

SPATIAL-TEMPORAL HETEROGENEITY AND SCALE PREDICTION OF LAND USE CARBON EMISSIONS IN THE YANGTZE RIVER ECONOMIC BELT IN CHINA

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Abstract. This study undertakes an analysis of land use and carbon emissions within the context of the Yangtze River Economic Belt in China, a region undergoing rapid development. Utilizing a combination of kernel density analysis and ArcGIS, the study examined spatiotemporal patterns, thereby unveiling a predominant single-peak distribution accompanied by a rightward shift. It is important to note that regional variations exist: a bimodal pattern is evident downstream, while polarization is observed midstream and a widened, right-shifted distribution is apparent upstream post-2020. Spatial analysis confirms a stable positive autocorrelation. Predictions derived from the GM (1,1) model indicate rising emissions under both the baseline scenario and the low-carbon 2030 scenario, though the latter shows a slower growth rate and the potential for earlier peaks in some areas, such as Shanghai and Jiangsu, by 2028. The potential for regional carbon reduction has been estimated at 25%-30% (upstream), 20%-25% (midstream), and 15%-18% (downstream). It is recommended that the upstream, midstream and downstream sectors respectively prioritize advancing the ecological transformation of industries, enhancing energy efficiency, and promoting green industrial development.

Keywords: *land use carbon emissions, kernel density estimation, spatial visualization, spatial autocorrelation, scenario forecasting, GM (1,1) model*

Introduction

Land use directly affects the carbon source and carbon sink functions of ecosystems by altering surface cover types (e.g. deforestation, grassland conversion, urban expansion). Different land use types exhibit distinct carbon absorption and emission characteristics and their spatial patterns change dynamically, leading to spatiotemporal heterogeneity in carbon emissions. In October 2023, at a symposium held in Nanchang to further promote high-quality development of the Yangtze River Economic Belt, President Xi Jinping proposed that the Yangtze River Economic Belt should be constructed as China's primary theatre for ecological priority and green development, the principal conduit for facilitating domestic and international dual circulation, and the primary catalyst for high-quality economic development. This strategic positioning, within the context of ecological civilization construction, renders the Yangtze River Economic Belt particularly important in terms of accelerating the achievement of high-quality development. Consequently, an analysis of the spatiotemporal evolution characteristics of land use carbon emissions in the Yangtze River Economic Belt can elucidate the effectiveness of regional policies, thereby providing targeted recommendations for the subsequent phase of carbon peaking and ultimately achieving carbon neutrality.

To date, a considerable body of research has been conducted by scholars in the field of carbon emissions. The following research areas are of particular interest: studies on the carbon

source and carbon sink effects of agricultural production activities (Hu et al., 2025), transportation carbon emissions effects, land use carbon emissions effects (Feng et al., 2025); spatio-temporal characteristics and interactive features of carbon emissions in industrial manufacturing (Wang et al., 2025); and the impact of carbon emissions intensity in the logistics industry (Zhang and Lan, 2025). The research scale encompasses national (Liu et al., 2025; Zhang et al., 2025), regional (Li et al., 2025), provincial (Feng et al., 2025; Han et al., 2025; Zhao et al., 2025), municipal (Xie et al., 2025). The research content encompasses a range of aspects, including the integration of urban and rural development and land use carbon emissions (Li et al., 2025), the simulation of land use carbon emissions scenarios (Sui et al., 2025), the interactive impact of digital economic development and land use carbon emissions (Zuo et al., 2025), the spatio-temporal coupling of land use carbon emissions and ecosystem service value (Fu et al., 2025), and the spatio-temporal evolution of land use carbon emissions (Li et al., 2025). While these studies have analyzed carbon emission patterns from different perspectives, research on the Yangtze River Economic Belt has primarily focused on either the upper reaches or the middle reaches (Wu et al., 2025; Liu et al., 2024), without conducting comprehensive studies from the perspective of the entire Yangtze River Economic Belt or its upstream, middle, and downstream regions. Moreover, extant studies have not incorporated China's 'dual carbon' development strategy to predict carbon peak conditions by 2030. Therefore, this study has selected the Yangtze River Economic Belt as its research area. Kernel density curves have been employed in order to comprehensively reflect the dynamic evolution characteristics of land use carbon emissions across the entire Yangtze River Economic Belt and its upstream, middle, and downstream regions. Furthermore, ArcGIS has been utilized to achieve spatial visualization of land use carbon emissions. The GM (1,1) model is applied in order to predict the scale of land use carbon emissions under the baseline and low-carbon scenarios by 2030. The aim of this is to understand the dynamics of land use carbon peaking in the Yangtze River Economic Belt. It is also intended to provide a reference point and insights for the early realization of the 'dual carbon' strategy and high-quality development.

