THE SPATIAL AND TEMPORAL HETEROGENEITY OF CARBON EMISSIONS FROM LAND USE AND THE ZONING OF CARBON BALANCES IN CHINA

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Abstract. The investigation of the spatio-temporal differentiation characteristics of land-use carbon emissions and carbon balance zoning is of significant value. An examination of China's land-use carbon emission hotspot distribution, alongside the spatial patterns of economic contribution coefficients and ecological carrying capacity coefficients, as well as carbon balance zoning, has yielded the following findings: (1) The initial growth in China's land-use carbon emissions is followed by a period of deceleration, which is characterized by pronounced positive spatial clustering. The distribution of emission hotspots is concentrated in Northeast China and the middle-lower reaches of the Yellow River, while cold spots are located along the southeast coast. The spatial distribution of economic contribution coefficients manifests an 'eastern-led, central transitional, western ecologically protected' pattern, while ecological carrying capacity coefficients demonstrate a 'western-dominated, coastal-emerging, multicentered networked structure'. The third category is that of carbon balance zones, which comprise low-carbon conservation areas, carbon sink development zones, comprehensive optimization regions, and economic development districts. Consequently, distinct regions should implement dual-carbon policies that are tailored to local conditions by integrating locational advantages with spatial ecological resource endowments.
Keywords: *carbon emissions, heatmaps, Tyrell's index, economic contribution coefficients, carbon ecological carrying capacity coefficients, spatial analysis, carbon balance zoning*

Introduction

Land use change is a significant contributor to global carbon emissions, exerting considerable influence on regional and global carbon cycles and climate change processes. It is estimated that, driven by industrialization and urbanization, global CO_2 emissions caused by land use account for approximately one-third of the total carbon emissions from human activities, with land use contributing approximately 24% to the greenhouse effect (Goldewijk and Ramankutty, 2004). In the context of rapid urbanization, industrialization, and agricultural intensification, China's land use patterns have undergone significant transformations. The conversion of farmland, the degradation of forest and grassland areas, and the expansion of construction land have been demonstrated to directly release large amounts of surface-stored carbon. Furthermore, these changes will have a substantial impact on the carbon source/sink function of ecosystems. It is imperative to scientifically elucidate the characteristics, driving mechanisms, and spatio-temporal evolution patterns of carbon emissions generated by China's land use activities. This is not only an urgent necessity but also a

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fundamental scientific foundation for accurately assessing national carbon budgets, formulating differentiated emission reduction strategies, and advancing the optimization of national territorial space and the achievement of the “dual carbon” goals.

From the perspective of research regions, scholars have successively conducted carbon emissions research at the regional (Li et al., 2019; Hou et al., 2022; Kuang et al., 2022; Yang et al., 2023; Han et al., 2024), provincial/municipal (Wu et al., 2020; Li et al., 2023a, b), and county (Zhang et al., 2022) levels. In relation to the field of research content, extant studies have concentrated on the quantification of carbon emissions (Zhang et al., 2023), the spatio-temporal characteristics and the influencing factors of carbon emissions (Zhao et al., 2023; Wei et al., 2023; Chen, 2024; Han et al., 2025), the forecasting of carbon emissions (Li et al., 2019; Wu et al., 2023), and the relationship between carbon emissions and economic development (Yang et al., 2023; Li et al., 2023) and ecological construction (Zhao et al., 2023), carbon balance zoning (Yang et al., 2022; Xu et al., 2023; Li et al., 2024). With regard to research methods, the carbon emissions coefficient method (Hou et al., 2022; Wei et al., 2023) and the Invest model analysis (Li et al., 2019) are widely applied. In summary, extant research findings are predominantly concentrated at the meso- or micro-scale, with a paucity of studies focusing on national-level carbon emissions. Moreover, current research frequently employs a solitary index to reflect spatiotemporal patterns of carbon emissions, and there is a paucity of research on carbon balance zoning. Therefore, the present study adopts a national macro-scale perspective, taking China’s 30 provincial-level administrative units as the study area. In addition, the study employs Python heatmaps, the Theil index, the carbon emission economic contribution coefficient, and the carbon ecological carrying capacity coefficient to reflect the evolution characteristics of land use carbon emissions. The spatial distribution patterns of land use carbon emissions are analyzed using ArcGIS’s spatial analysis functions, and carbon balance zones are comprehensively defined based on these results. The objective of this study is to furnish pertinent references and directives for the implementation of China’s “dual carbon” policy, with a focus on its adaptation to regional circumstances.

Materials and methods

Sample and data source

The classification of land use types is derived from Landsat TM imagery data obtained from the Chinese Academy of Sciences Resource and Environment Science Data Centre. The data pertaining to the socio-economic and energy sectors has been sourced from the *China Statistical Yearbook*, *China Urban Statistical Yearbook*, and *China Energy Statistical Yearbook* for 2014–2023. Due to the absence of pertinent data concerning Hong Kong, Macao, Taiwan, and Tibet, the study’s scope is constrained to 30 provincial-level administrative units within China. In order to facilitate subsequent analysis of regional heterogeneity in land use, carbon emissions and their ecological impacts, the provinces encompassed within China’s Eastern, Central, Western, and Northeastern regions are defined according to the statistical classification standards of the National Bureau of Statistics. The Eastern Region comprises the following provinces: Beijing, Tianjin, Hebei, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Hainan.

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Research methods

Estimation of carbon emissions

Direct carbon emissions

Carbon emissions from cropland, forest land, grassland, watershed and unutilized land are direct carbon emissions; carbon emissions from construction land are indirect carbon emissions (Li et al., 2023). The study utilized carbon emission coefficients to calculate direct carbon emissions for each land use type (*Table 1*), employing the following formula:

$$C = S_{\mathrm{I}} \times E_{\mathrm{I}} \quad \text{(Eq.1)}$$

where: C is carbon emissions, t; S_{I} is the area of each land type, hm²; E_{I} is the carbon emission coefficient of each land type (hm²/a).

Table 1. *Carbon emission coefficient of different land use types*

Land use types	carbon emission factor
Arable land	0.461
Forest land	-0.581
Grassland	-0.021
Water areas	-0.253

Indirect carbon emissions

Indirect carbon emissions from construction land, refer to the IPCC energy carbon emission coefficient method (IPCC, 2006; Li et al., 2023), the formula is as follows:

$$C_e = \sum_{i=1}^{N} B_i \times D_i \times E_i \quad \text{(Eq.2)}$$

where: C_e is the carbon emission from construction land, t; B_i is the consumption of a fossil energy source, t; D_i is the conversion factor of standard coal (kg/kg); E_i is the carbon emission coefficient of fossil energy source (t/t, in C). It is possible to obtain the standard coal conversion factor for energy and the carbon emission factor by means of reference to the *China Energy Statistical Yearbook* and relevant research (AQSIQ & SAC, 2020). For further details, please refer to *Table 2*.

