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Land Use Carbon Budget Pattern and Carbon Compensation Mechanism of Counties in the Pearl River Basin: A Perspective Based on Fiscal Imbalance

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Abstract: Implementing watershed carbon compensation under the constraint of fiscal imbalance is a crucial approach for China to achieve its "dual carbon" goals. Focusing on 257 counties within the Pearl River Basin (PRB), this paper first measured and modified the land use carbon emissions, carbon absorption, and the land use carbon budget (LUCB) from 2005 to 2020. Subsequently, their spatiotemporal patterns and the changes before and after the modifications were analyzed. Finally, this paper determined the subject–object, value, and priority order of carbon compensation using the modified LUCB as the baseline value, and a carbon compensation mechanism that combines vertical and horizontal directions was constructed. The following findings were obtained: (1) At the time scale, the proportion of construction land and forestland in the land use structure increased, and carbon emissions, carbon absorption, and the LUCB showed an overall upward trend from 2005 to 2020. (2) At the spatial scale, the areas with high carbon emissions and carbon deficits were mainly located in the lower reaches of the basin, whereas the areas with high carbon absorption and carbon surpluses were widely distributed in the upper and middle reaches. The carbon deficit in urban municipal districts and resource-based counties was relatively serious. (3) In 2020, the total amount of carbon compensation in the PRB was CNY −8088.61 million. The number of counties that needed to be paid and compensated was 75 and 182, respectively. The carbon compensation mechanism constructed in this paper can provide a reference for other countries and regions with financial imbalances to achieve regional carbon neutrality.

Keywords: carbon compensation; carbon budget accounting; spatiotemporal pattern; fiscal imbalance

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1. Introduction

In the course of global urbanization, land use/land cover change (LUCC) has released large quantities of CO_2, exacerbating the greenhouse effect. The Global Carbon Budget 2023 reported that 31% of total anthropogenic emissions were from LUCC during the period of 1850–2022 [1]. As the largest developing country and carbon-emitting nation [2], China has taken the initiative to assume international responsibility by putting forward the "dual carbon" goal [3], requiring local governments at all levels to take measures to reduce carbon emissions and enhance carbon sequestration [4]. However, China's fiscal system makes achieving this "dual carbon" goal difficult for local governments. Since the 1994 tax-sharing reform, China's fiscal system has been characterized by the upward transfer of fiscal power and decentralization of affairs, which has led to a growing mismatch of fiscal power and affairs among governments [5]. The asymmetry between fiscal power and expenditure responsibilities makes increasing spending on environmental protection challenging for local governments [6]. Although the central government has called for local governments to achieve the "dual carbon" goal, fiscal imbalances severely weaken their capacity and motivation, particularly in economically underdeveloped regions. These regions have low fiscal revenues but need to bear great environmental protection responsibilities because of their strong carbon absorption capabilities [7]. In this context, the State Council released ecological protection compensation regulations in April 2024 to establish and improve the ecological protection compensation mechanism, including vertical and horizontal directions. Carbon compensation have become an important way for China to achieve the "dual carbon" goal.

According to the ecological protection compensation regulations, watersheds are crucial areas for implementing ecological protection compensation. The Pearl River Basin (PRB) involves six provinces (Yunnan, Guangxi, Guizhou, Guangdong, Hunan, and Jiangxi) and two special administrative regions (Hong Kong and Macao) [8]. Except for Guangdong and special administrative regions, other regions in the basin belong to the central and western regions of China, exhibiting slow economic development and poor fiscal revenue capacity. However, these regions bear great environmental protection responsibilities because of their high carbon sequestration capacities. Guizhou and Jiangxi provinces are included in the first batch of the National Pilot Zones for Ecological Conservation because of their high environmental carrying capacity [9]. Wang et al. [10] also pointed out that Yunnan, Guizhou, and Guangxi provinces are the largest carbon sinks in China, accounting for approximately 31.5% of the terrestrial carbon sink. Therefore, the PRB is a typical region that needs carbon compensation. In addition, counties are the main carrying space for carbon emissions and absorption and are the basic unit for policy implementation in China [11]. However, a huge gap in financial resources exists among counties because of the decentralization of expenditure responsibilities and the upward transfer of fiscal power layer by layer [12]. Therefore, the county scale must be considered in the study of carbon compensation.

This paper aims to establish a combined vertical and horizontal carbon compensation mechanism to improve the match between fiscal power and affairs of local governments and promote the achievement of the "dual carbon" goal. This paper explores the spatiotemporal patterns of the land use carbon budget (LUCB) in the PRB from 2005 to 2020 through statistical methods and modifies the LUCB according to the principles of fairness and efficiency to reveal the actual situation of the LUCB in the PRB and to provide quantitative information for the construction of a carbon compensation mechanism.

2. Literature Review

Carbon compensation, a new field of ecological compensation arising under the "dual carbon" goals, holds remarkable practical importance for promoting regional carbon emission reductions [13]. Carbon compensation can be defined as the behavior of carbon emitters to provide certain compensation to carbon sink providers in an economic or noneconomic way [14]. In essence, it is compensation for the loss of opportunity cost caused by the cost of carbon sink protection or the abandonment of development opportunities via transfer payment [15]. Carbon compensation embodies the principles of fairness and efficiency. It can also help achieve the "dual carbon" goals by correcting fiscal imbalances. China's fiscal imbalances include vertical and horizontal imbalances. Vertical imbalances arise from the asymmetry between central and local fiscal revenues and expenditure responsibilities [16]. Horizontal imbalances stem from disparities in resource endowments and economic development across regions, leading to remarkable fiscal capacity differences among local governments [17]. Carbon compensation helps to narrow the fiscal gap in carbon surplus areas, thereby weakening the vertical fiscal imbalance; moreover, it supports the economic development of underdeveloped areas and curbs the polarization of fiscal revenue capacity among local governments, thereby weakening the horizontal fiscal imbalance [18].

Based on the basic logic and process of carbon compensation, existing research has explored the determination of the subject–object, value, and priority order of carbon compensation and has answered the questions of "who compensates, who is compensated", "how much to compensate", and "who compensates first, who is compensated first" in carbon compensation, respectively. These studies provide important literature support and method reference for the quantitative description of the carbon compensation mechanism in this paper.

The determination of the subject–object of carbon compensation requires a standard, and the standard of carbon compensation based on land use is the LUCB. The LUCB, which is the difference between carbon emissions and carbon absorption, involves accounting for both aspects. In terms of carbon emissions, the academic consensus is that energy-related carbon emissions from construction land are the primary source of carbon emissions. However, a debate over whether cropland is a carbon source or a carbon sink still exists. Recent studies have shown that cropland is close to carbon sinks [19,20]. Thus, only carbon emissions from construction land are considered in this paper. For the energy-related carbon emissions, existing research often relies on energy consumption data, using the carbon emission coefficient method provided by the Intergovernmental Panel on Climate Change (IPCC) or fitting equations based on nighttime light (NTL) data for estimation [21]. This paper employs the latter method to calculate carbon emissions. In terms of carbon absorption, existing studies mostly use the area of carbon sink land multiplied by the corresponding empirical coefficient in their calculations, and the accuracy and reliability need to be improved [22]. Recent studies have introduced net primary productivity (NPP) into the accounting of the LUCB to solve the aforementioned problem. NPP is the total amount of dry matter fixed by vegetation through photosynthesis per unit area and time, and it can be converted into carbon absorption using the photosynthesis equation [23]. Wei et al. [24] used NTL and NPP data to measure the carbon budget. They found that the eastern region of China releases most of the carbon emissions, whereas the western region contributes most of the carbon absorption. Fan et al. [25] used the same method to measure the LUCB, and it was included as an undesirable output to estimate land use carbon emission efficiency (LUCEE). NPP data can be obtained directly from existing datasets or indirectly through a quantitative model, such as the Carnegie Ames Stanford Approach (CASA) model. In this paper, NPP is calculated using the CASA model provided by Zhu et al. [26]. The model is based on China's measured NPP data. Moreover, parameters such as the maximum light use efficiency are modified, thereby making the NPP results in line with the actual situation in China.

In terms of carbon compensation value accounting, existing research has different opinions on carbon pricing. Some studies use a uniform pricing approach for the entire research area and employ carbon tax prices [27], carbon sink prices [28], shadow prices [29], or market prices [30]. Others adopt differentiated pricing based on actual conditions and vary the prices for different years and regions within the study area. For example, Song et al. [31] constructed a carbon compensation value system to measure the carbon compensation value level of cities in the Huai River Basin in different years and found that the carbon compensation value of most cities showed an increasing trend. Existing research on determining the priority order of carbon compensation mostly refers to the method provided by Wang et al. [32], which uses the ratio of carbon compensation amount to GDP to measure priority. Regions with a smaller ratio should be compensated first or receive compensation later. Conversely, regions with a larger ratio should be compensated later or receive compensation first. Yang et al. [33] used this method to measure the priority of carbon compensation of 30 provinces in China and found that their absolute values were small and showed a decreasing trend, indicating that interregional carbon compensation is feasible.

In the construction of the carbon compensation mechanism, existing studies have mostly constructed the carbon compensation mechanism from a single horizontal direction by mainly focusing on the local governments at the same level. Miao et al. [34] provided an interprovincial horizontal carbon compensation scheme and pointed out that economically developed provinces or provinces in the stage of rapid industrialization should compensate other provinces. Wang et al. [18] established a horizontal carbon compensation mechanism in the Yangtze River Delta. This mechanism integrates carbon footprint and carbon emission efficiency to balance fairness and efficiency. However, constructing a carbon compensation mechanism from vertical and horizontal directions is necessary because local governments are constrained by vertical and horizontal fiscal imbalances in environmental governance.

This work conducts research on carbon compensation and internalizes the externalities of carbon emissions, which is an important extension of sustainable development theory in the field of carbon reduction and holds remarkable theoretical implications. Moreover, the "dual carbon" goal and the constraints of fiscal imbalance have brought enormous environmental governance pressure to local governments. Therefore, determining the subject–object, value, and priority order of carbon compensation and constructing the carbon compensation mechanism possess great practical importance. The specific contributions of this work are as follows: First, existing research on watershed carbon compensation has not yet dealt with the county scale. This work takes the counties in the PRB as the research object, which is of great significance for the smooth implementation of the carbon compensation scheme and the enrichment of related research. Second, existing research on land use carbon compensation mostly uses the empirical coefficient method to calculate the LUCB, and its accuracy needs to be improved. This work employs NTL data and the CASA model to calculate the LUCB, which is further modified based on the principles of fairness and efficiency. Thus, the credibility of the results is further enhanced. Finally, existing studies have mostly constructed the carbon compensation mechanism from a single horizontal direction. This work constructs a combined vertical and horizontal carbon compensation mechanism based on the actual situation of vertical and horizontal fiscal imbalances in China. This mechanism is replicable and suitable for other regions of the country.

