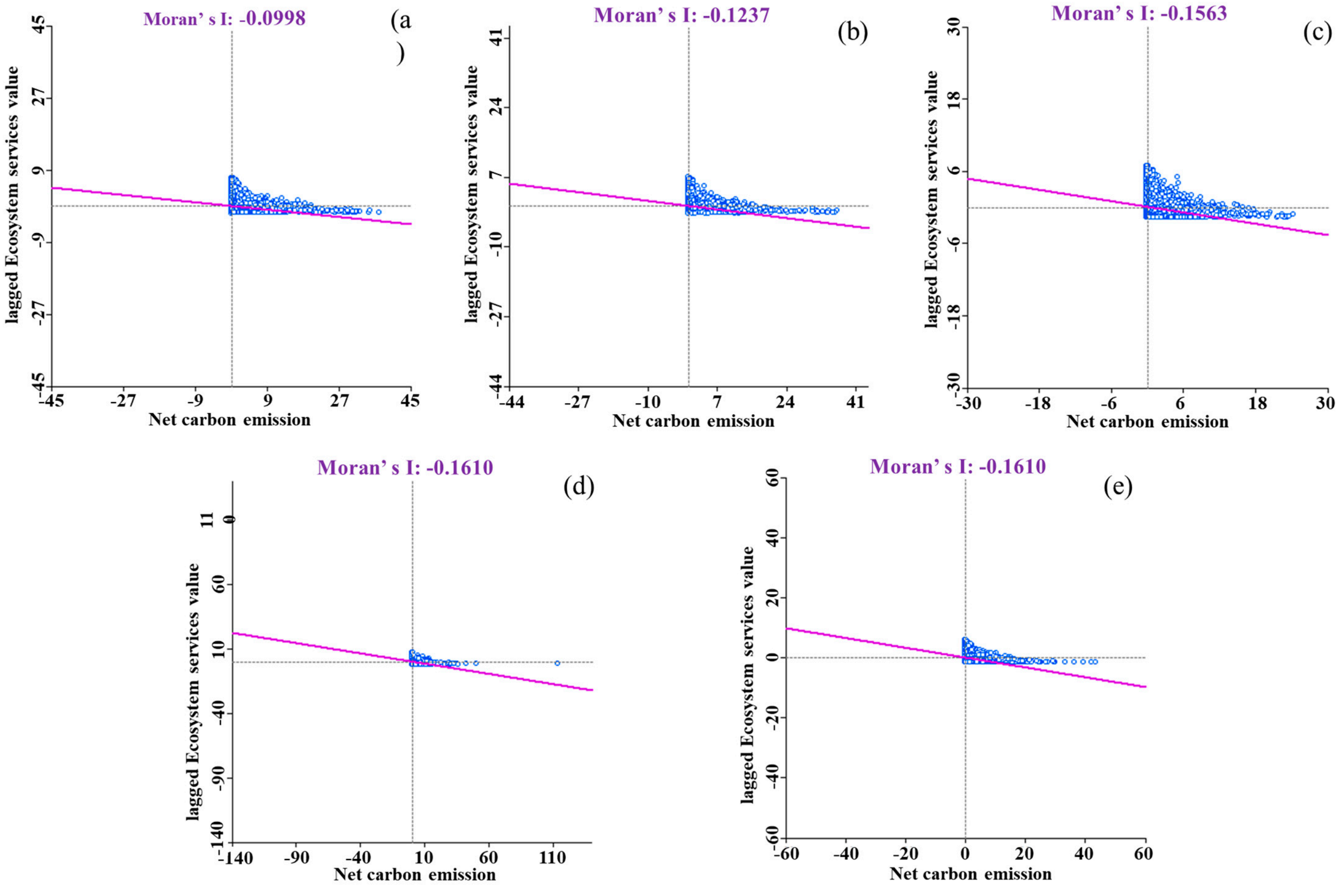