Materials and methods

Sample and data source

This study focuses on the Yangtze River Economic Belt as its research area. The Yangtze River Economic Belt is a region that spans China's eastern, central, and western geographical regions, encompassing a total of 11 provinces and municipalities. These include Shanghai, Jiangsu, Zhejiang, Anhui, Jiangxi, Hubei, Hunan, Chongqing, Sichuan, Yunnan, and Guizhou. The total land area encompassed by this region constitutes approximately 21% of China's total land area. The region's population and economic output both exceed 40% of the national total, thus classifying it as one of China's most comprehensive and strategically significant regions. The Yangtze River Economic Belt is regarded as a pivotal strategic region for the promotion of coordinated regional development in China. It fulfils a dual role, serving as both an important ecological security barrier and an engine of economic growth. It serves as a typical case study for exploring China's regional sustainable development and ecological civilization construction. The data on land use is derived from Landsat TM remote sensing imagery, with a spatial resolution of 30 meters, as provided by the Chinese Academy of Sciences' Resource and Environmental Science Data Platform. The data on socio-economic development was sourced from *China Statistical Yearbook* and *China City Statistical Yearbook*. The field of socio-economic data encompasses a wide range of indicators, including population size and socio-economic development, such as Gross Domestic Product (GDP) and the structure of the

industrial sector. The data on energy consumption were obtained from *China Energy Statistical Yearbook*. The study period was from 2013 to 2022.

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 (Han et al., 2025). In order to calculate land use carbon emissions, the study employed the IPCC carbon emission factor method (using a uniform carbon emission factor for cultivated land). It is acknowledged that there are variations in production techniques and input structures across different crops. In addition, there have been ongoing advancements in agricultural technology during the study period, which may result in dynamic shifts in emission factors. However, fixed coefficients were employed for the following reasons: firstly, macro-scale studies typically adopt this methodology to ensure consistency and comparability of time-series data; secondly, there currently exists no authoritative database of dynamic coefficients covering major crops throughout the study period. Therefore, the study utilized carbon emission coefficients to calculate direct carbon emissions for each land use type (*Table 1*), employing the following formula:

$$C = S_l \times E_l \quad (\text{Eq.1})$$

where: C is carbon emissions, t; S_l is the area of each land type, hm^2 ; E_l is the carbon emission coefficient of each land type (hm^2/a).

Indirect carbon emissions

Indirect carbon emissions from construction land, refer to the IPCC energy carbon emission coefficient method (Zhang et al., 2025), 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), and the conversion factor of standard coal and carbon emission coefficient refer to *China Energy Statistics Yearbook* (*Table 2*).

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

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

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
Crude Oil	1.4286	0.5857
Natural Gas	1.3300	0.4483
Electricity	0.3450	0.2720

Kernel density estimation

A kernel density curve is a non-parametric estimation method based on kernel density estimation that can describe the distribution characteristics of data through a continuous density curve (Zhang et al., 2022). The formula for kernel density estimation is as follows:

$$F(y) = \frac{1}{Nh} \sum_{i=1}^N K\left(\frac{y_i - y}{h}\right) \quad (\text{Eq.3})$$

where: $K(x)$ represents the kernel density function, describing the weight of all sample points y_i within the neighborhood of y ; N represents the number of observations; h represents the window width of the kernel density estimate. The position of the kernel density curve, the width and height of the peaks, the number of peaks, and the length of the distribution tail are characteristics that can reflect the central tendency, dispersion, polarization, and variability of the data. In the context of land use and carbon emission studies, kernel density curves have been utilized to analyze the distribution of carbon emissions and their temporal and spatial evolution.

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 (Zhang et al., 2022).

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:

$$\text{Moran's } I = \frac{n \sum_{i=1}^n \sum_{j=1}^n W_{ij} (X_i - \bar{X})(X_j - \bar{X})}{\sum_{i=1}^n (X_i - \bar{X})^2 \sum_{i=1}^n \sum_{j=1}^n W_{ij}} \quad (\text{Eq.4})$$

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; \bar{X} 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 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 G_i^*

Getis-Ord G_i^* 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.

GM (1,1) model

The utilization of grey forecasting models, with a particular emphasis on GM (1,1), has been comprehensively documented for their effective implementation in the realm of short- to medium-term forecasting within the domains of resources and the environment. These domains encompass critical areas such as energy consumption, carbon emissions, and water demand. The efficacy and reliability of these measures have been extensively validated, providing a robust theoretical and practical foundation for the methodological selection in this study. This study employs the GM (1,1) model from grey system theory to forecast land use carbon emissions, primarily based on the following considerations: Firstly, the study period spans 2013–2022, yielding a relatively short historical carbon emissions data sequence—a classic example of ‘small sample’ data. The GM (1,1) model has been demonstrated to be particularly effective in addressing scenarios that are characterized as ‘information-poor’, due to its ability to generate insights into underlying patterns through sequence operators, without the necessity of extensive datasets. Secondly, the Yangtze River Economic Belt has undergone rapid urbanization and industrialization. As the development phase continues, there is a concomitant annual accumulation of carbon emission effects, in accordance with the GM (1,1) model's superiority in fitting exponential trend sequences. In conclusion, the model is characterized by a simple structure with clearly defined parameters. This facilitates the construction of different future development scenarios by adjusting the core parameter (development coefficient). This facilitates the realization of the multi-scenario prediction objective that has been established for this study. The model transforms the original data sequence into an accumulated generation sequence through cumulative generation operations (1-AGO), thereby enhancing the regularity of the data. Specifically, for the original sequence $x^{(0)}$, its first-order cumulative generation operation (1-AGO) sequence is $x^{(1)}$, and the adjacent mean background value $z^{(1)}$ is the average of the two adjacent

terms of $x^{(1)}$. The GM (1,1) model is defined as the grey differential equation $x^{(0)}(k) + ax^{(1)}(k) = b$, where a is the development coefficient and b is the grey action. the GM (1,1) model is:

$$\hat{x}^{(0)}(k) = (1 - e^b) \left[x^{(0)}(1) - \frac{b}{a} \right] e^{-\hat{a}(k-1)} \quad (\text{Eq.5})$$

where: a and b represent estimated values, while k denotes the length of the original and predicted sequences, respectively. The parameters a and b are estimated using the least squares method to obtain the time response function of the model. This enables the prediction of land use carbon emissions.