3. Materials and Methods

3.1. Research Framework

The overall framework of this paper is shown in Figure 1. The necessity of constructing a combined vertical and horizontal carbon compensation mechanism is explained in the Introduction Section by discussing China's "dual carbon" goals and the current state of fiscal imbalance. The subject–object, value, and order of carbon compensation are determined in the Results Section according to the basic logic and process of the compensation mechanism. This is a quantitative description of the carbon compensation mechanism. First, we use the NTL data and the CASA model to calculate the carbon emission and absorption of the PRB from 2005 to 2020, and the difference between the two is the LUCB. Then, LUCEE and the ecosystem service value (ESV) are used to modify carbon emission and absorption, respectively, and the modified LUCB is used as the standard of carbon compensation. The subject–object and value of carbon compensation can be determined by this standard. Finally, we determine the priority order of the payment and compensation areas. In the Discussion Section, we construct the vertical and horizontal carbon compensation mechanism and quantitatively describe it with the example of the 2020 data.

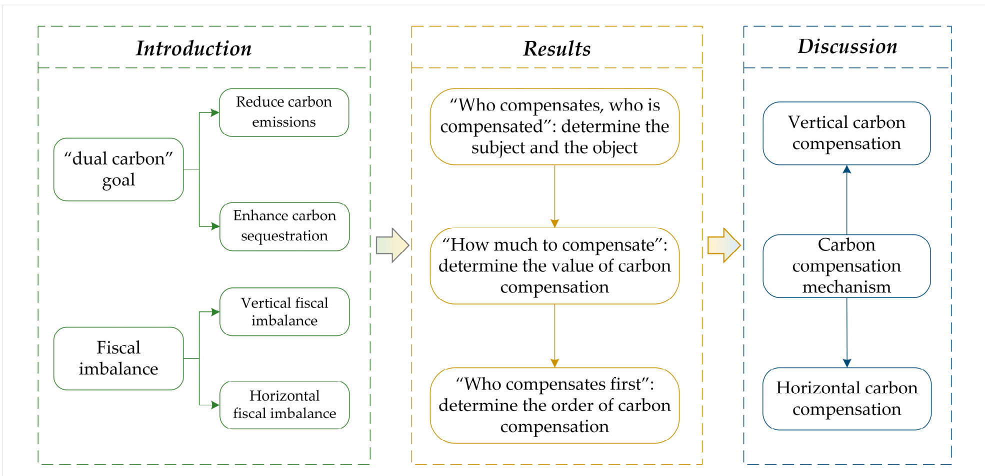

Figure 1. Overall framework of the paper.

3.2. Study Area Overview

The PRB is a composite basin consisting of the Xijiang, Beijiang, Dongjiang, and Pearl River Delta (PRD) water systems [35] (Figure 2). The Xijiang River is the mainstream and originates in Zhanyi District, Qujing City, Yunnan Province, whereas the Beijiang and Dongjiang rivers originate in Xinfeng and Xunwu counties in Ganzhou City, Jiangxi Province, respectively. All three eventually converge into the river network area of the PRD. Thus, the PRD belongs to the lower reaches of the PRB. The topography of the PRB is generally high in the northwest and low in the southeast, with the Yunnan–Guizhou plateau standing in the west and the PRD plain in the east. The regional development of the PRB varies greatly. In particular, the upstream areas belong to the western part of China, where economic development is slow; by contrast, Guangdong Province in the downstream region experiences rapid economic growth, with its GDP consistently ranking among the highest in the country. In 2023, the GDP of Guangdong Province was CNY 13,567.32 billion, whereas the total of other provinces was only CNY 15,960.11 billion.

The county is the main spatial unit of this paper. The boundaries of the river basin do not strictly align with administrative boundaries, indicating that the basin may encompass entire counties or only parts of them. This paper considers the potential spatial transfer of carbon, which can result in carbon transfer and carbon leakage issues [29]. Thus, all counties involved in the PRB are included in this paper. Data availability and administrative division adjustment are also considered. As a result, this paper adjusts the county administrative divisions between 2005 and 2020, merges some counties, and excludes Hong Kong and Macao. Finally, 257 county units in 46 cities of six provinces are selected as the study area. Jiangxi, Hunan, Guangdong, Guangxi, Guizhou, and Yunnan provinces include 9, 11, 81, 87, 35, and 34 of these county units, respectively. The specific information on the study area can be found in Figure S1 and Table S1 in the Supplementary Materials.

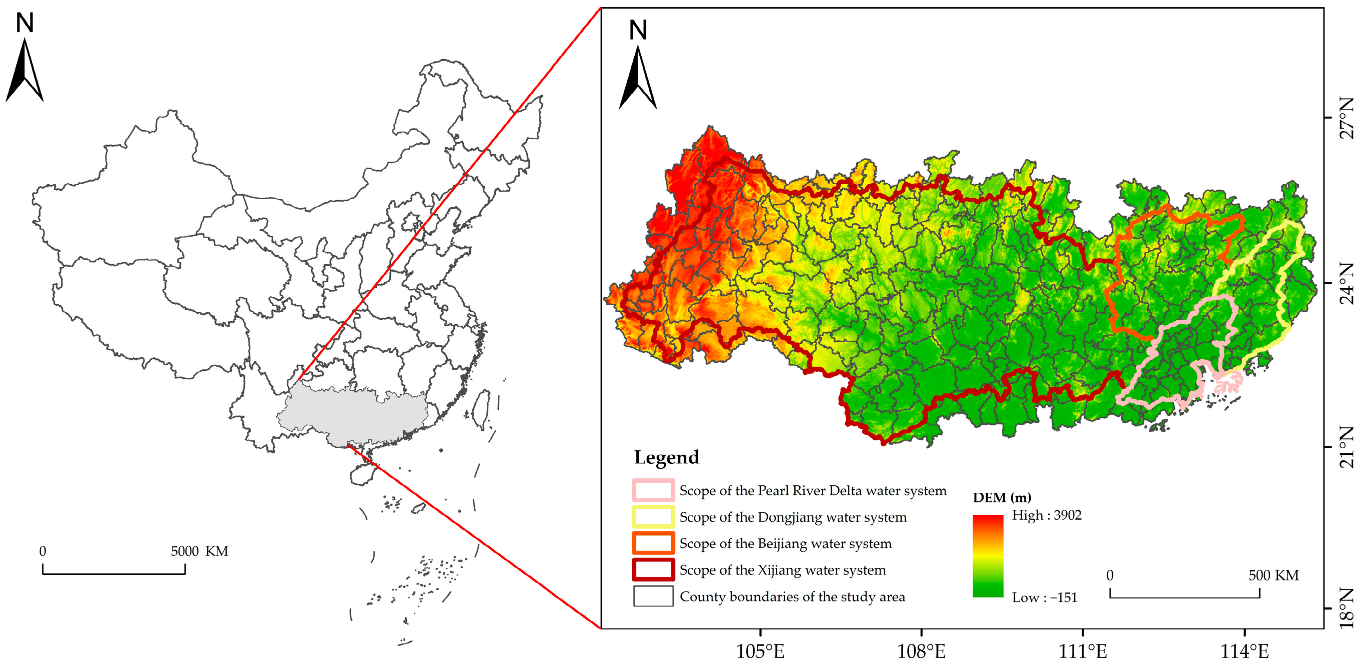

Figure 2. Overview of the study area.

3.3. Research Methods

3.3.1. Research Method for LUCC

The land use transfer matrix can clearly express the mutual transformation relationship between different land types at the beginning and the end of a period; thus, it can reflect the direction of transformation and quantitative structural characteristics among land use types [31]. In this paper, the land use transfer matrix is used to analyze the number of transfer-in and transfer-out of each land type area and the total change in the study area from 2005 to 2020 to illustrate LUCC. The matrix is as follows:

$$S_{ij} = \begin{bmatrix} S_{11} & S_{12} & \cdots & S_{1r} \\ S_{21} & S_{22} & \cdots & S_{2r} \\ \vdots & \vdots & \vdots & \vdots \\ S_{r1} & S_{r2} & \cdots & S_{rr} \end{bmatrix} \tag{1}$$

where S_{ij} is the area converted from land use type i at the beginning of the period to land use type j at the end of the period, and r is the category of land use type.

3.3.2. Estimation Method for Land Use Carbon Emissions

The carbon emission data for the paper were obtained using China's county carbon emissions dataset from 1997 to 2017, which was published in *Scientific Data* by Chen et al. [36]. These data were obtained by inverting the NTL data through the following: First, the method provided by IPCC was used to calculate the provincial energy carbon emissions. Then, the total NTL value was extracted using the NTL data. The relationship between the two was established. Finally, the total county NTL value was used to extrapolate the county carbon emissions.

Given that the data year of this dataset stops at 2017, this paper extends the dataset by fitting carbon emissions with the NTL data to obtain the carbon emissions for each county in the study area from 2018 to 2020 [37]. The specific approach is as follows: First, the county carbon emissions were summed to obtain the carbon emissions for each prefecture-level city from 1997 to 2017. Then, the NTL data for each prefecture-level city was fitted with the corresponding year's carbon emissions to obtain the fitting equations for each prefecture-level city's carbon emissions. Finally, the county's carbon emissions for 2018–2020 were estimated based on the proportion of NTL data between counties and prefecture-level cities. According to the fitting results, the logarithmic equation was the best-fitting model for most cities, with R^2 values exceeding 0.72 indicating a good fit. Therefore, logarithmic equations were uniformly used for fitting to ensure consistency in the paper [38]. The logarithmic fitting equations and their R^2 values for the 46 cities can be found in Table S2 in the Supplementary Materials.

3.3.3. Estimation Method for Land Use Carbon Absorption

In this paper, NPP was estimated using the CASA model provided by Zhu et al. [26]. In this model, NPP was estimated by the product of vegetation's photosynthetically available radiation and light use efficiency. The main calculation formulas are as follows:

$$NPP(x,t) = APAR(x,t) \times \varepsilon(x,t) \tag{2}$$

where $APAR(x,t)$ is the amount of photosynthetically available radiation absorbed by vegetation in grid x in month t, and $\varepsilon(x,t)$ is the actual light use efficiency of vegetation in grid x in month t.

$$APAR(x,t) = FPAR(x,t) \times SOL(x,t) \times 0.5 \tag{3}$$

where $FPAR(x,t)$ is the proportion of photosynthetically available radiation absorbed by vegetation in grid x in month t; $SOL(x,t)$ is the total amount of solar radiation received by grid x in month t, which is calculated by sunshine hours; and 0.5 is the proportion of solar radiation (wavelength 0.4–0.7 μm) that can be absorbed and utilized by vegetation in the total solar radiation.

$$\varepsilon(x,t) = T_{\varepsilon(x,t)} \times W_{\varepsilon(x,t)} \times \varepsilon_{max} \tag{4}$$

where $T_{\varepsilon(x,t)}$ is the temperature stress coefficient, which represents the effect of temperature on light use efficiency; $W_{\varepsilon(x,t)}$ is the water stress coefficient, which represents the effect of water on light use efficiency; and ε_{max} is the maximum light conversion efficiency of vegetation.