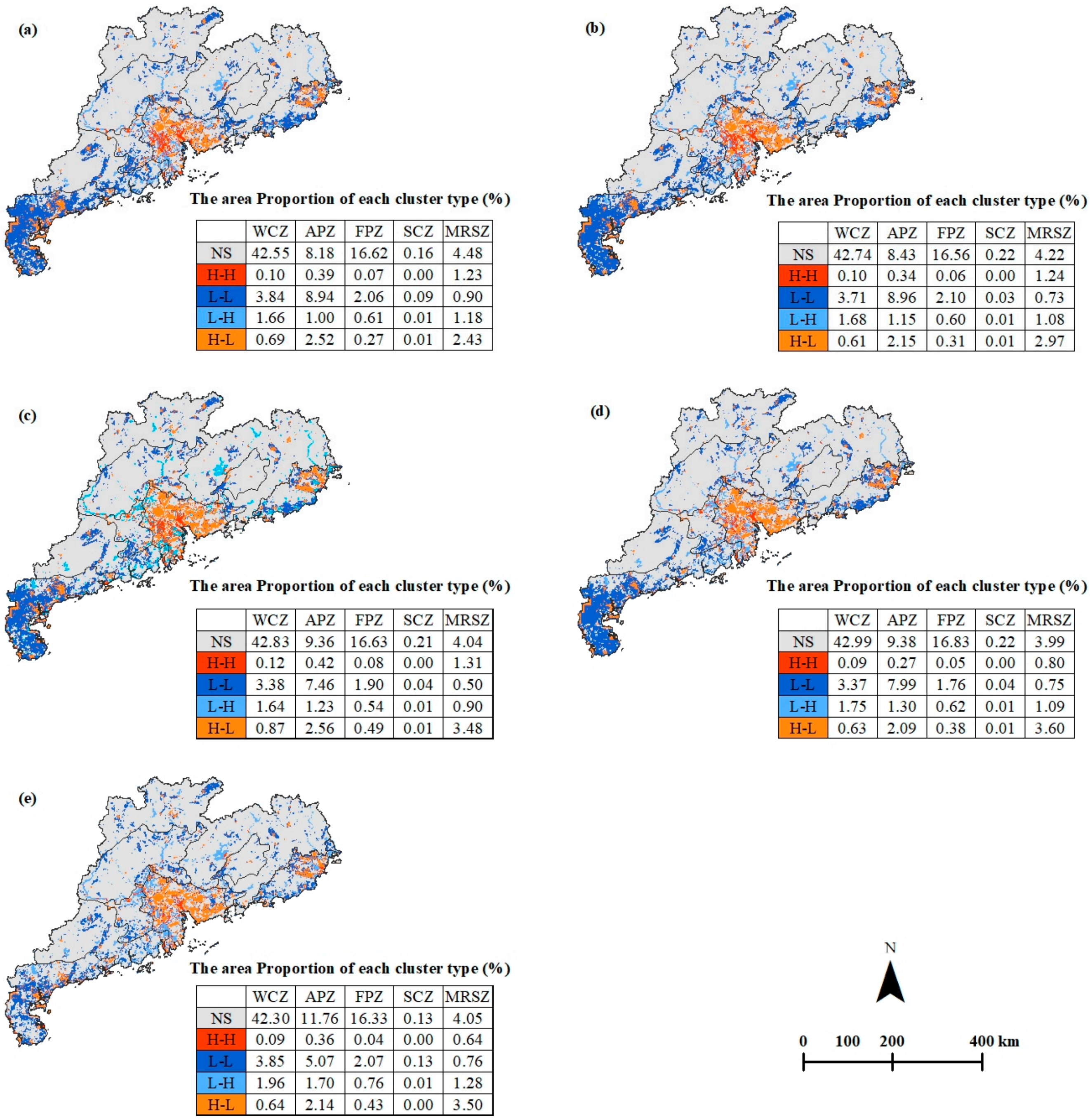


