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Spatial differentiation and functional zoning of carbon budget: evidence from Jiangxi Province

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Regional carbon budget and compensation are one of the current research hotspots, which is of great practical significance for dealing with climate change and promoting the coordinated development of low carbon. Based on energy consumption and land use data, a carbon budget and carbon compensation measurement model was established to analyze the change characteristics and spatial differentiation of the carbon budget of 11 prefecture-level cities in Jiangxi Province from 2010 to 2020 and carry out functional zoning, and further calculate the carbon compensation value of each prefecture-level city. The results showed that (1) during the study period, the carbon emissions in Jiangxi Province showed an increasing trend, with an average annual growth rate of 6.00 million tons, showing a spatial distribution pattern of "high in the west and low in the east." The province was mainly represented by net carbon sources. (2) During the study period, the forest land in Jiangxi Province was the main carbon sink. The carbon sink absorption capacity declined from 60.56 million tons in 2010 to 59.69 million tons in 2020. (3) The regional difference in the economic contribution coefficient of prefecture-level cities in Jiangxi Province is relatively tiny. The ecological support coefficient has apparent spatial heterogeneity, showing a spatial distribution feature of "high in the south and low in the north." (4) The 11 prefecture-level cities in Jiangxi Province could be divided into four regions: the carbon sink functional area, low-carbon optimization area, total carbon control area, and carbon intensity control area. By calculating the carbon compensation value and according to the difference in the carbon compensation value, the 11 prefecture-level cities in Jiangxi province are divided into four high-compensation areas, three low-compensation areas, and four compensated areas. The larger the carbon budget is, the higher the carbon compensation amount; conversely, the smaller the budget, the more carbon compensation amount can be obtained. According to the above conclusions, 11 prefecture-level cities should improve emission reduction mechanisms and strengthen the management of forest land utilization. Meanwhile, Jiangxi Province should formulate differentiated development, and compensation strategies should be developed to promote low-carbon, coordinated, and sustainable development among regions.

KEYWORDS

carbon budget, spatial differentiation, functional zoning, compensation, double carbon target

1 Introduction

In September 2020, the Chinese government announced at the 75th United Nations General Assembly that China pledged to strive to achieve peak carbon emissions by 2030 and be carbon-neutral by 2060 in global climate governance (Shao et al., 2019). Optimizing land use is the most effective and low-cost way to achieve carbon neutrality (Dohner et al., 2022). Statistics show that global CO_2 emissions from burning fossil fuels reached 33.8 billion tons in 2022. China is the world's largest carbon emitter, accounting for 29 percent of global greenhouse gas emissions. Unreasonable land use by humans, such as excessive dependence on and consumption of fossil fuels, deforestation, and development, leads to the increasing concentration of CO_2 and other greenhouse gases in the atmosphere (Mahowald et al., 2017), resulting in global warming. At the same time, along with the constant high temperatures, drought, and other extreme climates occurring frequently, seriously affecting human production and life, the necessity of mitigating climate change has become a global consensus (Ebi and Loladze, 2019). The carbon budget is the focus of research on global climate change and an essential element of the green development strategy (Kondo et al., 2018; Lahn, 2020). According to the Report on Tackling Climate Change in 2021, the average net carbon balance from 2000 to 2019 has a deficit of 6.22 billion tCO_2/year compared with the carbon-neutral target. There is tremendous pressure and a severe situation to achieve carbon neutrality. As a fundamental factor of human production, the change in the human land use structure in industrialization and urbanization will be directly related to the change in the carbon source and sink (Chuai et al., 2021). Research shows that land-use carbon emissions have accounted for 33% of the total carbon emissions over the past 150 years and 14% of the total carbon emissions during 2009–2018 (Friedlingstein et al., 2020). It also shows enormous potential to reduce carbon emissions (Jing et al., 2021). Conducting carbon budget research on land use is helpful in determining the pressure of carbon emission reduction and exploring the potential of carbon sink (Rogelj et al., 2019). In the context of the "double carbon" target, it is necessary to control the total amount of carbon emissions and achieve regional carbon reduction and fairness (Lu et al., 2023). Carbon compensation is a crucial way to promote inter-regional synergistic emission reduction, which is conducive to sustainable economic and environmental development (Han et al., 2024). Hence, in the context of climate change and low-carbon economy, in-depth research on carbon budget from the perspective of land use, functional zoning, and carbon compensation is conducive to quantitative assessment of human activity carbon emission intensity and ecosystem pressure, which is crucial for guiding regional green, low-carbon, and synergistic development.

At present, several scholars have conducted numerous research studies on the accounting of the carbon budget, the factors influencing it, and the relationship between it and land use. First, in carbon budget accounting at different scales, there is mainly a national scale (Sleeter et al., 2018; Arowolo et al., 2018), regional scale (Zhang et al., 2012; Houssoukpèvi et al., 2023), provincial scale (Yang F. et al., 2022; Yuan et al., 2022; Gui et al., 2023), and city and county scale (Deng et al., 2020). Second, heterogeneity in carbon intensity across land-use types is an influencing factor in the carbon budget (Keiichiro et al., 2016). Energy consumption from population growth, industrial development, and urban expansion are the leading causes of the carbon balance imbalance (Rogelj et al., 2015; Lambin and Meyfroidt, 2011). With the enhancement of natural vegetation activities in China, agriculture and forestry activities have a significant positive effect on the carbon budget of terrestrial ecosystems (Cheng et al., 2024). Some scholars also believe that soil carbon reserves provide a solution to the global problem of improving the soil quality and regulating carbon balance. Due to the differences in vegetation litter and rhizosphere (Shahzad et al., 2018), soil carbon reserves vary across different land use types. Changes in land use will directly or indirectly affect soil nutrients and soil carbon sequestration capacity (Yu and Song, 2023). The conversion of cultivated land, forest land, and grassland will have a more significant impact on the soil carbon sequestration capacity (Yu and Song, 2023). Over time, the reduction of the forest land area and farmland reclamation have caused substantial changes in the national land-use structure, leading to a rapid decrease in natural vegetation coverage, soil erosion, nutrient loss, and a significant decline in soil carbon sequestration capacity (Arunrat et al., 2022), thus affecting the change in the carbon expenditure of terrestrial ecosystems. Additionally, farmland transfer, land reclamation, and water and soil development activities are fundamental factors influencing regional carbon income and expenditure (Koch and Kaplan, 2022). Third, the relationship between carbon budget and land use is significant. Land use change is one of the main reasons affecting the carbon budget (Arora and Boer, 2010). Optimizing the land use structure based on the perspective of carbon budget not only meets the model of low-carbon economic development but also meets the requirements of enhancing sustainable development. Due to the heterogeneity between regions, carbon budget capacity varies; carbon compensation is a new field in the context of the low-carbon economy. Existing scholars have mainly conducted carbon offsetting-related research from both theoretical and empirical aspects. Initially, at the academic level, it defines the connotation and characteristics of carbon compensation based on welfare economics (Wu and Li, 2019), public goods theory (Feng et al., 2020), and ecological capital theory (Carpenter et al., 2009), and it systematically expounds the basic framework of carbon compensation and the carbon trading system. It proposes formulating a scientific and unified carbon compensation accounting mechanism based on regional differences (Yang et al., 2019) to build a balanced account of the "carbon sources–carbon sink" based on regional differences and establish a "national carbon compensation system." Second, at the practical level, scholars mainly focus on the calculation and application of carbon compensation, carrying out the calculation setting of carbon compensation standards in the forest (Latta et al., 2016), agriculture (Leifeld, 2023), and fishery (Cavan and Hill, 2022) and a lot of research on carbon balance (Wen et al., 2022), carbon compensation zoning, and optimization schemes.

The achievements of the existing scholars have greatly enriched the theories and methods in the carbon budget and compensation field. However, there are still many problems that deserve in-depth research and exploration. Overall, the comprehensive literature has some findings. First, most existing studies focused on large-scale regions such as countries, economic zones, and functional zones, ignoring the developmental differences of different areas. The research on carbon budget and carbon compensation at the municipal level needs to be more prosperous. As an integral unit of China's economic development, municipal space is helpful in scientifically assessing regional carbon ecological pressure by calculating carbon budget and carbon compensation at the municipal level. It has specific theoretical and practical significance in promoting regional low-carbon coordinated development. Second, most scholars mainly analyzed the carbon budget from the single index of total carbon emission and absorption, but they neglected to conduct further comprehensive studies on the multi-dimensional economic contribution of carbon emission and the ecological carrying capacity of carbon sink.