Tyrell's index

Tyrell's index can characterize the contribution of intra-group disparity and inter-group disparity to the overall disparity, ranging from 0 to 1, the smaller the value, the smaller the regional differences, the formula is (Li et al., 2023):

$$T = T_{BR} + T_{WR} \quad \text{(Eq.3)}$$

$$T_{BR} = \sum_{k=1}^{n} \left(\frac{C_k^t}{C_{total}^t} \right) \ln \left(\frac{C_k^t / C_{total}^t}{R_k^t / R_{total}^t} \right) \quad \text{(Eq.4)}$$

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$$T_{WR} = \sum_{k=1}^{n}\left(\frac{C_k^t}{C_{total}^t}\right)\sum_{i=1}^{v}\left(\frac{C_{ki}^t}{C_k^t}\right)\ln\left(\frac{C_{ki}^t / C_k^t}{R_{ki}^t / R_k^t}\right) \quad \text{(Eq.5)}$$

where: T, T_{BR}, T_{WR} are the overall, inter-regional and intra-regional differences in carbon emissions from construction land; n is the number of regions; v is the number of provinces; C_k^t is the carbon emissions from construction land in region k in year t; C_{total}^t is the carbon emissions from construction land in the Yangtze River Economic Zone in year t; R_k^t is the area of construction land in region k in year t; R_{total}^t is the area of construction land in the Yangtze River Economic Zone in year t; C_{ki}^t is the carbon emissions from construction land in province i in region k in year t; R_{ki}^t for the area of construction land in province i in region k in year t.

Table 2. *Standard coal conversion factors and carbon emission factors for different energy types*

Energy type	Standard coal conversion factor	Carbon emission factor
Raw coal	0.7143	0.7559
Coke	0.9714	0.8550
Washed Coal	0.9000	0.7559
Other washed coal	0.2857	0.7559
Gasoline	1.4714	0.5538
Kerosene	1.4714	0.5714
Diesel	1.4571	0.5921
Fuel oil	1.4286	0.6185

Thermal analysis

A heat map is a visualization tool based on geographical location that uses Python to intuitively reflect the spatial distribution characteristics of carbon emissions from land use in a region through color gradients. The fundamental principle underlying this approach entails the mapping of carbon emissions originating from specific geographical coordinates or grid cells onto a continuous color scale. This methodology is designed to elucidate the spatial aggregation of carbon emissions, thereby facilitating the effective identification of key carbon emission sources and their spatial distribution patterns.

Spatial auto-correlation analysis

Exploratory spatial data analysis is a collection of techniques used to analyze spatial data, the core of which lies in spatial auto-correlation to measure and test the spatial correlation pattern (convergence or heterogeneity) of the research object, mainly including global spatial auto-correlation and local spatial auto-correlation.

Global spatial auto-correlation

Global spatial auto-correlation is mainly used to analyze the degree of spatial aggregation of the research object in the whole region, and the most commonly used is Moran's I index, whose calculation formula is:

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$$\text{Moran's } I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n}W_{ij}(X_i-\bar{X})\quad(X_j-\bar{X})}{\sum_{i=1}^{n}(X_j-\bar{X})\sum_{i=1}^{n}\sum_{j=1}^{n}W_{ij}} \qquad \text{(Eq.6)}$$

where: n is the number of provincial regional units in the study area; X_i and X_j are the carbon emissions from construction land in regions i and j, respectively; is the mean value; and W_{ij} is the spatial weight matrix. The value range of Moran's I index is [-1,1], when Moran's $I < 0$, it indicates that there exists a When Moran's $I < 0$, it indicates the existence of negative spatial correlation, i.e. spatial heterogeneity; when Moran's $I > 0$, it indicates the existence of positive spatial correlation, i.e. spatial convergence; when Moran's $I = 0$, it indicates that the spatial distribution of carbon emissions from the construction land is independent of each other.

*Getis-Ord Gi**

Getis-Ord Gi* is a pivotal instrument within the ArcGIS framework for the identification of spatial clustering characteristics. The system is capable of accurately identifying local hotspots (high-value clusters) and cold spots (low-value clusters) of land use carbon emissions, thereby providing quantitative evidence for the targeted control of high-emission areas.

Carbon emission economic contribution coefficient

The carbon emission economic contribution coefficient (economy contributive coefficient，ECC) is a metric that expresses carbon productivity from the perspective of economic development. The formula is as follows:

$$\text{ECC} = (G_i/G)/(C_i/C) \qquad \text{(Eq.7)}$$

where: G_i and C_i are assigned to the GDP and carbon emissions of a specified region; G and C represent China's GDP and carbon emissions. The presence of an ECC greater than 1 is indicative of a region exhibiting elevated levels of energy efficiency and carbon productivity.

Carbon ecological carrying capacity coefficient

The carbon ecological support coefficient (ecological support coefficient，ESC) is utilized to express carbon sink capacity, defined as the ratio of carbon absorption within a specified area to China's total carbon absorption, divided by the ratio of carbon emissions within that area to China's total carbon emissions. The formula is as follows:

$$\text{ESC} = (\text{CS}_i/\text{CS})/(C_i/C) \qquad \text{(Eq.8)}$$

where: CS_i and C_i denote carbon absorption and carbon emissions within a designated area; CS and C represent carbon absorption and carbon emissions in China. ESC is greater than 1, indicating that the area has a high carbon sink capacity.

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Carbon balance zones

Carbon balance zoning is a spatial analysis methodology that categorizes study areas into distinct functional zones based on regional variations in carbon emission intensity, carbon sink capacity, economic development levels, and ecological carrying capacity. The fundamental principle underpinning this approach entails the identification of the spatial patterns of regional carbon cycle “sources” (carbon emissions) and “sinks” (carbon absorption). The utilization of threshold analysis, bolstered by dual carbon cycle activities within the “natural-socioeconomic” framework, establishes a foundation for the formulation of diversified low-carbon spatial management strategies.

Results and analysis

Characteristics of time-series changes in carbon emissions from land use

From 2013 to 2022, China’s land use carbon emissions exhibited a trend of accelerated growth, subsequently followed by a deceleration or decline in growth rates (*Fig. 1*). From 2013 to 2018, the carbon emissions from land use in all 30 provincial-level administrative units increased, with the highest growth rate observed in Hubei, reaching 81.55%. The growth rates in Beijing, Inner Mongolia, Heilongjiang, Zhejiang, Jiangxi, Guangdong, and Sichuan all exceeded 60%, indicating that the carbon emissions associated with land use were significant during this development phase. During the course of the 40-year development phase of reform and opening-up, distinct urbanization processes have been undergone successively by different regions of China. A salient feature of this process is the strong coupling between urban socio-economic development and the expansion of construction land. In the context of land use planning, the scale and growth rate of construction land are significantly larger than those of agricultural land and ecological land. A close spatial and economic feedback relationship exists between the structure of land use and industrial structure. The nature of industrial development exerts a significant influence on the demand for land use, with land use constraints acting as a pivotal factor in shaping the trajectory of industrial transformation. The rapid expansion of urban land, investment promotion activities that failed to screen industries scientifically or evaluate regional resource and environmental carrying capacity, and land use structures that had not been reasonably optimized according to regional development patterns have, to a large extent, led to the coexistence of economic growth expansion and environmental burden accumulation during this development phase. Consequently, diverse development regions have encountered varying degrees of adverse externalities stemming from land use, most notably heightened carbon emissions. From 2018 to 2022, particularly following China’s implementation of the “dual carbon” strategy in 2020, the growth rate of land use carbon emissions in the study area exhibited a substantial decline. In certain regions, including Beijing, Tianjin, Shanghai, Jiangsu, Zhejiang, Fujian, Guizhou, and Yunnan, land use carbon emissions exhibited negative growth, indicating that carbon sink reserves surpassed carbon source emissions, consequently enhancing the regional ecological environment. This is closely related to the high-quality development strategy that was proposed at the 19th National Congress of the Communist Party of China: high-quality development requires the abandonment of the previous extensive development model and its combination with the “dual carbon” development strategy. This will compel all development regions to optimize or upgrade their industrial

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structures. In rapidly urbanizing regions, there is a need to adjust development strategies towards industrial ecologization. In ecologically sensitive or fragile regions, the focus should be on developing towards ecological industrialization. Moreover, since 2020, China has implemented national spatial planning, with the “Three Zones and Three Lines” policy requiring implementation. The integrated development and management model for mountains, forests, fields, lakes, grasslands, and deserts necessitates dynamic optimization of land use structures. Consequently, during the 2018-2022 development phase, a series of positive trends emerged, including no significant expansion in the scale of construction land, the proper allocation of ecological land, and changes in energy consumption structure accompanying industrial transformation and upgrading, which have substantially enhanced China’s carbon sink reserve capacity.