Figure 7. Bivariate Moran′s I in 2000 (**a**), 2005 (**b**), 2010 (**c**), 2015 (**d**), and 2020 (**e**).

Specifically, according to the results of bivariate Moran's I from 2000 to 2020, a spatial negative correlation existed between the net carbon emissions and total ecosystem service value in Guangdong Province ($p < 0.01$, $Z < -1.96$). The degree of this negative correlation initially increased and then declined over time. The bivariate Moran's I values for each period approached zero, reflecting the random spatial distribution of the net carbon emissions and the total ecosystem service value.

The spatial clustering patterns for each period further confirm this randomness. From 2000 to 2020, the spatial relationship between the net carbon emissions and the total ecosystem service values was not significant in most areas, indicating that the spatial complexity cannot be captured by a simple linear relationship. The proportion of non-significant areas increased from 72% in 2000 to 74.56% in 2020. These non-significant clusters were predominantly found in the WCZ, APZ, and FPZ, which accounted for more than 40%, 8%, and 16% of the total area, respectively, across all periods (Figure 8).



(a) The area Proportion of each cluster type (%)

	WCZ	APZ	FPZ	SCZ	MRSZ
NS	42.55	8.18	16.62	0.16	4.48
H-H	0.10	0.39	0.07	0.00	1.23
L-L	3.84	8.94	2.06	0.09	0.90
L-H	1.66	1.00	0.61	0.01	1.18
H-L	0.69	2.52	0.27	0.01	2.43

(b) The area Proportion of each cluster type (%)

	WCZ	APZ	FPZ	SCZ	MRSZ
NS	42.74	8.43	16.56	0.22	4.22
H-H	0.10	0.34	0.06	0.00	1.24
L-L	3.71	8.96	2.10	0.03	0.73
L-H	1.68	1.15	0.60	0.01	1.08
H-L	0.61	2.15	0.31	0.01	2.97

(c) The area Proportion of each cluster type (%)

	WCZ	APZ	FPZ	SCZ	MRSZ
NS	42.83	9.36	16.63	0.21	4.04
H-H	0.12	0.42	0.08	0.00	1.31
L-L	3.38	7.46	1.90	0.04	0.50
L-H	1.64	1.23	0.54	0.01	0.90
H-L	0.87	2.56	0.49	0.01	3.48

(d) The area Proportion of each cluster type (%)

	WCZ	APZ	FPZ	SCZ	MRSZ
NS	42.99	9.38	16.83	0.22	3.99
H-H	0.09	0.27	0.05	0.00	0.80
L-L	3.37	7.99	1.76	0.04	0.75
L-H	1.75	1.30	0.62	0.01	1.09
H-L	0.63	2.09	0.38	0.01	3.60

(e) The area Proportion of each cluster type (%)

	WCZ	APZ	FPZ	SCZ	MRSZ
NS	42.30	11.76	16.33	0.13	4.05
H-H	0.09	0.36	0.04	0.00	0.64
L-L	3.85	5.07	2.07	0.13	0.76
L-H	1.96	1.70	0.76	0.01	1.28
H-L	0.64	2.14	0.43	0.00	3.50

Figure 8. Spatial clustering of net carbon emissions and ecological service value in 2000 (**a**), 2005 (**b**), 2010 (**c**), 2015 (**d**) and 2020 (**e**). WCZ, APZ, FPZ, SCZ, MRSZ refer to water conservation zone, soil conservation zone, agricultural products provision zone, forest product provision zone, and metropolitan residential security zone, respectively. NS, H-H, L-L, L-H, and H-L indicate different types of spatial clustering: NS denotes not significant, H-H represents High–High clustering, L-L indicates Low–Low clustering, L-H refers to Low–High clustering, and H-L denotes High–Low clustering. In these clustering types, *L* signifies low net carbon emissions or a low ecosystem service value, while *H* represents high net carbon emissions or a high ecosystem service value.

Approximately 30% of the study area exhibited clustered patterns, predominantly of the L-L type, where low net carbon emissions and low ecosystem service values co-occurred. The proportion of L-L clusters remained above 11% throughout the study period, gradually declining from 15.83% in 2000 to 11.88% in 2020, with more than half of these clusters consistently located in the APZ.