By providing these, this research aims to promote regional low-carbon, coordinated, and sustainable development and explores regional carbon compensation from a carbon budget and functional zoning perspective. With Jiangxi Province as the research object and each city as the primary research unit, the economic contribution coefficient of carbon emission and the ecological carrying coefficient of carbon absorption were included in functional zoning based on the carbon budget calculation. Furthermore, the carbon compensation value of each prefecture-level city was calculated. This has a certain reference value for Jiangxi Province to formulate differentiated carbon emission reduction and carbon sink enhancement schemes and provides experience for regional carbon compensation, which is more conducive to accelerating the coordinated development of economic development and ecological civilization construction in Jiangxi Province.

2 Research method

2.1 Land-use carbon budget accounting

The carbon budget mainly comes from the difference between carbon emission and absorption. The land is an essential carrier for human survival and development. According to the classification of land use status in this study, construction land in the study area is the primary carbon emission source. According to previous research, carbon emissions can be divided into energy consumption caused by human economic and social activities on construction land and human respiration; carbon sequestration is mainly calculated by using land-use areas such as cultivated land, forest land, grassland, water area, and unused land (Zhang et al., 2013).

2.1.1 Calculation of total carbon emissions

The total carbon emission of energy consumption represents the carbon emissions of construction land C_e. Based on the work of Li et al. (2019), the calculation formula is as follows:

$$\boldsymbol{C_e = E\sigma}. \tag{1}$$

In Formula 1, C_e is the carbon emissions generated by the energy consumption of a certain area (prefecture or province), E is the energy consumption of the region (tons of standard coal), and σ indicates the carbon emissions coefficient of unit energy consumption. Moreover, combined with the carbon emissions coefficient of different types of energy consumption and the standard coal conversion coefficient, the value is 1.87t/C/t.

Based on the work of Li et al. (2019), the formula for carbon emissions from human breathing in a specific region is as follows:

$$\boldsymbol{C_p = P\theta}. \tag{2}$$

In Formula 2, C_p is carbon emissions for human breathing in a specific region (t), P is the region's population, and θ represents the annual carbon emissions per person. Drawing on the research of Zhang et al. (2014), the annual carbon emissions per person are taken as 0.079 (tC/a).

Based on the research of Li et al. (2019), the formula for calculating the total carbon emissions C_z in a region is as follows (Formula 3):

$$\boldsymbol{C_z = C_e + C_p}. \tag{3}$$

2.1.2 Calculation of the total carbon absorption

The calculation formula of the total carbon absorption of all kinds of land (cultivated land, forest land, grassland, water area, and unused land) is as follows (Li et al., 2019):

$$\boldsymbol{C_i = L\lambda}. \tag{4}$$

In Formula 4, C_i is the amount of carbon absorption in a specific region (t), L represents the area of various soil types in this area (hm^2), and λ represents the carbon emission/carbon absorption coefficient of different land types. According to previous research (Yeh and Liao, 2017), in this paper, the carbon emissions coefficients of cultivated land, forest land, grassland, water area, and unused land are −0.13, −5.77, −0.022, −0.253, and −0.005t/(hm^2•a), respectively. When the carbon emissions coefficient is negative, it is indicated as carbon absorption.

2.1.3 Calculation of carbon budget

Carbon budget (C_t) is the difference between carbon emissions and carbon absorption in a region. Based on the work of Li et al. (2019), the formula is as follows (Formula 5):

$$\boldsymbol{C_t = C_z - C_i}. \tag{5}$$

2.2 Economic contribution coefficient of carbon emissions

The carbon emissions economic contribution coefficient (ECC) measures regional carbon emissions differences from the perspective of financial contribution, which can be used to evaluate the equity of the financial contribution of regional carbon emission. It is an essential indicator of the size of regional carbon production capacity. Based on the research of Liu et al. (2024), the formula is as follows:

$$\boldsymbol{ECC = \frac{\frac{G_i}{G}}{\frac{C_i}{C}}}. \tag{6}$$

In Formula 6, G_t and G represent the total GDP of a municipal unit and the provincial GDP in a specific area, respectively; $\frac{G_i}{G}$ is the proportion of GDP of a municipal department of local GDP; C_i and C represent the carbon emissions of the unit and the total carbon emission of the province in a specific area, respectively, and $\frac{C_i}{C}$ is the proportion of the carbon emissions of a particular city unit in the total carbon emissions of the region. If $ECC > 1$, it means that the economic contribution rate of land use in prefecture i is greater than the carbon emissions rate, indicating that the economic efficiency of carbon emission in this region is relatively high. If $ECC < 1$, the city has a relatively low energy utilization rate.

2.3 Ecological support coefficient of carbon absorption

Carbon sinks have a significant ecological value and are vital in maintaining the global environmental balance. However, protecting carbon sink resources has an enormous opportunity cost, inevitably affecting regional spatial development equity. As a characterization index of carbon offset ecological environment attributes, the environmental support coefficient reflects the ability of carbon sink absorption of each prefecture-level city in Jiangxi Province to absorb the total emissions from carbon sources from the perspective of ecological and environmental benefits. It measures the ecological capacity contribution of each prefecture-level city unit (Li et al., 2019) to reflect the absorption capacity of a city's carbon sink to the total carbon emissions from a local scale.

Based on the research of Liu et al. (2024), the calculation formula for the ecological support coefficient (ESC) of carbon absorption is as follows:

$$\boldsymbol{ESC} = \frac{\frac{\boldsymbol{CA_i}}{\boldsymbol{CA}}}{\frac{\boldsymbol{C_i}}{\boldsymbol{C}}}. \tag{7}$$

In Formula 7, CAi and CA represent the carbon absorption of i city land use and the provincial carbon absorption, respectively. If $ESC > 1$, it indicates that the carbon absorption capacity of the city i is relatively high, and the contribution rate of the carbon absorption is greater than the carbon emissions, which positively impacts the provincial carbon emissions absorption. If $ESC < 1$, it indicates that the contribution rate of the carbon absorption of the city i is less than that of the carbon emissions and the carbon absorption capacity is relatively low, which harms the provincial carbon emissions absorption.

2.4 Regional carbon compensation accounting

Based on the principle of carbon balance, the regional carbon budget is standardized to determine the reference value of carbon compensation. If the regional carbon budget is insufficient, it indicates that the region's carbon absorption capacity is vital. The ecosystem carbon sink can absorb not only the region's carbon emissions but also the surrounding areas' carbon emissions, contributing the ecological value to the coordinated development of the region. So, it is essential to receive carbon compensation funds. Otherwise, carbon compensation funds should also be paid. Based on the work of Zhao et al. (2016), the calculation formula is as follows:

$$\boldsymbol{L_i} = \boldsymbol{C_t} = \boldsymbol{C_z} - \boldsymbol{C_i}. \tag{8}$$

In Formula 8, L_i is the base value of carbon compensation in a particular area and C_i represents the carbon emissions in a specific region. When $L_i > 0$, the carbon compensation fund should be paid; when $L_i < 0$, the carbon compensation fund should be received; and when $L_i = 0$, the regional carbon balance should be achieved. At this time, it does not matter whether carbon compensation funds should be paid or received.

Nevertheless, in current situations, due to differences in economic development, energy use efficiency, and other factors, if only the carbon budget is considered the benchmark value of carbon compensation, the compensation amount to be paid by a particular region may be too high, resulting in deviation of calculation results. In order to make the carbon compensation results more objectively reflect the current situation, this research corrected the base value L_i and set a carbon emission threshold P_i for each region, and the calculation formula is as follows (Zhao et al., 2016):

$$\boldsymbol{P_i} = \boldsymbol{ECC} \times \boldsymbol{D}. \tag{9}$$

In Formula 9, P_i indicates the carbon emissions threshold for a region (t), ECC indicates the economic contribution coefficient of carbon emissions, and D shows the average value of carbon emissions from the 11 prefecture-level cities in Jiangxi Province from 2010 to 2020.