Results and analysis

Sequential dynamic evolution characteristics of land use carbon emissions

Characteristics of nuclear density curve across the entire Yangtze River Economic Belt

From the perspective of peak counts, the land use carbon emissions kernel density curve for the Yangtze River Economic Belt exhibits a single-peak dominant distribution pattern (Fig. 1). From 2013 to 2022, the distribution of carbon emissions from land use in the Yangtze River Economic Belt exhibited a consistent single primary density peak, indicating an absence of significant multi-polarization phenomenon in carbon emissions from land use in the Yangtze River Economic Belt. The position of the primary peak remained relatively stable over time, suggesting that the concentration trend of carbon emissions from land use in the Yangtze River Economic Belt exhibits temporal continuity; no peak splitting or new peaks emerged during the study period, indicating that the carbon emissions distribution pattern remains relatively unified.

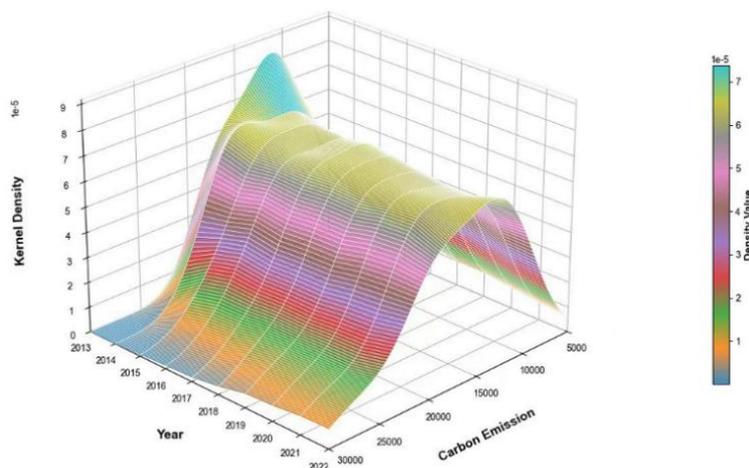


Figure 1. Carbon emissions density curve for land use in the Yangtze River Economic Belt from 2013 to 2022

From the perspective of spatial distribution, the peak location of land use carbon emissions in the Yangtze River Economic Belt shifted between 2013 and 2022 (Fig. 1), with the density peak gradually moving toward high-carbon emission regions. This phenomenon is concomitant with the accelerated economic development and

urbanization process that is currently underway in the Yangtze River Economic Belt. The corresponding carbon emission values at the peak have increased year by year, indicating an overall upward trend in carbon emission levels. The distribution center of land use carbon emissions is demonstrating a migration trend, with the overall density distribution shifting to the right (towards higher emissions) over time. This indicates that while the peak of land use carbon emissions is moving across the entire Yangtze River Economic Belt, the overall scale of carbon emissions is also shifting towards higher levels.

From the perspective of distribution patterns, the kernel density curve of land use carbon emissions in the Yangtze River Economic Belt exhibits a distinct right-skewed (positive skew) distribution trend. The right side of the curve (high-emission regions) exhibits a longer tail, while the left side (low-emission regions) is relatively steep, indicating that carbon emissions in certain regions or years are significantly higher than the average level. The kurtosis of carbon emissions from land use in the Yangtze River Economic Belt exhibited temporal variations from 2013 to 2022. In earlier years, the distribution was relatively flat (low kurtosis), while in later years, the distribution became more concentrated (high kurtosis), reflecting a trend of concentrated increases in carbon emissions.

From the perspective of distribution extensibility, the right side of the land use carbon emission kernel density curve for the Yangtze River Economic Belt from 2013 to 2022 exhibits strong extensibility, indicating potential and room for development towards higher carbon emissions, which aligns with the growth potential of carbon emissions in rapidly developing regions. The left side of the distribution is characterized by a relatively steep gradient and limited extensibility, indicating that the available scope for reducing carbon emissions is constrained. From 2013 to 2022, the distribution pattern transitions in a smooth and continuous manner, indicating that carbon emissions changes are a gradual process with strong temporal continuity. This finding is consistent with the annual economic development process of the Yangtze River Economic Belt.