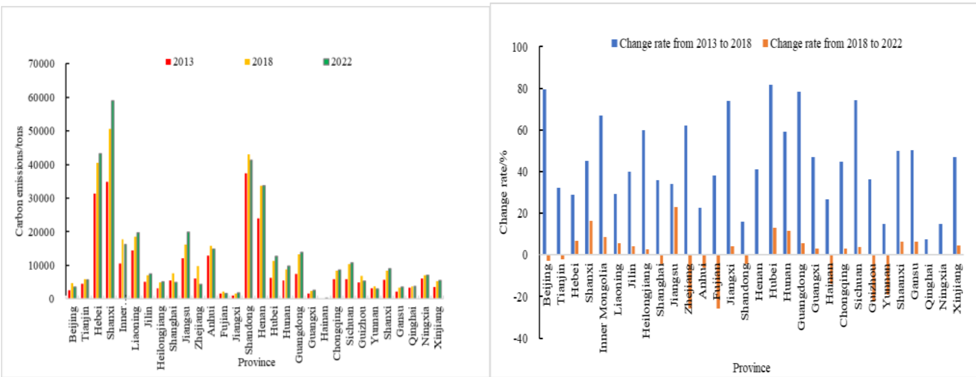

***Figure 1.** Time-series characteristics of carbon emissions from land use in China*

Analysis of spatial effect of carbon emissions from land use

Spatial auto-correlation analysis of carbon emissions

From 2013 to 2022, the global Moran’s *I* index ranged from 0.253 to 0.379, and was significantly above the 10% level. This finding indicates that China’s land use carbon emissions exhibit a significant and stable positive spatial clustering pattern (*Table 3*).

***Table 3.** Moran’s I of land use carbon emissions in China from 2013 to 2022*

Year	Moran’s *I*	*Z*	*P*
2013	0.357	2.154	0.005**
2014	0.376	2.572	0.100*
2015	0.379	2.580	0.004**
2016	0.371	2.551	0.025**
2017	0.348	2.124	0.009**
2018	0.350	2.135	0.075*
2019	0.253	1.325	0.005**
2020	0.314	1.693	0.004**
2021	0.271	1.407	0.005**
2022	0.306	1.621	0.004**

**0.05 significance level
*0.1 significance level

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Distribution of land use carbon emission hotspots

From 2013 to 2022, the primary emitting regions of carbon in China were identified as the northeast and the middle and lower reaches of the Yellow River, while the southeast coastal areas exhibited comparatively lower emissions. This phenomenon is intricately linked to China's energy consumption structure (*Fig. 2*). The Northeast region, an old industrial base, experienced an early development phase, relying on mineral resources to achieve rapid growth. Nevertheless, the carbon accumulation effects of economic development are evident, especially following China's implementation of its high-quality development strategy, wherein ecological civilization construction has become a top priority. This has given rise to a transformative challenge for the Northeast region's traditional development model, which has been overly reliant on energy consumption. The middle and lower reaches of the Yellow River basin are characterized by their abundance of energy resources, as evidenced by the presence of provinces such as Shanxi, Hebei, and which are notable for their mineral wealth. Notably, Henan, a significant producer of grain, contributes to the region's substantial carbon emissions due to its intensive land use patterns.

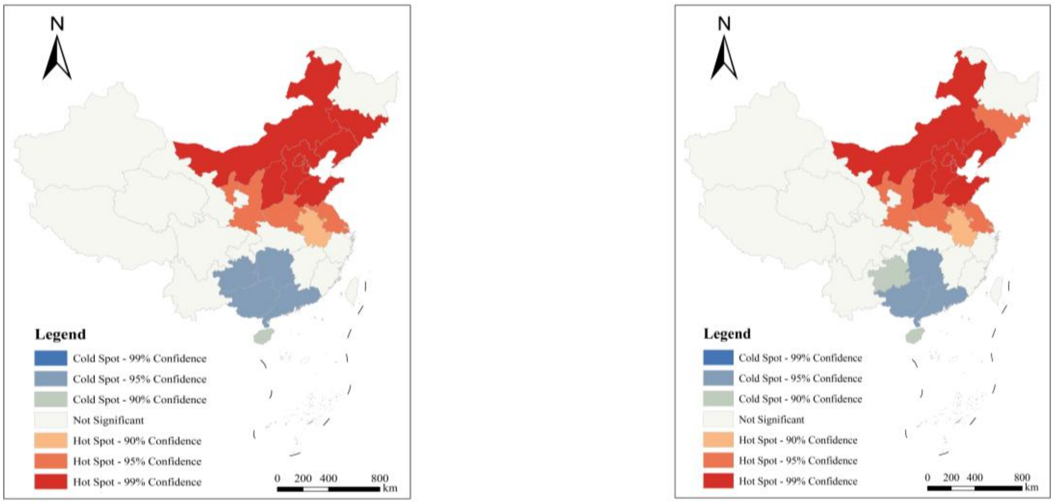

Figure 2. *Distribution of carbon emissions hotspots from land use in China from 2013 to 2022. The review number is GS (2024) 0650*

Regional disparities in land use-related carbon emissions

The overall differences (T) have been narrowing progressively since 2013, when it was 0.150, to 0.105 in 2022, representing a cumulative decrease of 30%. This indicates that there has been a significant decrease in the differences in land use carbon emissions among the provincial administrative units in China, and that regional coordination has been strengthened (*Table 4*).

There has been a significant decrease in regional disparities (T_{WR}) from 0.080 in 2013 to 0.035 in 2022, representing a decrease of 56.3%. This finding suggests that the carbon emissions gap from land use among provincial administrative units within each region has narrowed considerably. There are two possible explanations for this phenomenon. Firstly, regions have responded to the national ecological civilization strategy to varying degrees, promoting an energy revolution and strengthening the

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development and utilization of new clean energy sources. Secondly, under the new development pattern centered on domestic circulation, regions have begun industrial upgrading or relocation, and the process of industrial relocation is accompanied by technology diffusion, thereby reducing regional differences in carbon emissions from land use. The intra-regional disparity (T_{BR}) exhibited a decline from 0.045 to 0.035 between 2020 and 2022, indicative of adjustments in the integration process within regions under the guidance of the "dual carbon" goals.

Table 4. *Tyrell's index and contribution rate of carbon emission in China from 2013 to 2022*

Year	Overall difference	Regional differences	Regional disparities	Contribution rate of regional differences/%	Contribution rate of interregional differences/%
2013	0.150	0.080	0.070	53.3	46.7
2014	0.145	0.075	0.070	51.7	48.3
2015	0.140	0.070	0.070	50.0	50.0
2016	0.135	0.065	0.070	48.1	51.9
2017	0.130	0.060	0.070	46.2	53.8
2018	0.125	0.055	0.070	44.0	56.0
2019	0.120	0.050	0.070	41.7	58.3
2020	0.115	0.045	0.070	39.1	60.9
2021	0.110	0.040	0.070	36.4	63.6
2022	0.105	0.035	0.070	33.3	66.7

Inter-regional differences (T_{BR}) remain rigid: they remained stable at 0.070 from 2013 to 2022, indicating that the gap in land use carbon emissions between the four major regions–the eastern, central, western, and northeastern regions–has not been substantially improved. Following 2015, inter-regional disparities superseded intraregional disparities, emerging as the predominant source of overall variations. This phenomenon may be attributed to the varying development models across regions. The eastern region, with its economy predominantly services-based and characterized by high-tech industries, has witnessed a decline in land-use carbon emissions. Conversely, the central, western, and especially northeastern regions have undergone substantial development in heavy industry, heavy manufacturing, and energy base construction, resulting in a stagnation in inter-regional disparities in land-use carbon emissions.

