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Study on Land Use Carbon Emissions Differences and Carbon Balance Zoning in the Chengdu-Chongqing Metropolitan Area

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Abstract

This study followed a research process comprising carbon accounting, spatiotemporal variation analysis of carbon emissions, and carbon balance zoning. Based on land use and energy consumption data from 2010 to 2020, it analyses the characteristics of land use change in the Chengdu-Chongqing urban agglomeration over the past decade. Spatiotemporal variation analysis of carbon emissions was conducted separately for carbon sources, carbon sinks, and net carbon emissions. Finally, carbon balance zoning was conducted using carbon compensation rates, economic contribution coefficients, and ecological contribution coefficients to propose region-specific carbon reduction strategies. Findings indicate: (1) The Chengdu-Chongqing agglomeration exhibits increasing net carbon emissions from land use, with forested areas serving as primary carbon sinks and constructed land as major carbon sources; (2) Carbon source variations predominantly occur in the Chengdu Plain and the parallel ridges and valleys of eastern Sichuan, identifying these as priority areas for emission control. Carbon sink changes are mainly distributed in peripheral cities and intermediate cities with lower industrialization levels; (3) The Chengdu-Chongqing agglomeration is categorized into five carbon balance functional zones: the central region constitutes a high-carbon optimization zone, surrounded by carbon sink functional zones, low-carbon maintenance zones, economic development zones, and carbon intensity control zones. Research conclusions: Significant variations exist in regional carbon budgets. Carbon balance zoning types should be comprehensively evaluated based on local conditions, traditional development models adjusted, and green, low-carbon development promoted.

Keywords

Land Use Change; Carbon Emissions; Carbon Balance Zoning.

1. Introduction

Since the 1970s, land-use changes and excessive greenhouse gas emissions resulting from human activities have profoundly altered terrestrial ecosystems, directly impacting the Earth's carbon cycle. This has led to the frequent occurrence of extreme temperatures and weather events, while simultaneously eroding the sustainability of both human economic activities and the planet's ecosystems [1] As the predominant greenhouse gas, reducing carbon dioxide emissions is regarded as the primary pathway to addressing climate challenges. Relevant studies indicate that carbon emissions stemming from land use/land cover change account for approximately one-third of anthropogenic carbon emissions [2]. Consequently, the impact of human-induced land use change on the carbon cycle has garnered increasing attention across society and emerged as a global issue.

Internationally, scholars began investigating the carbon emission impacts of regional land use changes as early as the 1990s [3], discovering significant variations in carbon emissions from

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terrestrial ecosystems across different land use structures. Notably, the expansion of construction land exerted the most pronounced influence on regional carbon emissions. Domestic research, though commencing later, gradually expanded in scope by the early 21st century, yielding substantial outcomes[4]. Studies examining spatiotemporal variations in carbon emissions have spanned national, key regional, provincial, municipal, and county scales. However, constrained by energy statistical data limitations, most investigations have focused on large-scale key regions and provinces[5]. Regarding carbon balance zoning research, the majority of scholars have remained at the stage of carbon balance zoning based on carbon budgets and accounting, with few further considering the economic contribution of carbon emissions or the ecological role of carbon sinks. Although in recent years a small number of scholars have used calculated carbon data, including carbon sources, carbon sinks, and net carbon emissions [6], to further calculate carbon emission intensity, ecological carrying capacity coefficients, and economic contribution coefficients of carbon emissions [7], and have classified regions by comparing these coefficients [8], such research remains relatively scarce. Although consensus exists on the profound impact of land-use change on carbon emissions, significant variations in land-use patterns, land-use type transformations, and economic development levels across regions and provinces result in distinct spatiotemporal characteristics of carbon emissions. This underscores the pronounced regional specificity in delineating carbon-balanced zones and formulating mitigation strategies [9].

As the world's largest developing nation and most populous country, China is undergoing accelerated industrialization and urbanization. Research indicates that China's total carbon emissions have risen to second globally, with growth rates remaining concerning[10]. Projections suggest China will become the world's largest carbon emitter after 2030. To address global climate change, China has set targets for ‘carbon peaking’ and ‘carbon neutrality.’ However, compared to developed nations, China's massive carbon emissions mean achieving these dual carbon goals presents tighter timelines, greater magnitude, more challenges, and heavier responsibilities. Faced with this reality and the dilemma of responsibility, conducting research on regional land use carbon emissions, deeply analyzing the intrinsic link between carbon emissions and land use change, and advancing China's 2030 carbon peak target and regional carbon reduction strategies holds significant practical importance.

As China's fourth-tier economic region, the Chengdu-Chongqing Urban Agglomeration has witnessed rapid economic growth since its establishment, with significant achievements in urbanization and industrialization. This has been accompanied by dramatic shifts in land use patterns, a marked increase in carbon emissions, and substantial pressure to reduce carbon emissions. How to achieve low-carbon coordinated development, establish a high-quality development demonstration zone in the west, and propel high-quality development across the western region and the nation has become an urgent issue for the Chengdu-Chongqing Urban Agglomeration. Consequently, this study selects the Chengdu-Chongqing urban agglomeration as its research area. It calculates carbon sources and sinks for various land use types during the 2010-2020 period, analyses the spatiotemporal variations in carbon emissions, and then conducts a carbon balance zoning study for each city, district, and county within the research area based on the carbon emission Gini coefficient, economic contribution coefficient, and ecological coefficient. This aims to provide reference for formulating future low-carbon regulatory policies for the Chengdu-Chongqing urban agglomeration and even the whole country from a ‘dual carbon’ perspective.

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2. Research Area Overview and Data Sources

2.1. Research Area Overview.

In 2011, the Chengdu-Chongqing Economic Zone Regional Plan-conceived over two decades-was formally launched, marking the commencement of the Chengdu-Chongqing urban agglomeration's development. Situated in Southwest China, the Chengdu-Chongqing Urban Agglomeration lies within the Sichuan Basin and the upper reaches of the Yangtze River. It borders Gansu and Shaanxi to the north, Hubei to the east, and Yunnan and Guizhou to the south. Centered on Chengdu and Chongqing, it encompasses 15 cities in Sichuan Province (including Chengdu, Mianyang, and Ziyang), 27 districts (counties) in Chongqing Municipality (including the central urban area, Wanzhou, and Zhongxian), and portions of Kaizhou and Yunyang. The total area spans 185,000 square kilometres. However, as statistical yearbooks do not provide data at the district level, and to facilitate research, certain cities in Sichuan Province and Chongqing Municipality not originally included in the Chengdu-Chongqing City Cluster plan are incorporated into this study's scope. Specifically, the research covers all cities and counties in Sichuan Province except Guangyuan City, Aba Tibetan and Qiang Autonomous Prefecture, Ganzi Tibetan Autonomous Prefecture, Liangshan Yi Autonomous Prefecture, and Panzhihua City, along with the entirety of Chongqing Municipality.