Characteristics of the nuclear density curve of the Yangtze River Economic Belt sub-regions

The carbon emission kernel density curves for downstream land use from 2013 to 2022 exhibit a distinct bimodal distribution, with the two peaks corresponding to different carbon emission levels, reflecting significant regional differences (*Fig. 2*). The primary peak is situated in the higher carbon emission region, while the secondary peak is located in the relatively lower emission region. The bimodal structure demonstrated notable stability throughout the study period, thereby signifying the sustainability of this distribution pattern. The kernel density curve for carbon emissions from land use in the midstream region exhibits two main peaks, with the left peak representing regions with relatively low carbon emission levels (Anhui, Jiangxi) and the right peak representing regions with relatively high carbon emission levels (Hubei, Hunan). The overall rightward shift of the kernel density curve indicates that carbon emissions in the midstream region are generally increasing, with the right peak shifting more than the left peak, exhibiting obvious polarization characteristics and a ‘core-periphery’ pattern (*Fig. 2*). The upstream land use carbon emissions kernel density curve has shifted overall to the upper right, with the distribution width widening, especially after 2020 (*Fig. 2*). This indicates that carbon emissions disparities in the upstream region are widening, primarily between Sichuan-Chongqing and Yunnan-Guizhou. Despite both regions being located in the upstream area, their developmental trajectories diverge. The Sichuan-Chongqing region is exhibiting a pronounced industrialization trend, with the potential to rely more on high-energy-consuming industries

during its development process. In contrast, the Yunnan-Guizhou region, situated within China's southwestern ecological barrier zone, may instead rely on ecological tourism or clean energy sources. This results in divergent carbon emission pathways.

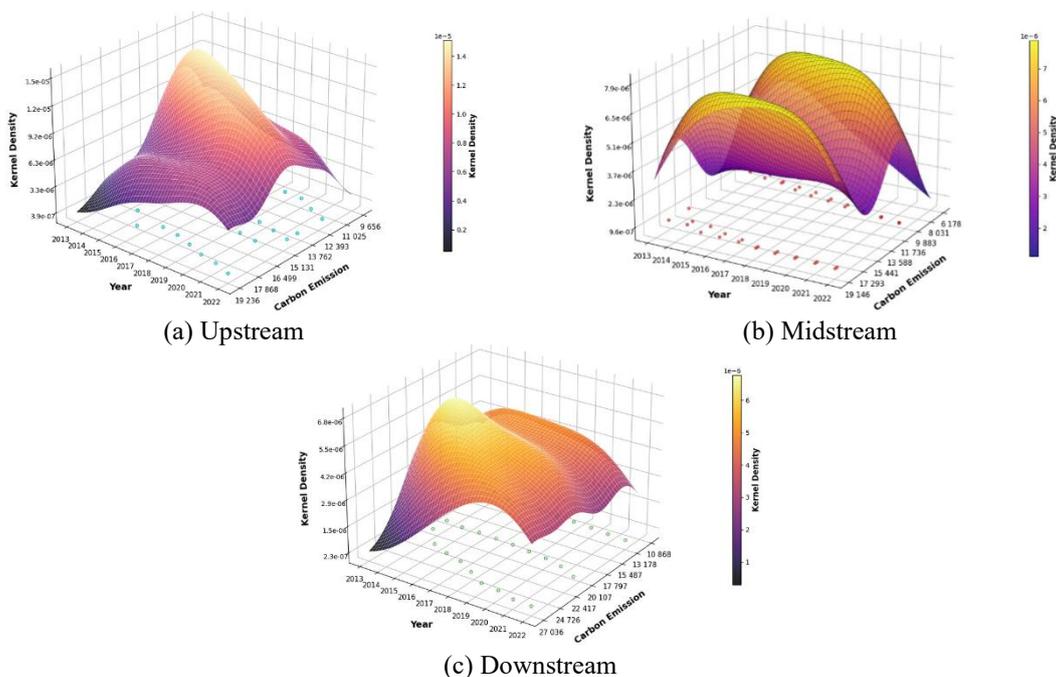


Figure 2. Land use density curves for the upper, middle and lower reaches of the Yangtze River Economic Belt

Spatial pattern evolution characteristics of land use carbon emissions

Spatial visualization layout

The study period has been divided into two developmental phases: 2013-2017 and 2017-2022. The 18th National Congress was convened in 2012, while the 19th National Congress was held in 2017. Consequently, the selection of 2013 as the study's starting year and the employment of 2017 as the discontinuity point facilitate the precise reflection of scale differences and evolving trends in land-use carbon emissions across the developmental phases preceding and following these two congresses. In 2013, the range of carbon emissions from land use in the Yangtze River Economic Belt was between 6178 and 18,262 tons, exhibiting a spatial distribution characterized by two core regions, Jiangsu and Shanghai, and Sichuan and Chongqing, which exhibited higher emissions, followed by the middle reaches, and Yunnan and Guizhou at the lower end (*Fig. 3*). This phenomenon is closely associated with the pace of industrialization and urbanization: The economic growth centers in the lower reaches, i.e. Shanghai and Jiangsu, exhibit dual characteristics of high population density and intense industrial development, leading to high carbon emissions. Sichuan and Chongqing, despite their location in the upper reaches, have emerged as leaders in the development of China's western regions. Relying on mineral resources and other natural endowments, these countries have experienced rapid development, with a traditional industrial structure dominated by the secondary sector (e.g., mineral processing and manufacturing). This has resulted in prominent carbon emission effects. In 2017, the range of land use carbon emissions in the Yangtze River Economic Belt was between 8710

