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Spatial-Temporal Dynamics of Carbon Budgets and Carbon Balance Zoning: A Case Study of the Middle Reaches of the Yangtze River Urban Agglomerations, China

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Abstract: Analysis of the spatial variation characteristics of regional carbon sources/sinks is a prerequisite for clarifying the position of carbon balance zones and formulating measures to reduce emissions and increase sinks. Studies of carbon sinks have often used the coefficient method, which is limited by sample size, measurement error, and low spatial resolution. In this study, 31 cities in the middle reaches of the Yangtze River urban agglomerations (MRYRUA) were studied with the improved CASA (Carnegie Ames Stanford Approach) model to estimate the grid-scale net ecosystem productivity (NEP) and explore the spatial-temporal evolution of carbon budgets from 2005 to 2020. By calculating the carbon balance index (CBI), economic contribution coefficient (ECC), and ecological support coefficient (ESC), carbon balance zoning was conducted. Corresponding suggestions are based on the carbon balance zoning results. From 2005 to 2020, carbon budgets increased and were high in the north-central region and low in the south. In addition, carbon sink functional zones were distributed in cities with rich ecological resources. Low-carbon economic zones shifted from the Poyang Lake Urban Agglomeration to the Wuhan City Circle; low-carbon optimization zones occurred from the Wuhan City Circle to the Poyang Lake Urban Agglomeration. Carbon intensity control and high-carbon optimization zones were distributed in cities with rapid economic development. Our results support the MRYRUA in achieving "double carbon" targets and formulating regional collaborative emissions reduction policies.

Keywords: CASA (Carnegie Ames Stanford Approach); NEP; carbon budgets; carbon balance zoning; middle reaches of the Yangtze River urban agglomerations (MRYRUA)

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1. Introduction

Since the industrial revolution, humans have produced carbon emissions from the use of fossil fuels [1], leading to the greenhouse effect and gradual warming of the climate [2]. Recently, the 28th Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) upheld the objectives, principles, and institutional arrangements of the UNFCCC and the Paris Agreement, demonstrating that climate change is a global challenge that requires concerted international cooperation. As the world's largest carbon emitter and energy consumer [3], China has taken the international responsibility of addressing climate change and made unremitting efforts to promote domestic energy conservation, emissions reduction, and ecological civilization [4–6]. However, achieving a carbon balance and further "carbon neutrality" is still a serious challenge for China.

Cities account for only 2% of the global land area but generate approximately 75% of global carbon emissions [7]. Urban agglomerations are important population and economic centers in China [8] and are strategic spaces that drive overall improvements in the national economy and support high-quality development [9]. Huge urban agglomerations have become areas of high energy consumption and carbon emissions. In China, urban agglomerations (mega metropolitan areas) contribute nearly 70% of carbon emissions [10]. Coordinated regional development [11] and collaborative emissions reduction by urban agglomerations are key areas for energy conservation and emissions reduction in China. Therefore, there is an urgent need to analyze the spatial-temporal changes in the carbon budgets of urban agglomerations and promote synergistic transitions. At the same time, the division of functional zones according to different carbon balances and the creation of carbon balance zoning are critical to low-carbon development in each functional zone and in promoting the synergistic management of the environment in urban agglomerations [12].

Achieving carbon neutrality requires the comprehensive consideration of "emission reduction" and "sequestration enhancement". Accurately estimating carbon emissions and improving carbon sequestration calculations and spatial location accuracy will help clarify regional carbon emission reduction pressures and the carbon sequestration potential. Currently, the methods for estimating carbon emissions include field surveys [13], empirical modeling [14], and the IPCC inventory method [15,16]. For example, Shan et al. developed a methodology for constructing CO_2 emission inventories for Chinese cities based on energy balance sheets [17]. To date, most studies have estimated carbon emissions based on these methods at the national [18], provincial [19], and municipal scales [20] using statistical data, but there is often uncertainty in the results from areas with a lack of information or poor data. Moreover, most scholars focus on carbon emissions. There has been less research on carbon sequestration, which must be improved to realize "carbon neutrality" [21,22].

Methods for calculating carbon sequestration include the sample plot inventory method, the IPCC parameter method, and the model simulation method. The sample plot inventory method can obtain point source data with higher accuracy [23], but it relies on sampling methods for overall accuracy and is time consuming, has a large error, and is generally used as a method for estimating carbon sequestration in small-scale regions [24]. The IPCC parameter method is commonly used for direct accounting of carbon sequestration [25]. Mohareb et al. calculated carbon sequestration for Toronto for 2005, using the IPCC parameter method (for direct sequestration) and peer-reviewed literature (for implicit sequestration), as a direct sequestration of 317,000 tons and an implicit sequestration of 234,000 tons [26]. However, the parameters of the IPCC coefficient method lack specific regional characteristics and are prone to errors. El Mderssio et al. compared the results of the direct field survey with results obtained using the IPCC parameters for the Central Atlas region and found that the directly calculated amount of carbon was 858,387 tons of dry matter, whereas the IPCC parameters estimated 1,201,789 tons [27]. Moreover, integrating carbon sequestration calculations into economic assessments and investigating the economic significance of carbon sequestration can aid in attaining regional carbon neutrality. Luo et al. investigated how local communities perceived the overall effects of carbon capture, utilization, and storage (CCUS) projects and quantified the influence of proximity to CCUS projects on neighboring housing prices [28]. Kazak et al. considered carbon sequestration in the valuation of forest properties using the income approach [29].

The development of Remote Sensing and Geographic Information System technology has provided basic support for carbon sequestration accounting and monitoring [30]. Net ecosystem productivity (NEP) is a key indicator that directly describes the carbon sources/sequestration capacity of terrestrial ecosystems [21,31,32] and is widely used in regional carbon sequestration assessments [33,34]. The CASA (Carnegie Ames Stanford Approach) model is a representative model based on light use efficiency [35], and it can effectively support accounting for long time periods and a large regional NEP because of its data availability, its ability to reflect the distribution of carbon sequestration in large-scale regions, and the ease with which it can be used for long-term monitoring and estimation of carbon sequestration. The CASA method accounts for the mechanism of the carbon cycle, which makes simulation results more accurate and reliable [36,37], and it requires a small number of physical parameters, which makes the error correspondingly small [35,38–40].

Carbon balance analysis and zoning has become an important research field in the context of global climate warming [41] and China's "double carbon" targets [42]. Most studies rely on indicators affecting the regional carbon balance to establish functional zoning and make low-carbon policy recommendations [43,44]. Vaccari et al. conducted a carbon balance study for the city of Florence and found that green spaces offset 6.2% of direct carbon emissions, which informed subsequent development planning in the city [45]. Ainsworth et al. analyzed the carbon balance of European grassland ecosystems and found that reducing the intensity of grassland management increased grassland ecosystem carbon sequestration [46]. Zamolodchikov et al. investigated the carbon balance of the Russian tundra using seasonal and geographical extrapolations and mathematical simulations [47]. Scholars have also started to study China's carbon balance and carbon sequestration potential. Zhang et al. took Suzhou as an example and used the spatial pattern of carbon emissions to construct a carbon balance zoning method and achieved carbon balance zoning at a micro-scale in the city [48]. Li et al. re-examined the carbon balance of China's terrestrial ecosystems under land use and climate change to guide low-carbon spatial planning policies in various regions [32]. Zhao et al. divided the Central Plains Economic Zone into a carbon intensity control zone, carbon balance zone, carbon sequestration functional zone, total carbon control zone, and low-carbon optimization zone based on the carbon balance zoning theory [49]. However, at the level of carbon balance analysis, the existing indicator system is difficult to implement and lacks accurate and practical standards for evaluating carbon functional zoning. Most studies have focused on provincial and county areas, ignoring the significance of urban agglomerations in China's carbon balance. Therefore, it is necessary to study the differences in ecological and carbon sequestration resource endowment and socio-economic development within urban agglomerations, analyze the spatial-temporal characteristics of carbon balance, and explore carbon balance zoning in urban agglomerations.

