land

MDPI

Article

Spatial-Temporal Evolution of Agricultural Carbon Balance at Township Scale and Carbon Compensation Zoning: A Case Study of Guangshui City, Hubei Province

Zhengkun Yang [1,2], Xuesong Zhang [1,2,*], Xiurong Hu [1,2] and Xiaowen Zhou [1,2]

[1] Hubei Province Key Laboratory for Geographical Process Analysis and Simulation, Wuhan 430079, China; yzk1162902781@163.com (Z.Y.); huxiurong@mails.ccnu.edu.cn (X.H.); zhouxw98@mails.ccnu.edu.cn (X.Z.)
[2] College of Urban and Environmental Sciences, Central China Normal University, Wuhan 430079, China
* Correspondence: zxsgis@263.net; Tel.: +86-133-0714-0333

Abstract: Optimizing agricultural carbon compensation zoning is crucial for establishing robust mechanisms in agricultural carbon compensation management, with significant implications for achieving national "dual carbon" strategic objectives. This study employs K-means and the three-dimensional magic cube approach to construct a novel evaluation index system for comprehensive carbon compensation zoning. By combining spatial land-use zoning, we delineate carbon compensation zones in Guangshui City, Hubei Province, and analyze the spatiotemporal variations of agricultural carbon balance, proposing optimization strategies. The results show that (1) from 2000 to 2021, agricultural carbon emissions and absorption exhibit a trend of increasing followed by decreasing, with spatial patterns of "higher in the northwest, lower in the southeast" and "higher in the southwest, lower in the northeast"; (2) the Gini coefficient of agricultural carbon emissions averages at 0.24, with economic contribution coefficients and ecological carrying coefficients ranging from 0.04–16.1 and 0.39–1.99, respectively, from 2000 to 2021; and (3) in 2021, Guangshui City comprises seven payment zones, four balance zones, and six compensation zones, ultimately forming eight optimized agricultural carbon compensation zones in alignment with regional agricultural carbon balance objectives. This study provides theoretical references for enhancing county-level agricultural carbon comprehensive compensation management mechanisms.

Keywords: agricultural carbon balance; three-dimensional magic cube; spatial-temporal evolution; carbon compensation zoning; Guangshui city

check for updates

Citation: Yang, Z.; Zhang, X.; Hu, X.; Zhou, X. Spatial-Temporal Evolution of Agricultural Carbon Balance at Township Scale and Carbon Compensation Zoning: A Case Study of Guangshui City, Hubei Province. *Land* **2024**, *13*, 820. https://doi.org/10.3390/land13060820

Academic Editor: Xiaoyong Bai

Received: 7 March 2024
Revised: 20 May 2024
Accepted: 5 June 2024
Published: 7 June 2024

Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

As rapid socio-economic developments unfold, the adverse impacts of climate change have become one of the crucial challenges that society faces today. Carbon dioxide (CO_2), as a significant greenhouse gas, contributes extensively to the accelerated pace of global warming, posing severe threats to sustainable human development. To address this issue, over 140 countries worldwide have reached a consensus on the "dual carbon" strategy goal. In alignment with the objectives of the Paris Agreement, China has explicitly stated its intention to peak carbon emissions by 2030 and achieve carbon neutrality by 2060. Since the significant strategic deployment of rural ecological civilization construction by the state, various levels of government departments across China have intensified their focus on rural ecological construction and environmental protection. In recent years, in pursuit of the national "dual carbon" strategy goals and to promote the coordinated development of regional economy, resources, and ecological environment, local governments have advocated for the development of green, low-carbon agriculture. This involves emphasis on controlling agricultural carbon emissions [1], promoting and upgrading industrial transformation [2], achieving carbon balance [3,4], and coordinating regional carbon emission

reduction efforts [5]. Against this strategic backdrop, the scientific delineation of agricultural carbon compensation management zoning, the optimization of its spatial layout, and the establishment of a comprehensive agricultural carbon compensation management mechanism hold significant practical significance and research value.

In the realm of carbon compensation research, scholars both domestically and internationally have embarked on studies from various perspectives, including the spatial-temporal differentiation of carbon balance [6,7], carbon compensation standards [8], carbon compensation zoning, carbon accounting [9,10], carbon emission effects [11], and carbon balance [12,13]. Regarding carbon compensation standards, Gao et al. conducted in-depth research on carbon responsibility allocation methods and incentive mechanisms based on carbon emissions and offset accounting [14]. Huber conducted a qualitative meta-analysis on the quality standards of carbon compensation [15]. Xiong studied the counties in China participating in agricultural carbon compensation [16]. In terms of carbon accounting, Zhang et al. conducted research on China's carbon budget from 1997 to 2017 and the challenges of achieving carbon neutrality [17]. Jing et al. conducted correlation studies on provincial-level carbon emission spatial-temporal differences and ecological compensation related to land carbon budget accounting in China [18]. Regarding carbon emission effects, An et al. focused on the data-driven predictive analysis of household carbon footprints in China [19], while Fasogbon et al. conducted real-time carbon footprint assessment based on energy consumption, providing a comprehensive analysis of future research prospects [20].

In terms of the scale of "carbon compensation" research, scholars have mainly approached this topic from a macro perspective, involving multiple cities. For instance, Xia et al. conducted a spatiotemporal study on the carbon balance and carbon compensation zoning in the Beijing–Tianjin–Hebei urban agglomeration, taking into account the functional differences across various regions [21]. Song et al. delved into the temporal and spatial patterns of carbon compensation potential and network connections in the Yellow River Basin urban agglomeration [22]. Huang et al. studied the spatial-temporal characteristics and determining factors of agricultural carbon compensation rates in China using geographic detectors [23]. Additionally, Song et al. explored the agricultural functional zoning and carbon effects in county-level urban agglomerations in the Pearl River Delta of China [24]. Currently, some scholars have started exploring this from a micro perspective. Long et al. conducted an in-depth analysis on the spatial-temporal changes and structural characteristics of carbon emissions at the county scale, using Wu'an City as an example [25]. Guo et al. conducted correlation studies on the urban low-carbon competitiveness of the Wuhan city cluster in China [26].

While reviewing relevant domestic and international research, it is evident that the current research on comprehensive carbon compensation regions primarily focuses on urban areas. However, there are still deficiencies in studying the micro-level aspects of agricultural carbon balance and the carbon compensation spatial layout, which hinder the fulfillment of the country's real needs in exploring and establishing a comprehensive watershed and regional carbon compensation management mechanism under the "dual carbon" strategy goals [27–29]. Therefore, this paper starts from the micro-scale of townships and takes Guangshui City, located in the main grain-producing area of the low hills and ridges in northern Hubei Province, as the research area. Based on the regional agricultural carbon balance relationship, this study conducts research on the agricultural carbon compensation zoning of Guangshui City. We analyzed the spatial-temporal characteristics of agricultural carbon balance in Guangshui City from 2000 to 2021 using an agricultural carbon balance accounting system. Furthermore, we constructed an evaluation system for comprehensive agricultural carbon compensation management zoning using standard revealed comparative advantage indices and K-means clustering analysis. Finally, the spatial partitioning of the entire region was achieved using the entropy weight-TOPSIS method and the three-dimensional magic cube method. Based on the actual situation of the research area and relevant research results [30], we comprehensively considered the three major categories of socio-economics, resource utilization, and ecological environment.

We optimized the indicators system for agricultural carbon comprehensive compensation management zoning, providing theoretical references for improving the comprehensive management mechanism of agricultural carbon compensation at the county level.

2. Materials and Methods

2.1. Study Area

The research area of this study is Guangshui City, Hubei Province, China, which includes 4 districts, 13 towns, and 3 township-level units. Guangshui City is located between the southern foothills of the Tongbai Mountains and the western end of the Dabie Mountains. It belongs to the low hills and ridges zone, with an overall terrain that is higher in the north and lower in the south (Figure 1). The rivers within Guangshui City's territory belong to the two major basins of the Yangtze River and the Huai River. The climate of Guangshui City is characterized by a North Subtropical Continental Monsoon climate, with moderate temperatures and seasonal variations in precipitation and temperature, resulting in four distinct seasons. Guangshui City serves not only as a crucial ecological security barrier for comprehensive management in five major river basins including the Xujia River Basin, the Yingshan River Basin, the Guangshui River Basin, the Jiangxidian River Basin, and the Feisha River Basin, but also as a national modern agricultural demonstration area and a demonstration area for urban–rural integration development. Therefore, selecting this area for studying the spatial-temporal evolution of agricultural carbon balance and carbon compensation zoning at the township scale holds significant practical significance.

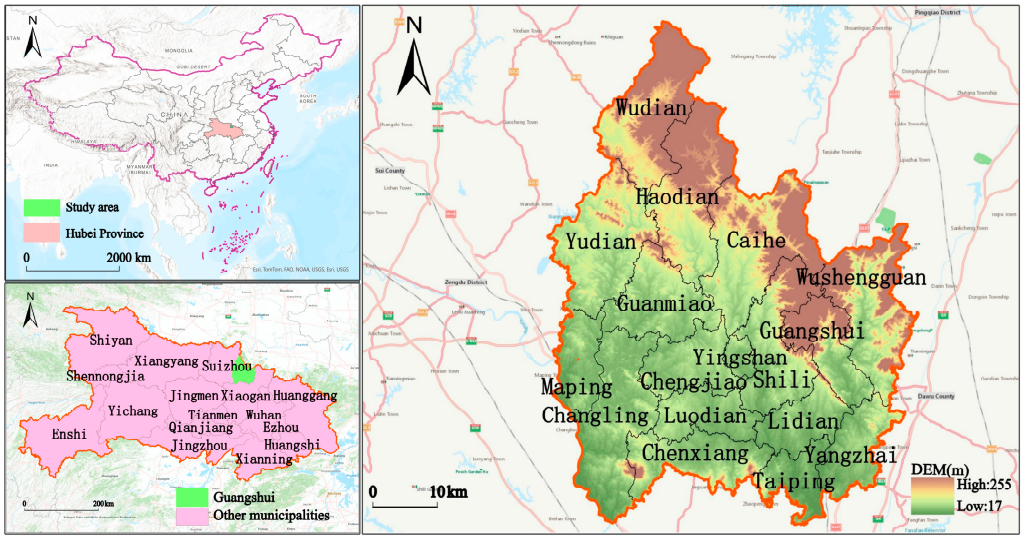

Figure 1. Geographic location and regional overview of Guangshui City.

2.2. Data

The socio-economic data utilized in this study from 2000 to 2021 primarily originate from the "Statistical Yearbook of Guangshui City". This dataset encompasses county-level GDP data, population data, urban population data, arable land area data, grain crop area data, economic crop area data, land area data, and data on agricultural land use and livestock farming. The raster data of land use are obtained from the website of the Resource and Environment Science and Data Center of the Chinese Academy of Sciences (http://www.resdc.cn (accessed on 20 December 2023)). These data primarily rely on Landsat satellite remote sensing images from the United States as the main source of information, with a spatial resolution of 30 m and a data accuracy exceeding 85%. The different datasets used in this study correspond to the different time spans, namely 2000, 2005, 2010, 2015, 2017, and 2021.

2.3. Methods

Throughout agricultural production, emissions of greenhouse gases result from various sources, including direct field emissions, livestock respiration, and the storage of manure. However, agricultural crops simultaneously serve as carbon sinks, absorbing carbon dioxide. To comprehensively understand the impact of agriculture on carbon emissions and absorption, this study establishes a carbon account for the entire agricultural production process. Building upon this, a computational model is constructed. By leveraging the agricultural carbon effect, integrating both carbon emissions and absorption, an assessment and analysis of agricultural carbon effects across 17 townships in Guangshui City, Hubei Province, is conducted.

This section provides a detailed overview of the entire research process and methodology. The specific research process is illustrated in Figure 2.

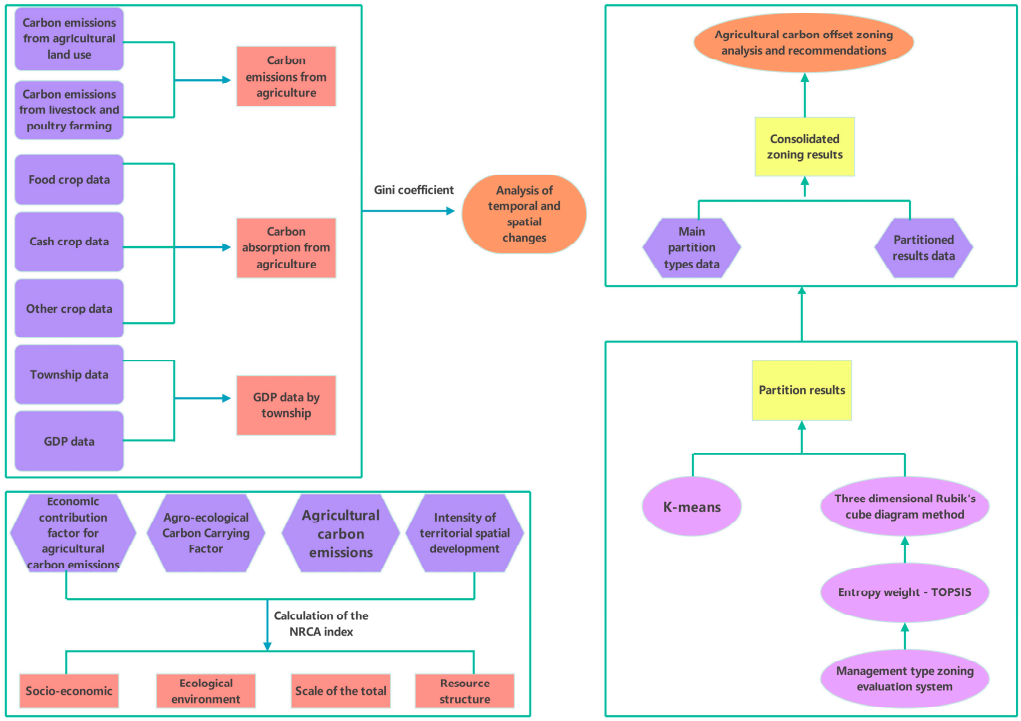

Figure 2. Research process. In Figure 2, bluedeep purple and pink represent the data and their interpretation, respectively. Light purple indicates the algorithms forming the model, yellow shapes represent the partition results, and orange represents further analysis.

2.3.1. Agricultural Carbon Emission Model

In theory, there exists a close relationship between agricultural carbon emissions and factors such as direct field emissions, livestock manure, and soil carbon storage. This study calculates the agricultural carbon emissions in the research area based on relevant research findings and in consideration of the actual conditions of the study area [31,32], focusing on two aspects as follows: direct field emissions and poultry and livestock manure.