In addition to the apparent differences in regional carbon budget, the carbon emissions per unit GDP of different prefecture-level cities also have temporal and spatial differences. Therefore, the carbon emissions per unit GDP of different prefecture-level cities in 2010 and 2020 (t/10,000 yuan) were combined to revise the carbon emissions. Based on the research of Zhao et al.(2016), the specific formula is as follows:

$$\boldsymbol{C_t^1} = \boldsymbol{C_t} \times \left(\frac{\boldsymbol{G_{t1-i}}}{\boldsymbol{G_{t2-i}}} - \frac{\boldsymbol{G_{T1}}}{\boldsymbol{G_{T2}}} + \boldsymbol{1} \right) \times \frac{\boldsymbol{G_{t1-i}}}{\boldsymbol{G_T}}. \tag{10}$$

In Formula 10, C_t^1 is the revised carbon emissions of a particular prefecture-level city; $G_{t1\text{-}i}$ and $G_{t2\text{-}i}$ indicate the carbon emissions per unit GDP of a prefecture-level city in 2020 and 2010, respectively (t/10,000 yuan); G_{T1} and G_{T2} indicate the carbon emissions per unit GDP of Jiangxi Province in 2020 and 2010 (t/10,000 yuan), respectively; and G_T is the average carbon emissions per unit of GDP of all prefecture-level cities in Jiangxi Province in 2020 (t/10,000 yuan). Based on the research of Zhao et al.(2016), the revised base value of carbon compensation is as follows:

$$\boldsymbol{L_i^1} = \boldsymbol{C_t^1} - \boldsymbol{C_i} - \boldsymbol{P_i}. \tag{11}$$

In Formula 11, when $L_i^1 > 0$, the carbon compensation fund should be paid; when $L_i^1 > 0$, the carbon compensation fund should be received; and when $L_i^1 = 0$, either the carbon compensation fund should be paid or received. The revised carbon offsets and emissions per unit of GDP are closer to reality.

On further measuring the value of carbon compensation by monetary quantity, based on the research of Zhao et al.(2016), the calculation formula of carbon compensation value is as follows:

$$M_i = \left| L_i^1 \times \alpha \times \gamma \right|. \tag{12}$$

In Formula 12, M_i represents the monetary amount of carbon compensation received or required to be paid by a region (10,000 yuan), α represents the unit carbon price (yuan/t), and γ represents the regional carbon compensation coefficient (Zhao et al., 2016).

$$\alpha = \left(\mathbf{P}_{\max} + \mathbf{P}_{\min} \big/ 2 \times G_{p1} \big/ G_{p2} \right). \tag{13}$$

In Formula 13, P_{max} and P_{min} represent the maximum and minimum values of domestic carbon sink prices, respectively (Miao et al., 2019), and international carbon sink prices of US \$10 to US \$15/t; this research uses the average RMB exchange rate published by the National Bureau of Statistics in 2020 to convert the USD to RMB. Here, G_{p1} and G_{p2} are the per capita GDP of Jiangxi Province and the whole nation in 2020 (10,000 yuan/person), respectively.

Different levels of economic development in different regions will lead to differences in the carbon offsetting capacity. Therefore, the actual payment capacity and economic development level of each region are further combined to determine the carbon compensation coefficient using the modified pal growth curve model. Based on the research of Zhao et al. (2016), the specific formula is as follows:

$$\gamma = \frac{K}{\left(1 + ae^{-bt}\right)}. \tag{14}$$

In Formula 14, γ is the regional carbon compensation coefficient, K is the regional economic development level, and the ratio of the GDP of a prefecture-level city to the GDP of Jiangxi Province is measured in this research. α and b are constants, and the value is 1. t represents the Engel coefficient of Jiangxi Province in 2020, and e is the base of the natural logarithm.

3 Data sources and descriptive statistics

3.1 Overview of the study region

Jiangxi Province is located in southeast China, on the south bank of the middle and lower reaches of the Yangtze River, the hinterland of the Yangtze River Delta, the Pearl River Delta, and the Southern Fujian Triangle. With jurisdiction over 11 cities and 100 counties, it is a significant ecological security barrier in southern China, facing the dual pressure of economic development and environmental protection. Since 2010, Nanchang, Ganzhou, Jingdezhen, Ji ‘an, and Fuzhou of Jiangxi Province have been successively ranked as the first, second, and third batches of national low-carbon pilot cities, respectively. In June 2016, Jiangxi Province was listed as one of the first batch of national ecological civilization pilot zones, further pushing the province to attach great importance to ecological civilization construction and actively explore the path of low-carbon economy development. Taking Jiangxi Province as an example, further exploring its carbon emission reduction potential is conducive to accelerating the construction of ecological civilization and realizing the green and low-carbon transformation development of Jiangxi Province.

3.2 Data sources

In this research, 11 prefectural and municipal administrative units in Jiangxi Province were selected as the research objects, and the carbon emissions data mainly adopted relevant statistical data from 2010 to 2020. Specifically, they include population, GDP, and fossil energy consumption. Due to the lack of fossil energy data in the whole society, GDP is used for conversion. When calculating energy consumption, the GDP deflator uniformly converts relevant data into the 2010 constant price. The economic data are mainly derived from the Statistical Yearbook of Jiangxi Province (2011–2021) and supplemented by the statistical yearbook and social development communique of prefecture-level cities. The land use data (2010, 2015, Issue 10,2020) and administrative boundary data (2015) on the study area were obtained from the Resource and Environment Science and Data Center of the Chinese Academy of Sciences with a spatial resolution of 1 km. In the national land-use classification system, using ArcGIS 10.2 software of land use type in Jiangxi province data and the administrative unit data space superposition, intersection, and extraction, land use is divided into six levels: cultivated land, forest land, grassland, water, construction land, and unused land; statistics in Jiangxi province and the prefecture each land use type data of Jiangxi Province and prefectures were counted.

3.3 Descriptive statistics of land use in Jiangxi Province

Based on the land use distribution layer of Jiangxi Province, statistics were carried out on the area of six primary land classes in Jiangxi Province, and the land use changes obtained are shown in Table 1. In 2020, Jiangxi Province’s land was mainly forest and cultivated land. The area of forest land was the most extensive, accounting for 61.34%, followed by cultivated land, accounting for 26.47%. The size of cultivated land, forest land, and unused land decreased during the study period, which was shown as follows: the area of cultivated land decreased by 91,118.6 hm^2 from 2010 to 2020, the unused space decreased by 16,343 hm^2, and the size of forest land decreased by 150,045.6 hm^2. Furthermore, the reasons for the decrease in forest land area in Jiangxi Province were explore. First, the conversion of forest land into land for construction and other purposes is the main reason for the decrease of forests. To adapt to the demand for population growth and industrial development, some forest land is used for urban construction, which decreases the forest land area (Song et al., 2020). Second, the management of forest land directly affects the condition of forest land resources. Research shows that the relevant departments have problems such as neglecting the management of forest land and poor management of forest land, leading to a declining trend in forest land. Third, the frequent occurrence of natural disasters is also an essential factor leading to a decreased forest land area (Yang X. et al., 2022). Data show that from 2010 to 2020, 841 forest fires occurred in Jiangxi Province, with an average annual number of 76 fires, which caused severe damage to forest resources, reducing forest resources and degrading the forest land area. The decline of the forest land area will cause a series of environmental problems, such as the reduction of biodiversity, local climate disorders, and the decline of forest

TABLE 1 Area and change proportion land use types in Jiangxi Province from 2010, 2015, and 2020.

year	Carbon sink						Carbon emission
	Land type	Cultivated land	Forest land	Grassland	Water area	Unused land	Construction land
2010	Area (hm^2)	4,498,347.1	10,361,860.1	682,741.8	691,644.8	69,843.0	341,652.5
	Proportion (%)	27.02	62.25	4.10	4.15	0.42	2.05
2015	Area (hm^2)	4,456,450.6	10,283,075.5	717,926.4	697,344.8	67,043.0	424,249.0
	Proportion (%)	26.77	61.77	4.31	4.19	0.40	2.55
2020	Area (hm^2)	4,407,228.5	10,211,814.5	715,045.6	718,540.0	53,500.0	542,287.5
	Proportion (%)	26.47	61.34	4.29	4.32	0.32	3.26

TABLE 2 Carbon emissions of all prefecture-level cities in Jiangxi Province from 2010 to 2020 (unit: million tons).