As the largest inter-regional urban agglomeration in China by land area, the middle reaches of the Yangtze River urban agglomerations (MRYRUA) is important in China's economic and social development. The MRYRUA is dominated by heavy industries, which requires high energy consumption and has caused rapid growth in carbon emissions in the region. At the same time, the MRYRUA has a large, heavily aggregated population with a correspondingly large demand for energy, and there is pressure to reduce emissions. Therefore, from the perspectives of industrial development and ecological improvement, the zoning of carbon balance is of great significance for realizing the "double carbon" goal.

In this study, we used 31 cities to analyze the spatial-temporal changes in the carbon balance in the MRYRUA from 2005 to 2020, based on carbon emission data from the Carbon Emission Accounts and Datasets (CEADs) and carbon sequestration data estimated with the CASA model. We adopted the carbon balance index (CBI), economic contribution coefficient (ECC), and ecological support coefficient (ESC) to carry out carbon balance zoning that enabled us to assess differences in the regional carbon balance, put forward corresponding strategies for reducing emissions, and formulate carbon-neutral development strategies in line with the actual development strategies for the MRYRUA (Figure 1).

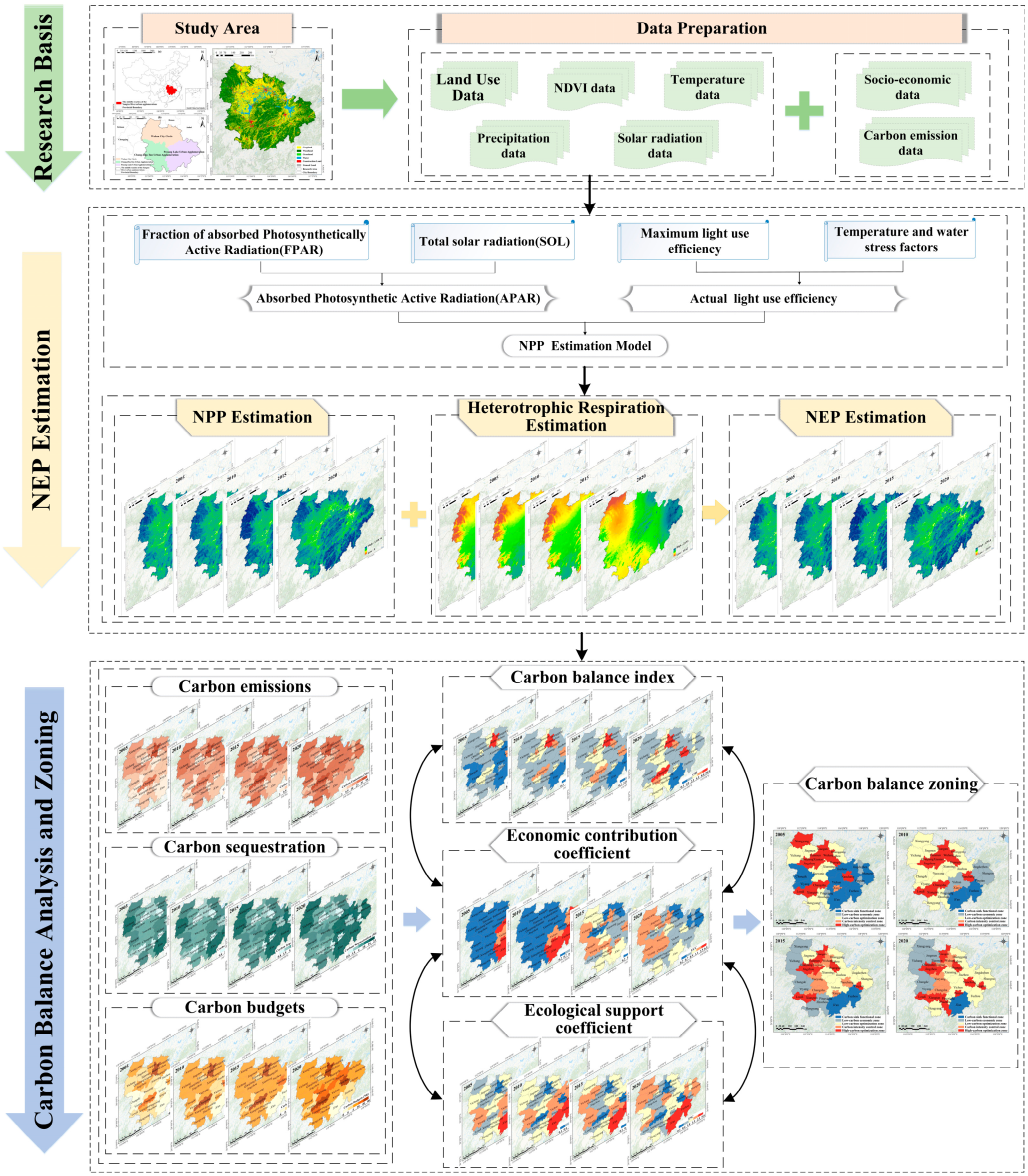

Figure 1. Research framework diagram.

2. Study Area and Data Sources

2.1. Study Area

The MRYRUA is located at 26°03′–32°38′ N, 110°45′–118°21′ E in the middle part of the Yangtze River Basin and covers an area of approximately 326,100 km^2. The MRYRUA is centered on Wuhan and dominated by the Wuhan City Circle in Hubei province, the Chang-Zhu-Tan Urban Agglomeration in Hunan province, and the Poyang Lake Urban Agglomeration in Jiangxi province. The MRYRUA spans Hubei, Hunan, and Jiangxi provinces (Figure 2). The MRYRUA has a subtropical monsoon climate, with an average annual precipitation of 800–1943 mm. The terrain is dominated by plains, with a small number of hills and mountains, and has an average altitude of 20–3105 m. The MRYRUA has a favorable natural geographic location and is bounded on the east and the west and connected to the south and the north.

By the end of 2020, the region had a resident population of 130 million, with an urbanization rate of 63.3%. The gross domestic product (GDP) of the MRYRUA in 2020 was 11.1 trillion yuan, of which primary industry accounted for 8.75%, secondary industry accounted for 40.81%, and tertiary industry accounted for 50.44%. From 2005 to 2020, the GDP of the MRYRUA grew from 4.2 trillion yuan to 11.1 trillion yuan, with an average annual growth rate of 11.0%, demonstrating great potential for development in the MRYRUA.

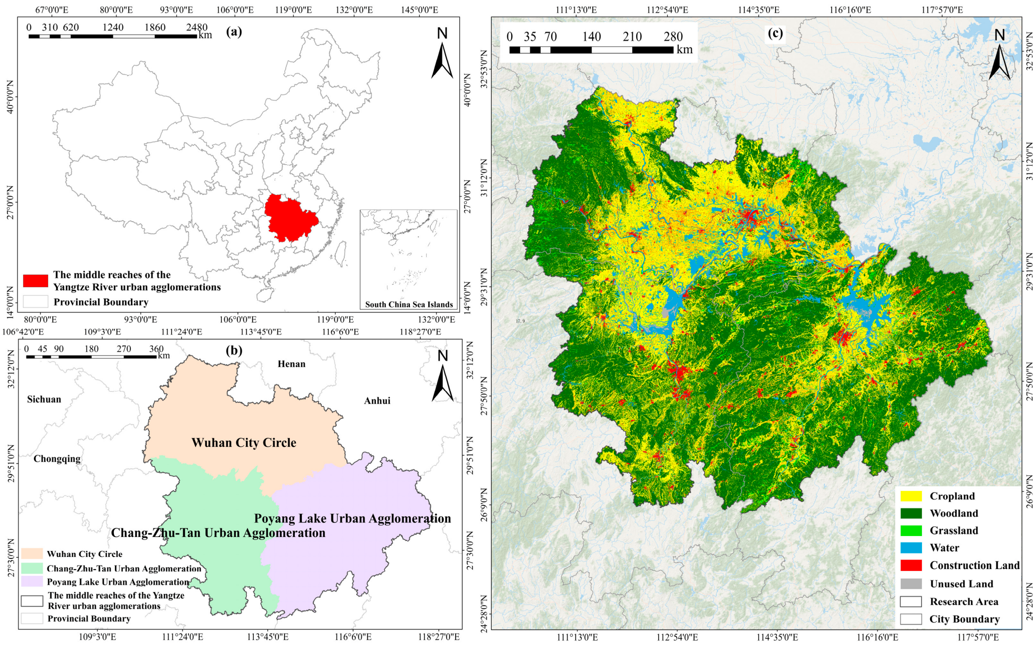

Figure 2. (**a**) The geographical location of the MRYRUA in China. (**b**) The location of the Wuhan City Circle, the Chang-Zhu-Tan Urban Agglomeration, and the Poyang Lake Urban Agglomeration in the MRYRUA. (**c**) Land use data for the MRYRUA in 2020.