The formula for calculating agricultural carbon emissions is as follows:

$$E = E_t + E_a \quad (1)$$

In the equation, E represents the total agricultural carbon emissions, while E_t and E_a represent the carbon emissions from direct field emissions and from poultry and livestock manure, respectively.

1. Calculation of direct field carbon emissions

In this study, the calculation of agricultural carbon emissions focuses on the following seven aspects: pesticides, fertilizers, agricultural films, effective irrigation area, the total power of agricultural machinery, plowing, and actual sowing area. These factors are combined with relevant carbon emission coefficients (Table 1) to calculate the agricultural carbon emissions. The calculation formula is as follows:

$$E_t = \sum q \times f_i \quad (2)$$

In the equation, E_t represents the total carbon emissions from agricultural land use, and q represents various factors in the research area, such as pesticides, fertilizers, agricultural films, effective irrigation area, the total power of agricultural machinery, and actual sowing area. Where the carbon emissions from agricultural machinery power are calculated as the sum of the following two terms: the product of the actual sowing area and the carbon emission coefficient for the sowing area, and the product of the agricultural machinery power and the carbon emission coefficient for the agricultural machinery power, where the plowing area is equal to the actual sowing area, and f_i represents the emission coefficient of the ith utilization mode.

In order to calculate the agricultural carbon emissions for each township, the total agricultural carbon emissions for the study area should be computed first. Then, these emissions should be associated with the corresponding spatial areas to calculate the agricultural carbon emissions for the respective land areas. The calculation formula is as follows:

$$E_i = \frac{E_t}{A} \times \sum A_j \quad (3)$$

where A represents the total area of the study region, E_t is the total agricultural carbon emissions for the study area, E_i represents the agricultural carbon emissions for the ith township grid, and A_j denotes the area of the jth patch within the ith grid.

Table 1. Carbon emission system of direct field emissions.

Source of Carbon Emissions	Emission Factor	Reference Source
Agrochemical	4.9341 kg(C)/kg	Oak Ridge National Laboratory, USA
Organic fertilizer	4.52 kg(C)/kg	Zhou J. et al. [33]
Agro-film	5.18 kg(C)/kg	China Agricultural University
Agricultural irrigation	19.8575 kg(C)/hm^2	Li Bo et al. [34]
Crop sown area	16.47 kg(C)/hm^2	Elhorst (2003) [35]
Gross power of agricultural machinery	0.18 kg(C)/KW	Elhorst (2003)
Plow	312.6 kg(C)/hm^2	China Agricultural University [36]

2. Calculation of Carbon Emissions from Poultry and livestock manure

Carbon emissions from poultry and livestock manure mainly include emissions from intestinal fermentation and feces. These emissions are calculated based on the corresponding emission coefficients [37] (Table 2). The calculation formula is as follows:

$$E_a = \sum_{i}^{n} N_{ai} \times (C1_{ai} + C2_{ai}) \times M_{CH4} \quad (4)$$

where E_a represents the total carbon emissions from poultry and livestock manure, i represents the type of livestock and poultry, N_{ai} represents the quantity of the ith type of livestock and poultry, and $C1_{ai}$ and $C2_{ai}$ represent the methane emission coefficients from intestinal fermentation and feces management, respectively, for the ith type of livestock and poultry. M_{CH4} represents the conversion coefficient of methane to carbon (6.82).

Table 2. Methane emission coefficients for livestock farming.

Animal	$C1_{ai}$	$C2_{ai}$	Animal	$C1_{ai}$	$C2_{ai}$
Pig	1	3.5	Cow	47	1
Sheep	5	0.16	Poultry	0	0.02
Horse	18	1.64	Donkey	10	0.9
Mule	10	0.9			

2.3.2. Agricultural Carbon Sequestration Model

In agricultural ecosystems, soil carbon storage typically exceeds that of crop vegetation. However, crop vegetation still represents a significant carbon reservoir with potential for expansion. When compared to crops, forests and grasslands exhibit more prominent carbon sequestration capabilities. Nevertheless, due to limited human intervention and inconsistent measurement standards, this study primarily focuses on narrow agriculture, specifically the carbon absorption of crops during their growth and development stages.

When calculating carbon absorption, this study selects agricultural crops from the following three aspects: grain crops, cash crops, and other crops [38–40]. The selected crop types mainly include maize, soybean, tuber crops, wheat, millet, cotton, oil crops, vegetables, and fruits. The carbon absorption of agricultural crops is calculated by combining various carbon absorption accounting coefficients (Table 3). The calculation formula is as follows:

$$C = \sum_{i}^{n} (C_i \times Q_i \times (1 - w_i)/H_i) \quad (5)$$

In the formula, C represents the total carbon absorption from agricultural crops, i represents the ith type of agricultural crop, C_i and Q_i represent the carbon absorption rate and the economic yield of the ith agricultural crop, respectively, and w_i and H_i represent the moisture content and economic coefficient of the ith agricultural crop [41,42].

Table 3. Calculation coefficients of crop carbon uptake (Unit: %).

Crop	Economic Factor	Carbon Sequestration Rate	Moisture Content
Sorghum	0.35	0.45	0.133
Maize	0.438	0.4709	0.13
Millet	0.4	0.45	0.12
Soybean	0.35	0.45	0.13
Wheat	0.434	0.4853	0.12
Oil plants	0.25	0.45	0.1
Cotton	0.1	0.45	0.08
Potato	0.675	0.4226	0.7
Vegetable	0.625	0.45	0.9
Melon and fruit	0.7	0.45	0.9

2.3.3. Model for Analysis of Agricultural Carbon Balance Characteristics

1. Agricultural carbon emissions Gini coefficient

The Gini coefficient is employed to measure the uniformity and regional disparities of specific indicators. In this study, the Gini coefficient method was utilized to assess the spatial disparities of agricultural carbon emissions in the research area [43,44]. The calculation formula is as follows:

$$Guni = \sum_{i} \sum_{j} \left| x_i - x_j \right| \div 2n^2 \overline{x} \quad (6)$$

In the formula, x_i represents the agricultural carbon emissions in region i, x_j represents the agricultural carbon emissions in region j, and n is the number of townships in the research area. The Gini coefficient ranges between 0 and 1, with larger values indicating greater disparities in agricultural carbon emissions between regions. A smaller Gini coeffi-

cient suggests smaller disparities in agricultural carbon emissions between regions, with 0.4 serving as the "warning line" for the Gini coefficient.

2. Agricultural Carbon Emission Economic Contribution Coefficient

The agricultural carbon emission economic contribution coefficient measures the differences in regional agricultural carbon emissions from the perspective of economic development, reflecting the magnitude of regional carbon productivity [45]. This coefficient is capable of assessing the contribution of agricultural carbon emissions to socio-economic benefits. The calculation formula is as follows:

$$ECC = \frac{G_i}{G} / \frac{C_i}{C} \tag{7}$$

In the equation, G_i represents the GDP of each township, C_i represents the agricultural carbon emissions of each township, G represents the total GDP of all townships in Guangshui City, and C represents the total agricultural carbon emissions of all townships in Guangshui City. If $ECC > 1$, it indicates that the economic contribution rate of Guangshui City is greater than the contribution rate of agricultural carbon emissions. Conversely, if $ECC < 1$, it indicates that the economic contribution rate of Guangshui City is less than the contribution rate of agricultural carbon emissions.

3. Carbon ecological carrying coefficient

The carbon ecological carrying capacity coefficient is used to measure the carbon compensation rate and the degree of carbon supply and demand imbalance in each township in the study area [46]. The calculation formula is as follows:

$$ESC = \frac{CA_i}{CA} / \frac{C_i}{C} \tag{8}$$

In the formula, CA_i represents the agricultural carbon absorption of each township, C_i represents the agricultural carbon emissions of each township, CA represents the total agricultural carbon absorption of all townships in Guangshui City, and C represents the total agricultural carbon emissions of all townships in Guangshui City. If ESC is greater than 1, it indicates that the agricultural carbon absorption contribution of Guangshui City exceeds its agricultural carbon emission contribution, demonstrating a higher agricultural carbon compensation rate. Conversely, if the ESC is less than 1, it indicates that the agricultural carbon emissions contribution of Guangshui City exceeds its agricultural carbon absorption contribution, suggesting a relatively lower agricultural carbon compensation rate.

2.3.4. Normalized Revealed Comparative Advantage Index

The standardization of the revealed comparative advantage index eliminates the bias resulting from varying country sizes [47]. This normalization enables a more precise assessment of a nation's competitive standing in international trade, offering a consistent metric for comparing the revealed comparative advantage across different countries. Typically, it serves as a measure of the competitive prowess of a specific product at the national or regional level. This index allows for a quantitative evaluation of regional situations from multiple perspectives. Drawing from the study by Yu et al. [48], this paper constructs a variable data system for the comprehensive compensation management types of Guangshui City from the four following aspects: agricultural carbon emissions, economic contribution coefficient of agricultural carbon emissions, carbon ecological carrying capacity, and land spatial development intensity (Table 4). The normalized revealed comparative advantage index is employed to calculate the comparative advantages of the following four indicators: total scale, socio-economic factors, ecological environment, and resource structure. The calculation formula is as follows:

$$NRCA_i^j = X_i^j / X - X_j X^i / XX \tag{9}$$

In the formula, X_i^j represents the indicator value of attribute j in township i; X_j represents the total sum of indicator values for attribute j across all townships; X^i represents the total sum of indicator values for all attributes in township i; X represents the total sum of indicator values for all townships and attributes; and attribute j includes the following four indicators: total scale, socio-economic factors, ecological environment, and resource structure.

Table 4. Variable data for carbon comprehensive compensation management zoning.

Descriptions	Factors	Years	Sources
Socio-economic attribute indicators	Economic contribution factor for agricultural carbon emissions	2000–2021	(GDP per township/total GDP of GWS)/(Agricultural carbon emissions per township/total agricultural carbon emissions of GWS)
Ecological environment attribute indicators	Agro-ecological carbon carrying factor	2000–2021	(Agricultural carbon absorption in each township/total agricultural carbon absorption in GWS)/(Agricultural carbon emissions in each township/total agricultural carbon emissions in GWS)
Scale of the total attribute indicators	Agricultural carbon emissions	2000–2021	Carbon emissions from agricultural land use + Carbon emissions from livestock farming
Resource structure attribute indicators	Intensity of territorial spatial development	2000–2021	Building land area/total area

2.3.5. A Method for Agricultural Carbon Comprehensive Compensation and Management Zoning Based on K-means and Three-Dimensional Enchantment Approach

Optimizing agricultural carbon compensation zoning is essential for the sound management of agricultural carbon compensation mechanisms. In order to further investigate the comprehensive agricultural carbon compensation management zoning in Guangshui City, this study referred to the research by Wang et al. [49]. Considering the realism and accessibility of the data, the study focused on three main aspects as follows: socio-economic factors, resource utilization, and ecological environment. The socio-economic category includes the average GDP per locality, population density, urbanization rate, and economic density. The resource utilization category encompasses the per capita arable land area, per capita area of grain crops, and per capita area of economic crops. The ecological environment category consists of the per capita carbon emissions, average carbon absorption per locality, and average carbon sequestration per locality. In combining these factors with the actual situation of the study area, an evaluation index system tailored to regional characteristics was constructed (Table 5). The data of the indicator system were calculated using the entropy weight-TOPSIS method in this study [50–54], with the social economy, resource utilization, and ecological environment representing the X-axis, Y-axis, and Z-axis, respectively. Subsequently, the three-dimensional magic cube graph method was employed to link the comprehensive compensation types of agricultural carbon in Guangshui City with the spatial land-use zoning, establishing a $4 \times 4 \times 4$ three-dimensional spatial coordinate axis and grading the data accordingly (Table 6). The zoning criteria were determined in order of absolute advantage and relative advantage (Table 7).

When the element grades in the three-dimensional magic cube spatial coordinates (a, b, c) are all not higher than 2, the category is referred to as a low-carbon control zone. This indicates that all three categories in the study area are in an absolute disadvantage state, necessitating the continued maintenance of the regional carbon balance. When there is only one category level at 3 in the three-dimensional magic cube spatial coordinates (a, b, c), and the levels of other categories are all less than 2, the category is termed as a low-carbon optimization zone. This suggests that one of the categories in the study area is in a relative advantage state, and economic development should be maintained in harmony without sacrificing agricultural carbon emissions. When the level of one category in the three-dimensional magic cube spatial coordinates (a, b, c) is 4, and the levels of other categories are all less than 3, the category is called a low-carbon emission reduction

zone. This indicates that one of the categories in the study area is in an absolute advantage state, necessitating the corresponding measures to reduce agricultural carbon emissions. Additionally, based on the research results and the relationship between the regional carbon balance, a theoretical framework for the zoning of comprehensive carbon compensation management in Guangshui City, Hubei Province, is constructed (Figure 3).

Table 5. Evaluation index system for carbon comprehensive compensation management zoning.

Destination Layer	Standardized Layer	Indicator Layer	Description of Indicators	Attributes
Evaluation of management type zoning	Socio-economic	The average GDP per locality	GDP by township	+
		Population density	Number of people per unit area of land	-
		Urbanization rate	Share of urban population in total population (%)	-
		Economic density	Ratio of township GDP to regional area	+
	Resource utilization	Cultivated land area per capita	Ratio of cultivated land area to population in a township	+
		Food crop area per capita	Ratio of grain crop area to population in township	+
		Cash crop area per capita	Ratio of cash crop area to population in township	+
	Ecological environment	Carbon emissions per capita	Ratio of carbon emissions to population	-
		Average carbon absorption per locality	Ratio of carbon absorption to land area (t/km^2)	+
		Average carbon sequestration per locality	Ratio of carbon sink to land area (t/km^2)	+

Table 6. Evaluation levels of carbon comprehensive compensation management zoning.

Grade Level	Differential Level	General Level	Good Level	Excellent Level
Close degree	0.00–0.30	0.31–0.60	0.61–0.80	0.81–1.00

Table 7. Standards for carbon comprehensive compensation management zoning.

Management Type Partition	Subsystem Element Type	Three-Dimensional Rubik's Cube Unit
Low-carbon control zone (LCCZ)	Tripartite restricted area	(x, y, z) ϵ [1,2]
	Social and economic development area	(3, y, z) $1 \leq$ y, z $\leq$2 (x, 3, z) $1 \leq$ x, $z \leq 2$
Low-carbon optimization zone (LCOZ)	Rational use of resources	(x, y, 3) $1 \leq x, y \leq 2$
	Ecological environment protection area	(4, y, z) $1 \leq y, z \leq 3$
	Social and economic development area	(x, 4, z) $1 \leq x, z \leq 3$
Low-carbon emission reduction zone (LCERZ)	Rational use of resources Ecological environment protection area	(x, y, 4) $1 \leq x, y \leq 3$

The framework and implementation strategy of the agricultural carbon compensation zoning model studied in this paper are both illustrated in Figure 4. The specific operational steps are as follows:

Step 1: Based on the standardized dominant comparative advantage indices, the original data are processed to obtain the indices of comparative advantages for various attributes of carbon comprehensive compensation management zoning (Table 8).