and 24,077 tons, which represented a significant increase from 2013. There was a slight change in spatial distribution, primarily reflected in Hubei joining the ranks of high carbon emitters (Fig. 3). This is directly related to Hubei's industrial structure, which is dominated by the secondary industry characterized by heavy processing and manufacturing. This industrial structure has resulted in Hubei's economic development becoming excessively reliant on conventional energy consumption, exhibiting significant characteristics of elevated pollution levels, substantial energy input, and considerable energy consumption. Moreover, the intensity of development and utilization of new clean energy sources, as well as the level of technological support, are insufficient, resulting in prominent negative externalities from Hubei's economic development and land use. In 2022, the range of carbon emissions from land use in the Yangtze River Economic Belt was from 10,678 to 27,036 tons, with a spatial distribution that was similar to that in 2017. However, the growth rate of carbon emissions across regions from 2017 to 2022 exhibited a decline in comparison to the 2013-2017 period, demonstrating a gradual increase.

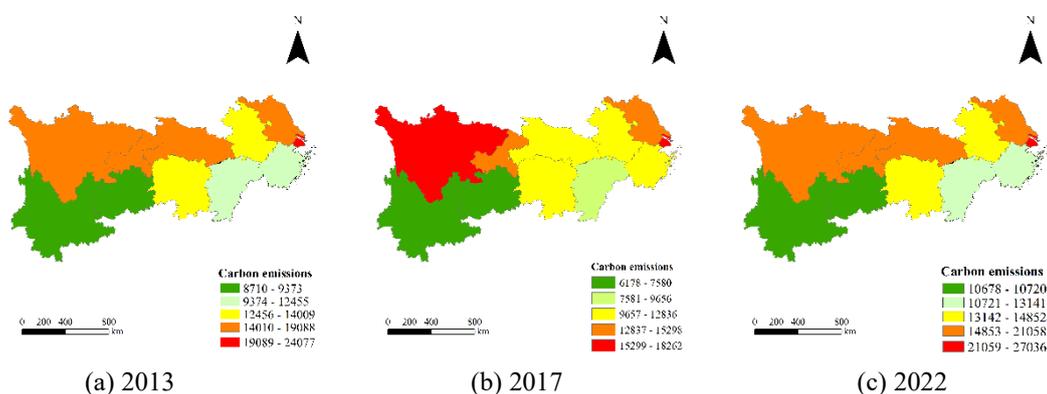


Figure 3. Spatial distribution of carbon emissions from land use in the Yangtze River Economic Belt from 2013 to 2022

Spatial correlation features

The global Moran's I module in ArcGIS was utilized to analyze the spatial correlation characteristics of land use carbon emissions in the Yangtze River Economic Belt from 2013 to 2022 (Table 3). The global Moran's I values for land use carbon emissions in the Yangtze River Economic Belt from 2013 to 2022 ranged from 0.304 to 0.372, with significance levels all at or above 10%, indicating a significantly stable positive spatial correlation.

The spatial distribution characteristics of cold spots and hot spots of land use carbon emissions in the Yangtze River Economic Belt were explored through spatial aggregation feature analysis. The results indicate that the areas of land use carbon emissions with the highest concentrations are located in the Yangtze River Economic Belt, specifically in the Yangtze River Delta region and the Chengdu-Chongqing urban agglomeration, while the areas with the lowest concentrations are primarily situated in the Yunnan-Guizhou region (Fig. 4).

Table 3. Global spatial autocorrelation characteristics of land use carbon emissions in the Yangtze River Economic Belt from 2013 to 2022

Year	Moran's <i>I</i>	Z value	P value
2013	0.372	2.526	0.005**
2014	0.356	2.410	0.010**
2015	0.364	2.463	0.004**
2016	0.327	2.251	0.005**
2017	0.335	2.301	0.053*
2018	0.310	2.239	0.003**
2019	0.304	2.218	0.007**
2020	0.349	2.380	0.002**
2021	0.353	2.407	0.005**
2022	0.357	2.412	0.003**

**0.05 significance level; *0.1 significance level

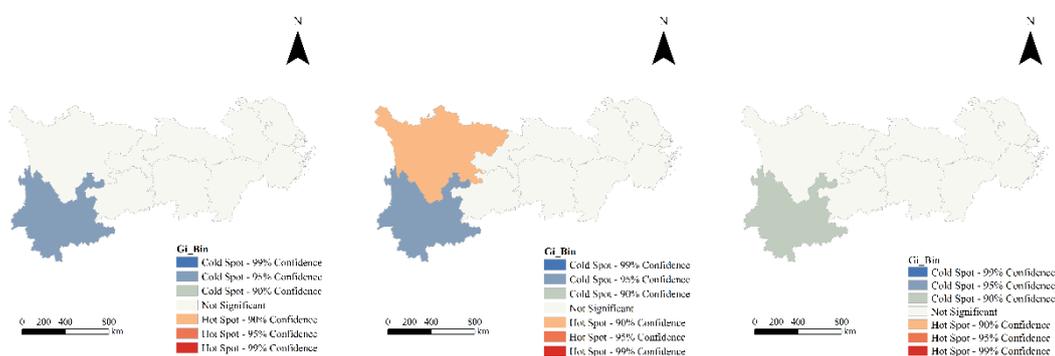


Figure 4. Distribution of hotspots and coldspots of land use carbon emissions in the Yangtze River Economic Belt

Land use carbon emission scenario prediction

In order to formulate a more scientific and reasonable regional carbon peaking plan, the study analyzed the scale of land use carbon emissions in the Yangtze River Economic Belt from 2013 to 2022. The study identified population size, socio-economic development (as measured by GDP and industrial structure), and energy consumption scale as the primary predictive variables, given their established correlation with carbon emissions. Utilizing the GM (1,1) model, which is well-suited to short-term forecasting, the study predicted the scale of land use carbon emissions in the Yangtze River Economic Belt by 2030 under both the baseline scenario and the low-carbon development scenario.