2.2. Data Sources

The data in this study include land use data, carbon emission data, and GDP data. The CASA model also requires temperature data, precipitation data, normalized difference vegetation index (NDVI), and surface solar radiation data (Table 1).

Table 1. Data used in this study.

Data Name	Data Type	Year	Source
Land use data	30 m × 30 m Raster data	2005, 2010, 2015, 2020	Resource and Environmental Science Data Center of the Chinese Academy of Sciences (https://www.resdc.cn/ accessed on 8 August 2023)
Carbon emission data	Text data	2005, 2010, 2015, 2020 *	Carbon Emission Accounts and Datasets (CEADs) (https://www.ceads.net.cn accessed on 12 August 2023)
Gross domestic product	Text data	2005, 2010, 2015, 2020	Statistical yearbook of CNKI (https://data.cnki.net/Yearbook accessed on 6 August 2023)
Temperature data	1 km × 1 km Raster data	2005, 2010, 2015, 2020	Resource and Environmental Science Data Center of the Chinese Academy of Sciences (https://www.resdc.cn/ accessed on 10 August 2023)
Precipitation data	1 km × 1 km Raster data	2005, 2010, 2015, 2020	Resource and Environmental Science Data Center of the Chinese Academy of Sciences (https://www.resdc.cn/ accessed on 11 August 2023)
Normalized difference vegetation index	1 km × 1 km Raster data	2005, 2010, 2015, 2020	National Aeronautics and Space Administration (https://ladsweb.modaps.eosdis.nasa.gov/search/ accessed on 12 August 2023)
Surface solar radiation data	10 km × 10 km Raster data	2005, 2010, 2015, 2020 *	National Tibetan Plateau Data Center (https://data.tpdc.ac.cn accessed on 9 August 2023)

*: As the county-level data from CEADs are only available up to 2017, the carbon emission data from 2018 to 2020 were estimated using the Autoregressive Integrated Moving Average (ARIMA) model utilizing these existing county-level data from CEADs [50]. Additionally, the surface solar radiation data for 2020 were spatially interpolated using site data obtained from the Climatic Data Center, National Meteorological Information Center, and China Meteorological Administration (https://data.cma.cn accessed on 10 August 2023).

3. Methods

3.1. NEP Estimation by CASA Model

In this paper, NEP is an important contributor to regional carbon balance estimation and is often used as a measure of carbon sequestration. Without considering the influence of other natural and anthropogenic conditions, the net ecosystem productivity (*NEP*) of vegetation is expressed as the difference between net primary productivity (*NPP*) of vegetation in the ecosystem and carbon emission from heterotrophic respiration (R_H). The specific formula is as follows:

$$NEP = NPP - R_H \quad (1)$$

where *NEP* is net ecosystem productivity of vegetation, *NPP* is net primary productivity of vegetation, and R_H is heterotrophic respiration.

(1) NPP estimation

An improved CASA model [51] was used to estimate *NPP* in the MRYRUA, which combined with heterotrophic respiration can be used to derive the amount of carbon sequestered by vegetation in the urban agglomerations. The main parameters of the CASA model are absorbed photosynthetic active radiation (*APAR*), which can be absorbed by the plants, and actual light use efficiency (ε). The specific formula is as follows:

$$NPP(x,t) = APAR(x,t) \times \varepsilon(x,t) \quad (2)$$

where $APAR(x,t)$ represents absorbed photosynthetic active radiation (g C·m^{-2}·month^{-1}) by image element x in month t, and $\varepsilon(x,t)$ represents light use efficiency (g C·MJ^{-1}) of image x in month t.

APAR represents the absorbed photosynthetic active radiation that directly irradiates the vegetation canopy, and the light use efficiency (ε) represents the efficiency of the conversion of *APAR* into organic carbon. We followed "Sense-by-Sense Estimation of Net Primary Productivity of Terrestrial Vegetation in China" and calculated *APAR* and ε by using solar radiation, precipitation, temperature, vegetation type, and MODIS data, using the following formulas:

$$APAR(x,t) = SOL(x,t) \times FRAR(x,t) \times 0.5 \quad (3)$$

$$FPAR(x,t) = \alpha FPAR_{NDVI} + (1-\alpha) FPAR_{SR} \quad (4)$$

$$FPAR_{NDVI} = \frac{(NDVI_{(x,t)} - NDVI_{(i,\min)})}{(NDVI_{(i,\max)} - NDVI_{(i,\min)})} \times (FPAR_{\max} - FPAR_{\min}) + FPAR_{\min} \quad (5)$$

$$FPAR_{SR} = \frac{(SR_{(x,t)} - SR_{(i,\min)})}{(SR_{(i,\max)} - SR_{(i,\min)})} \times (FPAR_{\max} - FPAR_{\min}) + FPAR_{\min} \quad (6)$$

$$SR(x,t) = \frac{(1 + NDVI_{(x,t)})}{(1 - NDVI_{(x,t)})} \quad (7)$$

$$\varepsilon(x,t) = T_{\varepsilon 1}(x,t) \times T_{\varepsilon 2}(x,t) \times W_{\varepsilon}(x,t) \times \varepsilon_{\max} \quad (8)$$

where $SOL(x,t)$ denotes total solar radiation at image element x in month t (MJ·m^{-2}·month^{-1}), *FPAR* is the fraction of photosynthetically active radiation absorbed by the canopy, and 0.5 is the ratio of the effective radiation of the sun utilized by the vegetation relative to total radiation. $NDVI_{(i,max)}$ and $NDVI_{(i,min)}$ represent, respectively, the maximum and minimum NDVI in plant type i. $FPAR_{min}$ and $FPAR_{max}$ are 0.001 and 0.95, respectively. $SR_{(i,min)}$ and $SR_{(i,max)}$ correspond to the 5% and 95% percentile of NDVI in plant type i, respectively, and a value of 0.5 was used for α. $T_{\varepsilon 1}(x,t)$ and $T_{\varepsilon 2}(x,t)$ are the stress effects of low and high temperatures on the light use efficiency. $W_{\varepsilon}(x,t)$ is the coefficient of water stress, and ε_{max} is the maximum light use efficiency.

(2) Heterotrophic respiration estimation

Based on previous studies, we used the model for heterotrophic respiration established by Zhuang et al. based on measured data [52]. Zhuang et al. investigated the relationship between carbon emissions and environmental factors and established a regression equation between temperature, precipitation, and carbon emissions to estimate heterotrophic respiration. The specific formula is as follows:

$$R_H = 0.22 \times (Exp(0.0913T) + Ln(0.3145R + 1)) \times 30 \times 46.5\% \tag{9}$$

where R_H denotes heterotrophic respiration (g C·m^{-2}·a^{-1}), T is temperature (°C), and R is precipitation (mm).