A structural reversal in contribution rates has been observed. The intra-regional contribution rate (β) decreased from 53.3% to 33.3% between 2013 and 2022, while the inter-regional contribution rate (α) increased from 46.7% to 66.7% during the same period. In 2022, the inter-regional contribution rate reached 66.7%, indicating that two-thirds of China's land use carbon emissions reductions are constrained by inter-regional imbalances. It is noteworthy that 2015 marked a significant turning point in contribution rates, with both intra-regional and inter-regional contribution rates reaching 50% in 2015. Subsequent to this, inter-regional disparities have continued to predominate in overall variations. This phenomenon may be attributed to China's ratification of the Paris Agreement in 2015, which provided incentives for the eastern regions to expedite the optimization and adjustment of land and industrial utilization structures, in accordance with national self-determined contribution objectives. Nevertheless, the

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absence of a coherent regional coordination and development mechanism has resulted in considerable disparities between regions.

Analysis of the ecological effects of carbon emissions from land use

From the perspective of temporal changes, the ecological effects of land use carbon emissions in China from 2013 to 2022 generally exhibited a trend of overall stability, followed by a significant increase (*Table 5*). From 2013 to 2020, the ecological effect levels demonstrated clear interannual stability, suggesting that the impact of land use carbon emissions on regional ecological environment quality during this period exhibited minimal fluctuations. During the 2021-2022 period, there was a marked upward trajectory in the ecological benefits, indicating tangible progress from China's dual carbon development strategy, which was introduced in 2020. This phenomenon is in alignment with China's evolving development landscape, which is characterized by its high-quality development and ecological civilization strategies. These strategies are consistent with the projected trajectory towards achieving carbon peak by 2030 and carbon neutrality by 2060. Following the formulation of the "dual carbon" strategy, China's provincial-level administrative units initiated industrial structure upgrades, energy structure optimization, and ecological environment construction, albeit to varying degrees and based on their respective resource endowments, development positioning, and optimization directions. The concept of the 'mountain-water-forest-field-lake-grassland-desert ecological community' has been implemented, leading to a significant increase in forest and grassland coverage and carbon sink reserves, thereby weakening the carbon emissions effects of land use and strengthening regional ecological effects. Overall, China's ecological effects remained stable from 2013 to 2020, with a significant nationwide increase beginning in 2021. This indicates the substantial effectiveness of the national "dual carbon" strategy and ecological civilization construction policies.

From a spatial distribution perspective, significant east-west gradient differences in ecological effects were exhibited in the study area from 2013 to 2022. In contrast, the eastern coastal regions experienced a comparatively early and rapid process of urbanization and industrialization. The process of population urbanization was a key driver of land urbanization, resulting in a substantial increase in the area of construction land. Once the requirements in terms of the size of the labor force and the economic development, as well as the land use needs, were met, this ultimately led to the process of industrial urbanization. In this process, urbanization and industrialization developed concurrently, resulting in a gradually diversifying energy consumption structure and an expanding scale of energy consumption, which strengthened land use carbon sources. Concurrently, during the transformation of land use structure, the expansion of construction land led to the occupation and compression of other land types, particularly ecological land, resulting in changes in land use types. This has resulted in a significant surge in land use carbon emissions during the economic development process in the eastern region, with Tianjin, Shanghai, and Jiangsu serving as prime examples. Notably, these regions have exhibited ecological effects that have consistently remained below 0.5, indicating a manageable level of ecological impact. Beijing, Zhejiang, and Fujian have demonstrated a consistent capacity to maintain ecological effect levels of approximately 0.7. In recent years, under the national high-quality development strategy, Beijing has gradually implemented industrial relocation, with a view to optimizing and adjusting its industrial and land use structures. The trend towards

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industrial ecologicalization is evident, with the city moving towards becoming a "double highland" of economic development and ecological construction. It is evident that Zhejiang and Fujian have been designated as national ecological civilization construction demonstration zones, and thus possess a high level of ecological livability. The ongoing development of ecological industrialization has been instrumental in maintaining elevated ecological impact levels in the eastern region. In central and western regions, particularly in western areas such as Guangxi, Chongqing, Sichuan, Guizhou, and Yunnan, ecological effect levels are notably high, which is closely related to their ecological baseline environment. These regions are located in southwestern China and possess unique geographical advantages. The development of the natural ecological barrier zone and the orientation of ecological industrialization are complementary, thereby enabling mutual compatibility between the land use structure and industrial structure in southwestern regions such as Sichuan-Chongqing and Yunnan-Guizhou. The integrated development of mountain-water-forest-field-lake-grassland-desert projects and green low-carbon industries has driven an increase in land use carbon sink levels, with ecological effect levels clearly ranking among the top.

Table 5. *Ecological effects of carbon emissions from land use in China from 2013 to 2022*

Area	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Beijing	0.567	0.568	0.567	0.567	0.567	0.570	0.566	0.571	0.574	0.574
Tianjin	0.440	0.439	0.439	0.440	0.440	0.443	0.440	0.440	0.498	0.498
Hebei	0.557	0.556	0.556	0.557	0.557	0.563	0.556	0.556	0.571	0.571
Shanxi	0.568	0.568	0.568	0.568	0.568	0.572	0.573	0.569	0.575	0.576
Inner Mongolia	0.555	0.552	0.554	0.555	0.555	0.563	0.554	0.554	0.568	0.568
Liaoning	0.557	0.556	0.557	0.557	0.557	0.565	0.556	0.556	0.569	0.569
Jilin	0.554	0.552	0.554	0.554	0.554	0.571	0.552	0.551	0.571	0.571
Heilongjiang	0.548	0.546	0.547	0.548	0.548	0.568	0.545	0.545	0.570	0.570
Shanghai	0.438	0.438	0.438	0.438	0.438	0.439	0.437	0.437	0.479	0.479
Jiangsu	0.406	0.405	0.407	0.406	0.406	0.412	0.406	0.407	0.463	0.463
Zhejiang	0.562	0.561	0.562	0.562	0.562	0.567	0.562	0.562	0.570	0.570
Anhui	0.532	0.530	0.531	0.532	0.532	0.544	0.533	0.533	0.548	0.548
Fujian	0.568	0.567	0.568	0.568	0.568	0.574	0.567	0.567	0.574	0.576
Jiangxi	0.556	0.555	0.556	0.556	0.556	0.569	0.557	0.556	0.569	0.569
Shandong	0.509	0.509	0.509	0.509	0.509	0.515	0.509	0.509	0.543	0.543
Henan	0.546	0.546	0.547	0.546	0.546	0.556	0.546	0.546	0.563	0.563
Hubei	0.548	0.547	0.548	0.548	0.548	0.560	0.547	0.547	0.562	0.562
Hunan	0.557	0.557	0.558	0.557	0.557	0.568	0.557	0.557	0.571	0.570
Guangdong	0.561	0.561	0.561	0.561	0.561	0.567	0.561	0.561	0.569	0.569
Guangxi	0.556	0.554	0.556	0.556	0.556	0.572	0.555	0.556	0.575	0.575
Hainan	0.542	0.539	0.541	0.542	0.542	0.560	0.543	0.542	0.566	0.566
Chongqing	0.562	0.561	0.562	0.562	0.562	0.572	0.561	0.572	0.574	0.574
Sichuan	0.560	0.558	0.558	0.560	0.560	0.573	0.558	0.558	0.574	0.573
Guizhou	0.565	0.563	0.563	0.565	0.565	0.576	0.566	0.566	0.577	0.577
Yunnan	0.561	0.559	0.560	0.561	0.561	0.575	0.558	0.558	0.576	0.576
Shaanxi	0.567	0.564	0.566	0.567	0.567	0.576	0.569	0.570	0.577	0.577
Gansu	0.540	0.537	0.539	0.540	0.540	0.560	0.541	0.540	0.567	0.567
Qinghai	0.505	0.501	0.503	0.505	0.505	0.514	0.501	0.503	0.527	0.527
Ningxia	0.548	0.547	0.548	0.548	0.548	0.554	0.548	0.554	0.559	0.559
Xinjiang	0.516	0.512	0.514	0.516	0.516	0.530	0.519	0.519	0.538	0.538

