RESEARCH ARTICLE

Spatial difference of carbon budget and carbon balance zoning based on land use change: a case study of Henan Province, China

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Abstract

Land use change is one of the key reasons for the rise in global carbon emissions. Incorporating practical methods for carbon governance into the major strategic decisions of countries around the world is important for controlling carbon emissions. This study aims to carry out a regional land use carbon budget assessment and build a carbon balance zoning optimization framework. As a result, China will be better able to implement low-carbon strategies and reach carbon peaking and carbon neutrality. Using the data of land use and energy consumption for Henan Province from 2000 to 2020, a carbon budget assessment system was constructed. According to the analysis of the geographical distribution of carbon budget, an evaluation system was developed and a carbon balance partition was established from the natural, economic, ecological and resource structure. A regionally differentiated development strategy was proposed. The findings revealed that: (1) Land use carbon emissions of Henan Province reflected a significant increasing trend, while the variation in carbon absorption of land use was stable. Carbon emissions increased by $87{,}120.25\times10^4$ t in 2020 compared to 2000, but the carbon absorption remained at approximately 1735×10^4 t over the years and there was an overall state of carbon deficit. (2) The geographical distribution of carbon emissions in Henan Province was characterized by higher in the central part and lower in the surroundings, and the distribution of carbon absorption was higher in the west and lower in the east. The distribution pattern was closely related to the level of land use and the structure of energy consumption. (3) From the carbon balance analysis, the 158 counties in Henan Province were divided into four carbon balance functional areas, namely the carbon sink functional area, low-carbon development area, carbon intensity control area, and high-carbon optimization area. Different optimized development strategies were proposed for each functional area.

Keywords Land use · Carbon budget · Carbon balance · Henan Province

Introduction

The fast growth of society and economic has led to a rise in global energy consumption, thus causing global warming to become an important issue facing society (Liu et al. 2019;

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Liu et al. 2022). To address global warming and reduce greenhouse gas emissions, the Chinese government formally signed the *Paris Agreement* in April 2016 and made the promise to aim for carbon peaking in 2030 and carbon neutrality in 2060 (China Energy Editorial Department, CEED 2020). Carbon emissions produced by human activities are the primary cause of the rise in global CO_2 emissions, and they are the main obstacle to achieving carbon neutrality (Piao et al. 2022; Yang et al. 2022). Carbon emissions generated by the change of land use/cover contribute 1/3 of the total carbon emissions by human activities (Lai et al. 2016), and the loss of natural land use/cover arising from land use change has hampered the establishment of eco-civilization and sustainable developing of the region. Therefore, incorporating carbon governance into the major strategic decisions and deployments of China in the new era and exploring an optimization strategy of carbon balance zoning is of great

importance to facilitate low-carbon transition of society and to achieve carbon peaking and carbon neutrality (Cai et al. 2021; Ding et al. 2022; Yue et al. 2022).

In recent years, many researches have concentrated on the intrinsic link between land use and carbon emissions, mainly establishing regional carbon budget accounting systems from various geographical viewpoints and spatial scales, and then analyzing pattern in space and affecting elements of carbon emissions (Wang et al. 2021), the spatial correlation (Wei and Chen 2021) and the spatiotemporal changes of carbon sources/sinks (Yi et al. 2015). As the research basis of the carbon balance, the content of the carbon budget accounting system focuses on the essential connotation between carbon emissions and carbon absorption, that is, it involves the components of both carbon sources and carbon sinks. First, carbon emissions from carbon sources come from human activities on the land (Li et al. 2015), such as industry (Zhang and Chen 2022), agriculture (Huang et al. 2020), and livestock (Zhang et al. 2020). These human activities can be specifically broken down into elements such as energy consumption, agricultural production, human respiration, livestock farming, solid waste, and wastewater. The methods that are widely utilized to calculate the carbon emissions resulting from these activities include the mass balance method (Liu et al. 2014), actual measurement method (Hang et al. 2020), and carbon emission factor method (Hao et al. 2011). Second, the primary source of the carbon absorption of the carbon sink is the effect of carbon dioxide absorption by terrestrial vegetation such as forests, grasslands, and croplands (Fang et al. 2007), which is often measured using a direct coefficient method or an indirect method (Xia and Chen 2020).