3.2. Carbon Budgets

The carbon budgets is a measure of the relationship between carbon emissions and carbon sequestration caused by natural factors and human activities in a certain area. It is specifically expressed as the difference between carbon emissions and carbon sequestration in the following formula:

$$CB_i = CE_i - NEP_i \tag{10}$$

where CB_i is the carbon budgets (t) of city cluster i in the MRYRUA, CE_i is the carbon emissions (t) of city cluster i in the MRYRUA, and NEP_i is the carbon sequestration (t) of city cluster i in the MRYRUA (Table 2).

Table 2. Regional carbon budget conditions.

	Condition of CE_i	Condition of NEP_i	Relationship between CE_i and NEP_i	Result of CB_i
Balance point	$CE_i \geq 0$	$NEP_i \geq 0$	$\lvert CE_i \rvert = \lvert NEP_i \rvert$	$CB_i = 0$
Carbon surplus	$CE_i \geq 0$	$NEP_i > 0$	$\lvert CE_i \rvert < \lvert NEP_i \rvert$	$CB_i < 0$
Carbon deficit	$CE_i \geq 0$	$NEP_i > 0$	$\lvert CE_i \rvert > \lvert NEP_i \rvert$	$CB_i > 0$
	$CE_i \geq 0$	$NEP_i < 0$	$\lvert CE_i \rvert > \lvert NEP_i \rvert$	$CB_i > 0$

3.3. CBI

Vegetation can effectively absorb CO_2 emissions from fossil fuel combustion through photosynthesis, thus maintaining the stability of carbon and oxygen in the biosphere and slowing the greenhouse effect. We quantified the relationship between energy carbon emissions and vegetation carbon sequestration based on the CBI, which reflects the impact of regional carbon emissions on ecological stress [53]. The formula is as follows:

$$CBI = CE_i / CS_i \tag{11}$$

where CBI is the carbon balance index, CE_i is the carbon emissions (t) in a given year in city region i, and CS_i is the carbon sequestration (t) in a given year in city area i, which represents NEP_i.

3.4. ECC

The ECC of carbon emissions is a measure of the variability of regional carbon emissions from the perspective of economic efficiency [54], which reflects the magnitude of regional carbon productivity and the degree of matching between regional carbon emissions and their economic contribution. The formula is as follows:

$$ECC = \frac{G_i}{G} / \frac{CE_i}{CE} \tag{12}$$

where ECC is the economic contribution coefficient of carbon emission; G_i is the GDP (yuan) of city unit i in the MRYRUA; CE_i is the carbon emissions (t) of city unit i; and CE is the total carbon emissions (t) of the MRYRUA.

3.5. ESC

The ESC is the quotient of the ratio of carbon absorption of a certain unit to carbon absorption of the whole region and the ratio of carbon emission of the unit to carbon emission of the whole region [44]. It reflects the strength of regional carbon sequestration capacity from the perspective of carbon balance. The formula is as follows:

$$ESC = \frac{CS_i}{CS} / \frac{CE_i}{CE} \tag{13}$$

where ESC is the ecological support coefficient of carbon sequestration; CS_i is the carbon sequestration (t) of city unit i; CS is the total carbon sequestration (t) in the MRYRUA; CE_i is the carbon emissions (t) of city unit i; and CE is the total carbon emissions (t) in the MRYRUA.

3.6. Carbon Balance Zoning

To alleviate the imbalance between "carbon emission and carbon sequestration" in the MRYRUA, which is caused by regional economic development, energy consumption, and land use, we based our study on the perspective of carbon budget balance and regional low-carbon coordinated development, using the CBI, ECC, and ESC as the basis for carbon balance zoning. When the CBI is greater than 1, an area is a carbon source, and when the CBI is less than 1, an area is a carbon sink. A zoning threshold of 1 was used for the CBI. When the ECC is greater than 1, regional energy utilization efficiency is high; on the contrary, this implies that the regional carbon productivity is relatively low. To reflect the energy utilization efficiency and carbon productivity of the region, 1 was used as the zoning threshold for the ECC. When the ESC is greater than 1, a region has higher carbon sequestration capacity; When the ESC is less than 1, this means that the carbon sequestration capacity is weak. Therefore, 1 was used as the zoning threshold for the ESC [48,55]. Based on previous research [56], we divided the urban units of the MRYRUA into five functional zones: carbon sink functional zones, low-carbon economic zones, low-carbon optimization zones, carbon intensity control zones, and high-carbon optimization zones (Table 3). Zoning provides a basis for carbon emission reduction policies, development targets for achieving carbon neutrality, and regional development in the MRYRUA.

Table 3. Basis for carbon balance zoning.

Zoning	Basis	Features
Carbon sink functional zones	$CS_i > CE_i$, ESC > 1	Carbon sequestration is higher than carbon emissions, with a higher ecological support coefficient, overall carbon sink function, and strong carbon sequestration capacity
Low-carbon economic zones	$CS_i < CE_i$, ESC > 1, ECC > 1	Carbon sequestration is lower than carbon emissions, but the ecological support coefficient and economic contribution coefficient are higher, and total net carbon emissions is slightly lower
Low-carbon optimization zones	$CS_i < CE_i$, ESC > 1, ECC < 1	Carbon sequestration is lower than carbon emissions, and the ecological support coefficient is high, but the economic contribution coefficient is low
Carbon intensity control zones	$CS_i < CE_i$, ESC < 1, ECC > 1	Carbon sequestration is lower than carbon emissions; ecological support coefficient is low, but the economic contribution coefficient is high, and net carbon emissions is high
High-carbon optimization zones	$CS_i < CE_i$, ESC < 1, ECC < 1	Total net carbon emissions is high and both ecological support coefficient and economic contribution coefficient are low

4. Results

4.1. Spatial-Temporal Variation of Carbon Budgets

4.1.1. Temporal Trends of Carbon Budgets

Based on estimated carbon emissions and carbon sequestration, carbon budgets were analyzed in the MRYRUA (Wuhan City Circle, Chang-Zhu-Tan Urban Agglomeration, and Poyang Lake Urban Agglomeration around Poyang Lake) from 2005 to 2020 (Figure 3).

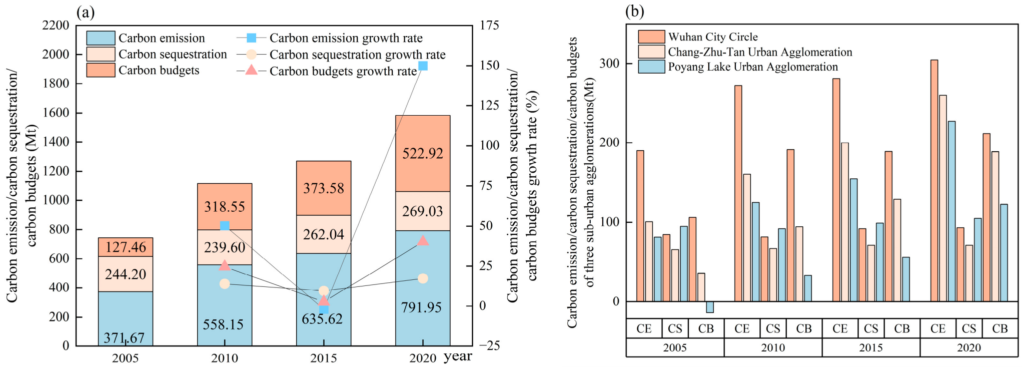

Figure 3. (**a**) Changes in carbon emissions, carbon sequestration, and carbon budgets in the MRYRUA from 2005 to 2020. (**b**) Changes in carbon emissions, carbon sequestration, and carbon budgets in three urban agglomerations from 2005 to 2020. Note: CE denotes carbon emissions, CS denotes carbon sequestration, CB denotes carbon budgets.