Comparison of total carbon emission scale forecasts

The land use carbon emissions for the Yangtze River Economic Belt in 2030 are presented under two different scenarios: the baseline development scenario and the low-carbon development scenario. These emissions are modelled using the GM (1,1) model. As can be observed, land use carbon emissions in the Yangtze River Economic Belt are projected to increase by 2030 under both the baseline development scenario and the low-

carbon development scenario. However, the increase in carbon emissions differs between the two scenarios: the increase under the low-carbon development scenario is significantly smaller than that under the baseline development scenario (Fig. 5). This demonstrates the scientific validity of China’s implementation of the green, low-carbon, and circular development philosophy, and also highlights the necessity of low-carbon principles in the implementation of the ‘dual carbon’ development strategy.

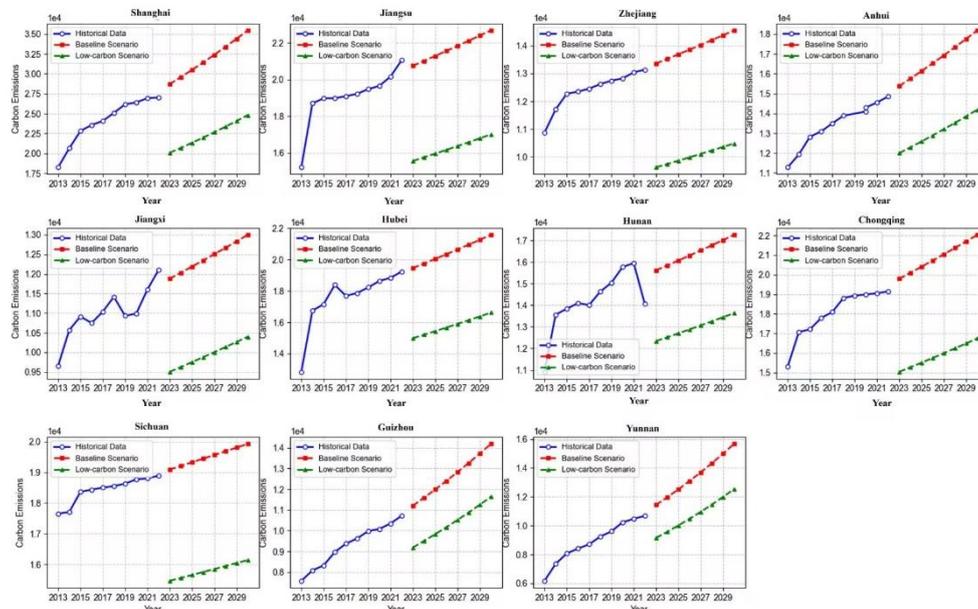


Figure 5. Predicted scale of land use carbon emissions in 2030 under the baseline scenario and low-carbon scenario

In accordance with the baseline development scenario, it is projected that land use carbon emissions in the Yangtze River Economic Belt will reach a peak in 2030, with the highest emissions recorded in Shanghai and the lowest in Yunnan. The correlation between this pattern and regional population, economic development scale, industrial structure, and energy consumption scale is statistically significant. In accordance with the low-carbon development scenario, the growth rate of land use carbon emissions in the Yangtze River Economic Belt is significantly reduced in comparison with the baseline scenario, with a reduction of 15%-20%. It is notable that certain provinces and municipalities (for example, Shanghai and Jiangsu) are expected to attain their maximum carbon emissions levels around 2028. This suggests that substantial reductions in carbon emissions can be achieved through the optimization of industrial structure and the enhancement of energy efficiency.

In the baseline development scenario and the low-carbon development scenario, the carbon emission reduction potential of land use in the upper, middle, and lower reaches of the Yangtze River Economic Belt differs significantly. In the low-carbon scenario, the carbon emission reduction potential in the upper reaches is expected to reach 25%-30%, 20%-25% in the middle reaches, and 15%-18% in the lower reaches. This exhibits a spatial differentiation pattern of upper > middle > lower reaches, which is exactly the opposite of the current economic development spatial pattern. The spatial layout is closely related to the economic saturation levels, industrial structure adjustment

potential, and ecological resource value enhancement potential of the upper, middle, and lower reaches of the Yangtze River Economic Belt. When the population and economic development capacity of the downstream regions of Jiangsu, Zhejiang, and Shanghai reach a state of saturation or even oversaturation, the concept of ecological civilization will compel these regions to undergo industrial structure transformation and shifts in economic growth models. In the midstream and, most notably, the upstream regions, the spatial ecological resource value advantages are becoming evident under the concept of ecological civilization. The prevailing development orientation of ecological industrialization has the potential to drive spatial ecological resources to become new emerging economic growth points for sustainable development. This, in turn, can result in rapid growth in carbon sink reserves and a broad scope for carbon emissions reduction.