City	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Nanchang	31.62	29.04	30.77	23.93	24.77	26.21	27.64	28.80	30.05	30.47	30.19
Fuzhou	7.40	7.50	8.17	7.63	8.00	8.39	8.93	9.30	9.73	10.25	10.34
Xinyu	1.69	18.37	17.71	17.42	18.04	17.92	17.75	18.18	17.67	18.15	17.97
Jian	1.02	8.82	9.27	7.77	8.26	8.73	9.40	9.55	10.28	10.82	11.01
Jingdezhen	5.50	5.92	6.30	6.65	6.97	7.41	7.74	7.83	8.02	8.32	8.62
Pingxiang	20.28	19.35	20.13	16.13	16.89	16.96	16.80	17.18	17.40	14.44	14.78
Shangrao	5.61	11.48	12.00	11.90	12.53	13.24	14.03	14.61	15.37	15.95	16.50
Ganzhou	5.53	15.19	16.06	13.79	14.67	15.57	17.90	18.69	19.83	20.83	21.09
Yichun	15.61	17.01	17.83	15.84	17.30	18.49	21.04	21.52	21.43	22.17	22.74
Yingtan	5.20	3.78	4.09	4.32	4.51	4.66	4.79	4.97	5.03	5.13	5.19
Jiujiang	15.51	17.56	19.44	20.06	20.83	22.13	23.79	24.22	26.07	26.94	27.76

carbon sequestration, oxygen release capacity, and air quality. In addition, the area of construction land, grassland, and water area all increased, and the size of construction land increased rapidly from 341,652.5 hm^2 in 2010 to 200,635 hm^2, accounting for 1.21% more. Grassland and water area increased by 32, 303.8 hm^2 and 26,895 hm^2, respectively.

4 Analysis of results

4.1 Carbon emissions and spatial distribution in Jiangxi Province

Using the data on energy consumption and population in Jiangxi Province from 2010 to 2020 and combined with the calculation method above, the calculation of energy consumption, human respiration, and other carbon emissions in Jiangxi Province was carried out. The results found that carbon emissions in Jiangxi Province showed an increasing trend during the study period, which increased from 120.97 million tons in 2010 to 186.99 million tons in 2020, with an average annual growth of 6.00 million tons, which is an increase of 54.57%. Carbon emissions in Jiangxi Province peaked in 2020, with carbon emissions from energy consumption at 183.42 million tons and carbon emissions from human respiration at 3.57 million tons. As the first inland open-economy experimental zone in the central region, Jiangxi Province has been accelerating the process of urbanization and industrialization since 2011, resulting in the land for construction increasing year by year, from 341,652.5 hm^2 in 2010 to 542,287 hm^2 in 2020. As a primary carbon source, construction land carries most of the energy consumption (Li et al., 2019), and a large amount of carbon emissions will be generated during the conversion of construction land. It implies a continuous increase in the total amount of carbon emissions from human activities, especially from energy consumption in economic construction.

The emissions of carbon sources from the prefecture-level cities in Jiangxi Province are shown in Table 2. During the research period, Nanchang city had the highest carbon emissions, and Yingtan city had the lowest carbon emissions, which is consistent with the actual development. Nanchang city is the provincial capital city with a concentrated population and a relatively developed economy. It is both a production center and a consumption center. Due to the impact of industrialization and urbanization development, energy consumption demands exuberant carbon

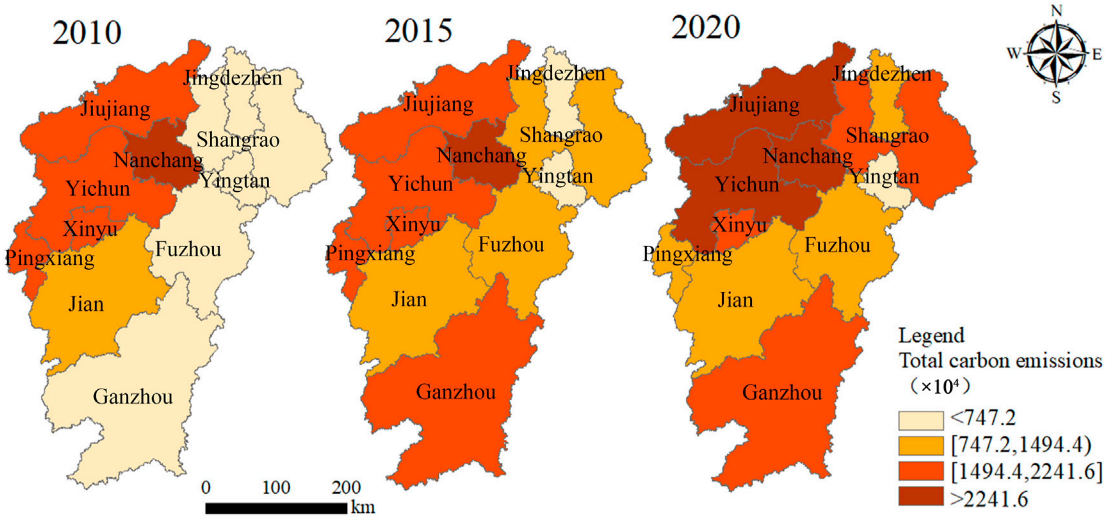

FIGURE 1
Spatial distribution of carbon emissions in all prefecture-level cities in Jiangxi Province from 2010 to 2020.

emissions, and its carbon emissions accounted for 16.14%. At the same time, the economic development of Nanchang city has attracted more population, and with the increasing population, the carbon emissions from human respiration have continued to grow. Yingtan city is located in the fifth echelon of economic growth in Jiangxi Province, with the smallest built-up area, a relatively weak industrial base, and low energy consumption. In 2020, the total energy consumption was 2.73 million tons, accounting for 2.78% of the total energy consumption of the province, with relatively little carbon emissions. Ganzhou city had the most significant increment of carbon emissions during the study period, which was 5.53 million tons in 2010 and increased rapidly to 21.09 million tons in 2020, with an annual increment of 1.41 million tons, which is an increase of 280%. Ganzhou city has a small industrial volume and a thin foundation. In 2010, the total energy consumption accounted for 4.1% of the province, and the carbon emissions were relatively low, so the carbon emissions in 2010 were at a low value in the section. Since 2010, Ganzhou has implemented a plan to attack the industry, and the scale of the secondary sector has expanded. The total industrial growth rate has doubled in 10 years, with an average annual growth rate of 8.9%, maintaining a high growth range, and the energy demand has increased dramatically. In 2020, Ganzhou's energy consumption accounted for 11.1% of the province's total consumption, and the carbon emissions from economic activities have increased rapidly. With the continuous improvement of urban functions and infrastructure, the population of Ganzhou increases year by year, resulting in the growth of carbon emissions generated by human respiration. From 2010 to 2020, the cities (districts) of Jiangxi Province's 11 prefecture-level cities (communities) with a decrease in total carbon emissions are Nanchang city, Pingxiang city, and Yingtan city, which is closely related to the adjustment and optimization of the regional industrial structure layout, the improvement of energy utilization efficiency, and the constraints of government policies and institutions.

Combined with the current situation of carbon emissions in Jiangxi Province from 2010 to 2020, carbon emissions were divided into four types: (1) less than 50% of the average carbon emissions in 11 prefecture-level cities; (2) 50%~100% of the average carbon emissions in 11 prefecture-level cities; (3) 100~150% of the total carbon emissions of the 11 prefecture-level cities; (4) higher than 150% of the average carbon emissions in the 11 prefecture-level cities. The research used ArcGIS software to visualize the spatial distribution of carbon emissions in 2010, 2015, and 2020; the results are shown in Figure 1. In terms of the spatial distribution characteristics, the spatial distribution pattern of carbon emissions in the prefecture-level cities of Jiangxi Province evolved from "high in the west and low in the southeast" to "high in the north and south and low in the middle" during the study period. In 2020, Nanchang, Jiujiang, and Yichun were prefecture-level cities with heavy carbon emissions, respectively. Large industrial cities in Jiangxi Province, Jiujiang, and Yichun have sizeable total energy consumption. With the increase in energy-intensive enterprises in the past year, energy consumption increases yearly, and the total carbon emissions are at a high value.