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Spatial and temporal heterogeneity of carbon emission economic contribution coefficients

Time-series characteristics of the economic contribution coefficient of carbon emissions

In 2013, China’s economic contribution coefficient of carbon emissions remained between 0.09 and 6.66, indicating that the economic contribution rates and carbon emission contribution rates of different provincial-level administrative units were in a relatively unbalanced state, with significant regional differences (*Fig. 3*). The distribution thresholds of the carbon emission economic contribution coefficient were as follows: 16 units had a coefficient less than 1, 10 units had a coefficient between 1 and 2, 2 units had a coefficient between 2 and 4 (Tianjin and Shanghai), and 2 units had a coefficient greater than 4 (Beijing and Guangdong). This finding suggests that during this developmental phase, the extensive economic development model and substantial outward expansion of construction land resulted in considerable negative externalities in industrial development and land use, with carbon emissions significantly exceeding carbon absorption effects. Consequently, in excess of 50% of the study areas demonstrated carbon emission economic contribution coefficients that were less than 1. By 2020, the carbon emission economic contribution coefficient in China remained within the range of 0.22 and 12.43, indicating that internal differences within the study areas have gradually widened since 2013. From the perspective of the numerical distribution thresholds of the carbon emission economic contribution coefficient, seven units have a coefficient less than 1, nine units have a coefficient between 1 and 2, five units have a coefficient between 2 and 4, and nine units have a coefficient greater than 4. The number of high-value regions has significantly increased compared to 2013, particularly with Zhejiang and Fujian entering the high-value region. This finding suggests that, during this developmental phase, the adoption of ecological industrialization as the guiding principle for industrial structure optimization has encouraged green industrial development. This has also resulted in the replacement of energy consumption structures and the gradual emergence of the supportive role of new clean energy in industrial development. This, in turn, has driven the coordinated development of economic growth and carbon production levels. In 2022, China’s carbon emission economic contribution coefficient remained within the range of 0.10 and 13.13, with ongoing intensification of internal disparities. From the perspective of the threshold values for the carbon emissions economic contribution coefficient, 15 units were found to have a coefficient below 1, 6 units had a coefficient between 1 and 2, 2 units had a coefficient between 2 and 4, and 7 units had a coefficient above 4 (Beijing, Tianjin, Shanghai, Zhejiang, Fujian, Guangdong, and Chongqing). In particular, following the proposal of the strategy of high-quality development at the 19th National Congress of the Communist Party of China, the provinces of Guangdong and Chongqing have thoroughly examined their geographical location, developmental positioning and resource advantages. They have achieved industrial ecologization (optimizing and adjusting the existing industrial structure in accordance with the direction of ecological civilization construction) and ecological industrialization (converting the value of spatial ecological resources into asset value) in order to realize the coexistence of economic development and ecological civilization construction. This has resulted in improved economic development levels and reduced carbon production levels.

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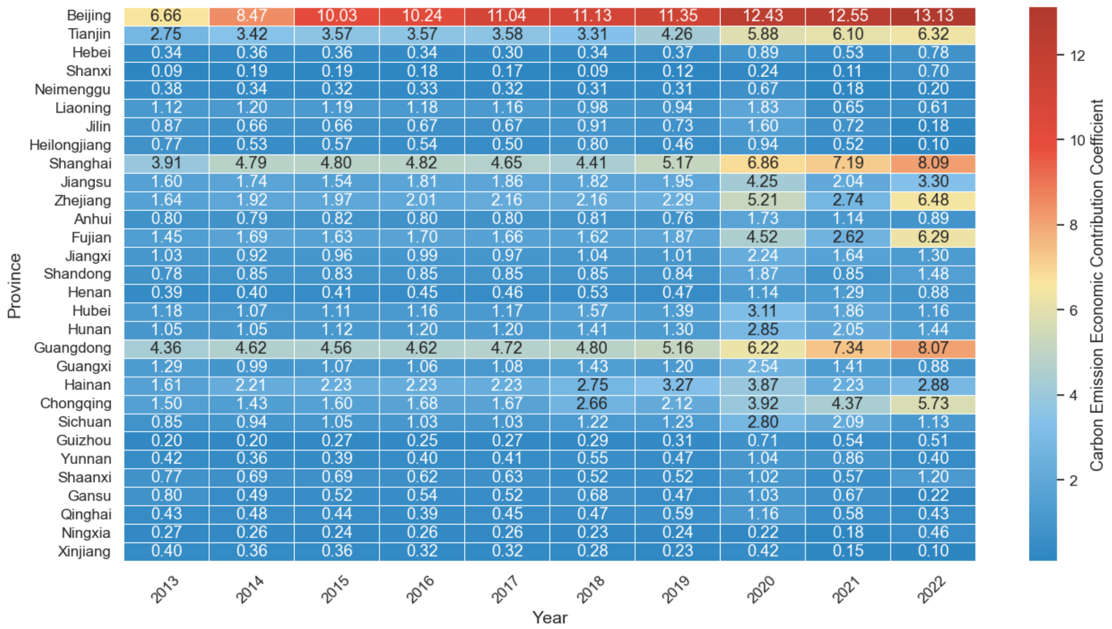

Figure 3. *Thermal distribution of China's carbon emission economic contribution coefficient from 2013 to 2022*

Spatial evolution characteristics of carbon emission economic contribution coefficients

The spatial distribution of the carbon emission economic contribution coefficient demonstrates an overall trend from 2013 to 2022, which exhibits an eastern > central > northeastern > western distribution pattern. High-value coefficients are primarily concentrated in the central and eastern regions, while low-value coefficients are mainly distributed west of the Hu Huanyong Line. This finding suggests that the central and eastern regions of China exhibit significantly higher levels of energy utilization efficiency and carbon production, a pattern that generally aligns with China's economic development (*Fig. 4*). In 2013, China's carbon emission economic contribution coefficient exhibited a spatial pattern characterized by "four core regions (Beijing, Shanghai, Guangdong, and Guangxi), single-point distribution, and continuous gradients." By 2020, the carbon emission economic contribution coefficient in the central and eastern regions had increased significantly, however, in some areas the coefficient was still below 1, indicating insufficient economic growth momentum. The natural geographical advantages and ecological resource endowments of these regions have not been fully utilized, and their resource advantages have not been converted into economic assets. In 2022, China's carbon emissions economic contribution coefficient exhibited a spatial pattern characterized by multiple core regions extending from Beijing, Tianjin, Shanghai, Zhejiang, Fujian, Guangdong, and Chongqing, a multi-center networked structure, and intensified polarization.