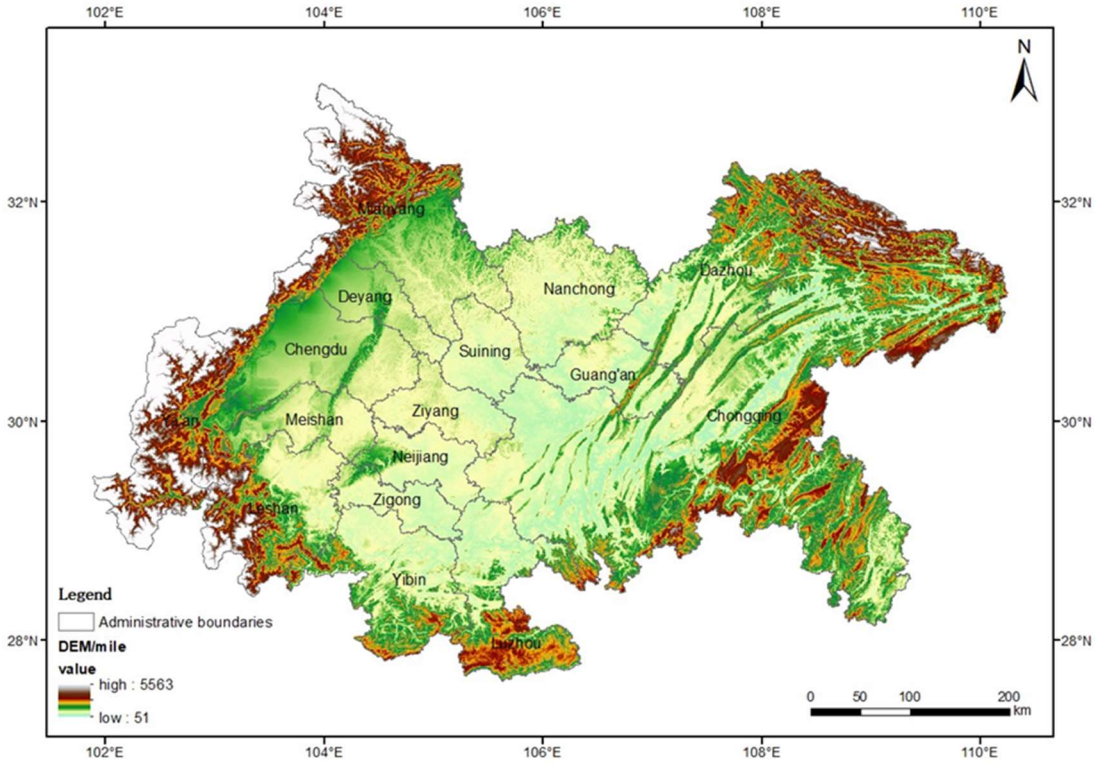


Fig. 1 Research Area Boundary Map

The topography of the Chengdu-Chongqing Metropolitan Area generally features lower elevations in the center and higher elevations around the periphery, presenting a complex terrain encompassing plains, mountains, and hills. The Sichuan portion encompasses the Chengdu Plain and the Central Sichuan Hills, characterized by low elevations predominantly ranging from 250 to 1,000 meters. Within Chongqing, while southern, eastern, and northern districts border mountain ranges with elevations exceeding 900 meters, the majority of the region lies within the Eastern Sichuan Parallel Ridges and Valleys, featuring predominantly low mountains and hills below 500 meters. The climate is predominantly subtropical monsoon

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humid, characterized by year-round warmth and moisture. Annual average temperatures range between 16–18°C, with abundant precipitation averaging 1,000 millimeters annually, coinciding with the warm season. Vegetation predominantly consists of subtropical evergreen broadleaf forests and mixed evergreen-deciduous woodlands. The region features complex water systems, excellent ecological foundations, fertile soils, abundant mineral resources, distinctive cultural heritage, and dense urban settlements. Economically, its investment, consumption, industrial output and foreign trade metrics rank among the nation's highest, establishing it as a pivotal platform for China's western development strategy. Advancing the Chengdu-Chongqing urban cluster will spearhead growth in China's western inland regions, bolster regional capacity for international engagement while expanding domestic demand, and thereby forge a new pattern of openness featuring east-west connectivity and integrated maritime-land development.

2.2. Data Sources.

To ensure the authenticity of the investigation, all data utilized in this research were sourced from publicly available data released by authoritative institutions.

The spatial data employed in this study comprised: China's 2021 administrative boundary vector data; National land use remote sensing data with a spatial resolution of 1km for the years 2010, 2013, 2015, 2018, and 2020, with a spatial resolution of 1 km. These were obtained from the National Geographic Information Resource Catalogue Service System website of the Ministry of Natural Resources (www.webmap.cn) and the Science and Data Centre Platform of the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences (https://www.resdc.cn).

The statistical data utilized in this study encompassed: the gross domestic product (GDP) of the Chengdu-Chongqing urban agglomeration, GDP figures for individual cities and counties, and fossil fuel consumption data (including raw coal, coke, natural gas, and liquefied petroleum gas) for the years 2010, 2013, 2015, 2018, and 2020. These were sourced from the Statistical Yearbooks of Chongqing Municipality and selected cities/counties in Sichuan Province. The conversion factors for standard coal and carbon emission coefficients for each energy source were derived from IPCC National Greenhouse Gas Inventory Guidelines [11] and the China Energy Statistical Yearbook (2022). To ensure the accuracy of indirectly calculated carbon emissions from energy data, the study additionally consulted the CEADs China Carbon Accounting Database for carbon emission data corresponding to the relevant years.