From 2005 to 2020, total carbon emissions in the MRYRUA exceeded total carbon sequestration, and carbon budgets increased. Carbon emissions increased by 113.08%, carbon sequestration increased by 10.16%, and carbon budgets increased by 310.25%. Changes in the carbon budgets were reflected by changes in carbon emissions, potentially due to the expansion in urban construction and the acceleration of the industrial process. Many factories and enterprises went into production, resulting in an increase in energy consumption and carbon emissions. From 2005 to 2010, carbon budgets increased by 149.91%. From 2010 to 2015, carbon budgets increased by 17.27%. During the “12th Five-Year Plan” period, environmental pollution and consumption of resources attracted national attention. From 2015 to 2020, carbon budgets increased by 39.98%. The MRYRUA have achieved certain results and actively responded to the national emissions reduction strategies and policies. However, energy conservation and emissions reduction remain challenges.

From 2005 to 2020, carbon emissions, carbon sequestration, and carbon budgets of the Wuhan City Circle, the Chang-Zhu-Tan Urban Agglomeration, and the Poyang Lake Urban Agglomeration generally increased. The Wuhan City Circle had the largest proportion of carbon emissions in the MRYRUA. The Poyang Lake Urban Agglomeration had the most carbon sequestration in the MRYRUA. Growth in carbon emissions, carbon sequestration, and carbon budgets in the Wuhan City Circle was similar to that in the MRYRUA, because Wuhan is an important industrial base and science and education base in the country. It carries the carbon emission activities of various cities and accounts for an important position in carbon emissions of the Wuhan City Circle and the MRYRUA. Over the past fifteen years, carbon sequestration of the Chang-Zhu-Tan Urban Agglomeration has increased. Following ecological restoration in this area, the carbon sequestration capacity of vegetation improved and excessive growth of carbon budgets was avoided. Carbon sequestration by the Poyang Lake Urban Agglomeration was highest among the three urban agglomerations and carbon budgets were the smallest, because this area has rich vegetation that functions as a carbon sink.

4.1.2. Spatial Evolution of Carbon Budgets

The spatial evolution of carbon emissions, carbon sequestration, and carbon budget patterns was analyzed in different cities (Figure 4). Overall, from 2005 to 2020, carbon emissions from the MRYRUA were high in the north-central region and low in the south. From 2005 to 2020, Wuhan experienced rapid economic development and was a high-value area of carbon emissions, followed by Changsha. Changsha transformed from the previous second-highest value area to a high-value area. Nanchang also changed from a middle-value area to the second-highest value area. The high-value areas of carbon emissions in the MRYRUA mainly increased along the periphery of provincial capital cities, which was reflected between 2010 and 2015 and became more obvious after 2015. These changes between 2010 and 2015 reflect the "13th Five-Year Plan", which implemented the overall regional development strategy and promoted common development among regions. The rapid development of inter-regional economies has led to an increase in carbon emissions.

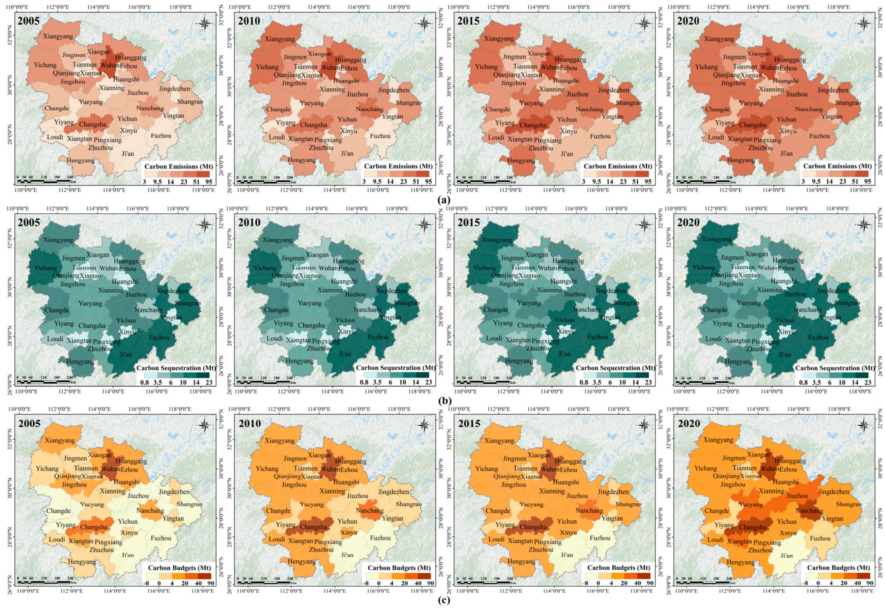

Figure 4. (**a**) Spatial-temporal evolution of carbon emissions in the MRYRUA from 2005 to 2020. (**b**) Spatial-temporal evolution of carbon sequestration in the MRYRUA from 2005 to 2020. (**c**) Spatial-temporal evolution of carbon budgets in the MRYRUA from 2005 to 2020.

Carbon sequestration in the MRYRUA was high on the periphery and low in the center. From 2005 to 2020, carbon sequestration was almost stable, reflecting the small impact of carbon sequestration on changes in carbon budgets. The spatial pattern of carbon budgets was similar to that of carbon emissions and was high in the central region, followed by the north, and lowest in the south. Carbon budgets increased the most from 2005 to 2010, and there was a trend in carbon budgets moving from low-value areas to high-value areas. From 2010 to 2015, carbon budgets moved from low-value areas to high-value areas in the Poyang Lake Urban Agglomeration. From 2015 to 2020, the highest value carbon budgets were in Wuhan and Changsha. Carbon budgets of the surrounding areas centered on Wuhan, Changsha, and Nanchang were relatively high. These cities are the economic centers of their respective urban agglomerations and have experienced rapid urban development and high carbon emissions. Generally, carbon emissions in the MRYRUA have exceeded carbon sequestration, and the pressure to reduce emissions is still high.

4.2. Carbon Balance Analysis

4.2.1. CBI

Based on the CBI, the relationship between carbon emissions and carbon sequestration in the MRYRUA can be further explored (Figure 5). The CBI of the MRYRUA increased 93.42% from 2005 to 2020. The CBI of Wuhan, Ezhou, and Nanchang increased, mainly due to an increase in urban population and energy consumption by industrial enterprises. From 2010 to 2015, the CBI of Wuhan, Ezhou, Xiaogan, Tianmen, and Xiangyang decreased.

From 2015 to 2020, the CBI of Xiangyang, Jingmen, and Tianmen decreased. This is because regions attach great importance to ecological and environmental protection and promote low-carbon, green, and sustainable urban development, which has inhibited the growth of the CBI.

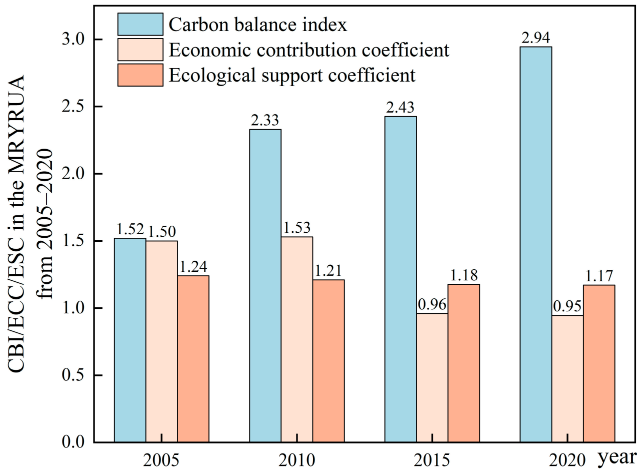

Figure 5. CBI, ECC, and ESC of the MRYRUA from 2005 to 2020.

The spatial patterns of the CBI in the MRYRUA from 2005 to 2020 are shown in Figure 6a. The CBI was high in the center and low in the periphery. The low-value areas of the CBI were in the southeastern Poyang Lake Urban Agglomeration and the northwest of the Chang-Zhu-Tan Urban Agglomeration. From 2005 to 2020, areas with a high CBI gradually shifted from Wuhan to the three provincial capitals. From 2010 to 2015, high-value areas of the CBI spread around Wuhan and Changsha. It may be due to rapid economic development that carbon emissions in construction areas have increased rapidly, while carbon sequestration has changed to a small extent, and the energy transition in some areas is slow. From 2015 to 2020, the CBI of the Chang-Zhu-Tan Urban Agglomeration was still lower than that of the other two urban agglomerations.