Carbon emissions are an absolute indicator, which is more valuable for horizontal comparison when combined with GDP (Garrone and Grilli, 2010), population, and other indicators. Carbon emission per unit of GDP is a relative indicator to measure carbon emissions generated by economic development. The carbon emissions per unit of GDP in Jiangxi Province have been decreasing during the study period, from 1.28t/×10^4 yuan in 2010 to 0.8t/×10^4 yuan in 2020, indicating that it was gradually weakening with the progress of technology. The spatial differences in carbon emissions per unit GDP of prefecture-level cities in Jiangxi Province were noticeable, showing a spatial distribution pattern of "high in the west and low in the east" and decreasing trend each year. Figure 2 shows that Pingxiang city and Xinyu city are the only prefecture-level cities with high carbon emissions per unit GDP in 2020. It indicates that these two prefecture-level cities were inefficient in energy use. Carbon emissions per unit of GDP in Ganzhou city increased during 2010–2015 and remained constant during 2015–2020. Some possible explanations are as follows: since 2010,

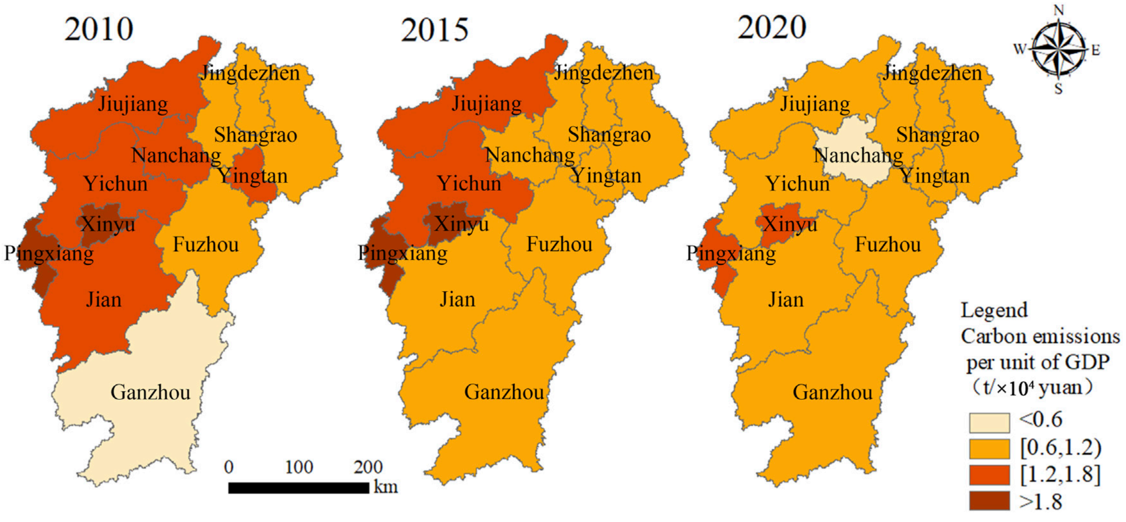

FIGURE 2
Spatial distribution of carbon emissions per unit of GDP in Jiangxi Province from 2010 to 2020.

Ganzhou has implemented the "3-year industrial attack plan," which has resulted in rapid industrial development and soaring economic aggregate. However, in the development process, the adjustment and optimization of the industrial structure have been ignored, resulting in the growth rate of carbon emissions exceeding the GDP growth rate, increasing carbon emissions per unit of GDP. During the study period, the carbon emission per unit of GDP decreased the fastest in Nanchang, from 1.47t/×10^4 yuan in 2010 to 0.57t/×10^4 yuan in 2020, which is a decrease of 61.06%. It can be seen that Nanchang, one of the first batches of low-carbon pilot cities in China, can actively adjust the energy and industrial structure and improve the efficiency of energy utilization in economic development. Some achievements have been made in promoting industrial transformation, upgrading, and developing a low-carbon economy.

4.2 Carbon absorption status in Jiangxi Province

The results of the study show that the carbon absorption capacity of Jiangxi Province has weakened during the study period, decreasing from 60.56 million tons in 2010 to 59.69 million tons in 2020, with an average annual decrease of 0.08 million tons. Affected by economic growth, construction land expanded, and some carbon sink land was eroded during the study period. For example, cultivated and forest lands were developed into construction land, decreasing 91,118.6 hm^2 and 150,045.6 hm^2 of cultivated land and forest lands, respectively, leading to the weakening of carbon sink absorption capacity. During the study period, the carbon absorption capacity of forest land in Jiangxi Province was the strongest. The carbon absorption capacity of forest land was 8.92 million tons in 2020, accounting for more than 95% of the total carbon absorption, and carbon sequestration in cultivated land was 5.73 million tons. The carbon absorption capacity of grassland was weaker than that of forest land, and the carbon absorption capacity was only 0.02 million tons, accounting for 0.03%, which was almost negligible.

The carbon sinks absorbed by prefecture-level cities in Jiangxi Province are shown in Table 3. According to the calculation of carbon sink uptake for five types of land use in Jiangxi Province, it can be seen that forest land is the primary source of carbon sinks, mainly due to the rich forest resources in Jiangxi Province, with a forest coverage rate of 63.1%. The age and type of forests exhibit a strong association with carbon sequestration in forest land (Li J. et al., 2023). Arbor and middle-aged forests make significant contributions to the carbon sequestration capacity of Jiangxi's forest land. In 2020, the area of arbor forests in Jiangxi Province amounted to 822.43 hm^2, and its carbon uptake was 47.75 million tons, accounting for 81.03% of the carbon uptake in the forest land. The area of middle-aged forests is 375.35 hm^2, accounting for 45.90% of arbor forests. Additionally, there are differences in carbon absorption between plantation and natural forests. Forest resources are dominated by natural forests in Jiangxi Province. In 2020, the area of natural forests accounted for 59.10% of the arbor forests, while the share of the stock reached 62.2%, with a strong carbon absorption capacity. The carbon sinks of cultivated land, grassland, water areas, and unused land are relatively small and weak.

Tillage practices affect the carbon sequestration capacity of cultivated land. Fallowing helps store soil organic carbon; older fallow fields accumulate more leaf litter and other organic debris from above- and below-ground biomass, making them produce more carbon sinks (Arunrat et al., 2023). On the other hand, crop rotation leads to an average loss of 40% of soil organic carbon over 5 years while increasing atmospheric carbon dioxide levels, which is not conducive to enhancing the carbon sequestration capacity of cultivated land. The carbon absorption capacity of Ganzhou city and Ji'an city was intense. In 2020, the absorption distribution rate of carbon sinks in Ganzhou city and Ji'an city accounted for 28.08% and 15.49%, respectively, which are closely related to the two prefectural-level cities' rich forest and cultivated land resources. The carbon absorption capacity of Nanchang city is the weakest, and the carbon absorption capacity will only account for 1.27% of the whole province in 2020. The possible reason for this is the rapid urbanization and industrialization in Nanchang,

TABLE 3 Carbon absorption in Jiangxi Province in 2010, 2015, and 2020 (unit: million tons).

City	2010	2015	2020
Nanchang	0.78	0.77	0.76
Fuzhou	7.42	7.38	7.37
Xinyu	0.98	0.97	0.94
Ji an	9.41	9.31	9.25
Jingdezhen	2.11	2.09	2.07
Pingxiang	1.52	1.50	1.50
Shangrao	7.99	7.95	7.93
Ganzhou	17.08	16.96	16.76
Yichun	6.30	6.25	6.25
Yingtan	1.19	1.18	1.17
Jiujiang	5.79	5.76	5.71

with the construction area expanding and compressing the land for carbon sinks, resulting in the lowest carbon uptake in the province.

4.3 Carbon budget, carbon emission economic contribution coefficient, and carbon absorption ecological support coefficient of Jiangxi Province

4.3.1 Carbon budget of Jiangxi Province

According to Table 4, the carbon budget of land use types in Jiangxi Province has the following characteristics: first, the total carbon budget does not match with the carbon emissions, the carbon absorption capacity is fragile, the complete carbon absorption is much lower than the carbon emissions, and the whole province is a net carbon source. Second, the growth rate of carbon emissions is much faster than that of carbon absorption. From 2010 to 2020, the carbon emissions of the whole province proliferated, while the carbon absorption decreased, with the increased rate of carbon emissions exceeding 50%, while carbon absorption showed a downward trend. Third, energy consumption is the primary carbon source, and forest land is the main carbon sink. Over the years, carbon emissions from energy activities accounted for more than 80% of the total carbon emissions, and carbon absorption from forest land accounted for more than 90% of the whole carbon sink. Jiangxi Province should concentrate on controlling carbon sources, improving energy use efficiency, encouraging carbon reduction and emission reduction actions, and increasing the green area within the region to enhance carbon absorption (carbon sink) capacity. Environmental quality should be paid attention to while developing ways to reduce carbon emissions of land use types in Jiangxi Province.