Carbon absorption can be estimated using the conversion coefficient between vegetation dry matter and absorbed CO_2 [39]. The formula is as follows:

$$CA_{it} = \frac{NPP_{it} \times S_{it} \times 1.62}{0.45} \tag{5}$$

where CA_{it} is the carbon absorption; S_{it} is the area of the region; and NPP_{it} represents the NPP per unit area. i and t are the region and year, respectively.

3.3.4. Estimation and Modification Method for the LUCB

The LUCB, which is equal to the difference between land use carbon emissions and carbon absorption (Equation (6)), is the standard for carbon compensation. Based on the principles of fairness and efficiency, this paper modifies carbon emissions and carbon absorption, respectively.

$$LUCB_i = CE_i - CA_i \tag{6}$$

where $LUCB_i$ is the LUCB of region i without the modification, and CE_i is the carbon emissions of region i.

Over-reliance on transfer payments may cause local governments to fall into the "incentive trap" [7]. Given the existence of transfer payments, local governments may take a negative attitude toward economic development and environmental management, leading to "lazy government". Therefore, the principle of efficiency should be considered in carbon compensation. LUCEE examines the degree of economic value maximization and ecological cost minimization achieved by a decision-making unit under certain factor inputs; it is also an important efficiency index that integrates the level of economic development and environmental governance [40]. In this paper, LUCEE is used to modify carbon emissions, and the carbon emissions of counties with efficiency values lower than the average are magnified (Equations (7) and (8)). The LUCEE in this paper is measured based on the super-SBM model with undesirable outputs, in which the input indicators are the area of construction land, the number of end-of-year employed people in units, and the total fixed asset investment. The desirable output indicator is the GDP, and the undesirable output indicator is the carbon emissions. The specific expression of the model can be found in reference [41].

$$\lambda_i = \begin{cases} 1 + (\overline{\alpha_i} - \alpha_i)/\overline{\alpha_i} & , \alpha_i < \overline{\alpha_i} \\ 1, & , \alpha_i \geq \overline{\alpha_i} \end{cases} \tag{7}$$

$$CE_{mi} = CE_i \times \lambda_i \tag{8}$$

where CE_{mi} is the modified carbon emissions of region i; λ_i is the modified coefficient of carbon emissions of region i; and α_i and $\overline{\alpha_i}$ are the LUCEE for region i and the mean value for all regions, respectively.

Differences exist in the natural endowment of different regions. Thus, the slightly naturally endowed regions become disadvantaged in carbon compensation because of the weak carbon sequestration capacity of vegetation. Based on the principle of fairness, this paper adopts ESV to modify carbon absorption, and the carbon absorption of counties with ESV lower than the average is amplified (Equations (9) and (10)). The formula for ESV can be found in reference [42].

$$\gamma_i = \begin{cases} 1 + (\overline{\mu_i} - \mu_i)/\overline{\mu_i} & , \mu_i < \overline{\mu_i} \\ 1, & , \mu_i \geq \overline{\mu_i} \end{cases} \tag{9}$$

$$CA_{mi} = CA_i \times \gamma_i \tag{10}$$

where CA_{mi} is the modified carbon absorption of region i; γ_i is the modified coefficient of carbon absorption of region i; and μ_i and $\overline{\mu_i}$ are the ESV for region i and the mean value for all regions, respectively.

3.3.5. Method for Determining the Subject–Object, Value, and Priority Order of Carbon Compensation

The modified LUCB determines the subject and object of carbon compensation (Equation (11)). Carbon deficit areas are payment zones, which need to pay the corresponding amount to compensate for their negative impacts on the ecological environment. In comparison, carbon surplus areas are compensation zones, which should be subsidized with the corresponding amount to reward the ecological contribution made by this area. The value of carbon compensation in this paper is determined based on the modified LUCB and carbon unit price (Equation (12)).

$$LUCB_{mi} = CE_{mi} - CA_{mi} \tag{11}$$

$$R_i = LUCB_{mi} \times P_c \tag{12}$$

where $LUCB_{mi}$ is positive, the region is a carbon deficit area, and $LUCB_{mi}$ is negative, the region is a carbon surplus area; R_i is the value of carbon compensation; and P_c is the carbon unit price, which is the average value of the trading price in China's carbon trading market from 2013 to 2020 (CNY 27.31) [30].

In the actual carbon compensation, multiple paying and receiving regions are involved. Therefore, the impact of the compensation amount on the payment regions and the degree of urgent need in the compensated regions must be considered to prioritize the payment and compensation. In this paper, we refer to the method provided by Wang et al. [32] to prioritize carbon compensation in each region (Equation (13)).

$$CCP_i = \frac{|R_i|}{GDP_i} \tag{13}$$

where CCP_i represents the priority index. When CCP_i is positive, the region is a payment zone. A smaller absolute value indicates that the region should pay the compensation amount on its economic development of the smaller impact, and should take the lead in the payment of the compensation amount. When CCP_i is negative, the region is a compensation zone. A larger absolute value indicates that the region should obtain an amount of compensation based on the impact on local economic development. A higher degree of urgency for compensation should result in a higher degree of priority to be compensated.

3.4. Data Sources

The NTL data required for carbon emissions measurement are from the research findings of Wu et al. (https://doi.org/10.7910/DVN/GIYGJU, accessed on 23 September 2023) [43]. China's county carbon emissions dataset from 1997 to 2017 can be downloaded from the CEADs (https://www.ceads.net.cn/data/county/, accessed on 12 April 2024).

The relevant meteorological data required for estimating carbon absorption, including temperature, precipitation, and sunshine hours, are from the China Meteorological Data Service Center (https://data.cma.cn/, accessed on 12 October 2023) and interpolated to obtain raster data. The NDVI data are from the China Tibetan Plateau Science Data Center (https://data.tpdc.ac.cn/zh-hans/data/10535b0b-8502-4465-bc53-78bcf24387b3, accessed on 15 October 2023) [44]. The land use data are from the annual China land cover dataset (CLCD) (https://zenodo.org/record/8176941, accessed on 15 October 2023) [45]. The land use data are resampled to ensure spatial resolution consistency with other data, all at a resolution of 250 m. Meanwhile, the land use types are reclassified into cropland, forest land, grassland, water area, construction land, and unused land by referring to the land use classification system of the Chinese Academy of Sciences.

The statistical data required for LUCEE measurement and carbon compensation prioritization are from the China County Statistical Yearbook, the statistical yearbooks of each city, and the statistical bulletins of each county. Individual missing data are completed by interpolation.

4. Results

4.1. Change Characteristics and Carbon Absorption Contribution of Each Land Use Type

4.1.1. Change Characteristics of Each Land Use Type

LUCC can affect the regional LUCB by changing the regional carbon source and carbon sink pattern. In this paper, the land use transfer matrix was used in describing the change characteristics of each land use type in the PRB during the 2005–2020 period from the two aspects of change quantity and dynamic transfer to analyze further the causes of LUCB change (Table 1). The results show that forestland and cropland are the major land use types in the PRB, accounting for most of the land area at the beginning and the end of the period.

Table 1. Land use transfer matrix in the PRB from 2005 to 2020 (km^2).

2020 2005	Cropland	Forestland	Grassland	Water Area	Unused Land	Construction Land	Transfer-Out
Cropland	121,957.04	26,399.27	1999.78	799.81	16.07	4098.12	33,313.05
Forestland	21,724.27	368,982.35	491.62	24.59	1.4	373.74	22,615.62
Grassland	3779.39	2755.69	4865.78	53.9	10.07	189.53	6788.58
Water area	1285.42	91.27	17.28	6306	8.7	359.6	1762.27
Unused land	0.93	0.04	1.2	4.22	2.7	3.14	9.53
Construction land	19.22	0.68	0.17	115.18	0.02	7976.36	135.27
Transfer-in	26,809.23	29,246.95	2510.05	997.7	36.26	5024.13	
Net transfer	−6503.82	6631.33	−4278.53	−764.57	26.73	4888.86	

In terms of the variable quantity in each category during the 2005–2020 period, the areas of forestland, construction land, and unused land increased by 6631.33, 4888.86, and 26.73 km^2, respectively, whereas the areas of cropland, grassland, and water area decreased by 6503.82, 4278.53, and 764.57 km^2, respectively. Construction land is the land use type with the highest growth rate without consideration of unused land, which increased by 60.27%. The decline rate of grassland was the highest, reaching 36.71%. The absolute value of the changes in each category is in the order of forestland > cropland > construction land > grassland > water area > unused land.

With regard to the dynamic transfer of each category, the transfer-in and transfer-out areas of cropland and forestland maintained a high scale, and a phenomenon of mutual transfer existed. The area transferred from cropland to forestland was 26,399.27 km^2, accounting for 90.26% of the transfer-in area of forestland, whereas the area transferred from forestland to cropland was 21,724.27 km^2, accounting for 81.03% of the transfer-in areas of cropland. Cropland has the largest area transferred out, totaling 33,313.05 km^2. It is the primary source of transfer-in area for all land use types. The areas of returning cropland to forestland and returning cropland for construction land expansion accounted for the largest proportion, representing 79.25% and 12.30% of the area transferred out of cropland, respectively. The reduced area of grassland was mainly transferred to cropland and forestland. The increased area of construction land was mainly transferred from cropland, accounting for 81.57% of the transfer-in area of construction land.

In summary, the land use structure of the PRB has always been dominated by carbon sink land. However, the proportion of carbon source land in the land use structure shows a rising trend with the gradual occupation of other land use types by construction land. In addition, a mutual transfer phenomenon exists in the carbon sink land, which is particularly manifested in the transfer of low-carbon sink land to high-carbon sink land. A large number of croplands and grasslands with relatively low carbon sinks have been transferred to forestland with high carbon sinks, resulting in an increase in the area of forestland at the end of the period.

4.1.2. Carbon Absorption Contribution of Each Land Use Type

In this paper, the carbon absorption of each land use type was measured using the CASA model on ENVI 5.6 software. Figures 3 and 4 show the annual average carbon absorption share and the time series change in carbon absorption for each land use type during 2005–2020, respectively.

Figure 3 shows that forestland and cropland, providing 96.31% of the annual average carbon absorption, are the main sources of carbon sinks. Forestland and cropland account for 68.82% and 27.49% of the annual average carbon absorption, respectively, whereas the carbon absorption contributions from other land use types are all below 2%. This phenomenon is closely related to the carbon sink capacity of different land use types and the size of the area. The carbon sink capacity of forestland and cropland is high, and the average annual area share is 95.08%. Thus, the carbon sink contribution is remarkable. Wetland has a high carbon sink capacity, but its area is small. Thus, the carbon sink contribution is limited. The carbon sink capacity of other land use types is low, and their area size is small, resulting in their limited contribution to carbon absorption.