The next most common clustering type was H-L, characterized by high net carbon emissions and low ecosystem service values. The proportion of H-L clusters increased over time, rising from 5.93% in 2000 to 6.72% in 2020. These clusters were mainly found in the APZ and MRSZ, with both zones accounting for over 2% of the total area during each period.

The L-H clustering type, where low net carbon emissions and high ecosystem service values clustered together, accounted for more than 4% of the total area in each period, increasing from 4.46% in 2000 to 5.17% in 2020. These clusters were mainly distributed across the WCZ, APZ, and MRSZ, with each zone accounting for more than 1% of the total area.

The H-H clustering type, where high net carbon emissions and high ecosystem service values clustered, never exceeded 2% of the total area in any period and showed a decreasing trend from 1.79% in 2000 to 1.13% in 2020. These clusters were primarily located in the MRSZ.

4. Discussion

4.1. Results Validation

In calculating carbon emissions, this study adopted a localized method to assess the carbon emissions. The results were validated using data from the Carbon Emission Accounts and Datasets (CEADs, www.ceads.net.cn, accessed on 14 March 2024), revealing an error margin of less than 6% for the period from 2014 to 2018, which is acceptable. Additionally, the results of this study were compared with those of Zhu et al. (2015) and Huang et al. (2023). The former used a land use-based approach, while the latter applied the Guidelines for Preparing Provincial Greenhouse Gas Inventories issued by the National Development and Reform Commission in 2011 [34,47]. The carbon emission estimates from this study fell between the two, showing the same temporal trends, further demonstrating the reliability of this study's assessment results. For the calculation of the ecosystem service value (ESV), this study's ESV estimates were compared with the results of Ye et al. (2021) for Guangdong Province in 2020 [35]. The error margin was found to be below 4% with consistent trends, which indicates the validity of this study's evaluation results.

Regarding the relationship between carbon emissions and the ecosystem service value, no prior studies have addressed the relationship between carbon emissions and the ESV in ecological functional zones in Guangdong Province. Zhang et al. (2023), in their study on the Guanzhong urban agglomeration, found a significant negative correlation between carbon emissions and the ecosystem service value [12]. Drawing a parallel between their findings on urban agglomerations and the results for the metropolitan residential security zone (MRSZ) in this study, a similar significant negative correlation was observed. In human-aggregated regions, although the degree of correlation varied, a consistent negative correlation existed, further corroborating the validity of this study's findings.

In conclusion, the evaluation results of this study are valid. The findings provide a clear and accurate explanation of carbon emissions, the ecosystem service value, and their relationship in Guangdong Province. The results offer valuable data references for related studies within Guangdong Province and for comparative research in other regions.

4.2. The Exploration of Carbon Emission Reduction and Sink Enhancement

Enhancing ecosystems' carbon sink capacity and reducing emissions from human activities are key strategies for achieving the dual carbon goals [48,49]. Guangdong Province has made notable progress in this regard. During the 13th Five-Year Plan, the province's forest coverage increased from 56.92% to 58.66%, and the forest stock volume grew from 502 to 584 million cubic meters, resulting in a forest carbon sink storage capacity of 310 million tons. For the 14th Five-Year Plan, Guangdong aims to further enhance its carbon sink capacity by improving forest quality and promoting ecological restoration. By 2025, the province plans to establish 333,000 hectares of high-quality water source conservation forests and 63,000 hectares of coastal protective forests through forest optimization and structural adjustments [50]. It is important to note that vegetation's carbon sink capacity is influenced by factors such as the species, climate, and area [16]. Identifying the emission thresholds for optimizing vegetation's carbon sink potential and addressing carbon sink saturation are key challenges in balancing emission reduction efforts with increased carbon absorption.

This study found that carbon absorption by ecosystems was much lower than carbon emissions, making it impossible to achieve carbon neutrality through ecosystems alone in the short term. In 2022, Guangdong's Carbon Peak Implementation Plan proposed adjustments in industrial, energy, and transportation structures to meet the dual carbon goals [51]. However, the study reveals significant spatial disparities in carbon emissions across the province, while the province's current "dual carbon" strategies exhibit a lack of regional differentiation and specificity, relying on largely uniform approaches [52]. Previous studies have categorized Guangdong's 21 cities into different carbon emission types based on the GDP and carbon emissions, proposing corresponding reduction priorities [53,54]. However, such classifications fail to account for regional natural environmental characteristics and overlook the ecological functions of different areas.