Step 2: The K-means algorithm is employed to cluster the indices of comparative advantages for various attributes. Appropriate clustering numbers are selected, and experimental operations and parameter adjustments are conducted to output zoning types.

Step 3: The three-dimensional magic method is utilized to map the data into a high-dimensional space. Suitable kernel functions are chosen, and experimental analysis and adjustments are carried out to obtain classification results.

Step 4: The classification results are analyzed and interpreted, providing further insights into the experimental data.

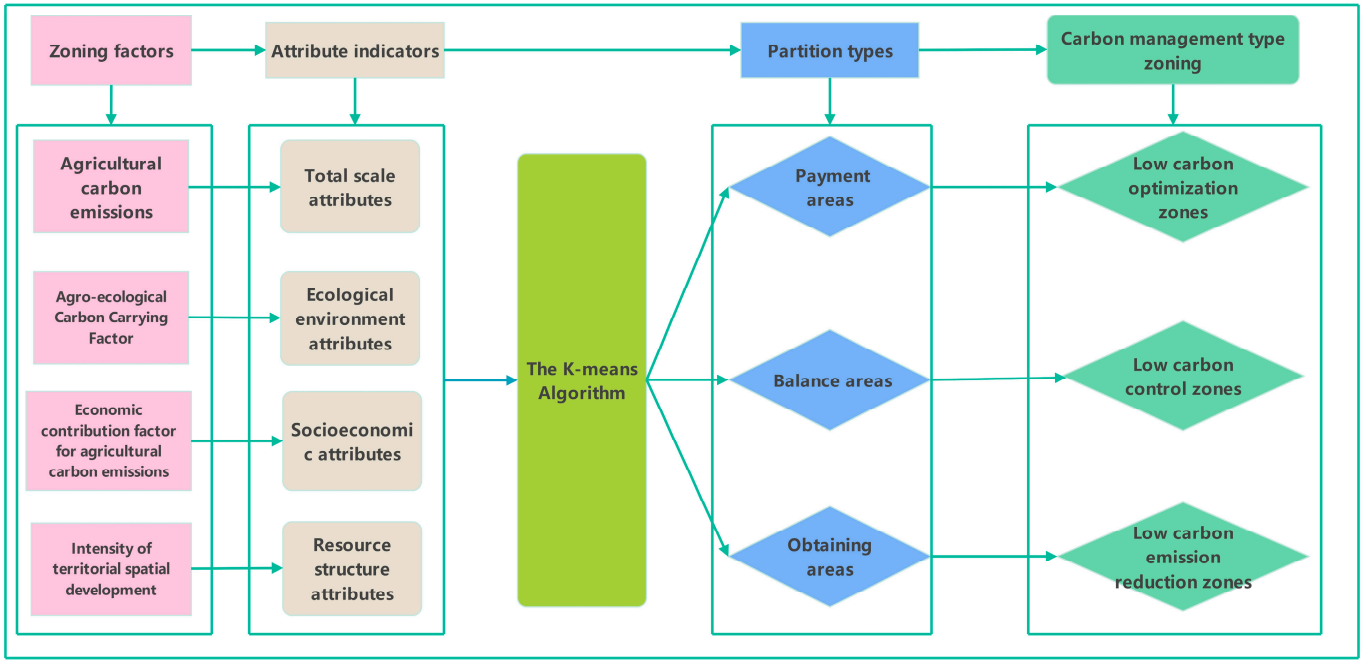

Figure 3. Theoretical framework.

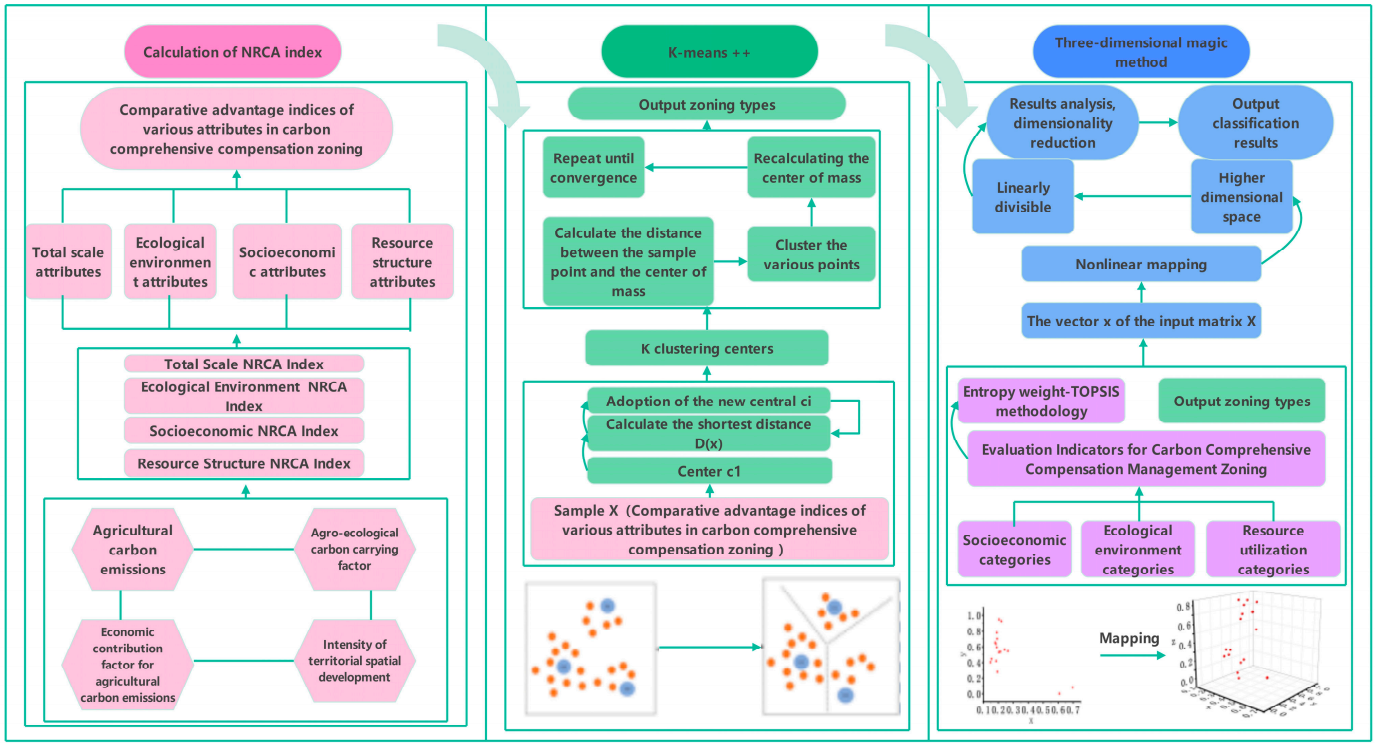

Figure 4. Structure of agricultural carbon compensation zoning model.

Table 8. Comparative advantage indices of various attributes in carbon comprehensive compensation zoning in Guangshui City.

Townships	Total Scale Attributes	Ecological Environment Attributes	Socioeconomic Attributes	Resource Structure Attributes
Changling township	0.98%	0.30%	−1.26%	−0.02%
Yudian township	1.04%	0.29%	−1.31%	−0.02%
Haodian township	1.14%	0.06%	−1.18%	−0.02%
Lidian township	−0.03%	1.63%	−1.59%	−0.01%
Luodian township	0.05%	1.56%	−1.59%	−0.01%
Maping township	0.25%	0.51%	−0.77%	0.00%
Yingshan district	−4.87%	−5.69%	10.27%	0.29%
Guangshui district	−2.14%	−4.02%	6.21%	−0.05%
Yangzhai township	−0.18%	1.34%	−1.14%	−0.02%
Guanmiao township	0.46%	0.84%	−1.28%	−0.02%
Wushenguan township	0.62%	−0.25%	−0.34%	−0.02%
Chengjiao district	−0.35%	0.47%	−0.10%	−0.02%
Wudian township	1.11%	0.01%	−1.12%	0.00%
Chenxiang township	0.31%	1.06%	−1.34%	−0.02%
Taiping township	−0.17%	1.63%	−1.42%	−0.04%
Caihe township	1.26%	0.06%	−1.30%	−0.02%

3. Results

3.1. The Spatiotemporal Characteristics of Agricultural Carbon Emissions Accounting

The temporal variation of agricultural carbon emissions in the study area from 2000 to 2021 exhibits a trend of initially increasing followed by decreasing (Figure 5). Specifically, Yingshan District has relatively low agricultural carbon emissions, with the total emissions remaining below 10,000 tons. Conversely, Changling Town, Yudian Town, Haodian Town, Caihe Town, and Wudian Town have higher and rapidly increasing agricultural carbon emissions, all exceeding 50,000 tons. Among them, Caihe Town has the highest total agricultural carbon emissions at 68,650 tons, followed by Changling Town with 60,760 tons. The agricultural carbon emissions of other townships have relatively slow growth rates.

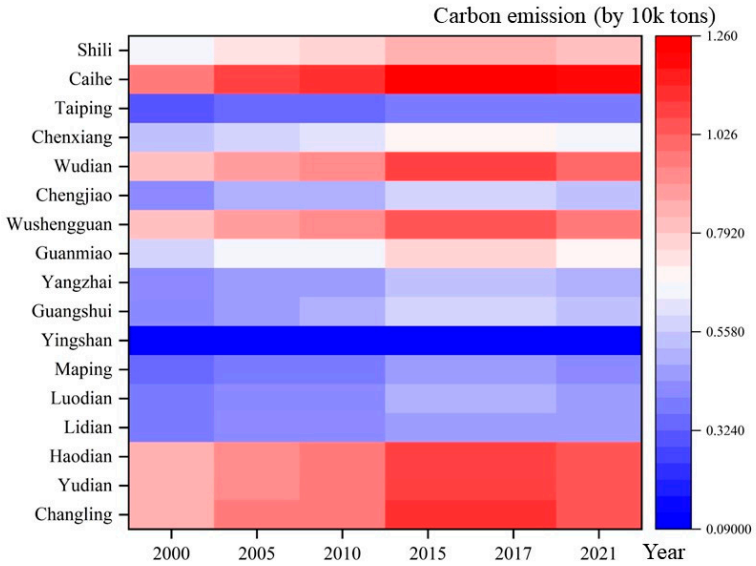

Figure 5. Agricultural carbon emissions in Guangshui City from 2000 to 2021 (10^4 t).

The spatial variation of agricultural carbon emissions in the study area (Figure 6) reveals the following trends: (1) From 2000 to 2010, the change in agricultural carbon emissions in Guangshui City was relatively moderate. Three areas, including relatively high-, medium-, and low-carbon emission zones, transitioned into high-, relatively high-, and medium-carbon emission zones, respectively. This transition mainly occurred in the northeastern, central, and southern marginal areas of the study area, with particularly significant changes being

observed in Caihe Town, Shili District, and Taiping Town. (2) From 2010 to 2017, there was a relatively significant change in agricultural carbon emissions in Guangshui City, with a slight increase in medium-carbon emission zones and a significant increase in high-carbon emission zones, exhibiting a spatial differentiation characterized by higher emissions in the northwest and lower emissions in the southeast, with significant regional differences. Prominent changes were observed in the northern and northeastern areas, particularly in Wudian Town, Yudian Town, Haodian Town, Wushengguan Town, and Changling Town. (3) From 2017 to 2021, there was a slight increase in medium-carbon emission zones and relatively high-carbon emission zones in Guangshui City, while the total carbon emissions in high- and relatively high-carbon emission zones showed a significant decrease, transitioning into relatively high- and medium-carbon emission zones, respectively. These transitions primarily occurred in the northern, southern marginal, and eastern areas of the study area, mainly involving Wudian Town, Chenxiang Town, and Wushengguan Town. Overall, Yudian Town, Changling Town, Haodian Town, and Caihe Town are the main areas of agricultural development in Guangshui City, characterized by a high population density, frequent agricultural production activities, and limited ecological land, resulting in large and rapidly increasing agricultural carbon emissions. Yingshan District is the main economic development area of Guangshui City, with a relatively developed secondary and tertiary industry and comparatively less incremental agricultural carbon emissions.

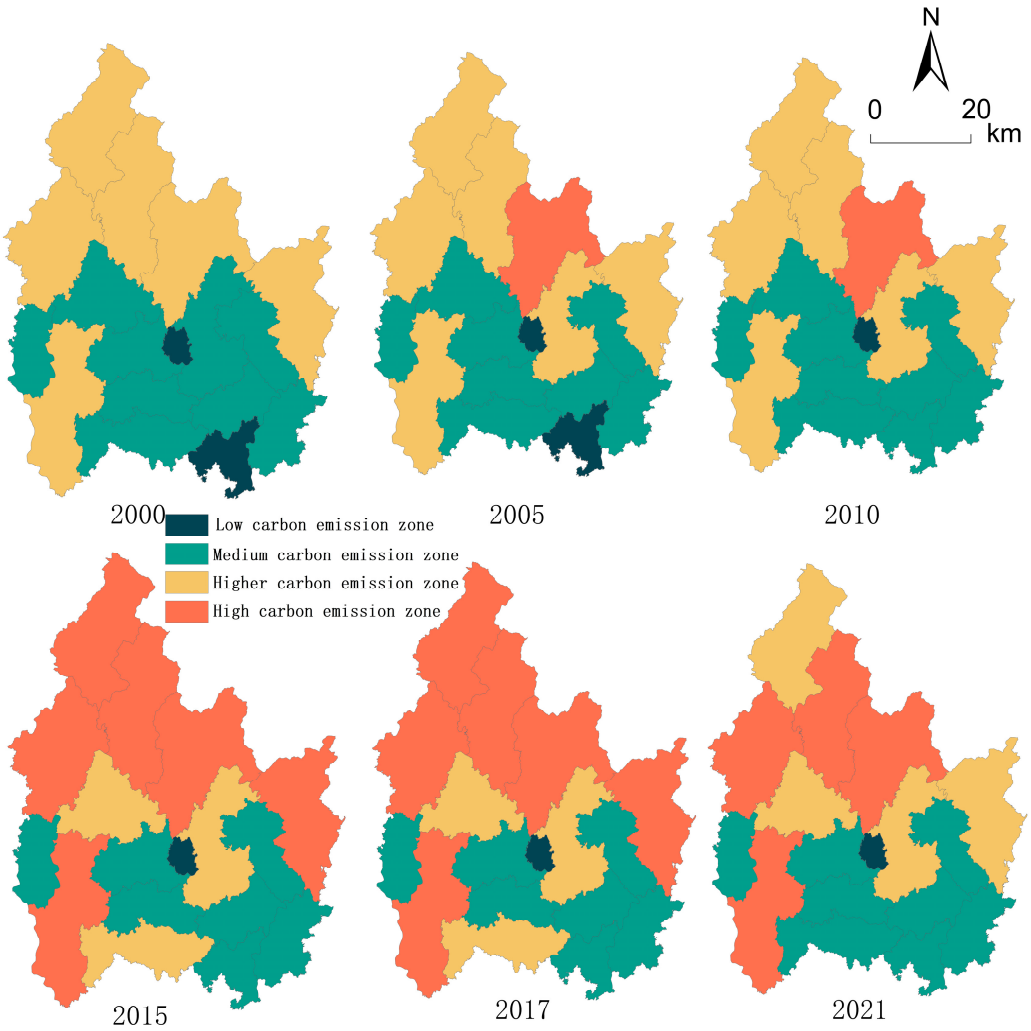

Figure 6. Spatial distribution of agricultural carbon emissions in Guangshui City from 2000 to 2021 (10^4 t).