Regional differences between upstream, midstream and downstream areas and peak paths

Analysis of differences in carbon emissions from land use in the upper, middle and lower reaches in 2030

Under the baseline and low-carbon scenarios, the scale of land use carbon emissions in the upper, middle, and lower reaches of the Yangtze River Economic Belt in 2030 differs (*Fig. 6*). The lower reaches region typically displays a substantial carbon emissions baseline, accompanied by a decline in growth rate, with the earliest anticipated peak in carbon emissions. Under the baseline scenario, the range of land use carbon emissions is between 65,000 and 70,000 tons, accounting for 40%-45% of the Yangtze River Economic Belt; in the low-carbon scenario, the range is from 55,000 to 58,000 tons, with a carbon reduction potential of 15%-18%. The middle reaches region has been observed to demonstrate a faster growth rate in carbon emissions, which is related to its development as a national manufacturing base. The baseline scenario indicates that land use carbon emissions in the Yangtze River Economic Belt range from 55,000 to 60,000 tons, constituting 35%-40% of the total emissions. Under a low-carbon scenario, the range is from 44,000 to 48,000 tons, indicating a 20%-25% carbon reduction potential. In the middle reaches region, Hunan and Hubei have high land use carbon emissions, which is closely related to their development as manufacturing bases under the Central Region Rise Strategy. The secondary industry accounts for the highest proportion of the industrial structure, leading to an expansion in energy consumption. This is particularly pertinent in the context of the current energy revolution, where the efficacy of the 'establish first, then dismantle' approach requires further enhancement. Conventional energy sources continue to play a significant role in economic development, while the utilization of clean new energy sources is constrained by technological limitations and industrial structure reforms, resulting in their comparatively limited impact on the processes of industrialization and urbanization. Consequently, the middle reaches region has become the area with the most significant growth in land use carbon emissions in the Yangtze River Economic Belt. The upstream region, due to its unique geographical location, demonstrates prominent spatial ecological resource advantages. Land use carbon emissions are comparatively minimal, ranging from 35,000 to 40,000 tons under the baseline scenario, accounting for 20%-25% of the Yangtze River Economic Belt; under the low-carbon scenario, they range from 26,000 to 30,000 tons, with a carbon emission reduction potential of 25%-30%.

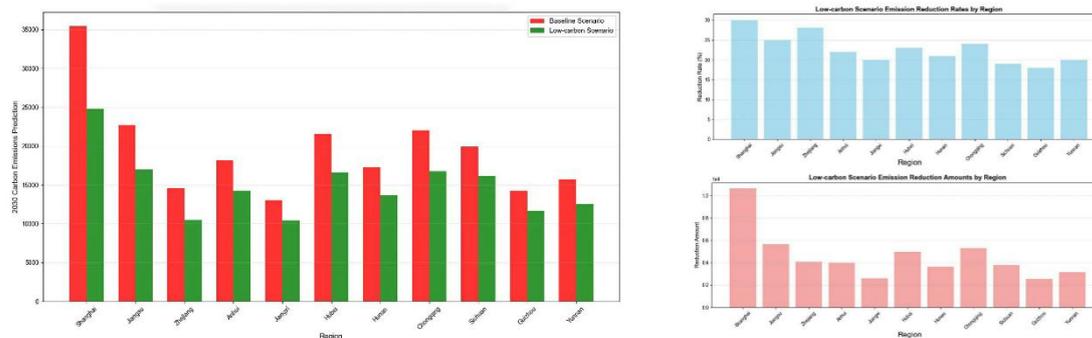


Figure 6. Comparison of land use carbon emissions in different regions under the baseline scenario and low-carbon scenario

Key focus areas for achieving ‘dual carbon’ targets across the upstream, midstream, and downstream sectors

The industrial structure of downstream regions is primarily dominated by the tertiary sector. On the one hand, there is a need to vigorously develop high-tech industries, particularly low-carbon development technologies and carbon capture technologies, while continuing to focus on high-end services and strategic emerging industries. Conversely, there is a necessity to adopt an industrial ecologicalization approach as a developmental orientation, implement an energy revolution, and promote the green transformation and development of traditional industries. The midstream region, particularly the areas of Hubei and Hunan that are characterized by high carbon emissions, exhibits an industrial structure that is predominantly oriented towards the secondary sector. In accordance with the national strategy for the establishment of large-scale manufacturing bases, the economic development of the country is contingent upon a considerable degree of energy consumption. Consequently, it is imperative to implement stringent industrial access restrictions, optimize the extant industrial infrastructure, and promote the development of a circular economy. Conversely, it has the potential to enhance the exchange of low-carbon development technologies with downstream regions, establish regional environmental standards, and optimize energy utilization efficiency. The development pathways within the upstream region can be categorized into two distinct types: the Yunnan-Guizhou development model, distinguished by its unique geographical location and abundant spatial ecological resources. New industries that prioritize environmental sustainability, such as health and wellness tourism, leisure and sightseeing tourism, and traditional cultural industries, have emerged as prominent sectors. In the context of ecological civilization, the concept of ecological industrialization has emerged as a pivotal strategy for maximizing the value of spatial ecological resources. This approach involves the transformation of resource advantages into asset advantages, thereby fostering the coexistence of ecological highlands and economic highlands within a development layout. The second is the Sichuan-Chongqing development model, which is characterized by strong development potential and sufficient industrialization space. Within the overarching framework of the ecological civilization concept, this model has the capacity to facilitate industrialization through the systematic advancement of high-tech industries, whilst concomitantly establishing an ecological compensation mechanism during the developmental process.