The spatial evolution pattern of China's carbon emission economic contribution coefficient from 2013 to 2022 reveals the successful transition of Zhejiang and Fujian, regions that have achieved industrial transformation and upgrading through reliance on the digital economy and green manufacturing. These regions have also capitalized on national policy opportunities to develop the ecological economy as a new economic growth point. In contrast, Beijing, Shanghai, and Guangdong, as the foremost economic

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development regions in China, demonstrate an increase in their carbon emission economic contribution coefficient. This indicates a shift from quantity-driven growth to quality-driven growth, accompanied by a continuous improvement in development efficiency. Liaoning, Jilin and Heilongjiang, as representatives of the Northeast’s old industrial bases, and Shanxi and Inner Mongolia, as typical resource-based provinces, have consistently low carbon emissions economic contribution coefficients. This indicates that, in the context of ecological civilization and high-quality development strategies, these provinces still face challenges in their development transformations, with a notable reliance on traditional manufacturing and mineral resources. It is evident that the regions of Xinjiang and Ningxia, due to their status as ecologically fragile western zones, are stable low-value zones with regard to carbon emissions economic contribution coefficients. The spatial pattern of China’s carbon emissions economic contribution exhibits a three-tiered structure: “eastern innovation leadership, central gradual transition, and western ecological conservation.” In the future, it is imperative to establish a regional low-carbon development system that integrates efficiency improvement, spatial balance, and green transformation.

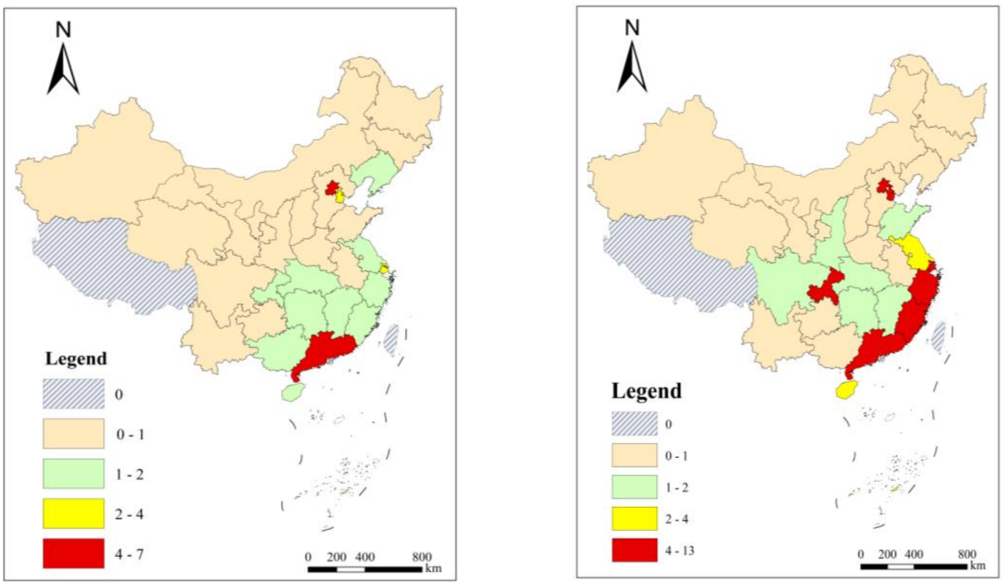

Figure 4. *Spatial evolution of China’s carbon emission economic contribution coefficient from 2013 to 2022*

Spatial and temporal variation of carbon ecological carrying capacity coefficient

Temporal variation characteristics of carbon ecological carrying capacity coefficient

In 2013, China’s carbon ecological carrying capacity coefficient remained within the range of 0.04 and 6.06, indicating that the resource and environmental carrying capacities of different provincial-level administrative units were in a relatively imbalanced state, with significant regional variations (*Fig. 5*). From the perspective of the distribution thresholds of the carbon ecological carrying capacity coefficient, 13 units were found to have a coefficient below 1, 8 units had a coefficient between 1 and 2, 8 units had a coefficient between 2 and 4, and 1 unit had a coefficient above 4 (Qinghai). This suggests that during this development phase, the extensive economic

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development model and the excessive outward expansion of construction land led to low thresholds for industrial introduction and investment development. A significant proportion of low-output, high-energy-consuming industries was responsible for the poor environmental effects of economic development and land use. The distribution of carbon sink areas, whether point-like or line-like, was found to be significantly less consequential than the concentrated carbon source effects of area-like distribution. This phenomenon resulted in a divergence between the natural, economic and ecological environments. Consequently, nearly half of the study areas exhibited carbon ecological carrying capacity coefficients below 1. By 2020, China's carbon ecological carrying capacity coefficient ranged from 0.01 to 7.47, with significant internal variations. The distribution thresholds of the carbon ecological carrying capacity coefficient were analyzed, revealing 10 units with a coefficient below 1, 3 units with a coefficient between 1 and 2, 9 units with a coefficient between 2 and 4, and 8 units with a coefficient above 4. A substantial increase has been observed in the number of high-value regions when compared with the year 2013. In 2022, China's carbon ecological carrying capacity coefficient remained within the range of 0.22 and 7.16, with 14 units exhibiting a coefficient below 1, 8 units ranging from 1 to 2, 6 units between 2 and 4, and 2 units above 4 (Fujian and Qinghai). The eastern coastal regions east of the Hu Huanyong Line have shown significant changes in carbon ecological carrying capacity. This is an indication that, under the pressure of the national ecological civilization development strategy and high-quality development strategy, there is an increasing emphasis on cultivating new concepts of economic development and transforming the mode of economic development.

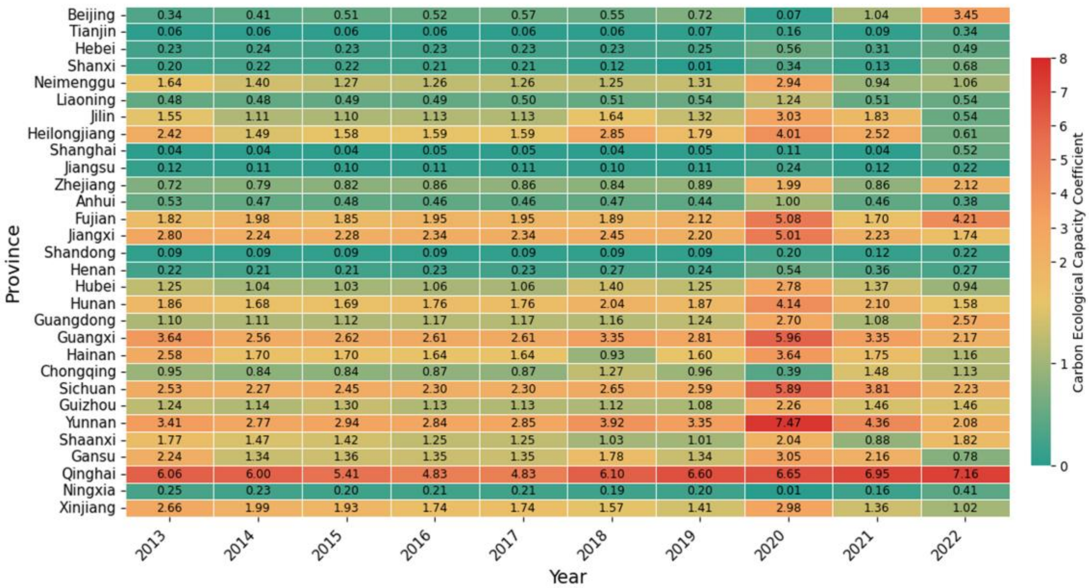

Figure 5. *Thermal distribution of China's carbon ecological carrying capacity coefficient from 2013 to 2022*