3.2. The Spatiotemporal Characteristics of Agricultural Carbon Absorption Accounting

According to calculations based on the agricultural carbon absorption model, the average annual agricultural carbon absorption in the study area from 2000 to 2021 was 519,200 tons, increasing from 440,600 tons in 2000 to 530,100 tons in 2021, with a net increase of 89,400 tons (Figure 7). Based on the spatial distribution of agricultural carbon absorption in the study area during different periods (Figure 8), the temporal variation of agricultural carbon absorption can be divided into two stages as follows: (1) From 2000 to 2010, the overall spatial-temporal distribution of agricultural carbon absorption in Guangshui City exhibited a "high in the southwest, low in the northeast" pattern, with significant regional differences. Significant changes were observed in the southwestern areas, including Changling Town, Guanmiao Town, Caihe Town, and Luodian Town, which underwent transitions from "relatively high carbon absorption to high carbon absorption". Some areas experienced minor fluctuations, such as the southern marginal areas, which underwent transitions from "relatively high carbon absorption to medium carbon absorption" and from "high carbon absorption to relatively high carbon absorption". (2) From 2010 to 2021, the southeastern areas, including Wushengguan Town, Lidian Town, Caihe Town, and Taiping Town, experienced a regression process from "high carbon absorption to relatively high carbon absorption" and from "relatively high carbon absorption to medium carbon absorption". The carbon absorption levels in other areas remained relatively stable, showing no significant trend.

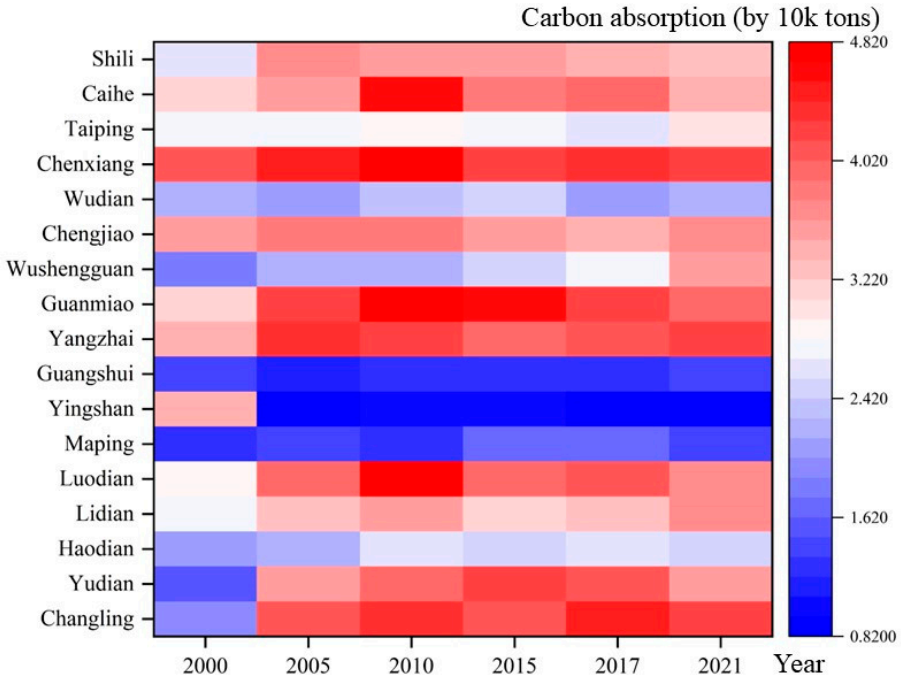

Figure 7. Agricultural carbon absorption in Guangshui City from 2000 to 2021 (10^4 t).

The carbon absorption of crops in the study area from 2000 to 2021 is shown in Figure 9. The carbon absorption of grain crops exhibited a trend of initially increasing followed by decreasing, reaching its peak of 422,100 tons in 2010 and gradually decreasing to 365,500 tons in 2021. This indicates the country's emphasis on food security strategies, resulting in a significant increase in the arable land area and agricultural carbon absorption. The carbon absorption of economic crops generally showed a slight fluctuating upward trend, increasing from 49,100 tons in 2000 to 98,400 tons in 2021. Other types of crops, being less significant in agricultural production, exhibited a stable trend with relatively low carbon absorption levels.

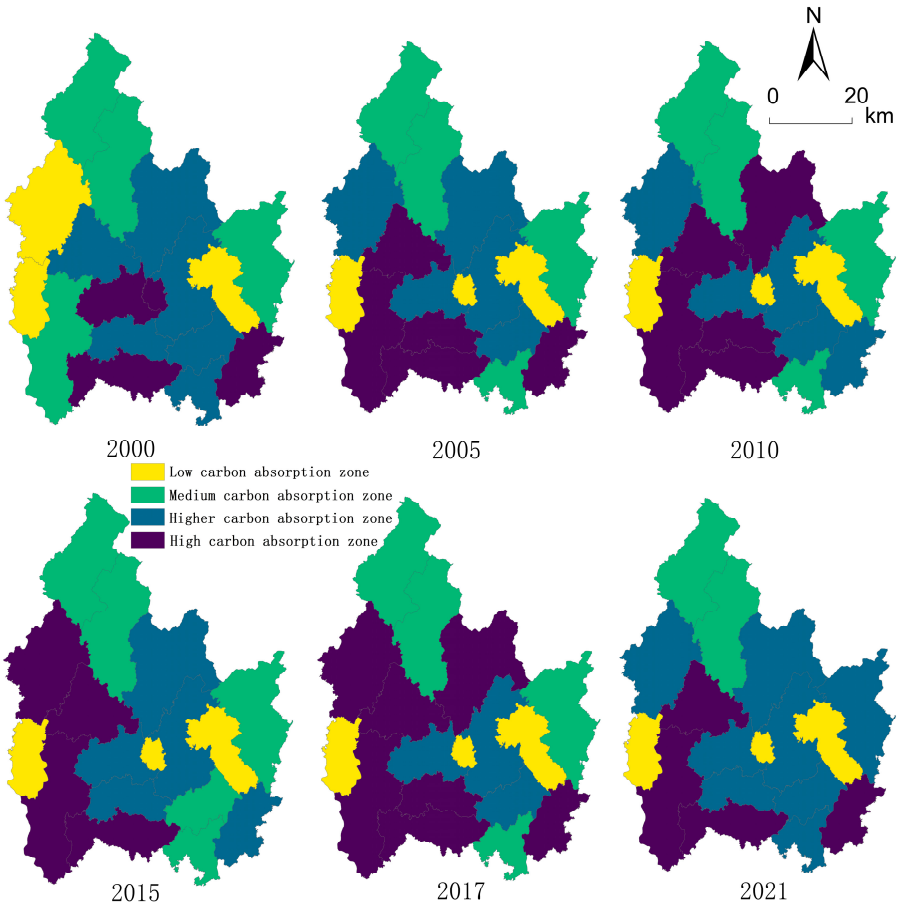

Figure 8. Spatial distribution of agricultural carbon absorption in Guangshui City from 2000 to 2021 (10^4 t).

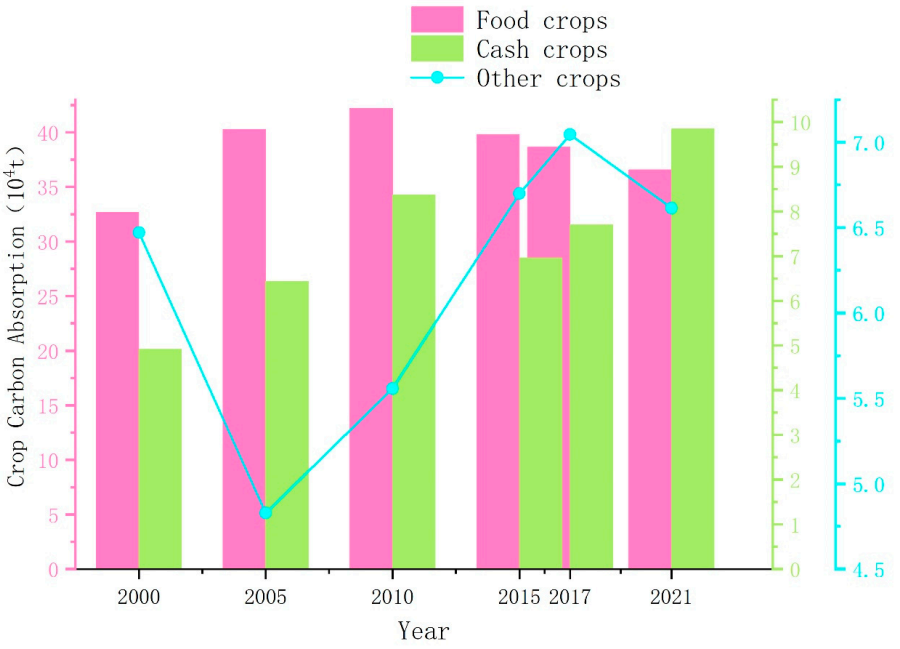

Figure 9. Carbon absorption of major crops in Guangshui City from 2000 to 2021 (10^4 t).

3.3. The Characteristics of Agricultural Carbon Balance

Based on the calculation of the agricultural carbon emission Gini coefficient model in the study area, the average Gini coefficient of agricultural carbon emissions from 2000 to 2021 was 0.24, with a fluctuation range between 0.2407 and 0.2410. Due to the

relatively micro-scale of the study area, the agricultural carbon emission Gini coefficient has remained stable, indicating that the agricultural carbon emissions of various townships in the study area are at a relatively even level. This demonstrates a relatively balanced development of various aspects including socio-economic, resource, and ecological environments in the process of development.

The agricultural carbon emission economic contribution coefficient represents the contribution rate of agricultural carbon emissions to the socio-economic aspects (Figure 10). The coefficient in Guangshui City from 2000 to 2021 ranged from 0.04 to 16.1, indicating significant differences in the level of agricultural carbon emissions and economic contribution among townships. The economically relatively backward areas such as Wudian Town, Yudian Town, Haodian Town, and Caihe Town in the northern and western peripheries of the study area, due to their remote locations and uneven resource distribution, have not been able to generate large-scale economic benefits, resulting in agricultural carbon emission economic contribution coefficients less than 1. Townships with agricultural carbon emission economic contribution coefficients greater than 1 are concentrated in the central part of the study area, particularly in economically developed areas such as Guangshui District, Yingshan District, and Chengxiang District, revealing their higher resource utilization rates in the city center, capable of generating significant economic benefits. Among the townships with agricultural carbon emission economic contribution coefficients greater than 1, Yingshan District and Guangshui District demonstrate higher economic contribution levels. The reason lies in their advantageous geographical locations, situated in the core of Guangshui City with concentrated resources and relatively developed industries, accounting for nearly half of the city's GDP, thus contributing significantly to economic benefits.

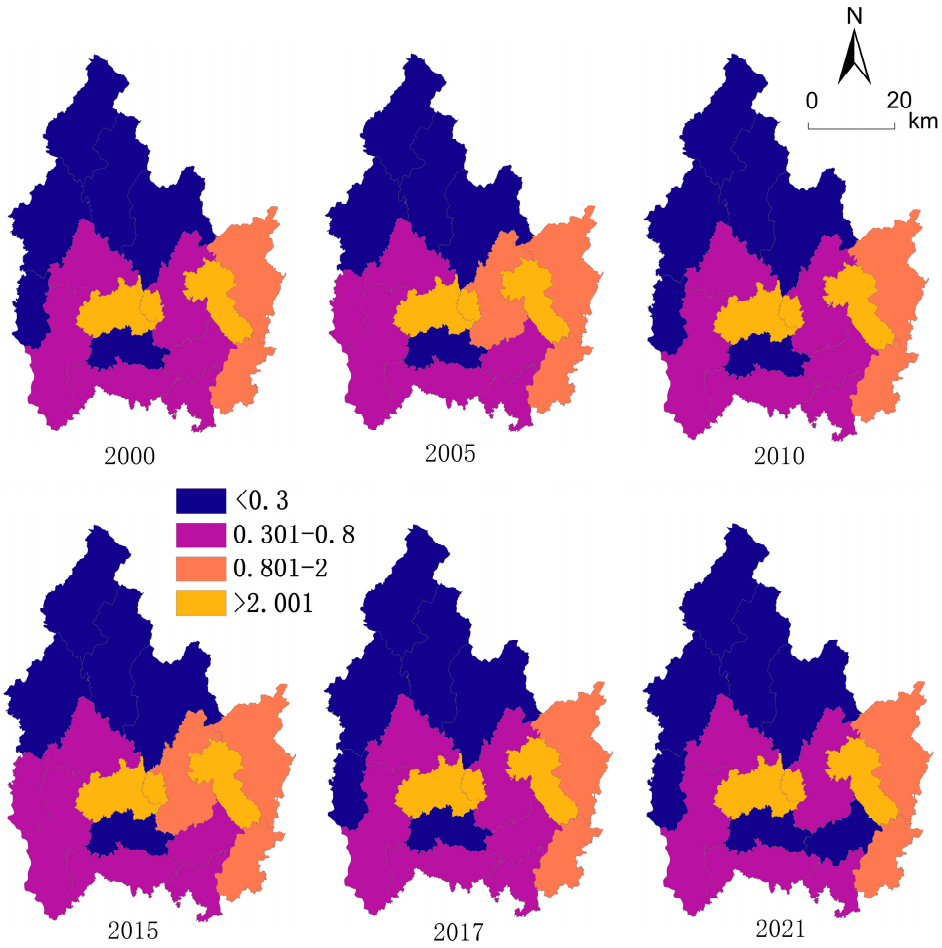

Figure 10. Economic contribution coefficients of agricultural carbon emissions in Guangshui City from 2000 to 2021.