Discussion

Whilst scholars have conducted specific studies on the estimation of carbon emission methods, the differentiation characteristics of space and time, and the influencing factors, there has been no focus on the Yangtze River Economic Belt—a crucial strategic region—from the perspectives of differentiation and specificity of the upstream, midstream and downstream regions. The carbon emission coefficient method employed in this study is subject to a certain degree of uncertainty. A substantial source of this uncertainty is attributable to the utilization of a constant carbon emission coefficient over the entire duration of the study. It is evident that diverse agricultural produce manifest distinguishable carbon emission characteristics, and the carbon emission intensity may have diminished during the study period due to the integration of low-carbon agricultural techniques, such as water-saving irrigation and conservation tillage. Consequently, the fixed coefficient approach may imply a degree of overestimation of carbon emissions during the latter part of the study period, particularly in regions experiencing rapid technological advancement. Notwithstanding, this systematic bias does not compromise the fundamental conclusions concerning the spatial differentiation patterns of carbon emissions. It is recommended that future research employ more refined carbon emission factor coefficients in order to achieve a more precise assessment outcome. Furthermore, there is a paucity of studies that have integrated research on the prediction of carbon emissions with the ‘dual carbon’ development strategy nodes. Consequently, this study employs kernel density curves to more clearly reflect the dynamic evolution trends of land use carbon emissions. Furthermore, by employing the GM (1,1) model, which is more appropriate for short-term predictions, the study establishes baseline development scenarios and low-carbon development scenarios to predict and analyze the scale of land use carbon emissions in the Yangtze River Economic Belt by 2030. This provides targeted optimization and adjustment recommendations for achieving carbon peaking in land use within the Yangtze River Economic Belt by 2030.

Conclusion

The study has indicated a rise in carbon emissions from land use in the Yangtze River Economic Belt. Furthermore, the growth rate of carbon emissions in each region has slowed down overall between 2017 and 2022 compared to the period from 2013 to 2017. The kernel density curve displays a single-peak dominant distribution pattern, with the center of the overall density distribution shifting to the right (towards higher emissions) over time. The right side of the curve, which corresponds to high-emission regions, exhibits a longer tail, while the left side, representing low-emission regions, demonstrates a comparatively steep decline. The distribution pattern transitions in a smooth manner, thereby demonstrating strong temporal continuity, which is in alignment with the annual economic development process of the Yangtze River Economic Belt. The nuclear density curve for carbon emissions from land use in the downstream region exhibits a significant bimodal distribution, with the main peak located in the higher carbon emission region and the secondary peak in the relatively lower emission region. The nuclear density curve for the midstream region exhibits two main peaks and an overall rightward shift, with the right peak shifting more than the left peak, showing a clear polarization feature and a ‘core-periphery’ pattern. The nuclear density curve for land use carbon emissions in the upstream region has shifted overall to the upper right, with the distribution width expanding, particularly becoming much broader after 2020. This finding suggests that

disparities in carbon emissions within the upstream region are increasing, with a notable distinction between the Sichuan-Chongqing and Yunnan-Guizhou regions.

This study has demonstrated that there is a significant and stable positive correlation between land use carbon emissions in the Yangtze River Economic Belt and their spatial distribution. In 2013, an analysis of land use carbon emissions in the Yangtze River Economic Belt revealed a spatial distribution pattern characterized by high emissions in Jiangsu, Shanghai, Sichuan, and Chongqing, followed by the middle reaches, and Yunnan and Guizhou at the bottom. Following 2017, Hubei began to join the ranks of high carbon emitters, a phenomenon that is directly related to the province's industrial structure, which is dominated by the secondary industry, particularly heavy manufacturing.

Projections indicate that both the baseline development scenario and the low-carbon development scenario for the Yangtze River Economic Belt are expected to result in an increase in land use carbon emissions by 2030. However, the increase in carbon emissions under the low-carbon development scenario is significantly smaller than that under the baseline development scenario, thereby demonstrating the scientific validity and necessity of China's implementation of the green, low-carbon, and circular development philosophy. Under the baseline development scenario, land use carbon emissions are projected to peak by 2030, with the highest emissions in Shanghai and the lowest in Yunnan. This pattern is strongly correlated with regional population, economic scale, industrial structure, and energy consumption. In accordance with the low-carbon development scenario, it is estimated that certain provinces and municipalities (such as Shanghai and Jiangsu) will attain their peak emissions around the year 2028. In accordance with the low-carbon scenario, it is estimated that the potential for carbon emission reduction in upstream regions will reach 25%-30%, 20%-25% in midstream regions, and 15%-18% in downstream regions. This is indicative of a spatial differentiation pattern of upstream > midstream > downstream.

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