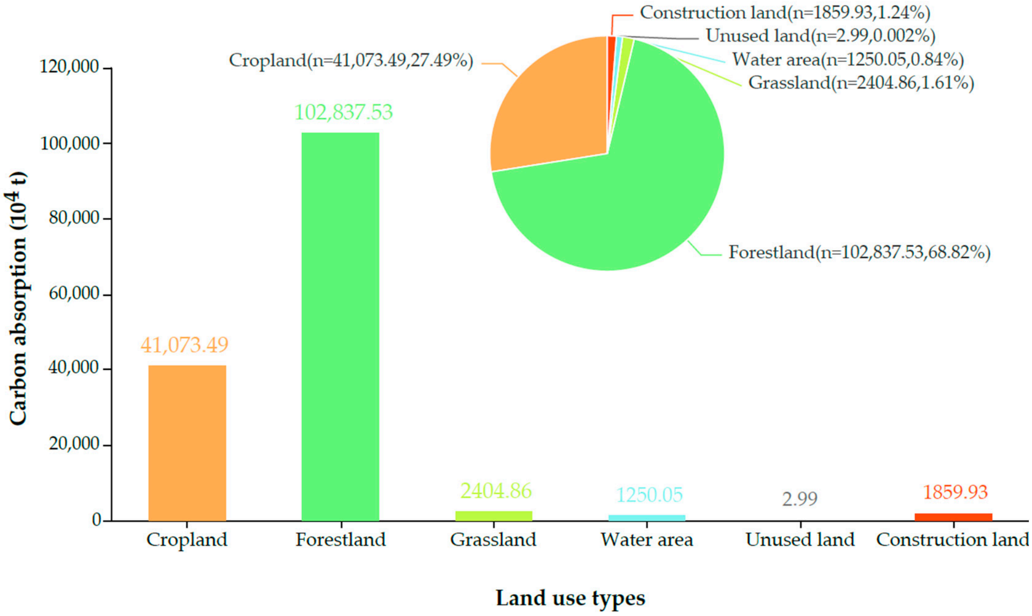

Figure 3. Annual average carbon absorption share for each land use type.

Figure 4 shows that the carbon absorption of other land use types increased from 2005 to 2020, but the carbon absorption of grassland decreased due to the reduction in area. The increase in carbon absorption observes the following order, from largest to smallest: forestland (123.83 million tons), cropland (34.70 million tons), construction land (11.25 million tons), water area (2.21 million tons), unused land (0.04 million tons), and grassland (−6.16 million tons). Among these land use types, cropland and water areas achieved an increase in carbon absorption despite a decrease in their areas. The increase in carbon absorption in cropland may be attributed to the improved efficiency in food production brought about by modern farming techniques and practices, which positively impact the vegetation carbon sequestration capacity of cropland [46]. The increase in the carbon absorption in the water area may benefit from ecological restoration and protection efforts, such as water environment management and wetland protection. The improvement of water quality is conducive to the optimization of aquatic ecosystems and the increase in the amount of vegetation. This improvement can positively affect the vegetative carbon sequestration capacity of the water area.

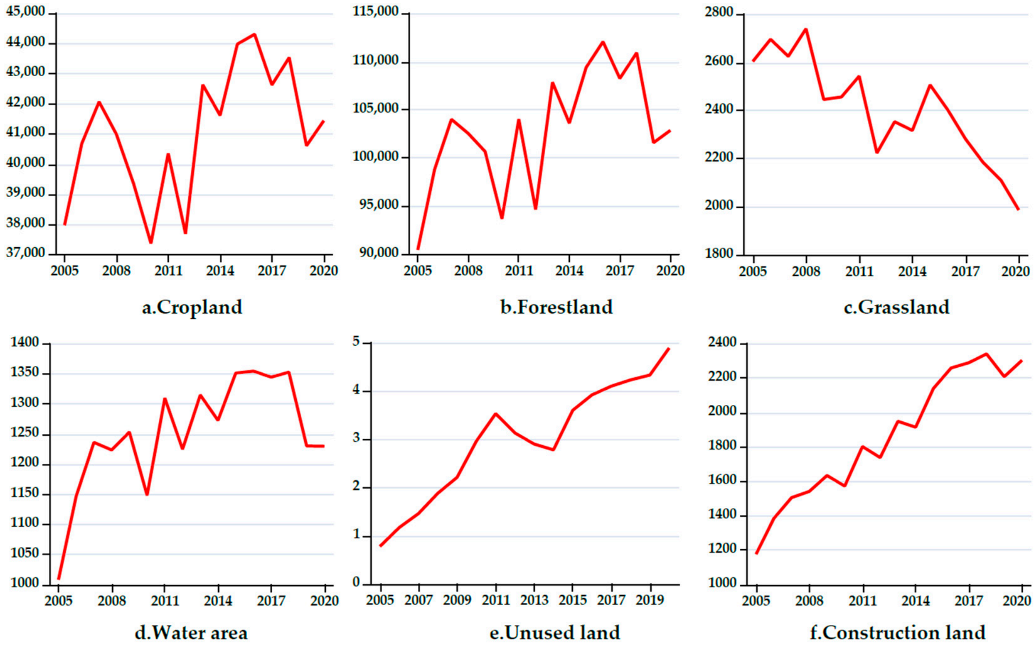

Figure 4. Time series changes in carbon absorption for each land use type (the unit is 10^4 tons).

4.2. Spatiotemporal Patterns and Changes in Carbon Emissions and Absorption

4.2.1. Time Series Changes in Carbon Emissions and Absorption

Figure 5 shows the changes in carbon emissions and absorption in the PRB before and after the modification from 2005 to 2020. Regardless of whether the modification was performed or not, the carbon emissions and absorption in the PRB show a fluctuating upward trend. This outcome is related to the remarkable increase in the area of carbon source land (construction land) and high-carbon sink land (forestland) in the basin. Before the modification, the total carbon absorption was always higher than the carbon emissions. However, the growth rate of carbon emissions is remarkably higher than that of carbon absorption. In 2005, the carbon emissions before modification were 493.18 million tons. They increased to 1000.28 million tons by 2020, indicating an increase of 102.82%. By contrast, carbon absorption increased from 1332.5 million tons in 2005 to 1498.47 million tons in 2020, an increase of only 12.46%. This finding indicates that during urbanization and industrialization, the carbon emissions generated by urban expansion and energy consumption in the basin are rapidly catching up with the carbon absorption of vegetation.

After the modification of the economic efficiency and ecological equity for carbon emissions and absorption, the characteristics of the total amount and growth speed of the carbon emissions and absorption are consistent with those before the modification. The growth rate of carbon emissions after the modification is higher than that before the modification, whereas the growth rate of carbon absorption after the modification is lower than that before the modification. The growth rate of carbon emissions in the study period after the modification was 112.14%, which is 9.32% higher than that before the modification. Moreover, the growth rate of carbon absorption after the modification is 11.34%, which is 1.12% lower than that before the modification. This finding indicates that the modification has a great impact on carbon emissions, resulting in a greater increase in carbon emissions than carbon absorption. The growth in carbon emissions due to the modification and its growth rate is consistently higher than the growth in carbon absorption throughout the study period. The gap between modified carbon emissions and absorption gradually decreases with the overall increase in the growth of carbon emissions and the overall decrease in the growth of carbon absorption.

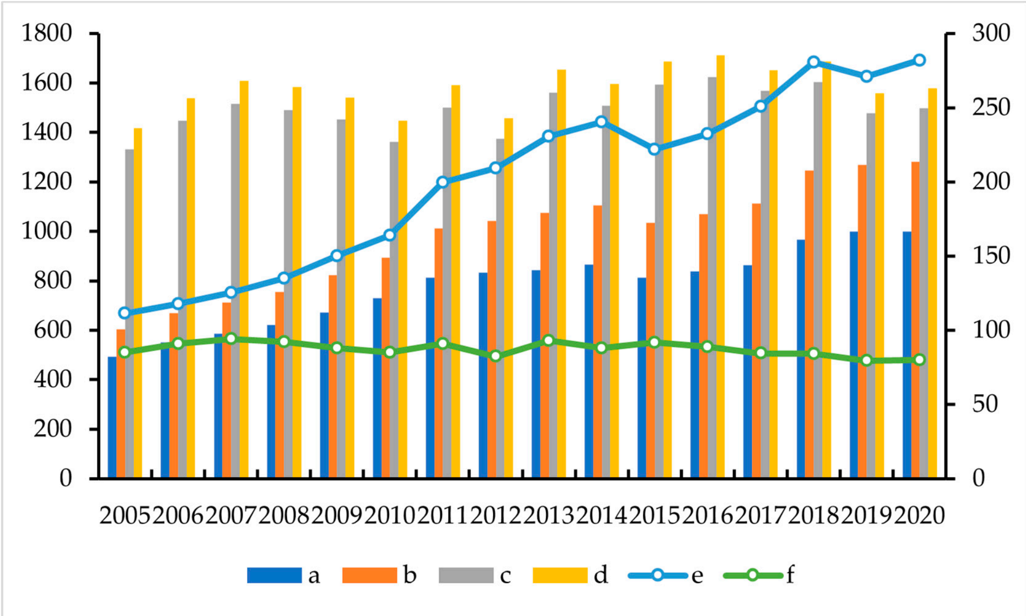

Figure 5. Time series changes in carbon emissions and absorption (the unit is 10^4 tons): a and b are carbon emissions before and after the modification, respectively; c and d are carbon absorption before and after the modification, respectively; e and f are growth in carbon emissions and absorption after the modification, respectively.

4.2.2. Spatial Distribution and Changes in Carbon Emissions and Absorption

Given the long study period, this paper analyzes the spatial distribution characteristics of carbon emissions and absorption before and after the modification based on the annual average data. Figure 6 shows the results visualized using ArcGIS 10.6 software, with dark colors representing large values.

In general, the spatial difference in annual average carbon emissions before modification is remarkable; in particular, it shows the spatial distribution gradually shrinking from the southeast and northwest directions toward the periphery. The low-value areas with less than 1 million tons are concentrated in the upper and middle reaches of the basin, mostly in economically underdeveloped areas, while the high-value areas with more than 5 million tons are concentrated in the lower reaches of the basin, mostly in economically developed areas.