The carbon ecological carrying capacity coefficient represents the carbon absorption capacity of various townships in the study area. In Guangshui City, the coefficient from 2000 to 2021 ranged from 0.39 to 1.99, indicating significant differences in the carbon supply and demand levels among townships (Figure 11). Specifically, townships in the northern and central areas of the study area all have carbon ecological carrying coefficients less than 1, mainly including Wudian Town, Haodian Town, Caihe Town, Guangshui District, and Wushengguan Town, indicating that the carbon emission contribution rate exceeds the carbon absorption contribution rate, indicating a relatively low carbon compensation rate. Conversely, townships in the southern areas represented by Lidian Town, Yangzhai Town, Taiping Town, and Luodian Town all have carbon ecological carrying coefficients greater than 1, indicating a strong carbon sink capacity.

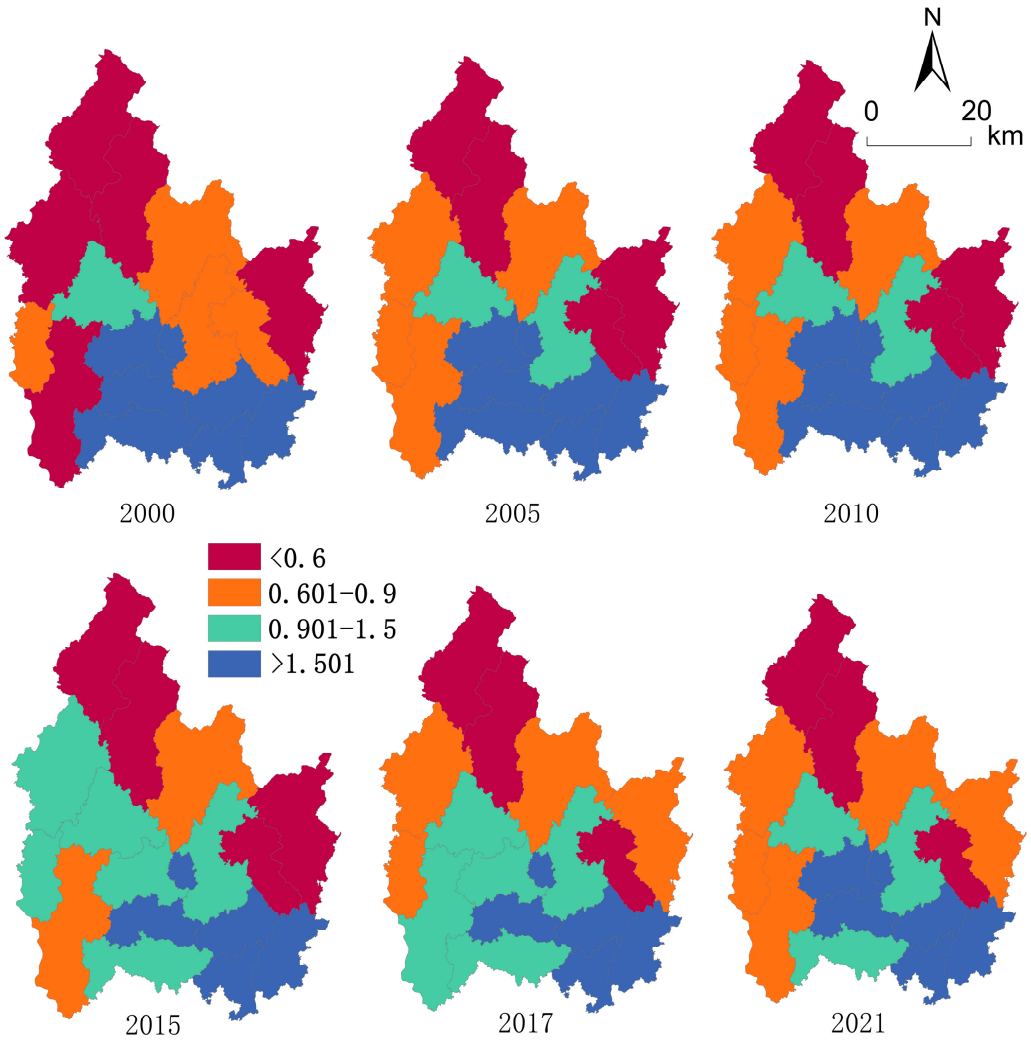

Figure 11. Ecological carrying coefficients of agricultural carbon emissions in Guangshui City from 2000 to 2021.

3.4. The Zoning of Comprehensive Agricultural Carbon Compensation in the Study Area

Based on the index system of comprehensive agricultural carbon compensation management zoning and the actual situation of the study area, the agricultural carbon compensation management zoning of each township in Guangshui City is conducted, as shown in Figure 12.

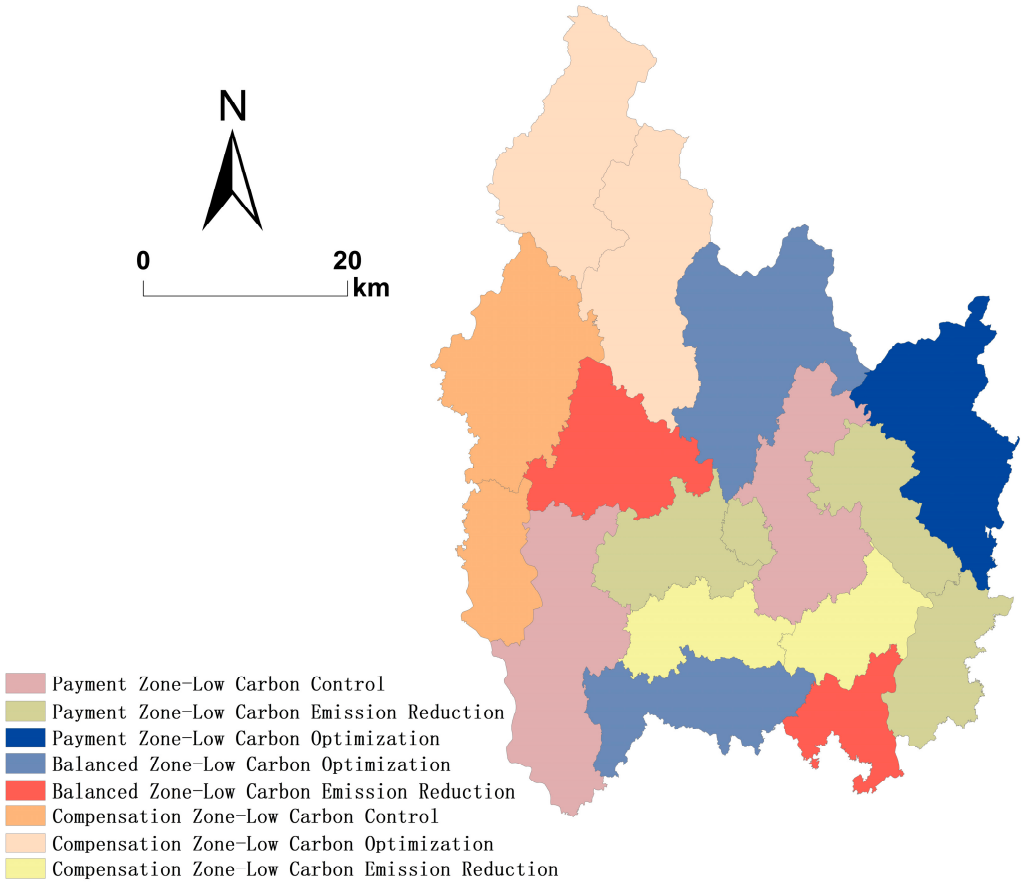

Figure 12. Zoning for agricultural carbon compensation management in Guangshui City.

3.4.1. Payment Zone

The payment zone refers to the area where compensation payments for agricultural carbon offsetting actions need to be made through economic or non-economic means. This area is mainly located in the central, southeastern, and southwestern parts of the study area (accounting for 88% of the GDP of the research area), including low-carbon emission reduction zones, low-carbon control zones, and low-carbon optimization zones, with a relatively high level of economic development. Overall, there is a severe mismatch between the economic contribution level of agricultural carbon emissions and the carbon emission ecological carrying capacity in the payment zone.

(1) Payment Zone—Low-Carbon Emission Reduction Zone

Yangzhai Town, Chengxiang District, Yingshan District, and Guangshui District account for a high proportion of GDP in Guangshui City, reaching 69%. Despite their relatively good economic development, their agricultural carbon emission economic contribution and carbon ecological carrying capacity are severely imbalanced. Therefore, Yangzhai Town, Chengxiang District, Yingshan District, and Guangshui District are designated as agricultural carbon comprehensive compensation payment zones. From the measurement results of the social–economic subsystem (Figure 13), the closeness degrees of the four regions are 0.19, 0.24, 0.61, and 0.70, respectively. From the measurement results of the resource utilization subsystem, the closeness degrees are 0.59, 0.56, 0, and 0.08, respectively. From the measurement results of the ecological environment subsystem, the closeness degrees are 0.9, 0.76, 0.92, and 0.28, respectively. Guangshui District, Yingshan District, and other townships have a closeness level of 4 in the social–economic subsystem, indicating an absolute advantage, but they are in a disadvantaged position in the ecological environment system with a poor carbon absorption capacity. Yangzhai Town, Chengxiang District, Yingshan District, and Guangshui District are areas with relatively high levels of

economic development and urban construction in Guangshui City. Agricultural carbon emissions make a significant contribution to the economy, thus designating them as agricultural carbon comprehensive compensation payment zones and low-carbon emission reduction zones.

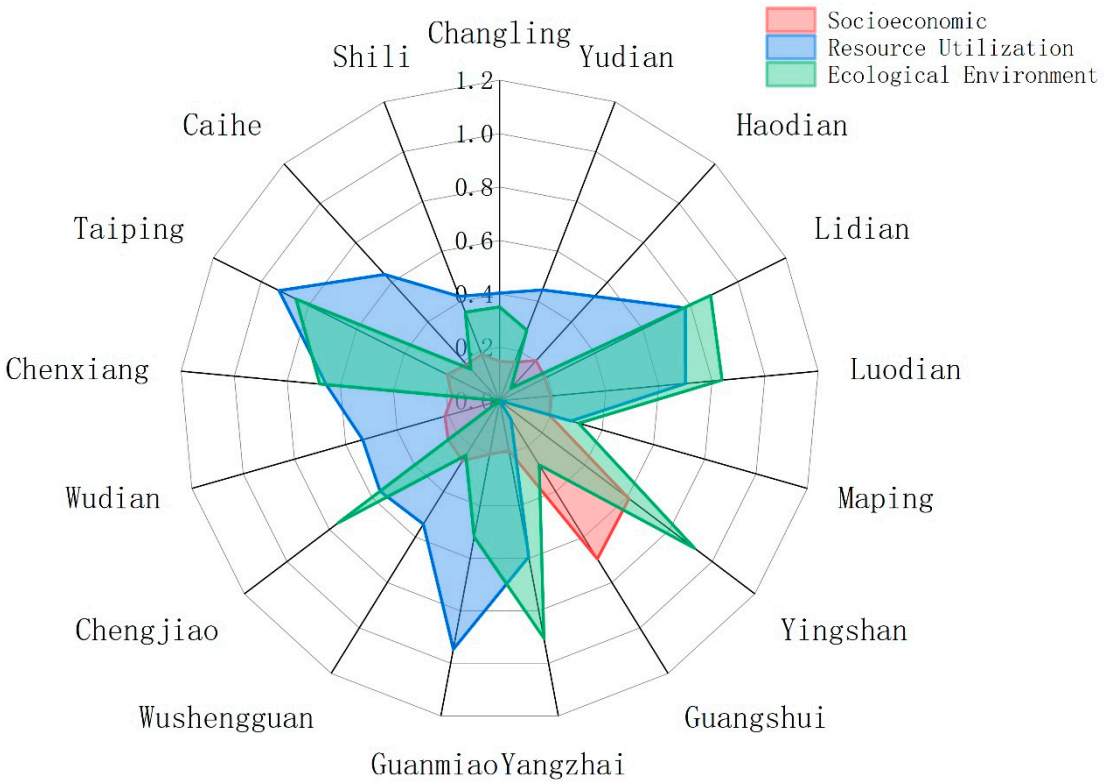

Figure 13. Measurement results of the three major subsystems in Guangshui City.

(2) Payment Zone—Low-Carbon Control Zone

Changling Town and Shili District have GDP levels in Guangshui City that are relatively moderate to high, indicating good economic development. The economic contribution of agricultural carbon emissions is relatively balanced with the carbon ecological carrying capacity. Therefore, Changling Town and Shili District are designated as agricultural carbon comprehensive compensation payment zones. From the perspective of the social–economic subsystem (Figure 13), their closeness degrees are 0.15 and 0.19, respectively. According to the calculation results of the resource–environment subsystem, their closeness degrees are 0.4 and 0.42, respectively. Combining the calculation results of the ecological environment subsystem, the closeness degrees are 0.35 and 0.36, respectively.

The closeness levels of this area are all below two. Therefore, Changling Town and Shili District are designated as agricultural carbon comprehensive compensation payment zones and low-carbon control zones, indicating that this area is relatively stable in terms of ecology, economy, and resources.

(3) Payment Zone—Low-Carbon Optimization Zone

Wushengguan Town ranks third in GDP in Guangshui City, indicating good economic development. However, the land space utilization is relatively low in this area. The carbon emissions in the agricultural sector are relatively low, while agricultural carbon absorption is high. There exists an imbalance between the economic contribution of agricultural carbon emissions and the carbon ecological carrying capacity. Therefore, Wushengguan Town is designated as an agricultural carbon comprehensive compensation payment zone based on the classification of carbon comprehensive compensation management types. Through the analysis of the three subsystems of social economy, resource utilization, and ecological

environment (Figure 13), the closeness degrees are 0.26, 0.54, and 0.24, respectively. Among the three subsystems, the resource utilization subsystem in Wushengguan is rated level 3 in terms of closeness. The utilization rate of resources and the economic contribution rate in the township are relatively high, and its geographical location is advantageous. This area is designated as both an agricultural carbon comprehensive compensation payment zone and a low-carbon optimization zone.