In terms of the practical application of the research results, many scholars have conducted in-depth discussions around the carbon cycle (Zhao et al. 2012), carbon footprint (Chen et al. 2022; Peng et al. 2016), carbon balance (Xu et al. 2022), and carbon compensation (Wu and Tian 2022). In relation to carbon balance zoning, research is mostly conducted at the national, provincial, and municipal scales, and county scale studies are relatively rare. In addition, from the perspective of methods, most studies (Wei and Chen 2021; Xu et al. 2022; Zhao et al. 2012) carbon balance zoning based on the economic contribution coefficient of carbon emissions and the ecological support coefficient of carbon absorption, and there is rarely a more comprehensive evaluation system. However, a carbon balance zoning scheme can comprehensively consider the natural, resource, economic, and other attributes of land use carbon budget, reflect the situation of county units as a whole, and propose more targeted and refined low-carbon development strategies for regional development through innovative balanced zoning methods.

As an important strategic location for the development of central China and the eco-protection and high-quality development of the Yellow River basin, rapid changes in land use and a sharp rise in carbon emissions brought about by industrialization and urbanization are challenges that Henan Province is currently addressing. It has been shown that land use change in Henan Province has changed dramatically in the past 20 years (Dai et al. 2021), and its carbon emissions rank second among the central provinces (Zhao et al. 2023). There is urgent requirement to harmonize the interaction between economic developing and the construction of eco-civilization to achieve green and sustainable development. On this basis, this study took the counties of Henan Province as the research unit, calculated the corresponding indicators based on the carbon emission impacts of various land categories, constructed a land use carbon budget accounting system. Nine indicators were used to measure the regional variation in the carbon budget among counties and cities, including the carbon emissions, carbon absorption, net carbon emissions, economic contribution coefficient of carbon emissions, ecological support coefficient of carbon absorption, carbon footprint, ecological carrying capacity, ecological deficit, and land use composite index. According to the evaluation system and regional characteristics, carbon balance zoning was carried out and corresponding low-carbon development strategies were proposed. The results will provide a scientific basis for future ecological civilization construction and sustainable development in Henan Province.