3. Research Methodology

3.1. Estimation of Land Use Carbon Emissions

Land use types implicated in carbon emissions primarily encompass arable land, woodland, grassland, developed land, water bodies, and unutilized land. Building upon existing research[1], this study categorizes land use carbon emissions into two types: direct carbon emissions and indirect carbon emissions. Among these, carbon emissions from construction land primarily result from human productive activities and are classified as indirect emissions. These will be calculated by determining carbon emissions from energy consumption. Carbon emissions from the other five non-construction land categories will be directly estimated using established emission factors derived from existing research, according to the following formula:

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

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In the formula, E denotes total land use carbon emissions; E_k denotes direct carbon emissions, encompassing both carbon sinks and certain carbon sources; E_t denotes indirect carbon emissions, in another words, its carbon sources from development land.

(1) Calculation of Direct Carbon Emissions

In direct carbon emission accounting, the carbon emissions for each land category are determined by multiplying the relevant coefficient by the corresponding land area. The specific calculation method is as follows:

$$E_k = \sum e_i = \sum A_i * \alpha_i \tag{2}$$

In the formula, E_k denotes direct carbon emissions; i represents land use types other than construction land, including arable land, forest, grassland, water, and unutilised land; e_i denotes the carbon emissions generated by a specific land use type; whether it represents a carbon source or sink is determined by the sign of e_i, negative values indicate a carbon sink, while positive values indicate a carbon source; A_i denotes the area of a specific land use type; α_i denotes the carbon emission coefficient for a specific land use type. A positive coefficient indicates carbon emissions (emission source), while a negative coefficient indicates carbon absorption (carbon sink).

The direct carbon emission coefficients were comprehensively determined based on relevant research. The final coefficients are detailed in Table 1.

Table 1. Carbon emission coefficients for primary land use types

Land use categories	Carbon emission factor / $(kg \cdot m^{-2} \cdot a^{-1})$	Reference source
Agricultural land	0.0497	[12,13]
forest	-0.0581	[14,15]
Grass land	-0.0021	[14,16]
Water	-0.0253	[17,18]
Unused land	-0.0005	[19]

(2) Indirect Carbon Emissions Calculation

Carbon emissions from construction land are estimated indirectly, characterized by CO_2 emissions generated from energy consumption in production and daily life. In accordance with the IPCC National Greenhouse Gas Inventory Guidelines, the selected energy sources comprise coal, coke, crude oil, petrol, kerosene, diesel, fuel oil, natural gas, and electricity. During calculation, the consumption of these various energy sources is converted into standard coal equivalents. The calculation formula is:

$$E_t = \sum e_{ti} = \sum e_{ni} * \theta_i * f_i \tag{3}$$

In the formula, E_t denotes total carbon emissions from construction land; i represents the type i of fossil fuel selected for study; E_i denotes carbon emissions generated by consumption of the type i of fossil fuel; e_i denotes consumption of the type i of fossil fuel; θ_i denotes the standard coal conversion factor for the type i of fossil fuel; f_i denotes the carbon emission factor for the type i fossil fuel. The standard coal conversion factors are sourced from the China Energy Statistical Yearbook (2022), while the carbon emission factors are derived from values

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in the IPCC National Greenhouse Gas Inventory Guidelines and supplemented by relevant literature. Specific details are presented in Table 2.

Table 2. Primary Energy Carbon Emission Factor

Energy Type	Standard Coal Conversion Factor/ $(kgce \cdot t^{-1}, kgce \cdot kw^{-1} \cdot h^{-1})$	Carbon Emission Factor/ $(tC \cdot t^{-1})$
Raw coal	714.3	0.7559
Coke	971.4	0.855
Crude oil	1428.6	0.5857
Petrol	1471.4	0.5538
Diesel	1457.1	0.5921
Fuel oil	1428.6	0.6185
Natural gas	1330.0	0.4438
Liquefied petroleum gas	1714.3	0.5042

3.2. Carbon Balance Zoning Analysis

Carbon balance zoning entails categorizes regions based on their carbon emission characteristics, economic conditions, and ecological status, utilizes corresponding indicators to facilitate the formulation of locally tailored carbon reduction and low-carbon development strategies. This approach represents one of several pathways towards carbon neutrality and embodies the practical application of research outcomes in low-carbon land and urban development. This study primarily reflects this approach through three key aspects: the carbon emissions Gini coefficient, the carbon emissions economic contribution coefficient, and the carbon emissions ecological contribution coefficient [20].

(1) Carbon Emissions Gini Coefficient

The *Gini* coefficient, proposed by Italian statistician and sociologist Corrado Gini in 1912, serves as an indicator for analyzes income distribution disparities across nations and regions. Originally confined to economic domains, it is now applied to resource allocation and environmental studies to measure spatial equilibrium or disparities among research factors, thereby assessing spatial equity levels [21]. This study employs the *Gini* coefficient to analyze the spatial equity of carbon emission compensation rates within the Chengdu-Chongqing urban agglomeration. The calculation formula is as follows:

$$Gini = \sum_i^n \sum_j^n |z_i - z_j| \div 2n^2 \bar{z} \tag{4}$$

In the formula, z_i、z_j denote the relevant indicator for region i and region j respectively, here selected as the carbon emission compensation rate; n epresents the total number of regions, here $n - 156$; $\bar{z}$ denotes the mean value of the relevant indicator across all regions in the study area, here referring to the average carbon emission compensation rate. The Gini coefficient ranges between 0 and 1. Values closer to 0 indicate smaller regional disparities and higher equity, while values closer to 1 signify greater disparities and lower equity.

(2) Economic Contribution Coefficient of Carbon Emissions

The Economic Contribution Coefficient (ECC) of carbon emissions reflects the economic output generated by carbon emissions within the study area from an economic benefit perspective [22]. This study employs the Economic Contribution Coefficient (ECC) to analyze variations in the economic productivity of carbon emissions within the Chengdu-Chongqing Urban Agglomeration [23]. The calculation formula is as follows:

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$$ECC_i = \frac{G_i}{G} / \frac{C_i}{C} \quad (5)$$

In the formula, i denotes a specific region, which in this study refers to a county, district or city within the Chengdu-Chongqing Metropolitan Area; G_i and G denote the GDP of region i and the Chengdu-Chongqing urban agglomeration respectively; C_i and C denote the carbon emissions of region i and the Chengdu-Chongqing urban agglomeration respectively. When the Economic Contribution Coefficient (ECC) of carbon emissions exceeds 1, it indicates that region i's economic contribution rate to the Chengdu-Chongqing urban agglomeration surpasses its carbon emission contribution rate [20], signifying higher economic benefits derived from carbon emissions for the urban agglomeration; conversely, it indicates lower benefits.