3.4.2. Balance Zone

A balanced zone refers to an area in agricultural carbon compensation activities where no payment is required, and no compensation is received. This area is mainly located in the southern and southwestern parts of the research area (accounting for 6.9% of the GDP in the research area), including low-carbon emission reduction zones and low-carbon optimization zones. The economic development level of this area is moderate.

(1) Balanced Zone—Low-Carbon Emission Reduction Zone

The GDP of Guanmiao Town and Taiping Town is at a moderate level in Guangshui City, but there is a significant gap between agricultural carbon emissions and carbon absorption. Due to the severe imbalance between their economic contribution and carbon ecological carrying capacity, Guanmiao Town and Taiping Town are designated as carbon comprehensive compensation balanced zones. In the division of agricultural carbon comprehensive compensation management types, according to the calculation results of the social–economic subsystem (Figure 13), the proximity degrees of these areas are 0.2 and 0.22, respectively; based on the measurement results of the resource–environment subsystem, the proximity degrees are 0.95 and 0.92, respectively; according to the measurement results of the ecological environment subsystem, the proximity degrees are 0.52 and 0.85, respectively. It can be seen that the proximity grades of the resource utilization subsystem in Guanmiao Town and Taiping Town are both four; however, the proximity grades of the other two subsystems are relatively low. Therefore, this area can be defined as a balanced zone for agricultural carbon comprehensive compensation and a low-carbon emission reduction zone.

(2) Balanced Zone—Low-Carbon Optimization Zone

The GDP of Chenxiang Town and Caihe Town are both at a moderate level in Guangshui City. They have less agricultural emissions but more carbon absorption in agriculture. Due to the imbalance between economic contribution and carbon ecological load, these two towns are classified as carbon comprehensive compensation balanced zones. In the division of agricultural carbon comprehensive compensation management types, according to the measurement results of the social–economic subsystem (Figure 13), the proximity degrees of these areas are 0.18 and 0.18, respectively; based on the measurement results of the resource–environment subsystem, the proximity degrees are 0.65 and 0.64, respectively; according to the measurement results of the ecological environment subsystem, the proximity degrees are 0.68 and 0.16, respectively. In the three subsystems, the resource utilization measurement grade is three, which is in a relatively advantageous position when compared to the measurement grades of the social–economic and ecological environment, indicating that this area is a balanced zone for agricultural carbon comprehensive compensation and a low-carbon optimization zone.

3.4.3. Compensation Zone

A compensation zone refers to the areas that receive economic or non-economic compensation in agricultural carbon compensation activities. These areas are mainly located in the western, northern, and central parts of the research area (accounting for 4.3% of the GDP of the research area), including low-carbon emission reduction zones, low-carbon control zones, and low-carbon optimization zones, where the economic development level is relatively backward.

(1) Compensation Zone—Low-Carbon Emission Reduction Zone

Lidian Town and Luodian Town are located in the southern part of the research area, with relatively underdeveloped economies, and their GDP levels are below average in Guangshui City. There is a significant imbalance between economic contribution and the carbon ecological carrying capacity. Therefore, Lidian Town and Luodian Town are identified as carbon comprehensive compensation receiving zones. In the zoning of agricultural carbon comprehensive compensation management, according to the measurement results of the social–economic subsystem (Figure 13), the proximity of these two areas is 0.19. From the perspective of the resource–environment subsystem's measurement results, the proximity is 0.78 and 0.7, respectively. As for the ecological environment subsystem's measurement results, the proximity is 0.88 and 0.84, respectively. In terms of the measurement grades of the three major subsystems, the ecological environment measurement grades of these areas are four, indicating an absolute advantage. Therefore, these areas are designated as agricultural carbon comprehensive compensation receiving zones and low-carbon emission reduction zones.

(2) Compensation Zone—Low-Carbon Control Zone

Yudian Town and Maping Town are located on the edge of the western part of the research area, with lagging economic development and low agricultural carbon emissions but relatively high agricultural carbon absorption. This leads to a significant imbalance between the economic contribution of agricultural carbon emissions and the carbon ecological carrying capacity. Therefore, Yudian Town and Maping Town are identified as agricultural carbon comprehensive compensation receiving zones. In the zoning of agricultural carbon comprehensive compensation management, according to the measurement results of the social–economic subsystem (Figure 13), the proximity of these two areas is 0.15 and 0.19, respectively. From the perspective of the resource–environment subsystem's measurement results, the proximity is 0.44 and 0.28, respectively. Finally, from the ecological environment subsystem's measurement results, the proximity of Yudian Town and Maping Town is 0.28 and 0.31, respectively. The measurement results of these two areas in the three important subsystems are all below two, indicating that their resource utilization and ecological environment subsystems are relatively backward. Therefore, these two areas are classified as agricultural carbon comprehensive compensation receiving zones and low-carbon control zones.

(3) Compensation Zone—Low-Carbon Optimization Zone

The northern part of the research area includes Haodian Town and Wudian Town. These two areas have relatively backward economic development, and there is a significant imbalance between their carbon emission economic contribution and carbon ecological carrying capacity. Therefore, they are identified as areas in need of carbon comprehensive compensation. According to the zoning results of agricultural carbon comprehensive compensation management, in terms of the social–economic subsystem, the proximity of the two areas is 0.2 and 0.21, respectively. From the perspective of the resource–environment subsystem, the proximity of both areas is 0.53. As for the ecological environment subsystem, the proximity is 0.06 and 0, respectively. In the measurement grades of the three major subsystems, the resource utilization proximity grades of Haodian Town and Wudian Town are both three, which are relatively higher than other subsystem proximity grades, indicating a more favorable position. Therefore, they are classified as agricultural carbon comprehensive compensation receiving zones and low-carbon optimization zones.

4. Discussion

4.1. Innovation

This paper explores the background of prioritizing ecological conservation and achieving the strategic goal of "dual carbon" [55–58], proposing a novel model for agricultural carbon compensation zoning to plan the agricultural carbon compensation areas at the

township level. This study provides a more effective reference for future similar research. Additionally, the innovation of this study mainly results from the two following aspects:

(1) At the township level, this paper optimizes the index system for comprehensive agricultural carbon compensation zoning and derives the zoning results for Guangshui City, Hubei Province, China. Current research on agricultural carbon compensation zoning in China mainly focuses on the macro scale of national and provincial levels and the meso scale of city and county levels, with little attention to the township level. Focusing on Guangshui City, located in the primary grain-producing area of northern Hubei Province, this study offers a more micro spatial scope. Compared with the macro scale, research on agricultural carbon emissions at the township level has significant advantages and features, enabling a more accurate exploration of the spatial distribution and patterns of agricultural carbon emissions in Guangshui City.

(2) From the perspective of research, firstly, current studies on carbon compensation zoning mainly focus on the zoning of carbon compensation in major functional areas [59–61], with zoning criteria mainly emphasizing the maximization of economic and ecological benefits [62–64], rarely incorporating a low-carbon evaluation index system for zoning research. Secondly, previous carbon emission accounting systems mainly include energy consumption, human respiration, solid waste, and wastewater, with an overly broad scope. In contrast, this study redefines the agricultural carbon emission accounting system primarily from the perspectives of direct field emissions and livestock breeding. Additionally, it selects the intensity of land-use development as a resource structure attribute index and incorporates agricultural carbon emissions as a total scale attribute index into the model, diversifying the research data. Furthermore, this study considers the dual characteristics of agricultural carbon emissions and carbon absorption, integrating the dual effects by using economic contribution coefficients and ecological carrying capacities, combining the following four aspects: total scale, ecological environment, social economy, and resource structure, thereby further improving the existing agricultural low-carbon evaluation index system [65]. This new system is more comprehensive than the previous one, addressing the shortcomings of the traditional system. By combining the actual situation of the study area and optimizing the spatial layout, this method achieves agricultural carbon compensation zoning at the township level. The results accurately assess the level of carbon emissions and are of practical significance for promoting regional low-carbon sustainable development. Additionally, since the new system adds three new indicators, namely total scale, ecological environment, and resource structure, it is more effective in improving the comprehensive agricultural carbon compensation management system at different scales and in leveraging its operating mechanisms.

4.2. Recommendation

Between various townships in Guangshui City, Hubei Province, there exists a severe imbalance between the economic contribution coefficient of agricultural carbon emissions and the carbon ecological carrying capacity, leading to a mismatch between agricultural carbon supply and demand. There are significant disparities in the social economy, resource utilization, and ecological environment measurements among different townships. Therefore, to promote the realization of the national "dual carbon" strategic goal, it is necessary to combine the actual situation of the study area and formulate corresponding control strategies which are tailored to local conditions in the process of constructing the regional agricultural carbon compensation zoning planning and the evaluation index system for agricultural low-carbon development levels.

(1) Optimize the agricultural industry structure to reduce agricultural carbon emissions. Guangshui City has conducted pilot work on the layout of low-carbon industrial structures in Hubei Province, introducing an evaluation system for low-carbon development levels and exploring a low-carbon industrial structure layout model at the micro level. This is achieved through a top-level low-carbon design to enhance the efficiency of agricultural carbon compensation and management in Guangshui City within Hubei Province.

(2) Different types of regions should adopt different low-carbon development directions and strategies. In payment areas and low-carbon emission reduction areas, efforts should be made to construct a low-carbon and efficient industrial system to increase the economic contribution rate of agricultural carbon emissions. Simultaneously, the contradiction between urban expansion and ecological environment needs to be coordinated, emphasizing the protection of the ecological environment. In payment areas and low-carbon control areas, spatial land-use patterns should be optimized, and township land expansion should be moderately coordinated to improve the land-use efficiency, control agricultural carbon emissions, expand green ecological spaces, and strengthen ecological pollution control. In payment areas and low-carbon optimization areas, township governments should adhere to the concept of ecological priority and green development. While maintaining low-carbon emissions, they should improve the land-use efficiency, expand the construction of green ecological spaces, and ensure the coordinated development of the ecological environment and the economy. In balance areas and low-carbon emission reduction areas, advanced technologies should be introduced to restore the ecological environment and promote regional low-carbon development. Additionally, efforts should be made to strengthen the protection of the farmland, actively improve the governance and comprehensive development of unused land, wasteland, saline-alkali land, etc., and enhance the carbon sequestration capacity of ecosystems. In balance areas and low-carbon optimization areas, township governments should strengthen the protection of existing ecological resources, increase forest coverage, develop green and low-carbon industries, promote industrial transformation and upgrading, and utilize the radiation effect of neighboring townships with high-level economic development in order to build a modern industrial system, thereby driving better local economic development and enhancing its economic level. In compensation areas and low-carbon emission reduction areas, efforts should be made to avoid the destruction of farmland caused by rapid urbanization. Without sacrificing the ecological environment, township governments should increase investment in agricultural infrastructure construction, enhance comprehensive agricultural productivity, improve economic benefits, and achieve the simultaneous development of economic growth and ecological environment protection. In compensation areas and low-carbon control areas, the rational planning of production space land is crucial to avoid uncontrolled expansion. While strengthening the protection and utilization of arable land resources, efforts should be made to vigorously develop low-carbon industries and drive the development of local ecological tourism industry, effectively improving the regional ecological economic benefits. In compensation areas and low-carbon optimization areas, the region should promote coordinated development in terms of economy, ecology, and resources, and should strictly control large-scale industrialization and urbanization expansion. Additionally, due to the relatively lagging economic development in this region, local governments need to actively develop ecological industries, optimize the layout of industrial structures, and enhance the production efficiency and economic benefits of agricultural products.

4.3. Problem Statement and Future Work

With the rapid development of socio-economy, rural ecological environment protection has become an important issue. Since the 17th National Congress of the Communist Party of China proposed the strategic deployment of ecological civilization construction, local governments have increasingly attached importance to rural ecological environment protection. In order to achieve the national "dual carbon" strategic goals and promote the coordinated development of regional economy, resources, and ecological environment [66–68], further research is needed concerning the following issues:

(1) The relationship between the agricultural carbon balance, carbon offsetting, and spatial scale is closely related. Generally, the larger the research scale, the more complex the social and economic factors involved, making it less conducive to formulating spatial optimization schemes for agricultural carbon offsetting. At the same time, there is relatively less regional-related research on agricultural carbon balance and management types at the

micro-scale. In the future, it is necessary to strengthen the research on the township and village scale to improve the agricultural carbon balance and carbon offsetting management mechanism at different spatial scales.

(2) Carbon compensation is an economic means for agricultural carbon emission entities to eliminate carbon emission externalities, aiming to reduce carbon emissions and promote sustainable coordinated development in regions. However, the development between regions and carbon emission reduction is actually influenced by complex factors such as the per capita GDP, urbanization rate, per capita disposable income of urban residents, proportion of forest land, grassland, and water area. Due to the relatively micro-scale of the research, it is difficult to collect complete social and economic data in the research area. This study only focuses on the economic, resource, and ecological factors affecting the agricultural carbon balance and carbon compensation zoning in Guangshui City.

In the future, promoting ecological improvement and protection through increasing forested areas can facilitate regional development and reduce carbon emissions. However, as socio-economic development accelerates, environmental issues become increasingly severe, presenting challenges to expanding forested areas, such as land-use conflicts, resource competition, and socio-economic impacts. Firstly, the municipal government of Guangshui needs to formulate comprehensive land planning and management policies to optimize resource allocation, ensuring the coordination of forest expansion with other land uses to avoid conflicts. Secondly, an effective ecological compensation mechanism must be established, providing reasonable economic incentives to farmers or landowners to encourage them to convert unused land into forests or engage in forest conservation. This indirect approach can reduce carbon emissions and promote high-quality development between regions. Thirdly, strengthening ecological protection and restoration is essential to reinforce existing ecosystems and prevent adverse impacts on local ecosystems due to increased forested areas. Particularly, focused efforts around Guangshui's Xujihe National Key Protection Watershed should be undertaken, including comprehensive water resource and water environment management, advancing ecological environment co-governance, and collectively constructing an ecological security barrier. Fourthly, policy support and incentives must be strengthened, with the formulation and implementation of measures supporting forest expansion. Policies rewarding carbon sequestration, ecological compensation, tax exemptions, among others, should be enacted to provide support and incentives for expanding forested areas.

(3) The valuation of various types of agricultural carbon compensation in the region has not been involved. In the future, it is necessary to determine the value standards of agricultural carbon compensation by combining various factors such as regional economic [69–71], ecological resources, industrial conditions, and the proportion of agricultural carbon absorption, incorporating them into the enterprise carbon trading market [72–74]. Through low-cost and high-efficiency methods, the construction of an agricultural carbon compensation mechanism system can be promoted to drive the high-quality development of the regional low-carbon economy and help achieve the national "dual carbon" strategic goals [75–77].