Study area and data

Study area

Henan Province is situated in the central–eastern region of China (Fig. 1), 31°23′–36°22′ N, 110°21′–116°39′ E. It spans four major river basins of the Yellow River, Hai River, Huai River, and Yangtze River. The general topography is higher on the west and lower on the east. The east–central part is the Huanghuaihai alluvial plain, the southwest is the Nanyang Basin, surrounded by mountains on the south, west and north sides. The land area of 167,000 km² includes 18 prefectures, 103 counties, and 54 municipal districts. Henan is a major economic province in China, according to the statistical bulletin of national economic and social development of Henan Province in 2020 and the data of the Seventh Population Census, which has the GDP of 549.97 billion RMB and the permanent population of 99.37 million in 2020. As a key area in China for population, agriculture, industry and energy consumption, Henan Province has a substantial carbon emissions base. With the release of the Outline of the Yellow River Basin Ecological Protection and High-Quality Development Plan, it has put forward higher requirements for the construction of ecological civilization in the provinces along the Yellow River. Henan Province has also responded positively to the call, in "14th Five-Year Plan for Ecological Environmental Protection and Ecological Economic Development of Henan
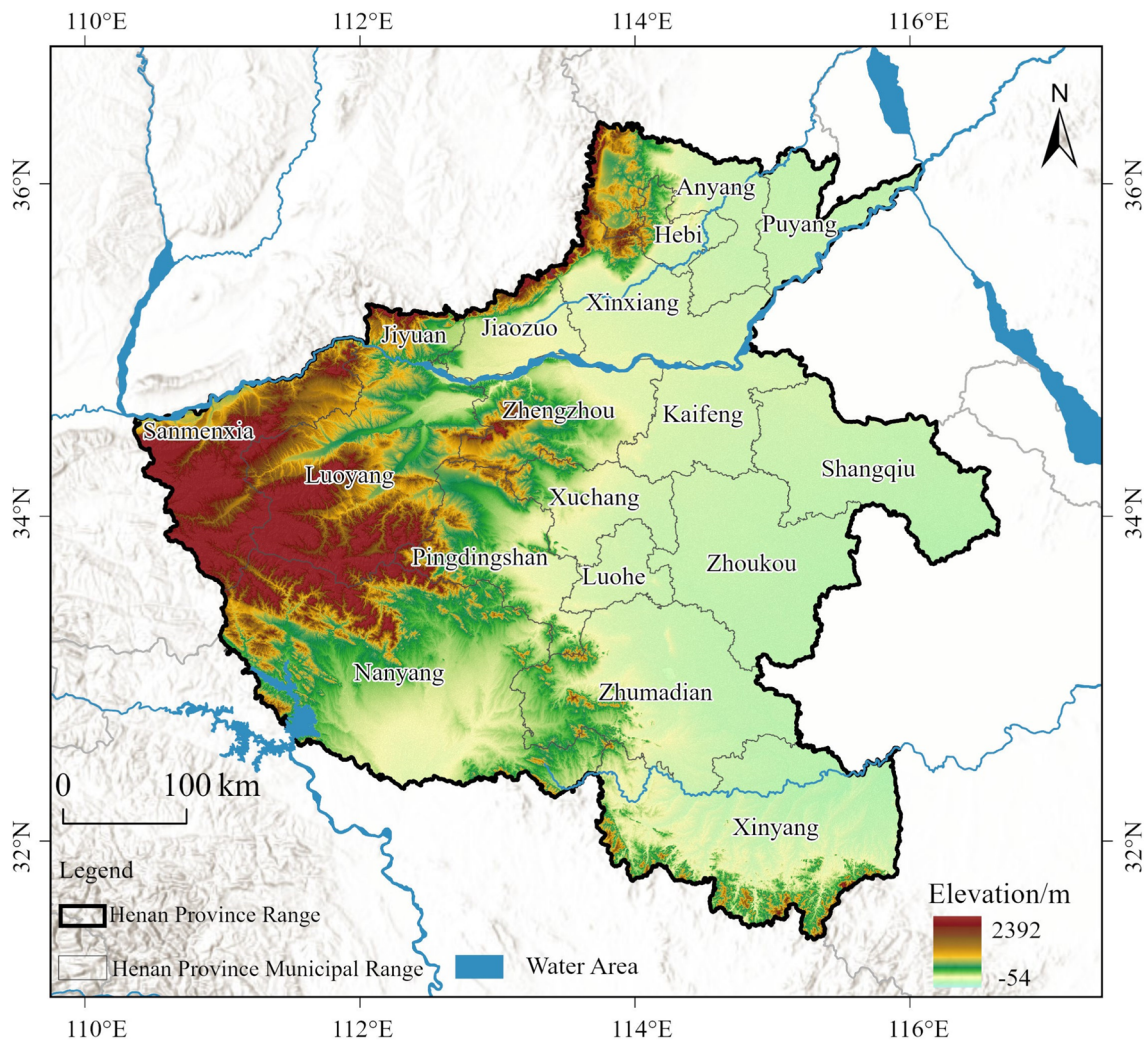
Fig. 1 The location of study area

Province," it explicitly requires carbon reduction as the key direction, promote the overall green transformation of economic and social development, and accelerate the construction of a strong ecological province. Therefore, more detailed research on the carbon budget and carbon balance is of great practical value to promote regional ecological civilization construction.