On analyzing the carbon budget of 11 prefecture-level cities in Jiangxi Province from 2010 to 2020 (Table 5), the carbon budget of Nanchang and Pingxiang showed a downward trend, while the carbon budget of other prefecture-level towns showed an upward trend. In 2020, Nanchang, Jiujiang, and Yichun ranked in the top three regions in terms of the total carbon budget, and the carbon budget of these three prefecture-level cities remained at the top. It is worth noting that the carbon budget of Fuzhou city, Ganzhou city, and Shangrao city was negative in 2010, indicating that carbon absorption was more significant than carbon emissions; the carbon budget of Ganzhou city and Ji'an city was negative in 2015, meaning that Ganzhou city and Ji'an city functioned as carbon sinks in 2015. In 2020, the carbon budget of the 11 prefecture-level cities was positive.

4.3.2 Spatial distribution characteristics of the economic contribution coefficient of carbon emissions

During the study period, the carbon emission economic contribution coefficient (ECC) of prefecture-level cities in Jiangxi Province mainly ranged from 0.6 to 1.8, indicating that the financial contribution rate and carbon emission contribution rate of prefecture-level towns were in a relatively balanced state, with relatively little regional differences and a downward trend over time. As shown in Figure 3, Ganzhou city and Shangrao city had a carbon emission economic contribution coefficient greater than 1.8 in 2010. In 2015 and 2020, all cities' carbon emission economic contribution coefficients were less than 1.8, indicating that the economic efficiency of carbon emission had declined. In 2020, the financial contribution coefficients of carbon emissions in each prefecture-level city were within the range of 0.6–1.8, which has a relative change compared with 2010, fully indicating that the regional differences in the economic efficiency of carbon emissions are decreasing. The spatial distribution is generally characterized by the feature of "high in the south and low in the north." The financial contribution coefficient of carbon emission is relatively high in the southern region and relatively low in the northern part.

TABLE 4 Carbon budget in Jiangxi Province from 2010 to 2020 (unit: million tons).

Year	Carbon emissions			Carbon absorption					Carbon budget
	Energy consumption	Human breathing	Summation	Cultivated land	Forest land	Grassland	Water area	Summation	
2010	117.45	3.53	120.98	0.59	59.79	0.02	0.18	60.58	60.40
2015	157.52	3.54	161.06	0.58	59.33	0.02	0.18	60.11	100.95
2020	183.42	3.57	186.99	0.57	58.92	0.02	0.18	59.69	127.30

TABLE 5 Carbon budget of 11 prefecture-level cities in Jiangxi Province from 2010 to 2020 (Unit: million tons).

Year	Nanchang	Fuzhou	Xinyu	Ji'an	Jingdezhen	Pingxiang	Shangrao	Ganzhou	Yichun	Yingtan	Jiujiang
2010	30.84	−0.02	15.96	0.78	3.40	18.76	−2.38	−11.55	9.31	4.01	9.72
2015	25.44	1.02	16.95	−0.58	5.32	15.46	5.29	−1.39	12.24	3.49	16.37
2020	29.43	2.97	17.02	1.76	6.56	13.28	8.58	4.33	16.49	4.03	22.05

4.3.3 Spatial distribution characteristics of the ecological support coefficient of carbon absorption

The carbon absorption ecological support coefficient (ESC) of Jiangxi Province showed noticeable regional differences, showing a spatial distribution feature of "high in the south and low in the north." During the study period, the regional differences decreased but remained stable, and the carbon absorption ecological support coefficient of all prefecture-level cities remained stable from 2015 to 2020. As can be seen from Figure 4, the carbon absorption ecological support coefficient of prefecture-level cities in the western and northern regions is less than one, which is generally lower than that in the southern and eastern areas. The carbon absorption ecological support coefficient of Ji'an city, Fuzhou city, and Ganzhou city was more than 1.8 from 2010 to 2020. The carbon absorption ecological support coefficient of Ganzhou city exceeded five in 2010, indicating that cities with high forest coverage rates have higher carbon absorption capacity, which positively affects the absorption of carbon emissions. From 2010 to 2020, the carbon absorption ecological support coefficient values of Nanchang, Xinyu, and Pingxiang were all less than 0.6, indicating that the carbon emission ratio of these cities significantly exceeded the carbon absorption ratio, which harmed the carbon emission absorption. Therefore, attention should be paid to it, and measures should be taken to improve the carbon sink capacity and alleviate the ecological pressure.

Furthermore, taking Shangrao city as an example, the equilibrium relationship between regional carbon emission contribution and economic growth is analyzed. The economic contribution coefficients of carbon emission in Shangrao city during the study period exceeded 1.2, indicating that the economic efficiency of carbon emission and the efficiency of energy use in the region were relatively high. Since 2010, Nanchang City in Jiangxi Province has been listed as one of the first national low-carbon pilot cities, and since then, Ganzhou City and Jingdezhen City, Ji'an City and Fuzhou City have been listed as the second and third national low-carbon pilot cities. At the same time, steadily advancing the work of energy conservation and reduction of energy consumption and the growth of the source consumption of the enterprises of high-energy-consuming industries has been effectively contained. In 2020, the gross regional product will be 262.43 billion yuan, while the energy consumption of 10,000 yuan GDP will be 0.346 tons of standard coal, which is a decrease of 74.5% compared with that in 2010. Since 2015, the reduction rate of energy consumption per unit of GDP in Shangrao city has been positive, indicating that the regional economic growth is steadily reducing energy dependence and gradually realizing the synergy between the contribution of carbon emissions and economic development.

4.4 Functional zoning and the carbon compensation value of Jiangxi Province

4.4.1 Functional zoning of Jiangxi Province

Based on the *status quo* of districted cities in Jiangxi Province, functional zoning of prefecture-level cities is carried out from the perspective of carbon budget by referring to the ideas of Zhao et al.

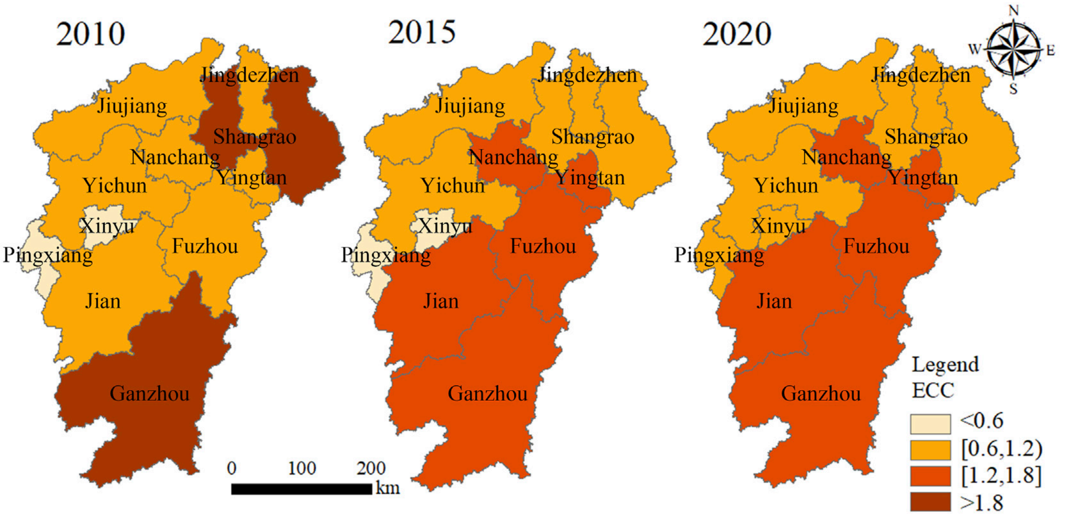

FIGURE 3
Spatial distribution of the economic contribution coefficient of carbon emission in Jiangxi Province from 2010 to 2020.