Spatial evolution characteristics of carbon ecological carrying capacity coefficient

The spatial distribution of the carbon ecological carrying capacity coefficient demonstrates an overall trend from 2013 to 2022, which exhibits a distribution pattern

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of western > central > northeastern > eastern regions. High-value coefficients are predominantly concentrated in western regions, while low-value coefficients are primarily distributed east of the Hu Huanyong Line (*Fig. 6*). This is related to the fragile ecological environment of the western regions, which include the middle and upper reaches of the Yellow River basin (Shaanxi, Gansu, and Ningxia), the upper reaches of the Yangtze River basin (Sichuan and Chongqing), the karst terrain region of southwestern China (Yunnan and Guizhou), and northwestern China (Xinjiang). These regions act as natural barriers for China and play an irreplaceable role in protecting the ecological environment. Consequently, the region's distinct geographical location, topography, and terrain impose stringent constraints on industrial layout, economic development, and land use. While urbanization and industrialization have developed rapidly in the central-eastern and northeastern regions, the western regions have relatively lower industrial density and land use intensity, slower carbon source accumulation, and more prominent ecological carbon sink capacity. In 2013, China's carbon ecological carrying capacity coefficient exhibited a spatial pattern characterized by "western dominance and Qinghai's standout performance." By 2022, Beijing had undergone the most significant changes: as the development core of the Beijing-Tianjin-Hebei region and the Bohai Rim Economic Zone, Beijing's economic development has exerted a strong "siphon effect," attracting significant resources and elements from surrounding areas. This has resulted in population density, industrial density, and land use intensity reaching or even exceeding saturation levels. In recent years, as a consequence of Beijing's engagement in industrial transfer activities in surrounding regions, there has been a significant improvement in the negative environmental impacts of land use. The city's ecological environment quality has shown signs of enhancement, leading to a substantial increase in its carbon ecological carrying capacity in the current development stage. Guangdong has been a pioneering force in the implementation of reform and opening-up policies, leveraging its unique geographical location and the dual advantages of the Guangdong-Hong Kong-Macao Greater Bay Area development. In recent years, there has been a notable enhancement in the efficiency of the region's industrial and land use structures, resulting in a substantial increase in the area's capacity to absorb and store carbon. In contrast to the approaches adopted by Beijing and Guangdong, Zhejiang and Fujian have utilized their spatial ecological resource advantages to implement the "Thousand Villages Project" and ecological civilization demonstration zone construction, respectively, in strict accordance with Xi Jinping's new era ecological civilization philosophy. A comprehensive, all-encompassing, and full-process development of spatial ecological resources has been conducted, with the value of these resources being realized through ecological industrialization, thereby fostering new economic growth points. In 2022, China's carbon ecological carrying capacity coefficient exhibited a spatial pattern characterized by western dominance, coastal emergence, and a multicenter networked structure.

The spatial evolution pattern of China's carbon ecological carrying capacity coefficient from 2013 to 2022 reveals notable variations in performance across development units. Western regions such as Qinghai demonstrate a notable lead in this regard, while Zhejiang and Fujian stand out as successful transformation regions. These regions have successfully leveraged digital economy and green manufacturing strategies to achieve industrial upgrading and transformation. Furthermore, these regions have capitalized on national policy opportunities to develop the ecological economy as a new

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source of economic growth. In contrast, Beijing and Guangdong, as frontier regions of China’s economic development, have shown an increase in the carbon ecological carrying capacity coefficient. This indicates a pronounced emphasis on green economic development in these regions. Liaoning, Jilin, and Heilongjiang, as representatives of the Northeast Old Industrial Base, and Shanxi and Inner Mongolia, as typical resource-based provinces, have low carbon ecological carrying capacity coefficients. This indicates that, within the strategic framework of ecological civilization development and high-quality development, reliance on traditional manufacturing and mineral resources remains significant, whether in the revitalization of the Northeast Old Industrial Base or the transformation of mineral resource-based regions. The carbon ecological carrying capacity of China has formed a new pattern characterized by “plateau support, coastal rise, central region enhancement, and Northeast transformation.” The establishment of a contemporary development system that integrates human society and nature in a harmonious manner is imperative. This can be achieved through the implementation of diversified regional strategies.

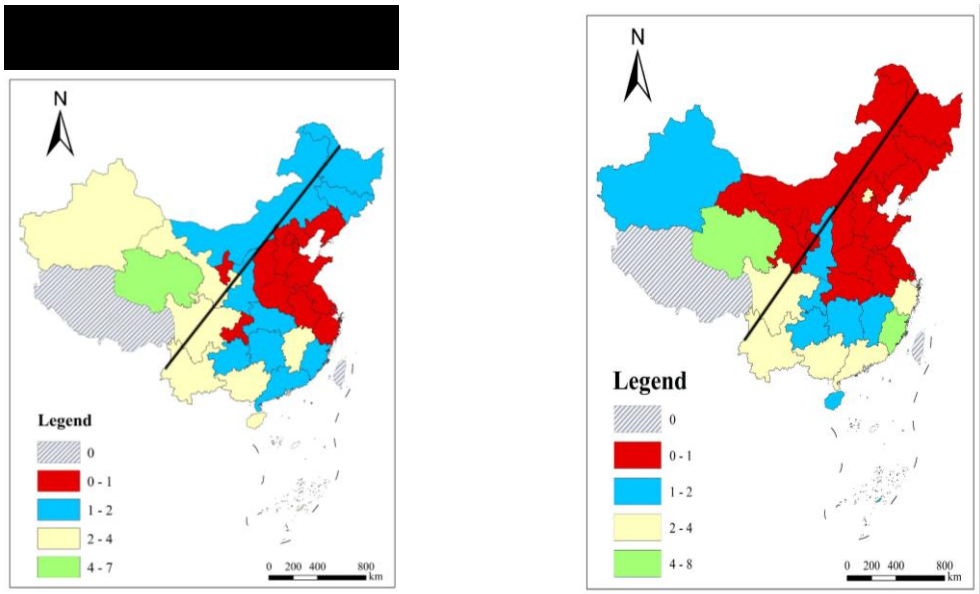

Figure 6. *Spatial evolution of China’s carbon ecological carrying capacity coefficient from 2013 to 2022*

Carbon balance zone

The 2013-2022 China land use carbon balance zones comprise four distinct categories: low-carbon preservation zones, carbon sink development zones, comprehensive optimization zones, and economic development zones (*Fig. 7*). In instances where the ESC and ECC exceed these thresholds, the designated region is categorized as a low-carbon conservation zone. The geographical area in question principally encompasses the provinces of Zhejiang, Fujian, Guangdong, Hunan, Chongqing, Sichuan, and Shaanxi. These regions are located in the eastern, central, and western parts of the country and are characterized by high energy utilization efficiency and carbon productivity levels, abundant carbon sink reserves, and harmonious development of socio-economic and ecological environments. The development of low-

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carbon retention zones can be categorized into three distinct types. Firstly, the ecological industrialization development path, as exemplified by Zhejiang, Fujian, Chongqing, and Sichuan, is characterized by abundant ecological resources, high and clearly defined spatial ecological resource values, and the integrated development and utilization of spatial ecological resources such as mountains, forests, fields, lakes, grasslands, and deserts to create new green economic growth points. Secondly, the eastern coastal developed regions, exemplified by Guangdong, are distinguished by their advantageous geographical location, strong policy sensitivity, and implementation capacity. These regions have the capacity to closely follow national high-quality development policies, reasonably optimize industrial structure, and achieve the dual goals of economic development and ecological construction through carbon market transactions. Thirdly, manufacturing bases in the central region, as represented by Hunan, are distinguished by intricate energy consumption structures and substantial energy consumption levels. Utilizing the central rise strategy, these regions have the opportunity to develop into national manufacturing hubs by optimizing energy consumption structures, promoting energy revolutions, and achieving clean development.