(3) Ecological Contribution Coefficient of Carbon Emissions

The ecological carrying capacity coefficient (ESC) of carbon emissions reflects the carbon sink capacity of the study area from an ecological perspective. This study employs the ecological carrying capacity coefficient (ESC) to analyze the Chengdu-Chongqing urban agglomeration, calculated as follows:

$$ESC_i = \frac{E_i}{E} / \frac{C_i}{C} \quad (6)$$

In the equation: i denotes a specific region; E_i and E represent the carbon absorption capacity of region i and the Chengdu-Chongqing urban agglomeration, respectively; C_i and C denote the carbon emission levels of region i and the Chengdu-Chongqing urban agglomeration, respectively, defined identically to Equation 5. When the Ecological Carrying Capacity (ESC) of carbon emissions exceeds 1, it indicates that region i contributes more to the carbon sink than to the carbon source for the Chengdu-Chongqing urban agglomeration, signifying higher carbon sink capacity in that region. Conversely, a value below 1 indicates lower carbon sink capacity.

4. Results and Analysis

4.1. Characteristics of Land Use Change

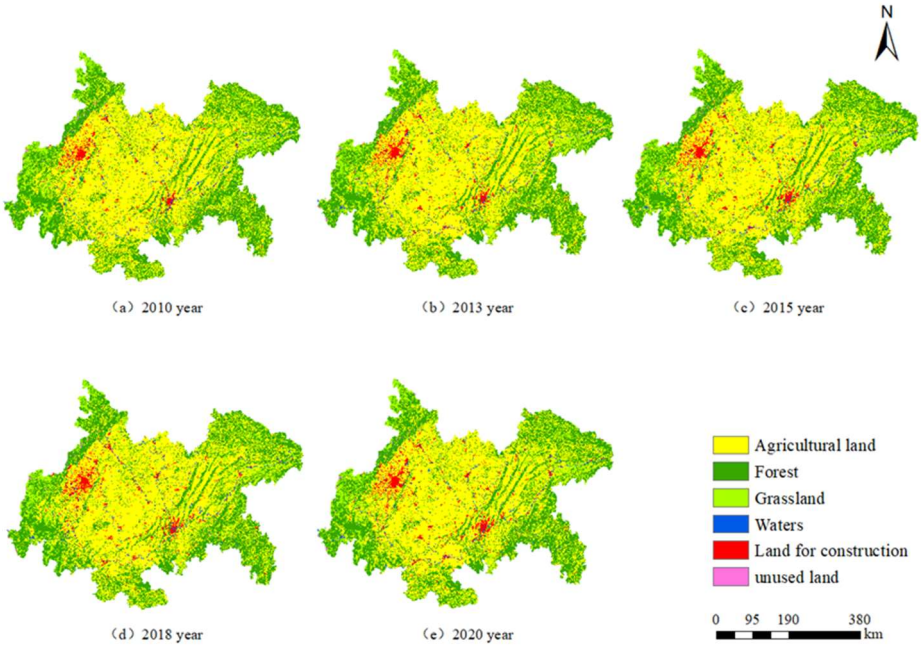


Fig. 2 Use Status Map of the Chengdu-Chongqing Metropolitan Area, 2010–2020

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The Chengdu-Chongqing urban agglomeration is dominated by arable land, forest land, and grassland, which collectively account for over 95% of its total area. Water bodies, construction land, and unutilized land constitute a relatively small proportion. From 2010 to 2020, arable land maintained the largest area among all land use types in the agglomeration, followed by forest land and grassland. However, the trends in land use types varied over time.

Table 3. Land Use Area and Structural Changes in the Chengdu-Chongqing Metropolitan Area, 2010–2020

Land Use Type		Arable land	Forest	Grassland	Water	Construction land	Unutilized land	Total
2010	Area/ km^2	131099.12	80779.96	19365.69	2992.21	4940.38	285.57	239462.93
	Proportions/ %	54.75	33.73	8.09	1.25	2.06	0.12	100%
2013	Area/ km^2	130316.96	80719.83	19343.33	3018.71	5776.35	287.58	239462.76
	Proportions/ %	54.42	33.71	8.08	1.26	2.41	0.12	100%
2015	Area/ km^2	129686.15	80774.42	19318.85	3168.63	6263.94	281.57	239493.56
	Proportions/ %	54.15	33.73	8.07	1.32	2.62	0.12	100%
2018	Area/ km^2	129282.51	80658.07	19343.45	3097.99	6798.78	282.21	239463.01
	Proportions/ %	53.99	33.68	8.08	1.29	2.84	0.12	100%
2020	Area/ km^2	128980.72	80545.45	19316.89	3192.52	7138.39	289.59	239463.56
	Proportions/ %	53.86	33.64	8.07	1.33	2.98	0.12	100%

Table 4. Changes in Total Land Use Area of the Chengdu-Chongqing Urban Agglomeration, 2010–2020 (Unit: km^2)

Land Use Type	Arable land	Forest	Grassland	Water	Construction land	Unutilized land
2010-2013	-782.16	-60.13	-22.36	26.5	835.97	2.01
2013-2015	-630.81	54.59	-24.48	149.92	487.59	-6.01
2015-2018	-403.64	-116.35	24.6	-70.64	534.84	0.64
2018-2020	-301.79	-112.62	-26.56	94.53	339.61	7.38

Specifically, as shown by Tables 3 and 4, the areas of water bodies, construction land, and unused land showed an increasing trend. Among these, the area of construction land continued to grow throughout the study period, rising from 4,940.38 km^2 in 2010 to 6,263.94 km^2 in 2015, and further increasing to 7,138.39 km^2 by 2020. This represents a total increase of 2,198.01 km^2, marking the largest expansion. The area of water bodies first increased, then decreased, and subsequently increased again. The increase exceeded the decrease, resulting in an overall increase in water area. km^2, representing the largest net increase of 2,198.01 km^2. Water bodies initially expanded, then contracted, and subsequently expanded again, with the net increase exceeding the decrease, resulting in an overall expansion of 200.31 km^2 during the study period. Unutilized land area also followed a pattern of initial increase, subsequent decrease, and final increase, showing an overall expansion. It rose from 285.57 km^2 in 2010 to 289.59 km^2 in 2020, representing a net increase of 4.02 km^2 during the study period.