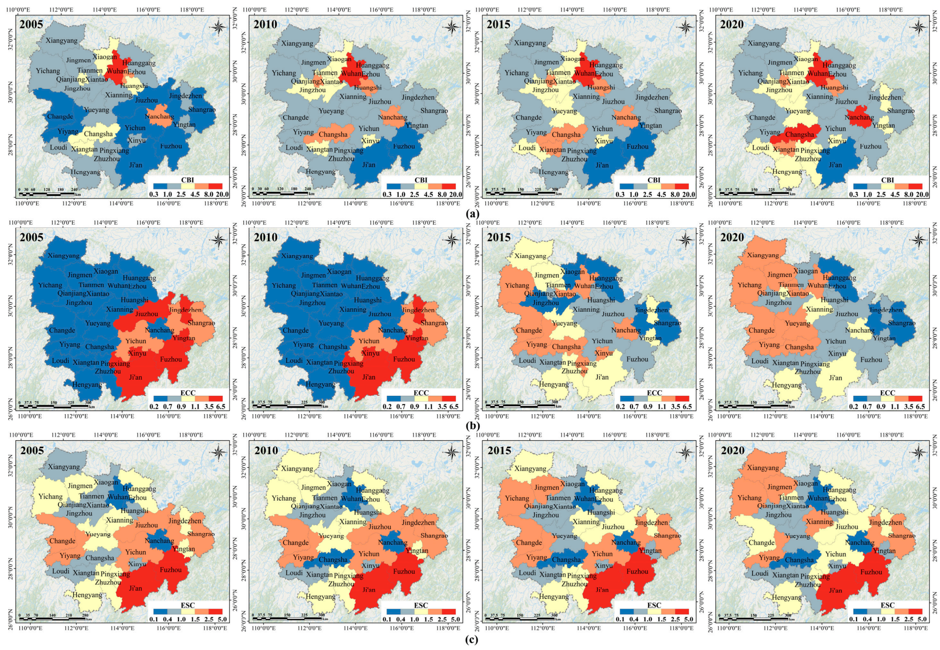

Figure 6. (**a**) Spatial distribution pattern of the CBI in the MRYRUA from 2005 to 2020. (**b**) Spatial distribution pattern of the ECC in the MRYRUA from 2005 to 2020. (**c**) Spatial distribution pattern of the ESC in the MRYRUA from 2005 to 2020.

4.2.2. ECC

From 2005 to 2020 (Figure 5), the ECC of the MRYRUA showed an overall decrease and the differences in the ECC of different cities gradually decreased. The ECC of the Wuhan City Circle and the Chang-Zhu-Tan Urban Agglomeration increased annually, while the ECC of the Poyang Lake Urban Agglomeration decreased. From 2005 to 2020, the ECC declined overall, indicating that the economic efficiency of carbon emissions decreased. In 2005, the ECC in the Wuhan City Circle and the Chang-Zhu-Tan Urban Agglomeration was smaller, ranging from 0.20 to 0.56. In 2015 and 2020, the ECC was mostly between 0.5 and 1.5, indicating that the ECC in each city was relatively balanced and regional differences were not obvious.

The ECC of the MRYRUA was low in the north-central location and high in the periphery (Figure 6b). From 2005 to 2020, the high-value area of the ECC changed from the Poyang Lake Urban Agglomeration to the other agglomerations. In 2005, the low-value areas of the ECC were distributed in Huanggang, Ezhou, and Xianning. They were affected by Wuhan's highly polluting industries and local economic development through extensive energy consumption. In 2015, the ECC in Fuzhou, Ji'an, and Yingtan was less than 1, indicating that the contribution rate of carbon emissions was greater than the economic contribution rate. Compared with 2015, change in the ECC was small. The ECC of the cities around Wuhan, Changsha, and Nanchang was larger than that of other regions. Overall, the economic efficiency of carbon emissions is relatively low.

4.2.3. ESC

From 2005 to 2020, the ESC of the MRYRUA decreased (Figure 5). The ESC in the Wuhan City Circle increased, while the ESC of most cities in the other two urban agglomerations decreased. Perhaps because of the concept that "Clear waters and green mountains are as valuable as mountains of gold and silver", China's ecological construction has accelerated, and regional carbon sink capabilities have become more significant. From 2005 to 2010, the maximum value of the ESC was 6.72% lower than in 2005. From 2010 to 2015, the ESC of the Wuhan City Circle increased, while the ESC of the Chang-Zhu-Tan Urban Agglomeration and the Poyang Lake Urban Agglomeration decreased. For fifteen years, Wuhan's ESC has been the smallest. Wuhan's extensive energy consumption creates more carbon emissions. At the same time, rapid industrialization and urbanization occupy more ecological space and reduce carbon sequestration levels. Thus, Wuhan has formulated total carbon emission control targets.

The spatial pattern of the ESC is similar to that of the ECC and is low in the center and high in the periphery of the MRYRUA (Figure 6c). From 2005 to 2020, the ESC in the central and northern regions was low, while the ESC in the southeastern and northeastern regions was high, with obvious differences between regions. From 2005 to 2010, the change was not significant in cities. From 2010 to 2015, the ESC of Yichang and Jingmen increased, indicating that this region had gradually attached importance to the protection of the environment. In the past fifteen years, the MRYRUA have vigorously promoted clean energy by balancing the relationship between economic development and ecological protection, reducing dependence on traditional energy sources, and improving energy utilization efficiency.

4.3. Carbon Balance Zoning

This study coupled the CBI, ECC, and ESC to divide the MRYRUA into five functional zones: carbon sink functional zones, low-carbon economic zones, low-carbon optimization zones, carbon intensity control zones, and high-carbon optimization zones (Figure 7). From 2005 to 2020, the number of carbon sink functional zones in the MRYRUA decreased significantly and were mainly distributed in the southern part of the Poyang Lake Urban Agglomeration. The number of low-carbon economic zones generally increased and the spatial distribution shifted from the Poyang Lake Urban Agglomeration to the Wuhan City Circle. The spatial distribution of low-carbon optimization zones shifted from the western region to the eastern region. The number of carbon intensity control zones increased, mainly in the middle of the MRYRUA. The spatial distribution of high-carbon optimization zones demonstrated little change.

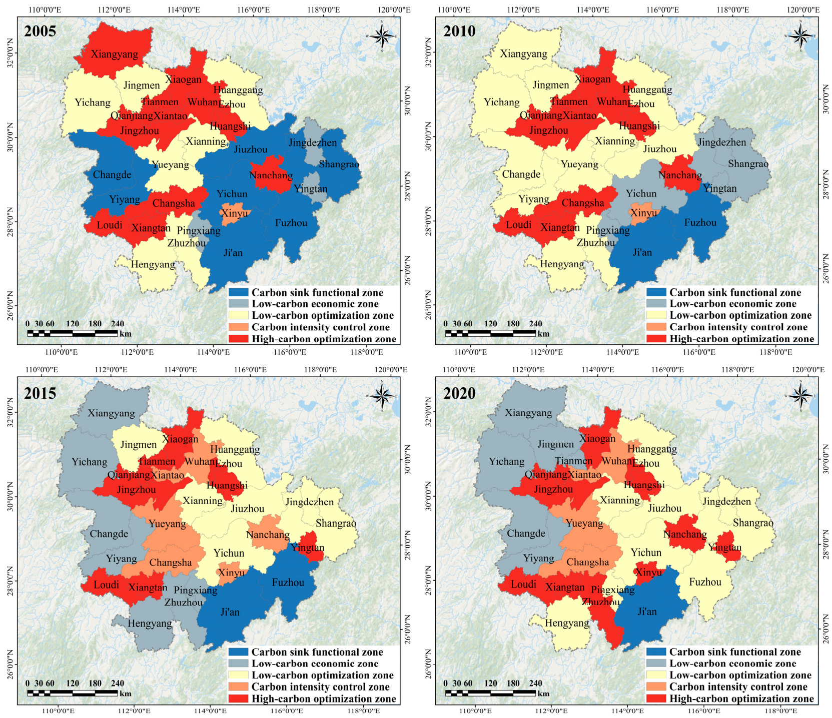

Figure 7. Carbon balance zoning in the MRYRUA from 2005 to 2020.