In particular, the high-value areas of carbon emissions are mainly urban municipal districts and resource-based counties. The municipal district is the core component of the city and the center of regional economic development. It is densely populated and economically developed, and its carbon emissions are higher than those of other counties. The annual average carbon emissions of many municipal districts rank among the highest. For example, the Nanning urban district has an annual average carbon emission of 21.59 million tons, second only to Dongguan City and Zhongshan City, which do not have county-level administrative districts. The top 10 municipal districts also include the Nanhai and Shunde districts in Foshan City, the Bao'an and Longgang districts in Shenzhen City, and the Guangzhou urban district, with an average annual carbon emission of more than 10 million tons. The development of resource-based counties is closely linked to resource development, and the mining of minerals and deforestation lead to high carbon emissions in these counties. Many resource-based cities are in the northwestern part of the PRB, including Liupanshui City, Anshun City, Bijie City, Qiannan Autonomous Prefecture, and Qianxinan Autonomous Prefecture. The average annual carbon emissions of Panzhou City, Liupanshui urban district in Liupanshui City, Xingyi City in Qianxinan Autonomous Prefecture, and Xixiu District in Anshun City exceed 5 million tons.

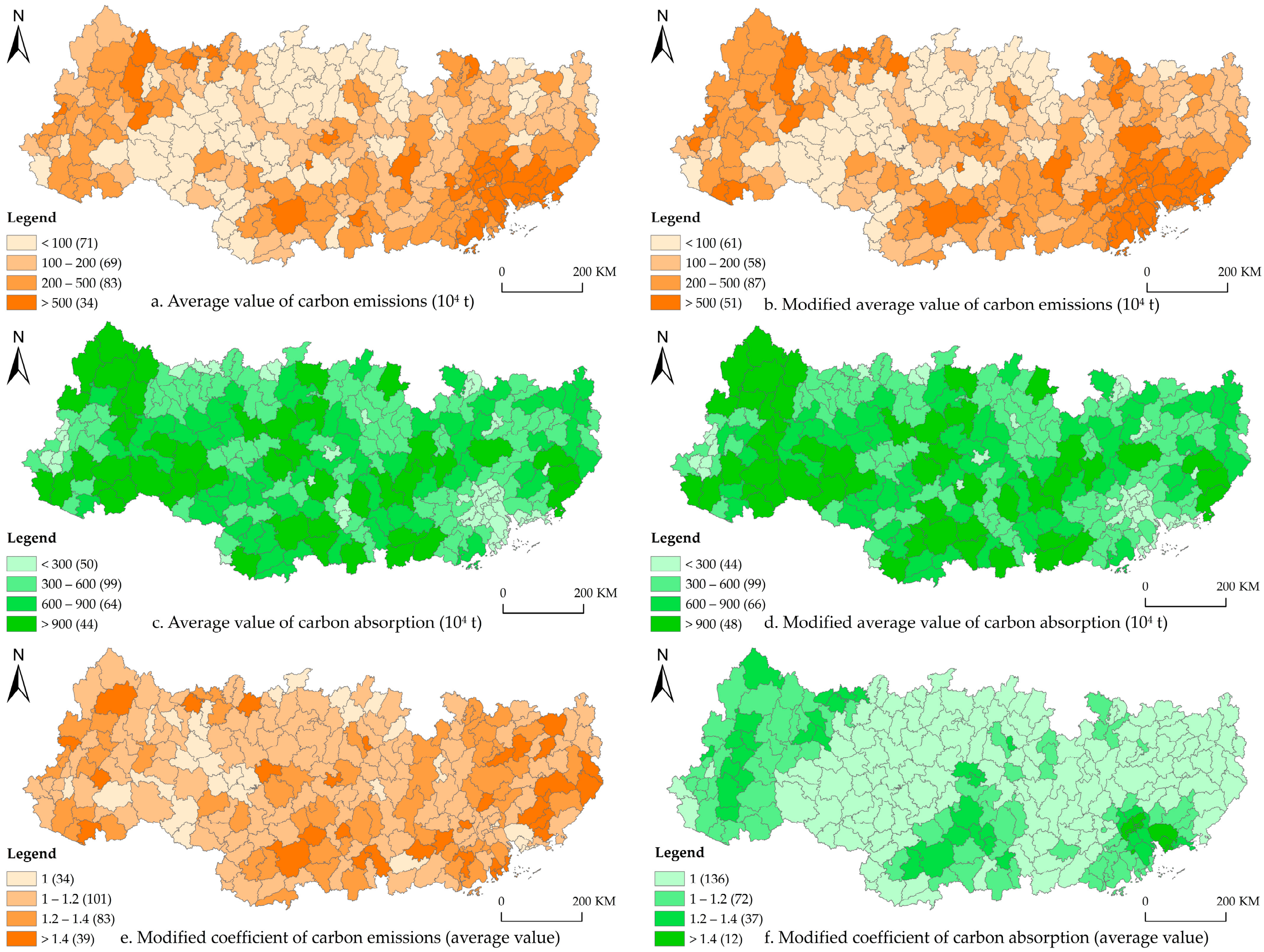

Figure 6. Spatial distribution in carbon emissions and absorption before and after the modification.

The spatial distribution characteristics of the annual average carbon emissions after the modification are the same as those before the modification. The difference is that after the LUCEE modification for carbon emissions, most of the counties (223) have increased carbon emissions because their efficiency is lower than the mean value. Nonetheless, the modified coefficient of carbon emissions is less than 1.4 for most of the counties. Only 39 counties have a value greater than 1.4, with the largest value being only 1.67. This ensures that carbon emissions are not overamplified by the modification and that both efficiency and fairness are considered. Only 34 counties have a mean LUCEE value that is not less than the mean (modified coefficient = 1). This finding indicates that the LUCEE level in PRB is generally low and that the regional differences are large. These 34 counties are generally economically developed or have low carbon emissions, and achieve high desirable output or low undesirable output with low inputs, reaching an efficiency value higher than the average level. The representatives of economically developed areas are Dongguan City and most districts and counties in Shenzhen and Guangzhou, whereas the representatives of low carbon emissions are Fenglan County, Donglan County, and Ziyuan County in Guilin City, which exhibit the lowest carbon emissions.

Regardless of whether the modification was performed or not, the annual average carbon absorption in the basin is generally "green", with unremarkable spatial differences. Many counties have high values of carbon absorption. Only 50 low-value areas had carbon absorption of less than 3 million tons before the modification. This number represents less than 20% of the counties in the watershed, which are mainly in the PRD. After the ESV modification of carbon absorption, only 121 counties have increased carbon absorption due to ESV below the mean. This number is much less than the number of counties participating in carbon emission modification. In addition, the magnitude of the carbon absorption modification is modest. The majority of counties have a modified coefficient of carbon absorption below 1.4, and only 12 have a modified coefficient of carbon absorption greater than 1.4. This finding indicates that the ESV levels in the watershed are generally high, and the regional differences are small. These 12 counties belong to the PRD, including Guangzhou City, Shenzhen City, Foshan City, Dongguan City, and Jiangmen City. These counties are poorly endowed and highly urbanized. Urban expansion results in the use of limited ecological land for construction, resulting in a much lower ESV than the average level in the basin.

4.3. Spatiotemporal Pattern and Changes in the LUCB

4.3.1. Time Series Changes in the LUCB

Figure 7 shows the changes in the LUCB before and after the modification of carbon emissions and carbon absorption in the PRB from 2005 to 2020. Whether it is corrected or not, the LUCB is negative during this period and shows a fluctuating upward trend. This finding shows that although the PRB has always been a carbon surplus area, LUCB is increasing. This phenomenon can potentially result in a carbon deficit. If regional carbon reduction measures are not taken, carbon emissions may exceed carbon absorption in the future, making the PRB a carbon deficit area.

After the modification, the LUCB increased remarkably. From 2005 to 2020, the total amount of the modified LUCB reached −9602.5 million tons, an increase of 1823.35 million tons compared with the total amount of the unmodified LUCB. In addition, the variation in the LUCB showed a remarkable upward trend over time. In 2005, the revised LUCB variation was only 26.03 million tons; by 2020, it increased to 202 million tons, an increase of 6.76 times. This finding is related to the previously mentioned phenomenon that the number of counties participating in carbon absorption modification is far less than the number of counties participating in carbon emission modification. Over time, the phenomenon of LUCEE deviating from the regional average in some counties is more evident than that of ESV deviating from the regional average, thereby leading to the modification of carbon emissions greater than that of carbon absorption and finally making the modified LUCB higher than before the modification.

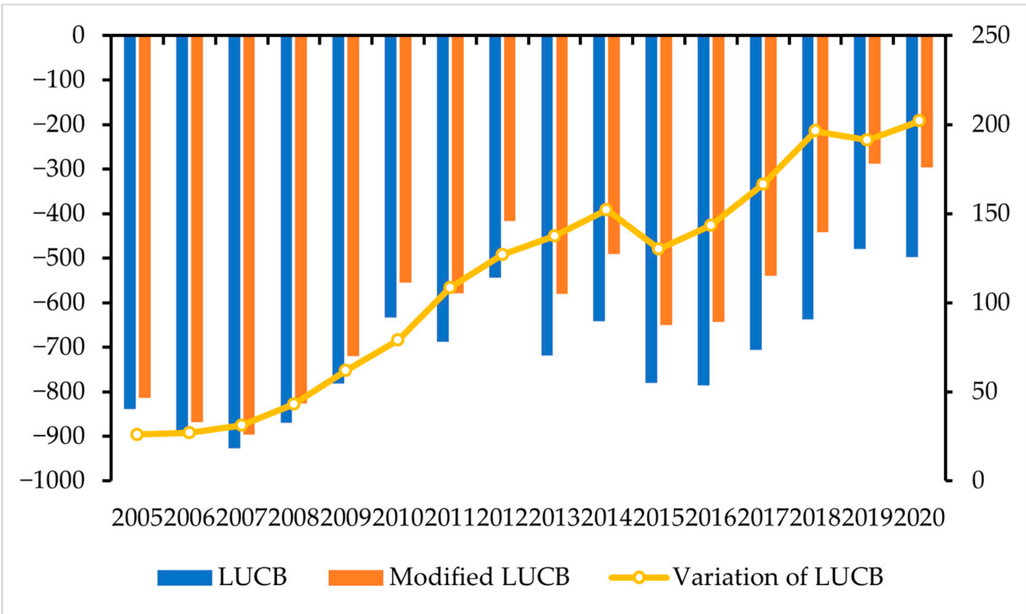

Figure 7. Time series changes in LUCB before and after the modification (the unit is million tons).

4.3.2. Spatial Distribution and Changes in the Modified LUCB

In this paper, four time nodes (2005, 2010, 2015, and 2020) were selected, and ArcGIS 10.6 software was used to visualize the modified LUCB and the variation (Figure 8) to explore the spatial distribution characteristic of the modified LUCB. After the modification of carbon emissions and absorption, a large number of carbon surplus counties are distributed in the upper and middle reaches of the PRB, whereas a small number of carbon deficit counties are distributed in the lower reaches. The number of carbon deficit and carbon surplus counties in 2020 was 75 and 182, respectively, which represents an increase of 24 carbon deficit counties and a decrease of 24 carbon surplus counties compared with 2005.