The areas of cultivated land, forest land, and grassland all decreased overall. Among these, cultivated land area has been continuously declining, decreasing from 131,099.12 km^2 in 2010 to 129,686.15 km^2 in 2015, and further decreasing to 128,980.72 km^2 in 2020. km^2, representing a 21,184.0 km^2 decrease over the decade-a significant reduction. Forest land first decreased, then increased, and subsequently decreased again, with the decrease far exceeding the increase. Overall, forest land decreased from 80,779.96 km^2 in 2010 km^2 in 2010 to 80,545.45 km^2 in 2020, a total decrease of 234.51 km^2 over the decade. Grassland area also

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followed a pattern of decrease, increase, and then decrease, showing an overall reduction of 48.80 km^2 during the study period.

In summary, between 2010 and 2020, the area and proportion of each land use type underwent varying degrees of change, though the trends differed. Overall, there was a significant absolute reduction in cultivated land and forest land, a gradual degradation of grassland, while construction land continued to expand. Unutilized land and water areas saw slight increases. Reviewing relevant data suggests this phenomenon stems from the rapid development of the Chengdu-Chongqing urban cluster over the past decade. Future development should prioritize enforcing the policy requirement of maintaining 1.8 billion mu of arable land, curbing excessive grazing, illegal logging, and unregulated expansion of construction land. Efforts should focus on carbon reduction, emission control, and optimizing land resource utilization methods.

4.2. Characteristics of Carbon Emission Changes

Table 5. Carbon Emissions of the Chengdu-Chongqing Urban Agglomeration, 2010–2020 (Unit: tons)

Carbon Accounting	2010	2013	2015	2018	2020
Carbon Sources	381680409	396919034	410808429	416928379	426476461
Carbon Sinks	-4809830	-4806960	-4813871	-4805375	-4801172
Net Carbon Emissions	376870579	392112074	405994558	412123004	421675289

As shown in Table 5, the net carbon emissions of the Chengdu-Chongqing Urban Agglomeration are influenced by both carbon sources and carbon sinks. Carbon sources increased from 381.68 million tons in 2010 to 426.48 million tons in 2020, showing an overall upward trend with an average annual increase of 4.48 million tons. The fastest growth period occurred between 2010 and 2013, with an increase of 15.24 million tons and an average annual growth rate of 1.35%. Subsequently, the growth rate gradually slowed. Carbon sinks decreased from 4.81 million tons in 2010 to 4.80 million tons in 2020, showing an overall downward trend with an average annual decrease of 0.01 million tons. Net carbon emissions increased from 376.87 million tons in 2010 to 421.68 million tons in 2020, representing an 11.89% increase. The average annual growth was 4.48 million tons, showing an overall upward trend but with a gradually slowing pace. This mirrors the trend in carbon sources and indicates that the carbon sinks within the Chengdu-Chongqing urban agglomeration are insufficient to offset carbon sources.

Table 6. Carbon Emissions Characteristics of Major Land Use Types in the Chengdu-Chongqing Urban Agglomeration, 2010–2020 (Unit: tons)

Land Use Type	2010	2013	2015	2018	2020
Arable land	6279648	6242182	6211967	6192632	6178176
Forest	-4693316	-4689822	-4692994	-4686234	-4679691
Grassland	-40668	-40621	-40570	-40621	-40565
Water	-75703	-76373	-80166	-78379	-80771
Construction land	375400761	390676852	404596462	410735747	420298285
Unutilised land	-143	-144	-141	-141	-145

Table 6 shows that among land use types contributing to carbon emissions, construction land accounts for nearly 98% of carbon sources, with this proportion continuing to rise. Although arable land covers a large area, it contributes only about 2% of carbon sources. Among carbon-absorbing land uses, forested land exhibits the strongest absorption capacity, accounting for 97% of carbon sinks, though its proportion shows a slight downward trend. Water bodies rank as the second-largest carbon sink after forested land, but their absorption capacity is

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significantly lower, contributing only about 1% of total carbon sinks, with a rising trend. Grasslands and unutilized land demonstrate relatively weaker carbon absorption capabilities.

From 2010 to 2020, carbon emissions from construction land showed the most pronounced change, increasing from 375.4 million tons in 2010 to 420.3 million tons in 2020. This represents an 11.96% increase compared to 2010, with an average annual increase of 4.49 million tons, though the growth rate gradually slowed. Carbon emissions from other land use categories showed limited variation. Emissions from cultivated land decreased annually, falling from 6.28 million tons in 2010 to 6.18 million tons in 2020, with an average annual reduction of 10,000 tons. Carbon absorption from forest land showed a declining trend from 2010 to 2013, increased from 2013 to 2015 (approaching 2010 levels), and then gradually decreased from 2015 to 2020, fluctuating but overall reducing by approximately 10,000 tons. Carbon absorption from grassland gradually decreased from 2010 to 2015, briefly increased from 2015 to 2018 before declining again, resulting in an overall decrease of 0.01 million tons, essentially maintaining previous levels. Carbon absorption by water bodies gradually increased from 2010 to 2015, briefly decreased from 2015 to 2018, and then continued to rise, fluctuating but increasing by 0.5 million tons overall. Carbon absorption by unutilized land remained largely stable at around 1.4 million tons.