Carbon sink functional zones are mainly distributed in areas rich in ecological resources, such as woodland and grassland in the MRYRUA. Their spatial distribution is similar to areas with high carbon sequestration. From 2005 to 2020, the number of carbon sink functional zones decreased. In 2005, carbon sink functional zones accounted for 38.62% of the MRYRUA, accounting for the largest area. In 2010 and 2015, carbon sink functional zones accounted for 12.60% of the MRYRUA. In 2020, the area of carbon sink functional zones had decreased. The economic development of carbon sink functional zones is relatively low, carbon sequestration is higher than carbon emissions, environmental quality is high, and the carbon sequestration capacity is strong, all of which have a significant impact on ecological security. In the future, we should continue to improve the environment in this area, maintain the carbon sink function of the ecosystem, and develop the area while protecting regional ecological functions.

The spatial distribution of low-carbon economic zones changed significantly from 2005 to 2020, gradually moving from scattered distribution to agglomeration, and the number of low-carbon economic zones increased significantly. Low-carbon optimization zones were converted into low-carbon economic zones. In 2005 and 2010, low-carbon economic zones accounted for 3.62% and 15.46% of the MRYRUA, respectively. In 2015 and 2020, the area of low-carbon economic zones had increased, and they were mainly distributed in the Wuhan City Circle and the Chang-Zhu-Tan Urban Agglomeration. Carbon sequestration in these cities is less than carbon emissions, but the carbon sink capacity is also strong. Along with economic development, it is also necessary to control carbon emissions, prioritize ecological and environmental protection, avoid ecological degradation, and maintain regional carbon-balanced development. In the future, it will be necessary to stabilize the carbon sequestration capacity of regional vegetation, develop low-carbon industries, improve carbon emission efficiency, balance economic development and the environment, and pursue sustainable development.

From 2005 to 2020, low-carbon optimization zones gradually shifted from the Wuhan City Circle and the Chang-Zhu-Tan Urban Agglomeration to the Poyang Lake Urban Agglomeration. Some carbon sink functional zones were converted into low-carbon optimization zones. In 2005, compared with the other three years, the area accounted for the smallest proportion; in 2010 and 2015, low-carbon optimization zones were mainly distributed in the Wuhan City Circle and the Poyang Lake Urban Agglomeration. Low-carbon optimization zones clearly moved to the Poyang Lake Urban Agglomeration. In 2020, the low-carbon optimization zones were distributed in the central and eastern part of the MRYRUA. The economic development of these cities is average, and their carbon sink capacity is weak. Regional carbon emissions will affect the development of other surrounding areas. In the future, it will be necessary to protect the environment, promote green, low-carbon, and sustainable cities, and appropriately accelerate high-quality urban development.

Carbon intensity control zones were mainly distributed in urban areas with rapid economic development. From 2005 to 2020, the number of carbon intensity control zones gradually increased and distributed along and around the provincial capital center. Low-carbon optimization zones shifted to carbon intensity control zones. In 2005, the carbon intensity control zones accounted for 0.90% of the MRYRUA; in 2015, the area of the carbon intensity control zones was 13.76% and, in 2020, the area was 10.80%, mainly in Wuhan, Changsha, and Yueyang. Carbon sequestration in this region is less than carbon emissions. Wuhan, Changsha, and Nanchang have rapid economic development, high urbanization, increased carbon emissions, and a reduction in the amount of ecological land, and the carbon sequestration capacity of the ecosystem has weakened. In the future, this part of the region can reduce regional carbon emissions, develop low-carbon industries, improve technological innovation, and strengthen its cooperation with surrounding low-carbon areas to achieve a "win-win".

High-carbon optimization zones were spatially distributed in blocks and were relatively scattered. Some low-carbon optimization zones shifted to high-carbon optimization zones. In 2005 and 2010, high-carbon optimization zones accounted for 27.65% and 22.01% of the MRYRUA, respectively, and were mainly distributed in Ezhou and Huangshi. In 2015, high-carbon optimization zones accounted for 14.42% of the MRYRUA and were mainly distributed in Ezhou, Huangshi, and Xiaogan. In 2020, high-carbon optimization zones accounted for 19.85% of the MRYRUA. Carbon sequestration in this region is lower than carbon emissions, which is not conducive to the realization of regional carbon neutrality, and there is room for improvement between the economic development and environmental protection. In the future, it will be necessary to increase carbon sinks, implement ecological restoration projects, carry out integrated protection and management of natural resources (mountains, rivers, forests, fields, lakes, grass, and sand), enhance the carbon sequestration capacity of ecosystems, and strengthen the coupling and coordination capabilities between economic development and ecological protection.

5. Discussion

Our study differed from previous studies on land use carbon emissions and land use carbon balance zoning [57] by using the CASA model to calculate carbon sequestration on a more accurate grid scale [58], analyzing the spatial-temporal pattern of carbon budgets, and exploring carbon balance zoning. Compared with Zhang's analysis of the impact of carbon emissions from the cities of Wuhan, Changsha, and Nanchang, we analyzed spatial-temporal changes in 31 cities [59]. We found that carbon sequestration in the MRYRUA from 2005 to 2010 was slightly different from the results of previous studies. Carbon sequestration in 2005 and 2010 was smaller than previously determined, while carbon sequestration in 2015 and 2020 was closer to previous research results. This may be explained by our use of the CASA model to calculate the carbon sink of grid cells to obtain carbon sequestration for each city. These results are more accurate, while previous studies used cultivated land, grassland, water bodies, and unused areas. Carbon sequestration is calculated based on individual plots as units, where each plot represents only one value. However, particular areas may exhibit uneven vegetation distribution. Using grid unit statistics helps minimize the error in estimating carbon sequestration, resulting in a closer approximation to the actual values. Compared with other urban agglomerations, the Wuhan City Circle had the largest carbon emissions from 2005 to 2020, potentially because the Wuhan City Circle is the economic center of the MRYRUA. Wuhan's economic development relies on industry, which results in extensive industrial carbon emissions. However, with adjustments to the industrial structure, carbon emissions in the Wuhan City Circle have moderated [60]. Carbon emissions in the Chang-Zhu-Tan Urban Agglomeration are relatively low. This may be because the development of heavy industry in the Chang-Zhu-Tan Urban Agglomeration has been relatively slow. The development of tertiary industry reduces energy consumption, and carbon emissions are relatively low. As carbon emissions increase in the Poyang Lake Urban Agglomeration, carbon sequestration is the highest in the MRYRUA. While the Poyang Lake Urban Agglomeration is developing, this area is also focused on improving carbon sinks.

Our results demonstrate that the degree of change in carbon emissions, carbon sequestration, and carbon budgets is different in the MRYRUA. The Wuhan City Circle plays an important role in the carbon budgets of the MRYRUA. Within fifteen years, due to expansion, carbon budgets within the Wuhan City Circle have increased from northwest to southeast. Carbon budgets of the Chang-Zhu-Tan Urban Agglomeration have also increased. This may be explained by the influence of "two-oriented" social construction and energy conservation and emissions reduction policies proposed by the country. The agglomeration continues to strengthen awareness of environmental protection and energy conservation. Compared with other urban agglomerations, the carbon budgets of the Poyang Lake Urban Agglomeration are smaller. Ji'an and Fuzhou have strong carbon sequestration capabilities, rich forest resources, and diverse ecosystems. However, cities in the northern part of the Poyang Lake Urban Agglomeration have experienced increased carbon emissions and larger carbon budgets. Perhaps due to the impact of the industrial transfer of Wuhan and Nanchang, industries may choose to set up their production bases in cities such as Jiujiang. From 2005 to 2020, growth in carbon emissions in the MRYRUA was obvious, but a goal of achieving carbon neutrality remains [61,62]. Therefore, measures to reduce emissions and increase sinks still require attention.