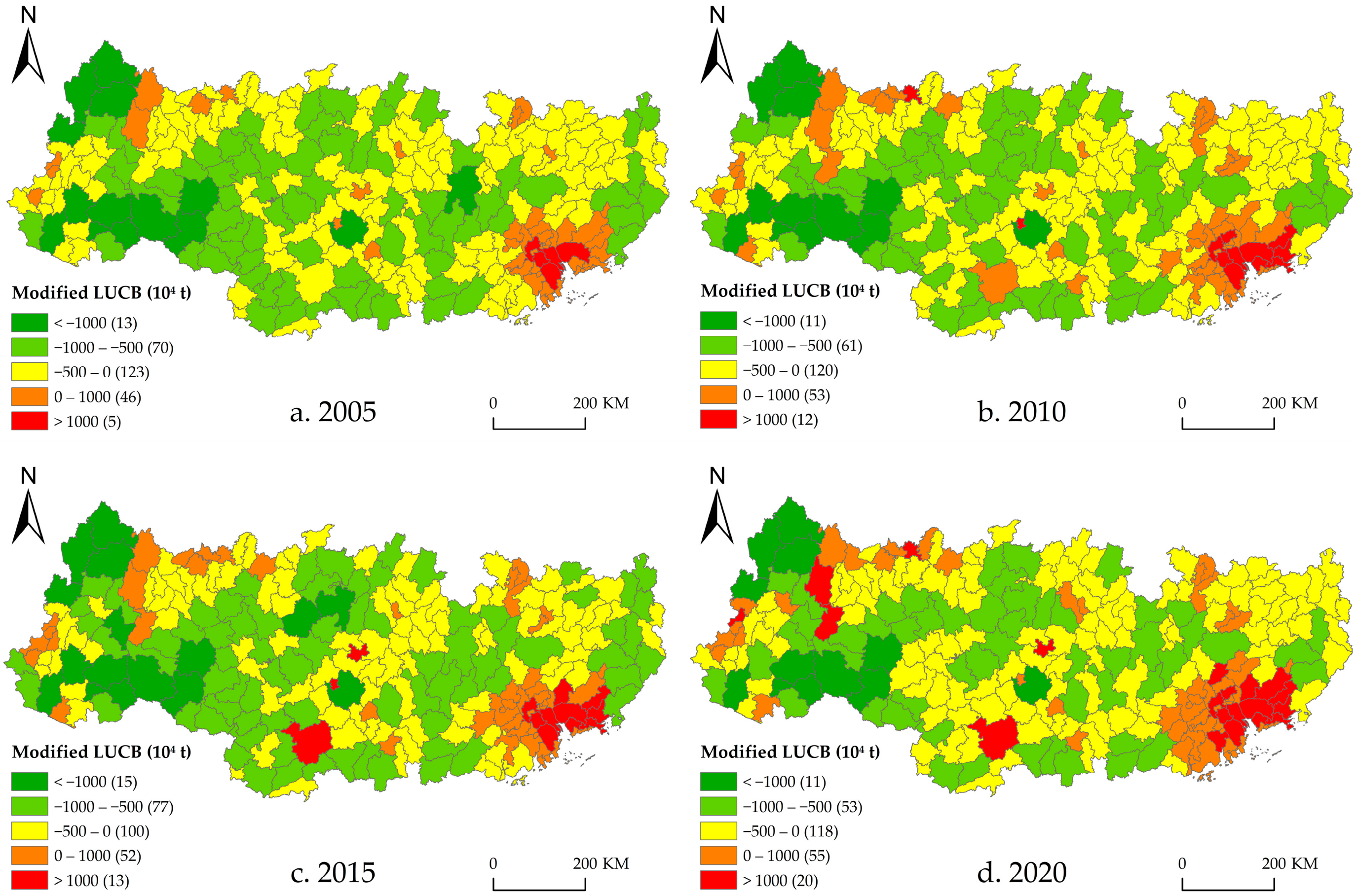

Figure 8. Spatial distribution in modified LUCB.

From 2005 to 2020, the high-value areas of the modified LUCB showed a trend of spatial distribution gradually expanding from southeast to northwest, and this trend became increasingly evident over time. In 2005, only five red areas had a modified LUCB greater than 10 million tons, and all of them were concentrated in the PRD. A total of 46 orange zones had a modified LUCB of 0–10 million tons. Most of them were located in or around the PRD, whereas a few were located in the municipal districts and resource-based counties in the upper and middle reaches of the basin, such as Huaxi District, the municipal district of Guiyang City, and Heshan City, the county-level city of Laibin City, known as the "coal capital of Guangxi". In 2010, the number of red and orange areas increased by seven. In 2015, the change was small, and the number of red and orange areas increased and decreased by one, respectively. In 2020, the red and orange areas increased by seven and three, respectively. Although the number increased, the spatial distribution characteristic of the modified LUCB in 2020 is the same as that in 2005. The difference is that the red areas extend to some counties in the upper and middle reaches, including Nanning urban district, Liuzhou urban district, Huaxi District, Xingyi Dity, Guandu District, and Panzhou City. These counties also belong to urban municipal districts or resource-based counties.

4.4. Determination of the Subject–Object and Value of Carbon Compensation

Given that the spatiotemporal pattern of the modified LUCB was described previously and that the study area involves numerous counties, this paper no longer describes the carbon compensation each year in detail. This paper only shows the specific results of carbon compensation in 2020 and provides quantifiable data for the subsequent construction of the carbon compensation mechanism.

According to the principle of "one level of government, one level of finance", China's current local finance consists of four levels: provincial, municipal, county, and township. This work does not consider the township level and focuses on the amount of money that should be paid or compensated by local governments at the provincial, municipal, and county levels in the PRB in 2020. Table 2 lists the payment amounts of provincial and municipal governments in the PRB in 2020. As a city under separate state planning, Shenzhen has a direct financial interface with the central government. Therefore, it is financially part of the provincial local government. Table 3 lists the payment amounts of the top and bottom 25 county local governments in the PRB in 2020. Specific information on carbon compensation for all counties in 2020 can be found in Table S3 in the Supplementary Materials.

Table 2. Payment amount of provincial and municipal governments in 2020 (CNY million).

Region	Amount	Region	Amount	Region	Amount	Region	Amount
Guangdong	**5750.97**	Qingyuan	−388.21	Baise	−1959.02	**Yunnan**	**−4962.9**
Shenzhen	**975.67**	Dongguan	1231.32	Hezhou	−491.96	Kunming	−63.27
Guangzhou	2141.08	Zhongshan	1107.63	Hechi	−1598.99	Qujing	−1822.7
Shaoguan	−553.46	Yunfu	−143.75	Laibin	−373.65	Yuxi	−171.25
Zhuhai	719.58	**Guangxi**	**−7310.12**	Chongzuo	−806.21	Honghe	−947.6
Foshan	1443.67	Nanning	273.01	**Guizhou**	**−1382.37**	Wenshan	−1958.07
Jiangmen	830.84	Liuzhou	−99.85	Guiyang	380.18	**Jiangxi**	**−744.75**
Maoming	−391.2	Guilin	−838.54	Liupanshui	564.74	Ganzhou	−744.75
Zhaoqing	−210.38	Wuzhou	−371.8	Anshun	−81.22	**Hunan**	**−415.11**
Huizhou	1021.11	Fangchenggang	−295.14	Bijie	−472	Shaoyang	−131.02
Meizhou	−142.94	Qinzhou	−414.34	Qianxinan	−421.5	Chenzhou	158.24
Heyuan	−645.76	Guigang	−147.53	Qiandongnan	−635.83	Yongzhou	−328.41
Yangjiang	−268.55	Yulin	−186.11	Qiannan	−716.74	Huaihua	−113.92

In 2020, the PRB belongs to the area of carbon sink value spillover, resulting in altruistic positive externalities. Moreover, the total regional compensation is CNY −8088.61 million. Regardless of the level of local government, the number of payment zones is less than that of compensation zones. Among the provincial local governments, only Guangdong Province (excluding Shenzhen City) and Shenzhen City are payment zones, and they are required to pay CNY 5750.97 and 975.67 million, respectively. The other five provincial local governments are the compensation zones, and the total amount of compensation available is CNY 14,815.25 million. Among them, Guangxi Province received the highest amount, reaching CNY 7310.12 million; Hunan Province received the lowest amount, reaching CNY 415.11 million. The municipal local governments comprise 11 payment zones and 34 compensation zones. Except for Liupanshui and Guiyang in Guizhou Province, Nanning in Guangxi Province, and Chenzhou in Hunan Province, the remaining seven cities are PRD cities, and all of them are among the top seven in terms of the amount of carbon compensation payments. The county-level local governments comprise 75 payment zones and 182 compensation zones. The top 25 payment zones are municipal districts or resource-based counties, except for Dongguan City and Zhongshan City, which do not have county-level administrative districts. The top 25 compensation zones are mainly distributed in Guangxi and Yunnan provinces, and they are counties with backward economic development and various carbon sink resources. Among them, five ethnic autonomous counties exist, accounting for 20%.

Table 3. Payment amount of the top and bottom 25 county local governments in 2020 (CNY million).

Rank	County	Amount	Rank	County	Amount	Rank	County	Amount
1	Dongguan	1231.32	18	Panzhou	289.01	241	Yangchun	−236.54
2	Zhongshan	1107.63	19	Qingcheng	276.95	242	Rongshui	−242.2
3	Nanning urban district	680.68	20	Xinhui	275.28	243	Shiping	−245.09
4	Liuzhou urban district	642.22	21	Heshan	260.48	244	Luoping	−247.96
5	Guangzhou urban district	621.12	22	Doumen	248.82	245	Longlin	−256.26
6	Shunde	522.06	23	Liupanshui urban district	247.51	246	Mile	−265.88
7	Nanhai	504.18	24	Huadu	244.1	247	Jianshui	−284.32
8	Huiyang	437.95	25	Jinwan	239.55	248	Xingbin	−300.35
9	Zengcheng	390.87	…	…	…	249	Yanshan	−334.4
10	Bao’an	389.3	233	Bobai	−198.32	250	Xundian	−349.45
11	Huaxi	380.18	234	Liping	−198.58	251	Funing	−365.24
12	Longgang	372.96	235	Dongyuan	−199.86	252	Tianlin	−372.39
13	Baiyun	366.73	236	Fuyuan	−223.92	253	Xuanwei	−400.68
14	Huicheng	365.62	237	Xinyi	−229.64	254	Qiubei	−441.13
15	Xingyi	338.18	238	Huanjiang	−232.12	255	Weining	−472
16	Guandu	291.16	239	Xilin	−235.02	256	Huize	−479.16
17	Boluo	289.13	240	Ningming	−235.06	257	Guangnan	−625.77

4.5. Determination of the Priority Order of Carbon Compensation

This paper calculates the priority of the payment zone and the compensation zone in the PRB in 2020 to determine the order of compensation and ensure the smooth progress of carbon compensation. For the analysis, this paper uses the natural breakpoint classification function of ArcGIS 10.6 software to divide the payment zone into priority payment zone, secondary payment zone, and potential payment zone, and the compensation zone into priority compensation zone, secondary compensation zone, and potential compensation zone (Figure 9).