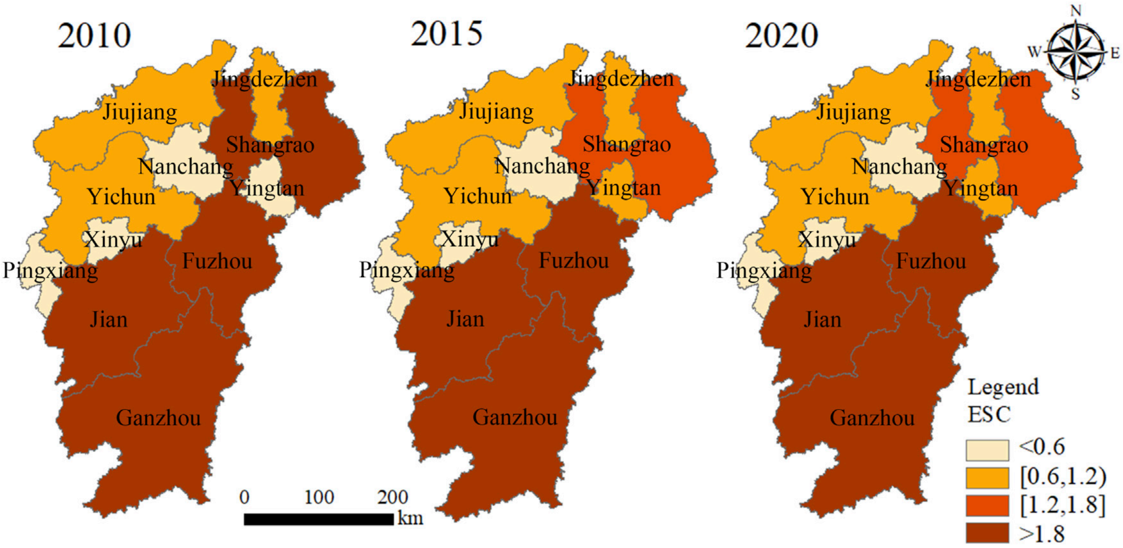

FIGURE 4
Spatial distribution of the ecological support coefficient of carbon absorption in Jiangxi Province from 2010 to 2020.

(Table 6), which can be divided into four categories, namely, carbon sink functional areas, low-carbon optimization areas, total carbon control areas, and carbon intensity control areas, with carbon reduction plans for different functional areas. Applicable zoning focuses on putting forward the future development direction from the perspective of low-carbon, but there are still significant differences among prefecture-level cities. The functional positioning of specific regions needs careful consideration of various factors. Applicable zoning only refers to regional carbon compensation and coordinated development. Yingtan and Jingdezhen are low-carbon optimization areas. The total carbon emissions and carbon emissions per unit of GDP of the two prefecture-level cities are low. Although the carbon sink level is average, the overall carbon emission pressure is relatively small. Ganzhou, Ji'an, and Fuzhou are carbon sink functional areas. The forest land area of these cities is relatively large. The carbon sink function is vital, the effect of carbon source control and environmental protection is good, the ecological pressure is relatively small, and it positively impacts the consumption of carbon emissions in Jiangxi Province. Nanchang has a moderately developed economic aggregate, high energy consumption and carbon emissions, and low ecological support capacity. It is the primary carbon source in Jiangxi Province and a total carbon control area. Jiujiang, Yichun, Xinyu, Pingxiang, and Shangrao are carbon intensity control areas. These cities have a significant proportion of industry, high energy consumption and

TABLE 6 Basis and characteristics of functional zoning of Jiangxi Province in 2020.

Functional zoning	Division basis	Regional characteristic	City
Carbon sink functional areas	ECC>1 and ESC>2	The economic contribution efficiency of carbon emission and the ecological support level of carbon absorption are relatively high; the carbon sequestration capacity is strong	Ganzhou, Ji'an, and Fuzhou
Low carbon optimization areas	ECC>1, ESC<1, and Ct < 7.47 (Mt)	The economic contribution efficiency of carbon emission is high, the ecological support level of carbon absorption is low, and the total carbon expenditure is low	Yingtan and Jingdezhen
Total carbon control areas	ECC>1, ESC<1, and Ct > 22.42 (Mt)	The economic contribution of carbon emissions is high, the ecological support level of carbon absorption is low, and the total carbon income and expenditure are incredibly high	Nanchang
Carbon intensity control areas	ECC<1, ESC<1, and carbon emission per unit of GDP >1t/10^4 yuan	The economic contribution rate of carbon emissions and the ecological support level of carbon absorption are both low, and the carbon emissions per unit of GDP are high	Jiujiang, Yichun, Xinyu, Pingxiang, and Shangrao

low utilization rate, and high carbon emission intensity but an average economic contribution rate, which harms the carbon emissions absorption of Jiangxi Province.

4.4.2 Calculation and analysis of the carbon compensation value in Jiangxi Province

The carbon compensation value of 11 prefecture-level cities in Jiangxi Province in 2020 is shown in Table 7. When the compensation amount is negative, carbon compensation funds are available; when the compensation amount is regular, compensation funds must be paid. The calculation shows that the carbon compensation value is similar to the function partition. The carbon sink function area and low carbon optimization area are mostly replenishment areas. In contrast, the carbon intensity control, total, and carbon intensity control areas are mostly payment areas. Among them, Jiujiang pays the highest carbon compensation funds, followed by Yichun, which produces 114.31 million yuan and 54.59 million yuan, respectively. These two prefecture-level cities have developed industries, large total energy consumption, significant carbon emissions, large carbon emissions per unit of GDP, and small ecological carrying capacity.

In contrast, Ji'an, Fuzhou, Yingtan, and Jingdezhen need to receive corresponding carbon compensation funds. These prefectural cities had a late start of industrial development and have small energy consumption, relatively small carbon emissions from human respiration and energy consumption, and a relatively small carbon budget. What needs illustration is that although some prefecture-level cities have a sizeable total carbon emission, they have a high economic contribution. Therefore, after the revision, the allowable carbon source quota will be increased, and the carbon compensation amount to be paid will be reduced. Conversely, regions with lower carbon emissions but a low degree of economic contribution receive a correspondingly lower amount of carbon compensation. This correction method considers the region's degree of financial assistance, so the final compensation scheme obtained considers equitable development within each prefecture.

According to the difference in the carbon compensation value among prefecture-level cities in Jiangxi Province, these cities can be roughly divided into three categories: high-compensation areas, low-compensation areas, and compensation areas. High-compensation areas include Jiujiang, Yichun, Ganzhou, and Xinyu; common compensation areas include Shangrao, Nanchang, and Pingxiang; the reimbursed areas include Ji'an, Fuzhou, Yingtan, and Jingdezhen. The relationship between carbon revenue and expenditure and the carbon compensation value of each functional area shows that the larger the carbon revenue and spending, the higher the amount of carbon compensation paid, and the smaller the carbon revenue and expenditure, the more carbon compensation amount is obtained. From the economic development perspective, the ecological bearing and carbon compensation value of prefecture-level cities, economic development, and environmental applicability must be more balanced. To achieve regional coordinated development, efforts should be made to narrow the financial gap among prefecture-level cities, achieve fair outcomes within the region, and promote regional coordinated and low-carbon development from the low-carbon level based on carbon compensation.

5 Discussion

Based on the land-use changes in Jiangxi Province, this study examined the spatial distribution characteristics of the carbon budget. This analysis helps identify the regional low-carbon economic development characteristics at the city level, providing a new perspective for optimizing the regional land-use structure and fully exploiting the carbon sink potential. Additionally, the study offers valuable insights for developing differentiated carbon compensation policies and promoting regional low-carbon development.

First, in terms of carbon balance, this study found that regional carbon balance has obvious spatial differentiation characteristics, which is consistent with the results of Li et al. (2019). The primary carbon source in Jiangxi Province is energy consumption, while the main carbon sink is the forest land carbon sink. The reasons why energy consumption is the primary carbon source are further analyzed. Since 2010, Jiangxi Province has experienced rapid economic development and further expansion of construction land, leading to significant energy consumption (Li Q. et al., 2023) and a rapid increase in carbon emissions. Additionally,

TABLE 7 Carbon compensation value of the prefecture-level cities in Jiangxi Province in 2020 (unit: million yuan).