(4) In response to the adverse impacts of construction land on rural ecological conservation, we propose the following recommendations: Firstly, regarding green infrastructure development, enhancing the green coverage within construction areas via increasing the planting of trees and lawns can effectively boost carbon absorption, thereby mitigating carbon emissions and bolstering the stability and ecosystem services. Secondly, in sustainable land-use planning, it is crucial to formulate scientifically sound land-use plans to prevent the excessive development of construction land. Instead, efforts should prioritize the preservation and restoration of natural ecosystems, ensuring the integrity and stability of the ecological systems. Furthermore, utilizing the Ecosystem Services Valuation (ESV) analysis method to address ESV value concerns in construction areas involves the following measures: Firstly, establishing a comprehensive ESV assessment index system, which includes indicators such as biodiversity, soil protection, and water resource conservation, to holisti-

cally evaluate the ecological impacts of construction projects. Through ESV assessments, adverse effects of construction activities on ecosystems can be promptly identified and addressed, thus maximizing the protection and enhancement of ESV values, consequently boosting the carbon sequestration capacity of ecosystems. Secondly, establishing a robust ecological compensation mechanism to offset ecological losses resulting from construction activities. This mechanism will facilitate the restoration and rehabilitation of the ecological environment. Utilizing the ESV analysis method, standards and scopes for ecological compensation can be determined, thereby safeguarding the sustainable development of the ecological environment.

(5) The agricultural carbon accounting model faces several limitations. Firstly, it suffers from partial perspectives. Our calculation methods primarily focus on direct field emissions and manure as carbon emission sources, and absorption from grain crops, cash crops, and other crops as carbon sinks. However, these methods only cover a fraction of the sources of carbon emissions and absorption, overlooking other factors that may affect carbon balance, such as soil carbon stocks and vegetation types. Consequently, our methods may not comprehensively and accurately reflect the true state of agricultural carbon balance. Secondly, there are issues of data scarcity and uncertainty. Our calculation methods rely on extensive data, including field emissions and crop growth data. However, in practical applications, obtaining these data may be challenging, and their accuracy may be subject to uncertainty. This lack of data and uncertainty may affect the accuracy and credibility of our calculation results. Thirdly, there are limitations in terms of locality Our calculation methods mainly target specific regions or agricultural production systems. Thus, there may be limitations in terms of locality, making it difficult to directly generalize to other areas or different types of agricultural production systems. This implies that our methods may not be universally applicable and may require adjustments and modifications based on specific circumstances. Lastly, there is asymmetry between carbon emissions and absorption Our calculation methods primarily focus on the total amount of carbon emissions and absorption, overlooking the temporal and spatial asymmetry between them. For instance, certain crops may absorb a significant amount of carbon during the growing season, while they may have minimal absorption at other times. Consequently, our methods may not accurately reflect the dynamic changes in carbon emissions and absorption. Overall, these limitations underscore the need for the further refinement and development of agricultural carbon accounting models to enhance their accuracy, reliability, and applicability across different contexts. To address these limitations, several measures can be considered as follows: (1) Comprehensive accounting methods: Develop more comprehensive accounting methods that consider a broader range of carbon emission sources and absorption sinks beyond direct field emissions and crop absorption. This may involve incorporating factors such as soil carbon stocks, vegetation types, and land-use changes into the accounting framework to provide a more holistic view of agricultural carbon balance. (2) Improved data collection and accuracy: Invest in efforts to improve data collection methods and enhance the accuracy of available data on field emissions, crop growth, and other relevant parameters. This may involve utilizing advanced remote sensing technologies, improved monitoring systems, and collaborative data-sharing initiatives to overcome data scarcity and reduce uncertainties in carbon accounting. (3) Generalizable models: Develop models that are more generalizable across different regions and agricultural production systems. This could involve refining existing models to account for regional variations in climate, soil conditions, and farming practices, as well as designing flexible frameworks that can be adapted to diverse agricultural contexts. (4) Temporal and spatial dynamics: Incorporate temporal and spatial dynamics into carbon accounting models to account for the asymmetry between carbon emissions and absorption. This may involve developing dynamic modeling approaches that capture seasonal variations in carbon fluxes and spatially explicit models that account for differences in carbon dynamics across landscapes. (5) Continuous refinement and validation: Continuously refine and validate agricultural carbon accounting models through ongoing research, field studies, and model inter-comparison exercises.

This may involve conducting sensitivity analyses, validation against independent datasets, and incorporating feedback from stakeholders to improve the accuracy, reliability, and applicability of the models over time.

(6) The NRCA may be subject to a multitude of potential influences. Firstly, concerning agricultural carbon emissions, the level of agricultural carbon emissions could impact both the overall scale indicators and ecological environment indicators. Elevated carbon emissions may skew the total scale indicators higher, while also potentially exerting adverse effects on the ecological environment, thereby diminishing the ecological environment indicators. Secondly, regarding the economic contribution coefficient of agricultural carbon emissions, this coefficient could wield significant influence over indicators of socio-economic factors. A higher coefficient would suggest a greater contribution of agricultural carbon emissions to the local economy, potentially elevating the socio-economic factor indicators. Thirdly, concerning carbon ecological carrying capacity, the level of carbon ecological carrying capacity could wield significant influence over the ecological environment indicators. A lower carbon ecological carrying capacity in a certain region may signify greater pressure on the ecological environment, consequently reducing ecological environment indicators. Lastly, in terms of land spatial development intensity, the intensity of land spatial development could impact the indicators of resource structure. Higher development intensity may precipitate changes in resource structure, thereby influencing the evaluation results of the resource structure indicators.

In future research endeavors, building upon existing findings, we can explore the following four aspects: Firstly, in the formulation of agricultural carbon balance and compensation policies, local governments can tailor the policies addressing agricultural carbon balance and compensation to different townships. For townships with high levels of carbon emissions, stricter emission reduction measures can be implemented, alongside compensation policies to promote low-carbon development. Conversely, for townships with low levels of carbon emissions, incentive policies can be offered to encourage the maintenance of their low-carbon status. Secondly, integrating agricultural carbon balance into urban planning can lead to seamless integration. By considering agricultural carbon balance in urban planning, rational land-use plans can be devised to enhance agricultural carbon absorption capacity and reduce emissions, thereby fostering low-carbon urban development. Thirdly, establishing an agricultural carbon balance and ecological compensation mechanism entails providing ecological compensation to high-emission townships based on their carbon emission and absorption statuses in order to achieve carbon balance. Such a mechanism not only promotes environmental protection, but also propels the sustainable development of township economies. Lastly, setting clear goals for agricultural carbon balance and sustainable development involves incorporating agricultural carbon balance into sustainable development objectives. Corresponding policies and measures can then be formulated to achieve the agricultural carbon balance and sustainable development of township economies and societies. These initiatives not only contribute to climate change mitigation, but also enhance the overall competitiveness and sustainability of townships.

5. Conclusions

Based on the township level, this study applied an agricultural carbon balance accounting system to analyze the spatiotemporal evolution pattern of agricultural carbon balance in Guangshui City, Hubei Province, from 2000 to 2021, as well as the characteristics of agricultural carbon balance. Meanwhile, through the planning of the agricultural carbon compensation zoning system, the study investigated the zoning of agricultural carbon compensation management types in the region, providing scientific references for promoting regional energy conservation, emission reduction, and low-carbon development. The main conclusions are as follows:

(1) From 2000 to 2021, both the total agricultural carbon emissions and absorption in the research area showed a trend of first increasing and then decreasing. Agricultural carbon emissions exhibited a spatial differentiation feature of "higher in the northwest and

lower in the southeast", with high-emission areas gradually expanding from the east to the north, showing significant regional differences in quantity. In contrast, agricultural carbon absorption showed a spatial differentiation feature of "higher in the southwest and lower in the northeast". The carbon absorption of major crops also showed a trend of first increasing and then decreasing during the study period. Economic crops and other types of crops accounted for a small proportion, resulting in limited agricultural carbon absorption. However, as the main crops, grain crops accounted for a large proportion of carbon absorption, with significant fluctuations.

(2) The average Gini coefficient of agricultural carbon emissions in the research area from 2000 to 2021 was 0.24, showing a relatively stable trend, indicating that the agricultural carbon emissions in Guangshui City were in a relatively evenly distributed state. The economic contribution coefficient and ecological carrying capacity coefficient of agricultural carbon emissions ranged from 0.04 to 16.1 and 0.39 to 1.99, respectively. This suggests that there is significant variation in the contribution of agricultural carbon emissions to the social economy among townships, leading to a mismatch between agricultural carbon supply and demand among townships.

(3) In 2021, using K-means clustering analysis, the 17 townships in Guangshui City were classified into three major areas of agricultural carbon comprehensive compensation as follows: payment areas, compensation areas, and balance areas, which were then overlaid with spatial land-use zoning to reconstruct into eight types. Specifically, in 2021, Yangzhai Town, Chengshao Street, Yingshan Street, and Guangshui Street were identified as payment areas and low-carbon emission reduction areas; Changling Town and Shili Street were payment areas and low-carbon control areas; Wushengguan Town was a payment area and a low-carbon optimization area; Guanmiao Town and Taiping Town were balance areas and low-carbon emission reduction areas; Chenxiang Town and Caihe Town were balance areas and low-carbon optimization areas; Lidian Town and Luodian Town were compensation areas and low-carbon emission reduction areas; Yudian Town and Maping Town were compensation areas and low-carbon control areas; and Haodian Town and Wudian Town were compensation areas and low-carbon optimization areas.

In summary, the main contribution of this study lies in exploring the spatial layout of agricultural carbon balance and compensation at the micro-scale, providing references for small-scale regional agricultural carbon compensation zoning, and improving the agricultural carbon balance and compensation management mechanism at different spatial scales. This study provides theoretical references for achieving the national "dual carbon" strategic goals.

Author Contributions: Conceptualization, methodology, software, formal analysis, visualization, writing—original draft, Z.Y.; conceptualization, project administration, funding acquisition, supervision, X.Z. (Xuesong Zhang); data curation, X.H.; data validation, validation, writing—review and editing, X.Z. (Xiaowen Zhou). All authors have read and agreed to the published version of the manuscript.

Funding: This study was financially supported by self-determined research funds from the basic research and operation of the Ministry of Education, Central China Normal University (CCNUKJC2024009).

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to the public as the team's follow-up study is still pending.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Zhang, Y.; Fang, G. Research on Spatial-Temporal Characteristics and Affecting Factors Decomposition of Agricultural Carbon Emission in Suzhou City, Anhui Province, China. *Appl. Mech. Mater.* **2013**, *291–294*, 1385–1388. [CrossRef]
2. Chen, P.; Kong, X. Tourism-led Commodification of Place and Rural Transformation Development: A Case Study of Xixinan Village, Huangshan, China. *Land* **2021**, *10*, 694. [CrossRef]
3. Houghton, R. Balancing the Global Carbon Budget. *Annu. Rev. Earth Planet Sci.* **2007**, *35*, 313–347. [CrossRef]