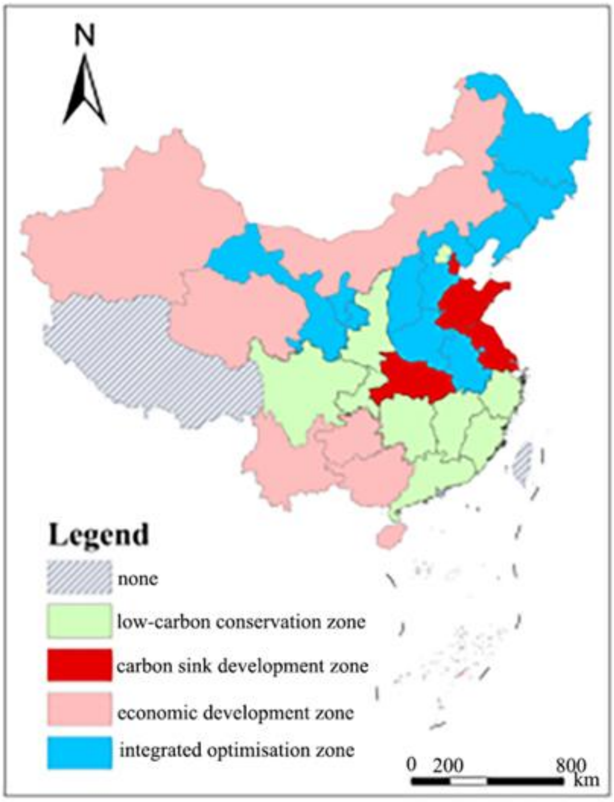

Figure 7. *Land use carbon balance zones in China*

In circumstances where the ESC is less than 1 and the ECC is greater than 1, the region is designated as a carbon sink development zone, a designation which is primarily applicable to the regions of Tianjin, Shanghai, Jiangsu, Shandong, and Hubei. The distribution of these areas is predominantly concentrated in the central and eastern regions. These regions are distinguished by their high energy utilization efficiency and

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carbon productivity levels, in addition to their advanced economic development. Nevertheless, the carbon emissions associated with economic growth are significant, with rapid expansion of construction land leading to the occupation of ecological land and resulting in low ecological carbon sink reserves. In the future, efforts should be made to accelerate the transition of the industrial structure towards green and low-carbon development based on the existing mature industrial structure. The implementation of stringent enforcement measures pertaining to national spatial planning is imperative to ensure the delineation of explicit boundaries between designated areas for ecological protection and urban development, thereby augmenting carbon sink capacity.

In circumstances where the ESC is less than 1 and the ECC is less than 1, the region is designated as a comprehensive optimization zone, which primarily encompasses provinces such as Hebei, Shanxi, Liaoning, Jilin, Heilongjiang, Anhui, Gansu, and Ningxia. These regions have been found to demonstrate comparatively low carbon absorption capacity and low carbon emission economic efficiency. The development models employed by these regions can be categorized into two distinct types. Firstly, a traditional resource-based development model, exemplified by Liaoning, Jilin, Heilongjiang, and Shanxi. It is imperative that these regions align with national development trends, thereby ensuring the reinforcement of the energy revolution, the enhancement of technological upgrades, and the improvement of energy utilization efficiency and clean production standards. Secondly, regions with vast development potential, such as Gansu and Ningxia, have the opportunity to explore green economic opportunities by developing local industry.

In scenarios where the ESC exceeds 1 and the ECC falls below 1, the region is designated as an economic development zone, predominantly encompassing provinces such as Guangxi, Xinjiang, and Qinghai. These regions possess abundant carbon sink reserves but comparatively low carbon production levels. In future development, these regions have the potential to leverage their geographical resource advantages to explore new economic growth points through emerging industries such as ecological leisure tourism and health and wellness tourism, while ensuring the functionality of natural ecological barriers. This will assist in the development of new productive forces and the promotion of the coordinated development of the socio-economic-ecological system.

Discussion

Li et al. (2023, 2022), Wu et al. (2024), Han et al. (2024), and Guo et al. (2023) all conducted carbon emission analyses, with a single province or specific region constituting the subject of their research. In their seminal contributions, Kuang et al. (2022) and Hu et al. (2023) have delved into the intricate relationship between carbon emissions, economic development, and ecological factors. However, the spatial scale of these studies is limited, and they have not incorporated multiple ecological characteristic indices. This study, which focuses on China as its research object, contributes to our understanding of the patterns of national land use carbon emissions changes from a macro-scale perspective. This, in turn, provides a reference point for achieving regional coordinated development within the context of the national spatial planning system. The present study comprehensively examines the trends in China's land use carbon emissions from a spatiotemporal perspective using ArcGIS and Python. It reflects carbon emission characteristics through regional differences, ecological

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effects, heat analysis, carbon emission economic contribution coefficients, and carbon ecological carrying capacity coefficients. Accordingly, the study undertakes a carbon balance zoning of China's land use, providing region-specific optimization recommendations for disparate areas in order to achieve the "dual carbon" strategy.

Conclusion

China's land use carbon emissions demonstrated a trend of accelerated growth, subsequently followed by a deceleration or decline in growth rates, with 30 provinces exhibiting substantial and persistent positive spatial clustering of carbon emissions. The distribution of carbon emission hotspots exhibited a concentration in the northeastern region and the middle and lower reaches of the Yellow River basin, while cold spots were predominantly located in the southeastern coastal regions. A gradual narrowing of overall differences in China's land use carbon emissions has been observed, coinciding with enhanced regional coordination.

The ecological effects of China's land use carbon emissions demonstrated a general stability, subsequently succeeded by a substantial increase, accompanied by significant east-west gradient disparities. From 2013 to 2020, the ecological effects remained stable overall, but began to show a significant nationwide increase starting in 2021. This indicates the substantial effectiveness of national-level "dual carbon" strategies and ecological civilization construction policies.

China's carbon emissions economic contribution coefficient displays the distinct characteristics of "Beijing-Tianjin-Shanghai-Fujian-Guangdong-Chongqing multi-core expansion, multi-center networked structure, and intensifying polarization," forming a spatial pattern of "eastern innovation leadership, central transitional zones, and western ecological conservation." In contrast, the carbon ecological carrying capacity coefficient exhibits a spatial distribution pattern of western dominance, coastal emergence, and multi-center networked structure.

The land use carbon balance zones of China are divided into the following categories: low-carbon conservation zones, carbon sink development zones, comprehensive optimization zones, and economic development zones. The distribution of low-carbon conservation zones is concentrated in Zhejiang, Fujian, Chongqing, Sichuan, and other regions; carbon sink development zones are concentrated in Jiangsu, Shandong, Hubei, and other regions; comprehensive optimization zones are concentrated in Jilin, Heilongjiang, Gansu, Ningxia, and other regions; and economic development zones are concentrated in Xinjiang, Qinghai, and other regions.

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