The substantial increase in carbon emissions from construction land and the decrease from cultivated land are primarily linked to the urban development of the Chengdu-Chongqing Metropolitan Area. The 2011 Regional Plan for the Chengdu-Chongqing Economic Zone marked the commencement of its construction. Since then, the Chengdu-Chongqing Urban Agglomeration has experienced rapid development. Construction land has continuously encroached upon farmland and other land types to achieve expansion, while human energy consumption has also increased day by day. Following the global advocacy for a low-carbon economy and China's proposal of “carbon peak” and “carbon neutrality,” local governments and relevant enterprises across the Chengdu-Chongqing region have actively responded. They have vigorously pursued energy conservation, emission reduction, and high-quality low-carbon development through innovative technologies. As a result, the growth rate of carbon emissions from construction land has slowed. Changes in carbon absorption capacity across forested areas, grasslands, water bodies, and unutilized land primarily correlate with development approaches and ecological policies. Previously, development prioritized speed, often sacrificing ecological environments for rapid growth. Vegetation degradation led to diminished carbon absorption capabilities. Subsequently, recognizing environmental protection's importance, the nation promoted high-quality development and implemented a series of ecological policies. As ecological environments gradually recovered, carbon absorption capacity steadily increased.

4.3. Carbon Balance Zoning and Optimization Recommendations

Based on References [20,23,24], the 156 urban districts and counties within the Chengdu-Chongqing Metropolitan Area are categorized into carbon sink functional zones, low-carbon maintenance zones, economic development zones, carbon intensity control zones, high-carbon optimization zones, and other areas. This classification is determined by whether the carbon compensation rate, economic contribution coefficient (ECC) of carbon emissions, and ecological carrying capacity coefficient (ESC) each exceed 1.

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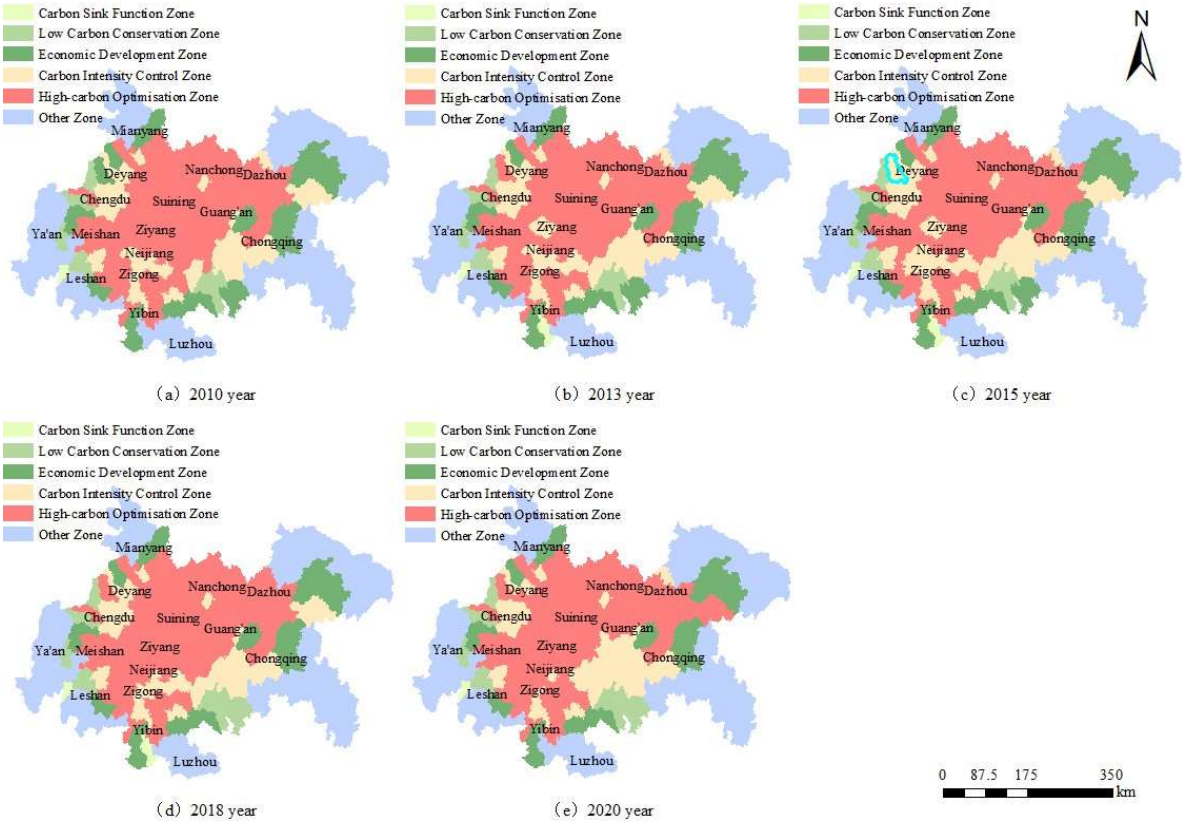


Fig. 3 Carbon Balance Zoning for the Chengdu-Chongqing Metropolitan Area, 2010–2020

(1) Carbon Sink Functional Zones

Areas qualify as carbon sink functional zones when all three criteria are met: Economic Contribution Coefficient (ECC) > 1, Ecological Carrying Capacity Coefficient (ESC) > 1, and Carbon Compensation Rate > 1. Municipalities and counties designated as carbon sink functional zones possess excellent ecological foundations capable of absorbing and storing substantial amounts of carbon dioxide. Concurrently, their economic development is relatively underdeveloped, with low production activity intensity and manageable carbon emissions that can be offset by carbon absorption capacity, often resulting in net surplus. These zones exhibit significant carbon sink effects. Protecting and developing carbon sink functional zones facilitates ecological conservation and restoration, enhances ecological service value, and provides substantial carbon sinks for other regions, thereby advancing regional carbon neutrality. Most areas of Leshan City and Yibin City on the periphery of the Chengdu-Chongqing Urban Agglomeration are designated as carbon sink functional zones. Specifically, Jinkouhe District in Leshan City maintained its carbon sink functional zone status from 2010 to 2020. Gong County in Yibin City was reclassified from other zones to a carbon sink functional zone from 2013 to 2018, but was reverted to other zones in 2020.