The amount of payment accounted for less than 0.9% of GDP in the rest of the payment zones, except for Heshan City, the “coal capital of Guangxi”. The amount of payment in this city accounted for 7.36% of GDP. This finding indicates that the payment amount has a small impact on the economy of most counties, and carbon compensation is practicable. A total of 46 priority payment zones exist, exceeding the number of secondary payment zones and potential payment zones combined. This finding indicates that most of the payment zones have a relatively strong economic capacity to pay and can be prioritized for compensation, thereby ensuring the smooth implementation of carbon compensation. The priority payment zones include counties with a high LUCB, such as Bao’an District, and counties with a low LUCB, such as Mengzi City. However, regardless of the LUCB level, the amount of carbon payment in these areas is within their affordability. After paying the compensation amount, they can still allocate part of the funds for carbon reduction and sink enhancement, and the balance between economic development and ecological protection can be realized through internal adjustment. A total of 21 secondary payment zones exist, mostly distributed around the priority payment zones. This kind of regional economic development indicates a good condition and shows a certain economic capacity to pay the amount of carbon compensation. Only eight potential payment zones exist, and their carbon payment amounts account for more than 0.5% of GDP. This means that a one-time payment of carbon compensation has a great financial burden on these areas. Therefore, such areas, particularly Heshan City, should be compensated later. In the implementation of carbon compensation, these regions can choose to delay the amount of carbon compensation or pay in installments after they reach a consensus. Thus, these areas can prioritize the use of funds for economic development and other aspects.

The priority compensation zones include 10 counties, all of which are located in Guangxi Province. Most of these areas are located in the upper reaches of the PRB, which bear considerable economic and opportunity costs for protecting the ecological environment, thereby resulting in lagging economic development. Carbon compensation funds are crucial to alleviating the pressure of ecological protection in these areas. Thus, compensation should be prioritized to enhance their enthusiasm for ecological protection. The secondary compensation zones are similar to the priority compensation zones, most of which are rich in carbon sinks and focus on environmental protection functions. In carbon compensation, the secondary compensation zones should also be given sufficient attention. The potential compensation zones are the most numerous, totaling 116 areas. The LUCBs of most of these areas are between −5 and 0 million tons, with a lower carbon sink value surplus. This finding indicates that these areas are in a coordinated equilibrium between economic development and ecological protection and should be compensated in a deferred manner. In the implementation of carbon compensation, these regions can choose to delay or receive the amount of carbon compensation in installments after a consensus is reached among the various regions, giving priority to subsidizing regions with highly difficult economies.

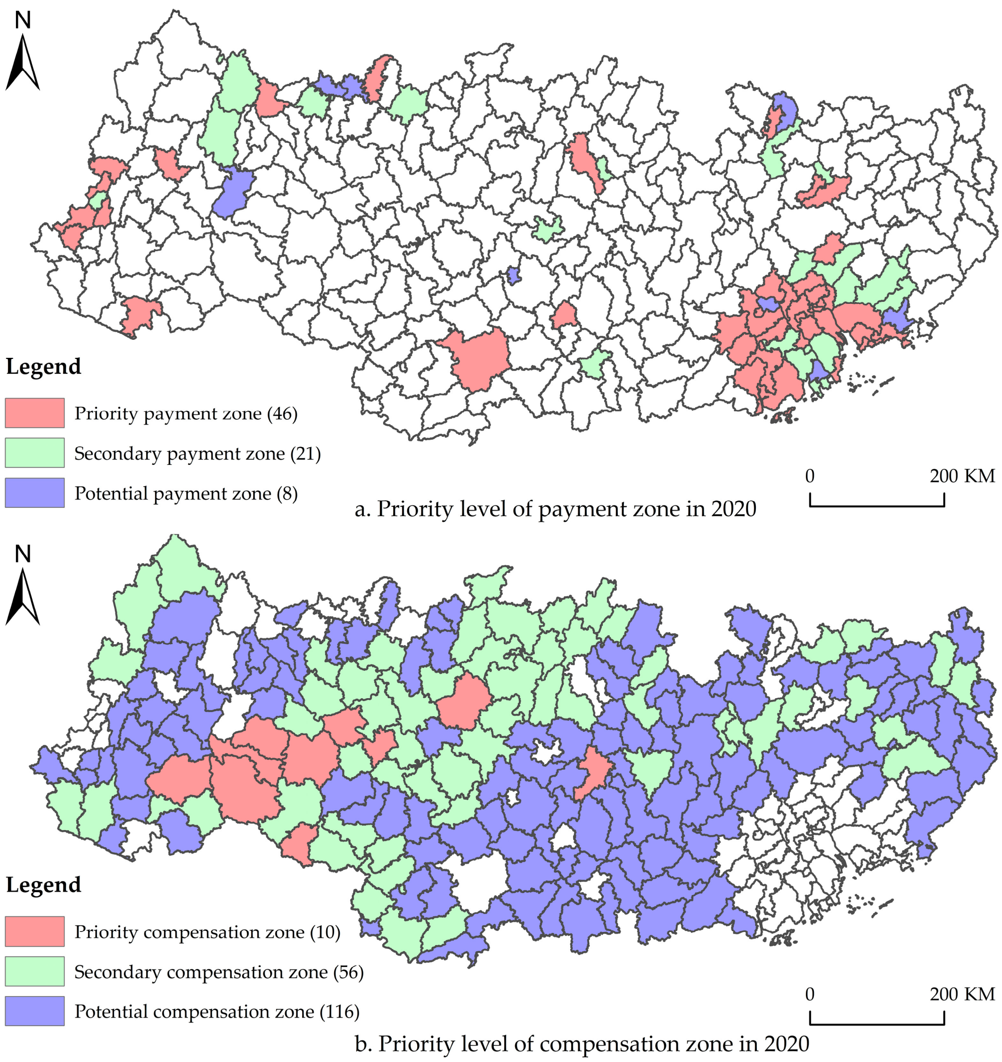

Figure 9. Priority level of carbon compensation in 2020.

5. Discussion

5.1. Construction of Carbon Compensation Mechanism

In environmental governance, a principal–agent relationship exists between the central and local governments in China [47,48]. The central government sets strategic goals and delegates specific environmental governance tasks to the local governments [49]. However, due to asymmetric information between central and local governments, ensuring that local governments implement the strategies set by the central government is difficult. Acting as "economic men" pursuing utility maximization, local governments may engage in short-sighted, rent-seeking behaviors that prioritize economic development at the expense of the environment [16]. Therefore, carbon compensation requires the involvement of the central government in a regulatory role. However, existing research generally focuses on horizontal carbon compensation between local governments [18,34], ignoring vertical carbon compensation and the important role of the central government in promoting the realization of the "dual carbon" goal. For example, Yang et al. [15] recognized the importance of vertical carbon compensation. However, they limited it to the provincial level and did not consider the central government. The central government is the advocate and organizer of carbon compensation, and it aims to achieve the goal of "double carbon" under the premise of ensuring sustainable development of each region; in comparison, the local governments are the specific participants, and they aim to achieve the maximization of regional economic and environmental benefits [50]. Without the participation of the central government, carbon surplus areas do not have enough enthusiasm to protect the environment, and carbon deficit areas do not take the initiative to compensate carbon surplus areas. Peng et al. [51] demonstrated that the absence of the central government would make it difficult to implement horizontal carbon compensation between regions by constructing an evolutionary game model. In addition, the fiscal imbalance that exists in China requires the central government to participate in carbon compensation to ensure the source of funds for the actual compensation process. Therefore, constructing a combined vertical and horizontal carbon compensation mechanism with the participation of the central and local governments is necessary.

In view of the principal–agent relationship of the Chinese government in environmental governance and the principle of financial allocation of "one level of government, one level of finance," this paper constructs a carbon compensation mechanism in vertical and horizontal directions. In the vertical direction, according to the hierarchy of China's administrative divisions, carbon compensation can be divided into vertical compensation from the central government to the provincial government, from the provincial government to the municipal government, and then from the municipal government to the county government, level by level. The compensation direction is from the superior government to the subordinate government. For counties implementing the fiscal "province–managing–county" reform, municipal governments do not participate in the vertical compensation because their finances are directly managed by the provincial government; for Dongguan City and Zhongshan City, which do not have districts or counties, county governments do not participate in the vertical compensation; for Shenzhen City, whose finances are directly interfaced with the central government, the provincial government does not participate in the vertical compensation. In the horizontal direction, if horizontal compensation is carried out on a level-by-level basis among governments at the same level according to the administrative division hierarchy, carbon compensation is difficult to carry out because too many carbon compensation subjects are involved. Therefore, horizontal compensation is coordinated by the provincial governments to simplify the process and improve efficiency because they have the largest fiscal power and the highest administrative division level in the local government. The compensation direction is from provincial governments with carbon deficits to those with carbon surpluses.

The compensation mechanism constructed in this paper is based on the special fund platform, and the specific flow is shown in Figure 10. The central government sets up a special fund as a platform for carbon compensation. It also creates the primary accounts containing six provinces and Shenzhen City, the secondary accounts containing 45 municipalities, and the tertiary accounts containing 257 counties. The secondary and tertiary accounts are managed by the primary account. The specific process of carbon compensation in the PRB is divided into two stages. The first stage is the vertical compensation from the central government and the horizontal compensation between regions represented by the provincial government. In 2020, the central government needed to allocate at least CNY 8088.61 million to the Carbon Compensation Special Fund, and Guangdong Province and Shenzhen City needed to make horizontal compensation to other provinces on behalf of their subordinate governments. These funds, amounting to CNY 6726.64 million, would flow to the primary accounts of Jiangxi, Hunan, Guangxi, Guizhou, and Yunnan. Guangdong Province and Shenzhen City should advance the compensation amount of their subordinate governments during the horizontal compensation process and pay the carbon surplus provinces for the first time to enable carbon surplus provinces to enter the second stage quickly. The second stage is the vertical compensation of local governments on a level-by-level basis. The provincial government pays the compensation amount to the secondary and tertiary accounts of the carbon surplus areas in the province in a step-by-step fashion. The carbon deficit county government submits the compensation amount to the secondary and primary accounts in a step-by-step manner. The compensation order of this stage is determined according to the priority of the payment and the compensation zones.