4. Chen, W.; Chen, J.; Cihlar, J. An integrated terrestrial ecosystem carbon-budget model based on changes in disturbance, climate, and atmospheric chemistry. *Ecol. Model.* **2000**, *135*, 55–79. [CrossRef]
5. Guo, S.; Zhang, Y.; Qian, X.; Ming, Z.; Nie, R. Urbanization and CO_2 emissions in resource-exhausted cities: Evidence from Xuzhou city, China. *Nat. Hazards* **2019**, *99*, 807–826. [CrossRef]
6. Lin, Q.; Zhang, L.; Qiu, B.; Zhao, Y.; Wei, C. Spatiotemporal Analysis of Land Use Patterns on Carbon Emissions in China. *Land* **2021**, *10*, 141. [CrossRef]
7. Bakx, T.R.M.; Trubins, R.; Eggers, J.; Akselsson, C. The effect of spatial and temporal planning scale on the trade-off between the financial value and carbon storage in production forests. *Land Use Policy* **2023**, *127*, 106583. [CrossRef]
8. Popp, M.; Nalley, L.; Fortin, C.; Smith, A.; Brye, K. Estimating Net Carbon Emissions and Agricultural Response to Potential Carbon Offset Policies. *Agron. J.* **2011**, *103*, 1132. [CrossRef]
9. Shvidenko, A.; Nilsson, S. Dynamics of Russian Forests and the Carbon Budget in 1961–1998: An Assessment Based on Long-Term Forest Inventory Data. *Clim. Chang.* **2002**, *55*, 5–37. [CrossRef]
10. Apps, M.; Kurz, W.; Beukema, S.; Bhatti, J. Carbon budget of the Canadian forest product sector. *Environ. Sci. Policy* **1999**, *2*, 25–41. [CrossRef]
11. Zhang, C.; Zhao, L.; Zhang, H.; Chen, M.; Fang, R.; Yao, Y.; Zhang, Q.; Wang, Q. Spatial-temporal characteristics of carbon emissions from land use change in Yellow River Delta region, China. *Ecol. Indic.* **2022**, *136*, 108623. [CrossRef]
12. Bondeau, A.; Smith, P.; Zaehle, S.; Schaphoff, S.; Lucht, W.; Cramer, W.; Gerten, D.; Lotze-campen, H.; Muller, C.; Reichstein, M.; et al. Modelling the role of agriculture for the 20th century global terrestrial carbon balance. *Global Chang. Biol.* **2010**, *13*, 679–706. [CrossRef]
13. Mcguire, A.; Sitch, S.; Clein, J.; Dargaville, R.; Esser, G.; Foley, J.; Heimann, M.; Joos, F.; Kaplan, J.; Kicklighter, D.; et al. Carbon balance of the terrestrial biosphere in the Twentieth Century: Analyses of CO_2, climate and land use effects with four process-based ecosystem models. *Glob. Biogeochem. Cycles* **2001**, *15*, 183–206. [CrossRef]
14. Gao, Y.; Liu, G.; Meng, F.; Hao, Y.; Chen, C.; Casazza, M. A carbon responsibility allocation approach with incentives mechanism based on carbon emissions and carbon offsets accounting. *J. Clean Prod.* **2024**, *434*, 139814. [CrossRef]
15. Huber, E.; Bach, V.; Finkbeiner, M. A qualitative meta-analysis of carbon offset quality criteria. *J. Environ. Manag.* **2024**, *352*, 119983. [CrossRef] [PubMed]
16. Xiong, C.; Chen, S.; Yang, D. Selecting Counties to Participate in Agricultural Carbon Compensation in China. *Pol. J. Environ. Stud.* **2019**, *28*, 1443–1449. [CrossRef]
17. Zhang, S.; Bai, X.; Zhao, C.; Tan, Q.; Luo, G.; Wu, L.; Xi, H.; Li, C.; Chen, F.; Ran, C.; et al. China's carbon budget inventory from 1997 to 2017 and its challenges to achieving carbon neutral strategies. *J. Clean. Prod.* **2022**, *347*, 130966. [CrossRef]
18. Jing, X.; Tian, G.; Li, M.; Javeed, S. Research on the Spatial and Temporal Differences of China's Provincial Carbon Emissions and Ecological Compensation Based on Land Carbon Budget Accounting. *Int. J. Environ. Res. Public Health* **2021**, *18*, 12892. [CrossRef] [PubMed]
19. An, N.; Huang, C.; Shen, Y.; Wang, J.; Yu, Z.; Fu, J.; Liu, X.; Yao, J. Efficient data-driven prediction of household carbon footprint in China with limited features. *Energy Policy* **2024**, *185*, 113926. [CrossRef]
20. Fasogbon, S.; Igboabuchukwu, C. Real-time carbon footprint assessment based on energy consumption: A comprehensive review for future research prospects. *Renew. Sust. Energy Rev.* **2024**, *192*, 114225. [CrossRef]
21. Xia, S.; Yang, Y. Examining spatio-temporal variations in carbon budget and carbon compensation zoning in Beijing-Tianjin-Hebei urban agglomeration based on major functional zones. *J. Geogr. Sci.* **2022**, *32*, 1911–1934. [CrossRef]
22. Song, H.; Li, Y.; Gu, L.; Tang, J.; Zhang, X. Spatiotemporal Pattern of Carbon Compensation Potential and Network Association in Urban Agglomerations in the Yellow River Basin. *ISPRS Int. J. Geo-Inf.* **2023**, *12*, 435. [CrossRef]
23. Huang, J.; Sun, Z.; Du, M. Spatiotemporal characteristics and determinants of agricultural carbon offset rate in China based on the geographic detector. *Environ. Sci. Pollut. Res.* **2023**, *30*, 58142–58155. [CrossRef] [PubMed]
24. Song, Z.; Liu, F.; Lv, W.; Yan, J. Classification of Urban Agricultural Functional Regions and Their Carbon Effects at the County Level in the Pearl River Delta, China. *Agriculture* **2023**, *13*, 1734. [CrossRef]
25. Long, Z.; Pang, J.; Li, S.; Zhao, J.; Yang, T.; Chen, X.; Zhang, Z.; Sun, Y.; Lang, L.; Wang, N.; et al. Spatiotemporal variations and structural characteristics of carbon emissions at the county scale: A case study of Wu'an City. *Environ. Sci. Pollut. Res.* **2022**, *29*, 65466–65488. [CrossRef] [PubMed]
26. Guo, H.; Yang, C.; Liu, X.; Li, Y.; Meng, Q. Simulation evaluation of urban low-carbon competitiveness of cities within Wuhan city circle in China. *Sustain. Cities Soc.* **2018**, *42*, 688–701. [CrossRef]
27. Wang, L.; Qu, Z.; Yang, W.; Ren, E.; Tang, T. Coupled Urbanisation and Ecological Protection along the Yellow River Basin in the Context of Dual Carbon. *Sustainability* **2023**, *15*, 5728. [CrossRef]
28. Liu, M.; Chen, Y.; Chen, K.; Chen, Y. Progress and Hotspots of Research on Land-Use Carbon Emissions: A Global Perspective. *Sustainability* **2023**, *15*, 7245. [CrossRef]
29. Sobrino, N.; Monzon, A. Towards Low-Carbon Interurban Road Strategies: Identifying Hot Spots Road Corridors in Spain. *Sustainability* **2018**, *10*, 3963. [CrossRef]
30. Zhao, R.; Zhang, S.; Huang, X.; Qin, Y.; Liu, Y.; Ding, M.; Jiao, T. Spatial variation of carbon budget and carbon balance zoning of Central Plains Economic Region at county-level. *Acta Geogr. Sin.* **2014**, *69*, 1425–1437.

31. Vleeshouwers, L.; Verhagen, A. Carbon emission and sequestration by agricultural land use: A model study for Europe. *Glob. Change Biol.* **2010**, *8*, 519–530. [CrossRef]
32. Qi, Y.; Liu, H.; Zhao, J. Prediction model and demonstration of regional agricultural carbon emissions based on Isomap–ACO–ET: A case study of Guangdong Province, China. *Sci. Rep.* **2023**, *13*, 12688. [CrossRef] [PubMed]
33. Zhou, J.; Li, B.; Xia, L.; Fan, C.; Xiong, Z. Organic-substitute strategies reduced carbon and reactive nitrogen footprints and gained net ecosystem economic benefit for intensive vegetable production. *J. Clean. Prod.* **2019**, *225*, 984–994. [CrossRef]
34. Li, B.; Zhang, J.; Li, H. Temporal and spatial characteristics and influencing factors of agricultural carbon emissions in China. *China's Popul. Resour. Environ.* **2011**, *21*, 7.
35. Elhorst, J. Specification and Estimation of Spatial Panel Data Models. *Int. Reg. Sci. Rev.* **2023**, *26*, 244–268. [CrossRef]
36. Tian, Y.; Zhang, J.; Li, B. Research on agricultural carbon emissions in China: Measurement, spatio-temporal comparison and decoupling effect. *Resour. Sci.* **2012**, *34*, 2097–2105.
37. Mackay, A. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. *J. Environ. Qual.* **2008**, *37*, 2407. [CrossRef]
38. Tian, Y.; Zhang, J. Differentiation of net carbon effect of agricultural production in China. *J. Nat. Resour.* **2013**, *28*, 1298–1309.
39. Zhang, X.; Fan, C.; Ma, Y.; Liu, Y.; Li, L.; Zhou, Q.; Xiong, Z. Two approaches for net ecosystem carbon budgets and soil carbon sequestration in a rice–wheat rotation system in China. *Nutr. Cycle Agroecosyst.* **2014**, *100*, 301–313. [CrossRef]
40. Luo, H. Research progress on carbon storage of cropland vegetation in China. *J. Ecol. Environ.* **2014**, *23*, 692–697.
41. Wang, X. Estimation of atmospheric CO2 uptake and its multiplication by global crops. *J. Meteorol.* **1996**, *54*, 466–472.
42. Han, Z.; Meng, Y. Spatial and temporal differences of carbon footprint in regional farmland ecosystems: A case study of Jiangsu Province. *J. Agric. Environ. Sci.* **2012**, *31*, 1034–1041.
43. Dagum, C. A new approach to the decomposition of the Gini income inequality ratio. *Empir. Econ.* **1997**, *22*, 515–531. [CrossRef]
44. Luptáčik, M.; Nežinský, E. Measuring income inequalities beyond the Gini coefficient. *Cent. Eur. J. Oper. Res.* **2020**, *28*, 561–578. [CrossRef]
45. Zhang, B.; Yin, J.; Jiang, H.; Qiu, Y. Spatial–temporal pattern evolution and influencing factors of coupled coordination between carbon emission and economic development along the Pearl River Basin in China. *Environ. Sci. Pollut. Res.* **2023**, *30*, 6875–6890. [CrossRef] [PubMed]
46. Yang, X.; Zhang, F.; Luo, C.; Zhang, A. Farmland Ecological Compensation Zoning and Horizontal Fiscal Payment Mechanism in Wuhan Agglomeration, China, From the Perspective of Ecological Footprint. *Sustainability* **2019**, *11*, 2326. [CrossRef]
47. Balassa, B. Trade liberalisation and "revealed" comparative advantage. *Manch. Sch.* **1965**, *33*, 99–123. [CrossRef]
48. Yu, R.; Cai, J.; Leung, P. The normalized revealed comparative advantage index. *Ann. Reg. Sci.* **2009**, *43*, 267–282. [CrossRef]
49. Wang, W.; Cao, K.; Lin, J. Research progress and prospect of multi-scale evaluation framework and index system for sustainable cities. *Urban. Dev. Res.* **2022**, *29*, 1–7.
50. Hwang, C.L.; Yoon, K. Multiple Attribute Decision Making. *Lect. Notes Econ. Math. Syst.* **1981**, *404*, 287–288. [CrossRef]
51. Zelany, M. A concept of compromise solutions and the method of the displaced ideal. *Comput. Oper. Res.* **1974**, *1*, 479–496. [CrossRef]
52. Yoon, K.P.; Hwang, C.L. *Multiple Attribute Decision Making: An Introduction*; Sage Publications, Inc.: Thousand Oaks, CA, USA, 1995; ISBN 0-8039-5486-7.
53. Elikbilek, Y.; Tysz, F. An in-depth review of theory of the TOPSIS method: An experimental analysis. *J. Manag. Anal.* **2020**, *7*, 20. [CrossRef]
54. Shipley, M.F.; Korvin, A.D.; Obid, R. A decision making model for multi-attribute problems incorporating uncertainty and bias measures. *Comput. Oper. Res.* **1991**, *18*, 335–342. [CrossRef]
55. Zhang, J.; Lin, H.; Li, S.; Yang, E.; Ding, Y.; Bai, Y.; Zhou, Y. Accurate gas extraction (AGE) under the dual-carbon background: Green low-carbon development pathway and prospect. *J. Clean. Prod.* **2022**, *377*, 134372. [CrossRef]
56. Miao, Y.; Kong, C.; Wang, L.; Mu, J.; Lu, X.; Bao, J.; Li, H. A provincial lateral carbon emissions compensation plan in China based on carbon budget perspective. *Sci. Total Environ.* **2019**, *692*, 1086–1096. [CrossRef] [PubMed]
57. Dou, R.; Hou, Y.; Lin, K.; Si, S.; Wei, Y. Transforming digital value chain ecosystems for dual-carbon target: An exploration of the BDS-RAS framework. *Comput. Ind. Eng.* **2024**, *188*, 109861. [CrossRef]
58. Zhou, C.; Wang, S.; Feng, K. Examining the socioeconomic determinants of CO2 emissions in China: A historical and prospective analysis. *Resour. Conserv. Recycl.* **2018**, *130*, 1–11. [CrossRef]
59. Wang, W.; Wang, W.; Xie, P.; Zhao, D. Spatial and temporal disparities of carbon emissions and interregional carbon compensation in major function-oriented zones: A case study of Guangdong province. *J. Clean. Prod.* **2020**, *245*, 118873. [CrossRef]
60. Guo, Y.; Tong, Z.; Chen, H.; Wang, Z.; Yao, Y. Heterogeneity study on mechanisms influencing carbon emission intensity at the county level in the Yangtze River Delta urban Agglomeration: A perspective on main functional areas. *Ecol. Indic.* **2024**, *159*, 111597. [CrossRef]
61. Xiang, S.; Wang, Y.; Deng, H.; Yang, C.; Wang, Z.; Gao, M. Response and multi-scenario prediction of carbon storage to land use/cover change in the main urban area of Chongqing, China. *Ecol. Indic.* **2022**, *142*, 109205. [CrossRef]
62. Ma, B.; Huang, J.; Li, S. Optimized allocation of land use in Beijing-Tianjin-Hebei urban agglomeration based on ecological-economic trade-offs. *Adv. Geosci.* **2019**, *38*, 26–37.

63. Chen, H.; Shi, Y.; Ke, X.; Hao, J.; Chen, A. Optimized spatial allocation of land use in Zhengzhou city under the goal of ecological and economic coordination. *Resour. Sci.* **2019**, *41*, 717–728.
64. Zhao, H.; He, J.; Liu, D.; Han, Y.; Zhou, Z.; Niu, J. Incorporating ecological connectivity into ecological functional zoning: A case study in the middle reaches of Yangtze River urban agglomeration. *Ecol. Inform.* **2023**, *75*, 102098. [CrossRef]
65. Tan, S.; Yang, J.; Yan, J. Development of the Low-carbon City Indicator (LCCI) framework. *Energy Procedia* **2015**, *75*, 2516–2522. [CrossRef]
66. Zhang, Z.; Hu, B.; Shi, K.; Su, K.; Yang, Q. Exploring the dynamic, forecast and decoupling effect of land natural capital utilization in the hinterland of the Three Gorges Reservoir area, China. *Sci. Total Environ.* **2020**, *718*, 134832. [CrossRef] [PubMed]
67. Wang, S.; Liu, X.; Zhou, C.; Hu, J.; Ou, J. Examining the impacts of socioeconomic factors, urban form, and transportation networks on CO2 emissions in China's megacities. *Appl. Energy* **2017**, *185*, 189–200. [CrossRef]
68. Wang, S.; Fang, C.; Wang, Y.; Huang, Y.; Ma, H. Quantifying the relationship between urban development intensity and carbon dioxide emissions using a panel data analysis. *Ecol. Indic.* **2014**, *49*, 121–131. [CrossRef]
69. Song, H.; Zhang, X.; Zou, J.; Gu, L.; Li, Y.; Tang, J. A study on the value of carbon compensation in the Huai River basin based on land use from 2000 to 2020. *Phys. Chem. Earth Parts A/B/C* **2023**, *132*, 103490. [CrossRef]
70. Bento, A.; Kanbur, R.; Leard, B. On the importance of baseline setting in carbon offsets markets. *Clim. Chang.* **2016**, *137*, 625–637. [CrossRef]
71. Sapkota, Y.; White, J. Carbon offset market methodologies applicable for coastal wetland restoration and conservation in the United States: A review. *Sci. Total Environ.* **2020**, *701*, 134497. [CrossRef]
72. Wu, Y.; Liu, X.; Tang, C. Carbon Market and corporate financing behavior-From the perspective of constraints and demand. *Econ. Anal. Policy* **2024**, *81*, 873–889. [CrossRef]
73. Eric, R.W. Knight. The economic geography of European carbon market trading. *J. Econ. Geogr.* **2011**, *11*, 817–841. [CrossRef]
74. Yu, X.; Shi, J.; Wan, K.; Chang, T. Carbon trading market policies and corporate environmental performance in China. *J. Clean. Prod.* **2022**, *371*, 133683. [CrossRef]
75. Ou, J.; Liu, X.; Li, X.; Chen, Y. Quantifying the relationship between urban forms and carbon emissions using panel data analysis. *Landsc. Ecol.* **2013**, *28*, 1889–1907. [CrossRef]
76. Wang, C.; Lin, J.; Cai, W.; Zhang, Z. Policies and Practices of Low Carbon City Development in China. *Energy Environ.* **2013**, *24*, 1347–1372. [CrossRef]
77. Shi, L.; Xiang, X.; Zhu, W.; Gao, L. Standardization of the Evaluation Index System for Low-Carbon Cities in China: A Case Study of Xiamen. *Sustainability* **2018**, *10*, 3751. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.