This study also highlights significant differences in CEs, the ESV, and their relationships across ecological functional zones. To achieve the dual goals of carbon neutrality and ecological environmental protection, targeted emission reduction and carbon sink enhancement measures are needed for each ecological zone. In the APZ and MRSZ, where CEs and the ESV were strongly correlated, strategies should balance ecological conservation with emission reduction. In the APZ, improving agricultural land ecology and transitioning energy use will enhance carbon sequestration. In the MRSZ, reducing high carbon emissions through structural adjustments in energy, industry, and transportation, alongside creating ecological landscapes, can support green development. For other regions with more variable relationships between CEs and the ESV, energy structure adjustments remain necessary. In the WCZ, ecological protection and restoration should focus on enhancing both water conservation and carbon sequestration. In the FPZ, expanding the forest area and improving biodiversity can strengthen carbon sequestration. In the SCZ, afforestation, engineering projects, and sustainable farming practices should enhance both soil conservation and the carbon sink capacity.

4.3. Limitations and Prospects

This study, based on extensive data collection and processing, investigated the relationship between carbon emissions and ecosystem services from the perspective of ecological functional zones. It analyzed the impact of carbon emissions on ecosystem services, as well as effective ways to reduce emissions, increase carbon absorption, and enhance ecosystem service values. However, the study did not further analyze the mechanisms linking carbon emissions and ecosystem services. Future research can delve deeper into the following areas: (1) Mechanisms influencing the relationship between regional carbon emissions and ecosystem services: this involves developing an indicator system to identify the factors affecting the relationship between carbon emissions and ecosystem services, thereby uncovering the mechanisms underlying this relationship. (2) Synergy between carbon neutrality and ecosystem services: Build a synergistic model for reducing emissions, increasing carbon absorption, and enhancing ecosystem services based on this study. Analyze the critical thresholds for these synergies under the dual pressures of human activity and extreme climate events, providing valuable results for the coordinated development of carbon neutrality and ecosystem services.

5. Conclusions

This study developed localized time series data on carbon emissions and ecosystem service values using multi-source data and diverse methodologies. It explored the temporal and spatial relationships between carbon emissions and ecosystem service values from the perspective of ecological function zones. The findings reveal the following trends from 2000 to 2020:

(1) Both carbon emissions and absorption have gradually increased over time, with the increment in carbon emissions far exceeding that of carbon absorption. The total carbon emissions rose from 210.78 million tons to 503.96 million tons, an increase of 293.17 million tons, while carbon absorption increased from 7.05 million tons to 21.15 million tons, an increase of 14.10 million tons. The WCZ was the dominant carbon sink area, while the MRSZ was the dominant carbon source area.

(2) The total value of ecosystem services decreased from CNY 596.95 billion to CNY 504.56 billion, representing a decline of CNY 92.39 billion. The WCZ had the highest ESV, consistently accounting for more than 50% of the total. The FPZ, APZ, and MRSZ accounted for approximately 30%, 16%, and over 9% of the total ESV, respectively, while the SCZ accounted for the smallest proportion, less than 1%.

(3) There was a negative correlation between the net carbon emissions and the total ecosystem service values, both temporally and spatially. Specifically, the net carbon emissions in the MRSZ and APZ exhibited significant correlations with the total ecosystem service values over time, with the former showing a negative correlation and the latter a positive correlation. Spatially, the distribution of the net carbon emissions and ecosystem service values was predominantly random, with clustering patterns primarily reflecting L-L and H-L clustering types, mainly found in the APZ and MRSZ.

This research elucidates the temporal and spatial evolution trends of carbon emissions and ecosystem services in different ecological functional zones. These findings provide a scientific reference for subsequent efforts in emission reduction, carbon absorption, and habitat protection in the study area.

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