City	Nanchang	Fuzhou	Xinyu	Ji'an	Jingdezhen	Pingxiang	Shangrao	Ganzhou	Yichun	Yingtan	Jiujiang
Amount	16.20	−26.06	39.51	−44.76	−5.11	13.13	20.80	43.22	54.59	−14.01	114.31

human production and living activities, such as industrial activities, transportation activities, and residential household activities, consume large amounts of energy and generate large amounts of carbon emissions. The industrial sector is the primary energy-consuming sector. During the study period, Jiangxi province was in a period of accelerated industrialization, resulting in a rigid growth in energy consumption demand. The energy consumption structure is dominated by fossil fuels, mainly coal and oil, which have high carbon emissions. In 2020, the energy consumption of industries above the scale in Jiangxi province was 58.17 million tons of standard coal, with a yearly increase of 2.9%. The residential living sector is the second largest energy-consuming sector. The United Nations Environment Program's Emissions Gap Report 2020 mentions that approximately 2/3 of global emissions are related to household activities. Carbon emissions from residential energy consumption are significantly influenced by household structure, lifestyle, and residential location (Rong et al., 2020). In addition, transportation is a primary energy-consuming industry (Tian et al., 2023). According to the annual statistics of the International Energy Agency (IEA) in 2019, carbon dioxide emissions from the transportation industry account for one-fifth of the global carbon emissions. These emissions primarily come from carbon dioxide emissions generated by energy consumption of various types of vehicles during transportation.

Second, in terms of carbon compensation, this study found that areas with high economic development have high carbon emissions, while areas with better ecosystems mainly have high carbon sinks, consistent with Long et al. (2021) and Wu et al. (2023). Based on these insights and existing studies (Xia and Yang, 2022), the carbon compensation value is divided according to the regional carbon expenditure level and economic contribution. The carbon sink function areas and low carbon optimization areas are primarily covered areas, while the total carbon control and intensity control areas are primarily payment areas. An important correlation exists between different degrees of carbon balance zoning and regional economic development (Li J. et al., 2023). The economic development level of various regions in Jiangxi Province has significant differences. Relevant ecological restriction policies should be formulated according to the development status of sub-regions of different values when promoting regional carbon emission reduction. Changing the way of energy utilization and improving energy efficiency can effectively reduce carbon emissions. This is crucial for achieving regional carbon balance (Ren et al., 2024) and promoting the "dual-carbon" goal. Additionally, Jiangxi Province has the highest carbon sequestration in forested areas. Increasing the area through afforestation and conservation measures can improve the ecological environment and enhance the carbon sink function of forest ecosystems, which is vital for mitigating climate change. Therefore, it is essential to pay more attention to the varying carbon absorption capacities of different forest vegetation types and formulate more scientific and reasonable carbon compensation policies.

Finally, there are some limitations to our study: (1) in terms of the selection of research scales, most of the existing studies have focused on large-scale areas such as countries, economic zones, and functional zones, often ignoring the development differences among various regions (Jing et al., 2021; Zhang et al., 2014). Some scholars have carried out research on carbon expenditure from the perspective of counties (Zhao et al., 2016). This study examined the partition of functional zoning and carbon compensation value in the city area. Future research should be deepened, taking the county as the research unit and combining the main functional areas to study the carbon compensation mechanism of different functional areas to improve the guiding role of reality. (2) The accounting of carbon income and expenditure and carbon compensation. In this study, when measuring carbon emissions and absorption, the coefficient refers to the study of Li et al. (2019). The data results are consistent with the results of the existing studies, but due to the differences in energy intensity and vegetation cover, the final results may have some deviations.

6 Conclusion and suggestions

6.1 Conclusion

By analyzing the carbon budget of Jiangxi Province from 2010 to 2020, this study draws the following conclusions: (1) during the study period, carbon emissions from human activities in Jiangxi Province showed an increasing trend, rising from 120.97 million tons in 2010 to 186.99 million tons in 2020, with an average annual growth rate of 6.60 million tons, which is up to 54.57%. Jiangxi Province is mainly a net carbon source, with carbon emissions from human activities far exceeding the carbon sink uptake of the ecosystem. Energy consumption is the primary carbon source. (2) During the study period, forest land in Jiangxi Province was the main carbon sink. The carbon sink absorption capacity declined from 60.56 million tons in 2010 to 59.69 million tons in 2020, with an average annual decline of 0.08 million tons. The amount of carbon absorbed by the forest land declined with the decrease in area, and the carbon absorption capacity of other land uses was low. (3) During the study period, regional differences in the carbon emission economic contribution coefficient (ECC) of prefecture-level cities in Jiangxi Province were relatively small, while the economic contribution rate and carbon emission contribution rate were relatively balanced. The ecological support coefficient (ESC) of carbon absorption exhibited apparent spatial heterogeneity, showing a distribution pattern of “high in the south and low in the north.” (4) From the perspective of the carbon budget, 11 prefecture-level cities in Jiangxi Province were divided into four categories: carbon sink functional area, low-carbon optimization area, total carbon control area, and carbon intensity control area. The carbon compensation value of each prefecture-level city was calculated. Based on the difference in the carbon offset value among prefecture-level cities, they were categorized into three categories: high-compensation area, low-compensation area, and compensation area. The larger the carbon budget, the higher the carbon compensation amount paid; conversely, the smaller the carbon budget, the more carbon compensation amount can be obtained.

6.2 Suggestions

Combined with the above analysis, the following policy suggestions are put forward: (1) improve energy conservation and emission reduction policies and mechanisms. Accelerate the construction of a clean, low-carbon, safe, and efficient energy system, and improve the efficiency of resource and energy utilization. Jiangxi Province should take advantage of economic development to accelerate the transformation of its economic development; vigorously develop high-tech, tertiary, and modern service industries; and actively promote the green upgrading of industries. At the same time, introducing and applying energy-saving and new energy technologies along with other advanced technologies should improve the energy consumption structure, enhance energy utilization efficiency, and promote green low-carbon transformation actions. Additionally, the proportion of carbon sources and sinks should be coordinated, land should be developed rationally, the land use structure should be optimized, land use should be intensified to improve land use efficiency, and the contradiction between land use and carbon emissions should be coordinated. (2) Forest land has a large potential for carbon emission reduction in the utilization process. Priority should be given to protecting ecological land, such as forest land, strengthening the planning and management of forest land utilization, thereby enhancing the capacity of carbon sinks by improving the effectiveness of land use. Regions in Jiangxi Province should actively implement forest protection and afforestation programs to improve forest coverage, thereby enhancing the capacity of ecosystems to sequester carbon and increase sinks. At the same time, they should focus on establishing an incentive mechanism for carbon sinks, providing corresponding incentives according to the ecological benefits and carbon sinks of the projects. Carbon sink projects should be actively carried out, and mechanisms for realizing the value of ecological carbon sink products should be established through carbon sink trading and other means, synergistically promoting economic development and ecological construction. (3) All urban units in Jiangxi Province should formulate differentiated carbon emission reduction plans, according to the actual situation of local economic development. In the future, the low-carbon optimization zone should pay attention to its advantages in developing the economy and expanding urban construction while coordinating environmental protection and improving ecological capacity. The total carbon control area should strengthen urban functional services, build a modern industrial system, develop low-carbon and high-tech industries, encourage enterprises to implement carbon capture and fixation technologies, and enhance the economic benefits of carbon emissions. Carbon intensity control areas should control carbon emission intensity, restrict the development of high-carbon industries, improve energy efficiency, and promote the low-carbon transformation of industrial structures. In the future, carbon sink functional areas should strive to improve environmental quality, focus on the carbon sink function of the ecosystem, stabilize the source of carbon sink, and alleviate the pressure of carbon emission in the province. (4) A government-led regional horizontal differentiated carbon compensation mechanism should be established. Based on regional carbon budget accounting, compensation funds can be paid from carbon intensity control areas and total carbon control areas (economically or industrially developed sites) to carbon sink areas and low-carbon optimization areas (less developed areas). This can be done to purchase carbon sink emission indicators from less developed areas to meet their own development needs. Horizontal carbon compensation between prefecture-level cities can narrow the regional development gap and achieve intra-regional development equity. Jointly, these efforts contribute to realizing the "carbon peak and carbon neutrality" goal.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material; further inquiries can be directed to the corresponding author.

Author contributions

LW: conceptualization, formal analysis, funding acquisition, and writing–review and editing. JL: data curation, investigation, and writing–original draft. ZJ: investigation, methodology, and writing–original draft. WZ: conceptualization, formal analysis, and writing–review and editing. QH: investigation and writing–review and editing. SS: conceptualization, funding acquisition, software, and writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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