Moving forward, these areas must prioritize ecological preservation while optimizing development models for low-carbon growth. They should strive to increase carbon sinks and reduce emissions, providing carbon offsets for high-emission regions within the cluster. Simultaneously, they should leverage ecological advantages to drive economic development, actively pursuing prosperity while safeguarding ecosystems. Take Jinkouhe District in Leshan City as an example. It boasts tourism resources such as the Jinkou Grand Canyon-one of China's Ten Most Beautiful Canyons-China's only Railway Corps Museum, and the Dawashan Wetland Tourism Area. With its excellent natural ecology, the district holds vast potential for low-carbon development. Future efforts should prioritize ecological conservation and green low-carbon

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development, promote the economic utilization of ecological resources, cultivate the "Ecology+" brand, drive development through eco-tourism to boost GDP growth, and simultaneously advance industrial restructuring. Actively developing green low-carbon industries will achieve a scientific and high-quality development model.

(2) Low-Carbon Preservation Zones

Areas qualify as low-carbon preservation zones when the Economic Contribution Coefficient (ECC) of carbon emissions > 1, the Ecological Carrying Capacity Coefficient (ESC) > 1, and the carbon compensation rate < 1. Compared to carbon sink functional zones, areas designated as low-carbon retention zones exhibit relatively sound ecosystems with abundant carbon sink resources. They also feature higher economic development levels, greater human activity intensity, and higher carbon emissions that cannot achieve regional carbon neutrality. However, ecological pressure remains manageable, and carbon emission intensity is maintained at a low level. Peripheral areas of the Chengdu-Chongqing urban cluster-western Chengdu, eastern Ya'an, northern Leshan, and southern Chongqing-are classified as low-carbon retention zones. During the study period, the number of low-carbon retention zones increased. Specifically, Dayi County and Dujiangyan City in Chengdu, Emeishan City and Shawan District in Leshan, Yucheng District in Ya'an, and Jiangjin District in Chongqing have consistently been designated as low-carbon preservation zones. Since 2018, Qijiang District in Chongqing has transitioned from an economic development zone to a low-carbon preservation zone due to increased economic benefits from carbon emissions to the urban agglomeration, improved energy efficiency, and reduced carbon emissions per unit of GDP.

Moving forward, these regions must preserve existing ecosystems while advancing low-carbon development models based on current frameworks. They should transform ecological advantages into economic potential, ensuring coordinated economic and ecological progress to achieve regional carbon neutrality as soon as possible. For instance, Daxi County and Dujiangyan City in Chengdu, Emeishan City and Shawan District in Leshan City, and Yucheng District in Ya'an City. These predominantly agricultural areas boast rich national cultural heritage and tourism resources, serving as pioneers in ecological civilization and demonstration zones for cultural tourism development. For these regions, future efforts should focus on protecting existing vegetation and developing eco-agriculture to reduce carbon emissions from agricultural activities while enhancing the carbon sink function of forested areas. Concurrently, they should actively promote eco-cultural tourism development to convert ecological endowments into development potential. Jiangjin District and Qijiang District in Chongqing City feature heavy industry as the primary industrial structure. Future efforts should focus on promoting low-carbon industrial transformation and establishing green industrial parks to reduce carbon emissions from industrial production. Furthermore, as a strategic hub for Chongqing-Guizhou cooperation, Qijiang District should actively develop green logistics to lower carbon emissions from material transshipment.

(3) Economic Development Zone

When the Economic Contribution Coefficient (ECC) of carbon emissions < 1, the Ecological Carrying Capacity Coefficient (ESC) > 1, and the carbon compensation rate < 1, the area is classified as an Economic Development Zone. Compared to low-carbon preservation zones, economic development zones exhibit ecological conditions similar to low-carbon preservation zones with considerable carbon sink functions. However, their economic activity intensity is generally moderate, featuring industrial clustering but low energy efficiency, resulting in higher carbon emissions per unit of GDP growth. Energy efficiency in industrial activities requires low-carbon optimization, and while the ecological carrying capacity coefficient is relatively high, it cannot achieve regional carbon balance. Municipal districts and counties classified as economic development zones are primarily distributed along the periphery of the Chengdu-Chongqing urban agglomeration. During the study period, the number of low-carbon maintenance zones

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decreased. Among them, Qionglai City in Chengdu, Mianzhu City in Deyang, Linshui County in Guang'an, Muchuan County in Leshan, Hejiang County and Naxi District in Luzhou, Jiangyou City in Mianyang, Mingshan District in Ya'an, Gaoxian County and Junxian County in Yibin, Junlian County in Ya'an City, Fengdu County, Kaizhou District, Yunyang County, and Zhong County in Chongqing City have consistently been designated as low-carbon preservation zones. After 2013, Pengzhou City in Chengdu was reclassified as a high-carbon optimization zone. Following 2018, Qijiang District in Chongqing transitioned from an economic development zone to a low-carbon preservation zone, adopting a more low-carbon development approach.

Municipal districts and counties classified as economic development zones should focus on preserving existing ecological environments, fortifying the ecological barrier of the Chengdu-Chongqing urban cluster, and transforming ecological advantages into drivers of economic growth. They should develop “ecology-plus” industries, leveraging green mountains and clear waters to propel regional development. Simultaneously, they should enhance energy efficiency, promote low-carbon industrial transformation, increase the economic contribution per unit of carbon emissions, and advance toward carbon neutrality. Agricultural powerhouses like Qionglai City and industrial powerhouses like Kaizhou District, characterized by concentrated economic activity, industrial clusters, excellent ecological foundations, and abundant tourism resources, should actively integrate the primary, secondary, and tertiary industries. This will drive industrial upgrading, achieve low-carbon transformation, and boost the economic contribution per unit of carbon emissions.

(4) Carbon Intensity Control Zones

Areas classified as carbon intensity control zones exhibit an economic contribution coefficient (ECC) > 1, an ecological carrying capacity coefficient (ESC) < 1, and a carbon compensation rate < 1. Compared to economic development zones, these areas generally have moderate ecological conditions with significant potential for developing carbon sink functions. They feature relatively high economic levels and energy efficiency, yet also exhibit high carbon emissions and substantial economic contribution from carbon emissions, making regional carbon balance unattainable. Municipalities and counties classified as carbon intensity control zones are primarily distributed in the western and southern regions of the Chengdu-Chongqing urban cluster. Among these, the main urban areas of Chengdu and Chongqing have consistently been categorized as such. During the study period, the number of carbon intensity control zones initially increased before decreasing, showing an overall downward trend.