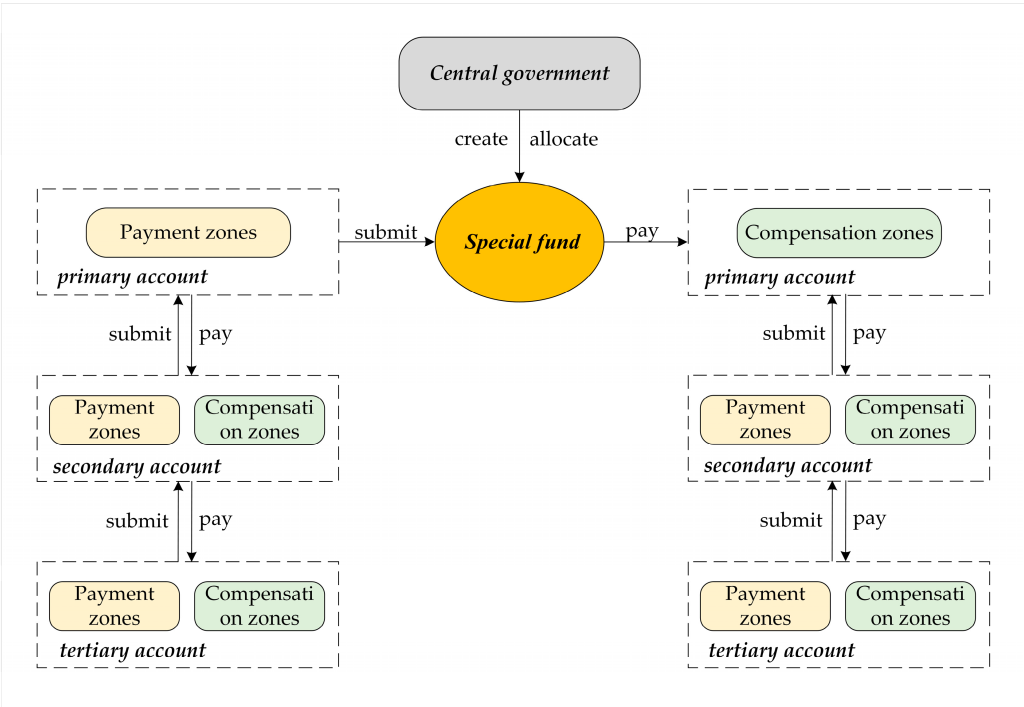

Figure 10. Carbon compensation flow chart.

5.2. Analysis of Results

The proposal of the "dual carbon" goal and the constraints of fiscal imbalance brought great pressure on local governments in managing the environment. The mismatch between vertical and horizontal fiscal power and affairs seriously affects the ability and enthusiasm of local governments to engage in carbon reduction and sink enhancement and damages the well-being of local people. Therefore, carbon compensation must be carried out to promote regional coordinated green development. This paper analyzes the spatiotemporal pattern of LUCBs in 257 counties in the PRB from 2005 to 2020. On this basis, a feasible vertical and horizontal carbon compensation mechanism is constructed.

The results show that LUCC in the PRB during the study period was characterized by a substantial increase in construction land and the conversion of low-carbon sink land (cropland) to high-carbon sink land (forestland); this finding is consistent with the research results of Lan and Qu [52]. The former is due to the needs of economic development, urbanization, and industrialization, whereby construction land of higher economic utility takes up more ecological land of lower economic utility, resulting in a gradual increase in the proportion of construction land in the land use structure [53]. The latter is due to the implementation of the national strategy for "ecological civilization construction" and the Grain for Green program [54].

The results also show that the PRB was a carbon surplus area from 2005 to 2020, which is relatively rare in the existing carbon compensation research. After using the empirical coefficient method to measure the LUCB of the study regions, most of the existing research usually shows these regions to be carbon deficit regions, such as the Huai River Basin [31], the Yellow River Basin [55], the urban agglomeration in the middle reaches of the Yangtze River [21], and Hunan Province [56]. These studies usually use uniform empirical coefficients to assess the carbon emissions or absorption of various land use types, and the complexity of carbon emissions and absorption in different land use types is ignored. Even construction land, as the carbon source land, has the effect of carbon sequestration [57]. These studies usually characterize cropland and construction land directly as carbon sources without considering their role as carbon sinks, resulting in an underestimation of carbon absorption in the whole region. In this work, the CASA model was used to calculate the NPP of different land use types. The cropland in the PRB had a remarkable contribution to carbon absorption, and the construction land contributed a small amount of carbon absorption. The CASA model results were more accurate than the empirical coefficient method results. The high coverage of green vegetation was also the reason why the PRB is a carbon surplus area. The proportion of forestland and cropland in the land use structure of the PRB has always been high. A large amount of cropland was converted into forestland because of the implementation of the national strategy for "ecological civilization construction" and the Grain for Green program. Thus, the carbon absorption in the PRB showed an upward trend during the study period. Cheng et al. [58] also supported this conclusion. They found that in South and Southwest China, plantation forests are mainly converted from cropland and shrubland, and the expansion of plantation forests remarkably contributes to the rapid growth of carbon stocks.

The carbon compensation in the PRB generally presents the pattern of downstream compensation for the middle and lower reaches, municipal districts, and resource-based counties to compensate other counties. The carbon surplus areas are mainly distributed in the middle and upper reaches, whereas the carbon deficit areas are mainly distributed in the lower reaches and part of upstream areas; this finding is consistent with the research results of Zhang et al. [59]. Resource-based counties have higher energy consumption than other counties, resulting in high carbon emissions. However, most municipal districts have high carbon emissions and weak carbon sink capacities because of their high level of economic development and limited green ecological space and carbon sink resources. In addition, the modification of carbon compensation value in this work fully considers the principles of economic efficiency and ecological fairness, and LUCEE and ESV are used to modify carbon emissions and absorption, respectively. Unlike other studies [14,22], this paper adopts a non-correction strategy with a modified coefficient of one for counties with LUCEE and ESV higher than the mean. This strategy is in line with this study's original intention of avoiding the excessive reduction in carbon emissions in some areas caused by high LUCEE, leading to insufficient or no payment. The reduction in carbon absorption in ecologically better areas is also avoided, leading to insufficient compensation.

5.3. Policy Recommendations

(1) Each county in the PRB should take differentiated measures to reduce carbon and increase sinks according to the actual situation. Most of the municipal districts have a high level of economic development and limited carbon sink resources. Thus, they become carbon deficit areas. These areas should limit the excessive expansion of

construction land and increase regional carbon storage through artificial afforestation. Some resource-based counties have become carbon deficit areas because of their large energy consumption. These regions should develop clean energy, promote industrial transformation, and focus on reducing energy carbon emissions. Carbon surplus areas have made significant contributions to the process of achieving regional carbon neutrality. However, they also need to improve LUCEE, promote economic development, and seek more benefits for local people.

(2) The mismatch between vertical and horizontal fiscal power and affairs is the root cause of the need for carbon compensation. Therefore, fiscal system reform should be carried out, and the matching degree of fiscal power and affairs among governments at all levels should be improved. Clarifying the scope of expenditure responsibilities of governments at all levels in environmental governance, avoiding the downward transfer of expenditure responsibilities from higher levels of government, and expanding the expenditure burden of grassroots governments are also necessary. Additional fiscal power should be delegated to areas with high pressure on environmental protection to enable them to obtain more benefits in environmental governance.

(3) Watershed carbon compensation should not be limited to the level of transfer payments. The upper and middle reaches of the PRB (the compensation area) have abundant natural resources, labor, land, and other production factors, whereas the lower reaches (the payment area) have comparative advantages in capital, technology, and management. After the carbon compensation mechanism matures, the two sides can further establish a two-way economic cooperation relationship to achieve complementary advantages. For example, the compensated district government can attract enterprises in the payment area by setting up "enclave industrial parks" to realize the transfer of production factors in geographical space and improve the enthusiasm of local governments for cross-regional coordinated development.

6. Conclusions

A scientific and effective compensation mechanism is crucial to the actual implementation of carbon compensation. This paper considers the problems of information asymmetry and financial imbalance between the central and local governments in the principal–agent process and constructs a carbon compensation mechanism combining the vertical and horizontal directions. This mechanism aims to internalize the externality of carbon emissions and holds substantial theoretical and practical importance. The specific steps of this paper are as follows: First, the NTL data and the CASA model were used to calculate the carbon emissions and absorption of 257 counties in the PRB from 2005 to 2020. Subsequently, LUCEE and ESV were used to modify the carbon emissions and absorption, respectively. The modified LUCB was used as the baseline value of carbon compensation to determine the subject–object, value, and priority order of carbon compensation. Finally, based on the perspective of fiscal imbalance, a carbon compensation mechanism combining vertical and horizontal directions was constructed.

The main conclusions are as follows: (1) In terms of time series changes, the area of forestland, which is the largest contributor to carbon absorption, and the area of construction land, which is the carbon source land, both increased in the PRB, leading to an increase in carbon emissions and absorption in the basin from 2005 to 2020. The growth rate of carbon emissions is remarkably faster than that of carbon absorption. Thus, there is a potential risk that some areas in the PRB could turn into carbon deficit areas. In addition, the modification of carbon emissions is greater than that of carbon absorption, thereby increasing the modified LUCB variation remarkably. (2) In terms of spatial distribution, regardless of whether the modification was performed or not, the high-value areas of carbon emissions are mainly distributed in the PRD in the lower reaches of the basin, and a small amount is distributed in the northwest of the basin. Carbon emissions in municipal districts and resource-based counties are relatively high. Many high-value areas of carbon absorption exist, which are widely distributed in the upper and middle reaches of the basin.

(3) The total amount of carbon compensation in the PRB in 2020 is negative, indicating that the region belongs to the carbon sink value spillover area. Regardless of the administrative division level of local governments, the number of compensation zones is more than that of payment zones.

This paper has the following limitations: First, limited by data and methods, this paper does not consider the carbon transfer problem in the PRB. Second, China's carbon trading market is not yet mature; thus, the carbon unit price used in this paper is the national average price during the study period, which may not objectively reflect the carbon compensation value of various regions. Third, this paper discusses the carbon compensation mechanism of administrative units at all levels from the macro level. In the follow-up study, the role of enterprises and markets in carbon compensation at the micro level needs to be examined further. Finally, this paper measures the LUCB based on multisource data, which suffers from the shortcomings of the difficulty in obtaining data and cumbersome data processing. This situation is also the reason 2005–2020 was selected as the study period.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land13081141/s1, Figure S1: Map of study area with numbered labels; Table S1: List of administrative regions involved in the study area; Table S2: Logarithmic fitting equations and their R^2 values for the 46 cities; Table S3: Carbon compensation information for all counties in 2020.

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