Based on the spatial-temporal dynamics of carbon budgets, the CBI, ECC, and ESC were calculated, and carbon balance zoning was conducted. Carbon sequestration remained relatively stable, and an increase in carbon emissions was the main reason for the increase in the CBI, which is consistent with Chen's calculation of the global CBI [63]. Although carbon balance zoning in this study was similar to that of Xiong's, it differed in the selection of zoning indicators. Xiong used the carbon productivity to measure regional carbon emissions from the perspective of economic benefits, while we used the ECC to characterize regional carbon productivity [44]. This indicator is more consistent with the energy utilization rate among cities within the MRYRUA. Compared with Wen's study on China's carbon balance zoning, our comparison of regional carbon emissions and carbon sequestration is conducive to the analysis of carbon balance characteristics and also makes the zoning results more detailed and reliable [55]. From 2005 to 2020, the number of carbon sink functional zones decreased, and most carbon sink functional zones were converted into low-carbon optimization zones. This may be because urbanization and industrialization were affected by the economic development of surrounding cities. As a result, land was used for industrial construction, causing the original carbon sink functional zones to be gradually occupied or destroyed. The carbon sequestration capacity of cities in the MRYRUA is inadequate to offset the total carbon emissions from energy consumption fully. Some low-carbon optimization zones shifted to carbon intensity control zones and high-carbon optimization zones. Limited land resources have caused construction to encroach on ecological land, resulting in an increase in carbon emissions and a reduction in carbon sequestration, which is consistent with Chuai's research on construction expansion and carbon emissions [64]. Carbon intensity control zones and high-carbon optimization zones are important sources of carbon emissions. Limiting the massive expansion of construction is of great significance to regional carbon emissions reduction. In the future, it will be necessary to accelerate technological innovation, promote the transformation of high-carbon industries into low-carbon industries, optimize the energy structure, and improve energy utilization efficiency to achieve low-carbon development [65–67].

Our study has certain limitations. The smallest research unit was a city, and carbon balance policies do not take the county into consideration, which is not conducive to differentiation within a city. In the future, counties should be used as research units to achieve regional carbon balance goals and low-carbon development. Spatial elements were also ignored in carbon balance zoning, and spatial correlation was not analyzed. In the future, by building a spatial correlation network of carbon emissions and carbon sequestration between regions, using the CBI, ECC, and ESC, network spatial correlation characteristics and indicators related to economic development can be added to provide more accurate, multi-perspective zoning results and reference values for the formulation of low-carbon policies in different regions. In addition, the theory of comparative advantage can be introduced in the quantification of carbon balance zoning indicators, and regional carbon balance zoning can be carried out by calculating the standard comparative advantage index.

6. Conclusions and Policy Implications

6.1. Conclusions

In this study, we calculated carbon budgets and expenditures of 31 cities in the MRYRUA from 2005 to 2020, analyzed the spatial-temporal pattern of carbon budgets, and formulated carbon balance zoning. The main results are summarized below.

(1) From 2005 to 2020, carbon emissions and carbon budgets increased, the increase in carbon sequestration was relatively small, and changes in carbon budgets were reflected by changes in carbon emissions. Carbon emissions from the Wuhan City Circle accounted for the largest total carbon emissions in the MRYRUA. Carbon emissions and carbon sequestration by the Chang-Zhu-Tan Urban Agglomeration increased. The Poyang Lake Urban Agglomeration had the most carbon sequestration in the MRYRUA. Carbon emissions in the MRYRUA were high in the north-central region and low in the south. Carbon sequestration was high in the periphery and low in the center. Carbon budgets were high in the central region, followed by the north, and lowest in the south.

(2) From 2005 to 2020, the CBI of the MRYRUA increased. From 2005 to 2020, the CBI increased by 93.42% and was high in the center and low in the periphery. The low-value areas of carbon balance were distributed in the southeastern area of the Poyang Lake Urban Agglomeration and the northwest area of the Chang-Zhu-Tan Urban Agglomeration. The ECC decreased overall, and differences in the ECC of different cities gradually decreased. The ECC of each city of the Wuhan City Circle and the Chang-Zhu-Tan Urban Agglomeration increased annually. The ECC was low in the north-central region and high in the periphery. The area with a high ECC gradually shifted from the Poyang Lake Urban Agglomeration to the Wuhan City Circle. The ESC of all cities in the Wuhan City Circle increased, while the ESC of most cities in the other two urban agglomerations decreased. The spatial pattern of the ESC was similar to that of the ECC and was low in the center and high in the periphery. Obvious differences in the ESC occurred between regions.

(3) From 2005 to 2020, the number of carbon sink functional zones significantly decreased. These zones were distributed in areas with rich ecological resources. The number of low-carbon economic zones generally increased. The spatial distribution gradually shifted from the Poyang Lake Urban Agglomeration to the Wuhan City Circle, and the number of low-carbon optimization zones fluctuated greatly, mainly from the Wuhan City Circle and the Chang-Zhu-Tan Urban Agglomeration to the Poyang Lake Urban Agglomeration. The number of carbon intensity control zones increased and these

zones were mainly distributed in the provincial capital center and its surrounding cities. High-carbon optimization zones were spatially distributed in blocks and were relatively scattered.

6.2. Policy Implications

The spatial pattern of carbon budgets in the MRYRUA is unbalanced, and there are differences in the ECC and the ESC between cities. Based on a spatial-temporal analysis of carbon budgets and the results of carbon balance zoning, we put forward the following suggestions:

(1) Build a regional carbon balance adjustment mechanism oriented toward the goal of carbon neutrality. Based on the CBI, ECC, ESC, and carbon balance zoning results, carbon emissions reduction targets can be set. For Wuhan, Changsha, Nanchang, and surrounding cities, targets should formulate a carbon emission quota and monitoring system and set carbon emission caps for various industries. In addition, carbon sequestration in the southern part of the Poyang Lake Urban Agglomeration is relatively large. We should continue to strengthen carbon sink management, increase the carbon sequestration capacity, alleviate carbon emissions, and coordinate carbon emissions and carbon sequestration in the MRYRUA.

(2) Develop differentiated carbon emission reduction and carbon sink enhancement strategies based on regional characteristics. Carbon sink functional zones rich in ecological resources should continue to be maintained, ecological protection and restoration should be strengthened, carbon sink resources (such as forests, grasslands, and wetlands) should be increased, vegetation coverage should be increased, and the carbon sequestration capacity of the regional ecosystem should be improved. Carbon intensity control zones and high-carbon optimization zones should focus on carbon emissions reduction and continue to move toward low-carbon economic zones and low-carbon optimization zones. In addition, we should control the speed of urban expansion, guide regional development in a low-carbon direction, ensure the coordination of carbon balance and economic development, and improve regional economic-ecological-social benefits.

(3) Facilitate the exchange of technology among different regions. Urban agglomerations consistently promote collaborative efforts to reduce emissions. Carbon sink functional zones, carbon intensity control zones, and high-carbon optimization zones should enhance the dissemination of technologies. Carbon intensity control and high-carbon optimization zones experiencing rapid economic development can offer technical support to carbon sink functional zones. Similarly, carbon sink functional zones can mitigate carbon emissions generated by carbon intensity control and high-carbon optimization zones. Strengthening inter-regional cooperation and coordination can establish a carbon equilibrium mechanism that balances economic development with ecological protection.

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