Municipalities and counties within carbon intensity control zones should prioritize ecological conservation within their regions, optimize ecological spatial patterns, construct ecological corridors, and enhance regional carbon sink functions. develop green agriculture, implement integrated conservation and restoration of mountains, waters, forests, farmlands, lakes, grasslands, and deserts to enhance carbon sequestration capacity across land types; encourage enterprises to research, develop, and apply energy-saving and emission-reduction technologies to advance industrial decarbonization; and promote low-carbon lifestyles by replacing fossil fuels with clean energy. Districts like Wuhou and Jinjiang in Chengdu's urban core, Nanan District in Chongqing's urban core, serve as pillars of economic growth in this zone. Characterized by industrial clustering, high economic activity intensity, and efficient land use, these areas face ecological challenges requiring improvement. Future efforts should optimize regional ecology through expanding urban green spaces and creating pocket parks. Implementing low-carbon policies targeting production will reduce greenhouse gas emissions per unit of GDP, emphasizing decoupling economic growth from carbon emissions. Technological innovation and structural adjustments will achieve a win-win outcome for both economic development and environmental sustainability.

(5) High-Carbon Optimization Zones

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Areas where the Economic Contribution Coefficient (ECC) of carbon emissions < 1, the Ecological Carrying Capacity Coefficient (ESC) < 1, and the carbon compensation rate < 1 are classified as high-carbon optimization zones. Compared to carbon intensity control zones, these areas face challenges in industrial transformation and upgrading, exhibit poorer ecological conditions, and require urgent development of carbon sink functions. They exhibit average economic levels, low energy efficiency, carbon emissions far exceeding absorption capacity, low economic contribution from carbon emissions, and significant pressure on regional carbon balance. Policy guidance and technological innovation are essential to reduce carbon emission intensity. Municipalities and counties classified as high-carbon optimization zones are primarily concentrated in the centrally located, industrially developed Chengdu-Chongqing urban cluster. During the study period, the number of high-carbon optimization zones initially decreased before increasing, showing an overall upward trend.

For urban districts and counties in high-carbon optimization zones, future development must prioritize: 1. Transitioning from outdated development models to high-quality growth by halting low-level, high-energy-consumption, and high-pollution projects in favor of high-efficiency, high-quality, sustainable initiatives; 2. Restructuring industries by phasing out excess capacity in cement, construction, steel, and other sectors to avoid carbon emissions from unnecessary production; Third, they should transform their energy mix by reducing consumption of fossil fuels like coal, developing and deploying clean energy sources such as wind and solar power, and increasing the proportion of clean energy in total industrial energy consumption. Finally, they should attract relevant scientific and research talent to ensure development plans are scientifically grounded and effectively implemented. Concurrently, ecological conservation efforts-such as rehabilitating inefficient forests-should be prioritized to enhance carbon sinks while reducing emissions. Areas like Chenghua District and Pidu District in Chengdu, and Yuzhong District in Chongqing, represent early-development regions with advanced heavy industries and relatively high carbon emission intensity. Moving forward, these areas should implement measures to optimize industrial structures, improve energy efficiency, reduce carbon emissions, pursue green GDP, and gradually enhance local ecosystems.

5. Conclusion and Discussion

The Chengdu-Chongqing urban agglomeration is predominantly characterized by cultivated land, followed by forest land, grassland, and construction land, which collectively account for a much smaller proportion than cultivated land. Water bodies and unutilized land constitute a negligible portion. Spatially, arable land is widely distributed, primarily concentrated in the Sichuan Basin and the hilly regions of central Sichuan. Forest and grassland are mainly found along the western urban peripheries bordering western Sichuan and in the parallel ridge-and-valley areas of eastern Sichuan. Construction land is predominantly located near the Chengdu-Deyang-Meishan-Ziyang metropolitan area and the main urban districts of Chongqing, with additional distributions in various urban districts and counties. Other land types are less prevalent. Chronologically, the area and proportion of each land use type have undergone varying degrees of change. The absolute quantities of arable land and forest land have significantly decreased, grassland has gradually degraded, construction land has continuously expanded, while unutilized land and water bodies have slightly increased.

Carbon sources in the Chengdu-Chongqing urban cluster increased from 381.68 million tons in 2010 to 426.48 million tons in 2020, showing an overall upward trend but with a gradually slowing growth rate. Carbon sinks decreased from 4.81 million tons in 2010 to 4.80 million tons in 2020, exhibiting an overall downward trend. Net carbon emissions increased from 376.87 million tons in 2010 to 421.68 million tons in 2020, showing an overall upward trend but with a gradually slowing growth rate, mirroring the trend in carbon sources. Among land use types

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contributing to carbon emissions, construction land accounted for nearly 98% of carbon sources, with this proportion continuing to rise; although arable land covers a large area, it contributed only about 2% of carbon sources. Among land use types absorbing carbon emissions, forested land possesses the strongest absorption capacity, accounting for 97% of carbon sinks, though this proportion shows a slight downward trend. Water bodies represent the second-largest carbon sink after forested land, but their absorption capacity is significantly lower, contributing only about 1% of total carbon sinks, with a rising trend. Grasslands and unutilized land exhibit relatively weaker carbon absorption capabilities. Therefore, emission reduction efforts should focus on maintaining or expanding existing forest areas while primarily reducing carbon emissions from construction land.

During the study period, based on whether the carbon compensation rate, economic contribution coefficient (ECC) of carbon emissions, and ecological carrying capacity coefficient (ESC) each exceed 1, the Chengdu-Chongqing Urban Agglomeration was categorized into carbon sink functional zones, low-carbon maintenance zones, economic development zones, carbon intensity control zones, high-carbon optimization zones, and other areas. Tailored emission reduction and carbon sink enhancement strategies were proposed based on each region's resource endowment, providing reference recommendations for future low-carbon land use configurations and high-quality urban development in the Chengdu-Chongqing agglomeration.

Data acquisition errors exist in this study. When calculating carbon sources from land use, particularly construction land, data limitations constrained the analysis to carbon emissions from fossil fuel consumption. This approach excluded emissions from rural biomass combustion, renewable energy sources, and carbon sequestration potential across different vegetation types, inevitably affecting the results. Furthermore, discrepancies in statistical methodologies across different editions of the Statistical Yearbook led to inconsistent data for the same year, introducing additional variability in the findings.

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