Data and processing

The study took 158 counties (cities, districts) administrative units in Henan Province as the research object. The main data included population, GDP, energy consumption, and agricultural production, which were sourced from the Statistical Yearbook of Henan Province and the statistical yearbooks of counties and cities. The data of 30m land use in Henan Province from 2000 to 2020 (at 5-year intervals) and administrative district data came from the Resource and Environment Science and Data Center of the Chinese Academy of Sciences (https://www.

resdc.cn/). To help with follow-up research, the land use data were recategorized into six types: cultivated land, forest land, grassland, water, construction land, and unused land. Note that particular counties and districts lack comprehensive data on energy consumption, to supplement to the corresponding data calculation value, this study utilizes the energy balance sheet of the whole society at the prefecture and city level, by calculating the ratio between the output value of secondary industry among counties and cities, and then obtaining the energy consumption of county-level indicators.

Research methods

Land use degree change

This paper is based on the existing research results (Wu et al. 2022; Zhuang and Liu 1997), and a composite index of land

use degree was obtained by assigning hierarchical values to each land type. Following is the calculating formula:

$$La = \sum L_j \times U_j \qquad (1)$$

where *La* is the composite index of land use degree, ranging from [100~400]; L_j is the grading index of the *j*th land use type; and U_j is the proportion of the graded area of the *j*th land use type (Table 1).

Calculation of the carbon budget

The carbon budget refers to the relative relationship and equilibrium between carbon sources and sinks brought on by all natural and human activities over a certain period (generally 1 year). It includes three linked systems: intra-system carbon flow, horizontal carbon flux, and vertical carbon exchange (Zhao and Liu 2015). According to the current status of land use and related research (Lv and Liu 2019; Mo and Wang 2021), the county carbon budget calculation system of Henan Province established in this study included both carbon emissions from human activities and carbon absorption of natural ecosystems. Carbon emissions from human activities mainly came from construction land and agricultural land. Construction land included energy consumption and population respiration, while agricultural land included agricultural production activities and livestock respiration. The main part of carbon absorption in the ecosystem includes cultivated land, forest land, grassland, and water area.

Carbon emission accounting

1. Carbon emissions from agricultural land

Cultivated land both absorbs and emits carbon, making it a carbon sink and source at the same time. Agricultural land is a carbon source, and the input of different agricultural resources in agricultural production activities, which accounts for the majority of the carbon. (Wen et al. 2022). Therefore, as the carbon emission measurement indicators of agricultural production activities, the total power of agricultural machinery, consumption of chemical fertilizer, consumption of chemical pesticides, use of plastic film for agriculture, effective irrigation area, and sown area of farm crops were chosen. Following is the calculating formula:

$$CE_{agr} = \sum A_j \times \delta_j \qquad (2)$$

Table 2 Greenhouse gas emission coefficient of livestock

Breeds	Emission factor of CH$_4$ (kg/unit)		Emission factor of N$_2$O (kg/unit)
	Intestinal fermentation	Fecal excretion	Fecal excretion
Hogs	1	3.5	0.53
Cattle	55	2	0.34
Sheep and goats	5	0.16	0.33
Poultry	—	0.02	0.02

where CE_{agr} is the carbon emission of agricultural production activities. A_j and δ_j are the carbon indicators and carbon emission coefficients of the *j*th agricultural production activity. Among them, the carbon emission coefficients of agricultural machinery, fertilizer, pesticide, agricultural film, effective irrigation, and sown area of farm crops were 0.18 kg/kWh, 0.89 kg/kg, 4.93 kg/kg, 5.19 kg/kg, 266.47 kg/ha, and 16.47 kg/ha, respectively.

Other agricultural land is primarily used for animal husbandry, where the carbon emissions originate from livestock enteric fermentation and manure management (Hu and Wang 2010). In this paper, hogs, cattle, sheep, and poultry were selected as the research objects to estimate the carbon emissions from animal husbandry. Following is the calculating formula:

$$CE_{an} = CE_{CH_4} + CE_{N_2O}$$
$$= \sum_{k=1}^{n} \left(M_k \times [(I_k + F_k)] \times C_{CH_4} + N_k \times C_{N_2O} \right) \qquad (3)$$

where CE_{an}, CE_{CH4}, and CE_{N2O} are the carbon emissions of animal husbandry, methane, and nitrous oxide. M_k is the number of the *k*th livestock. I_k and F_k are the methane carbon emission factors of livestock enteric fermentation and manure excretion (Table 2). N_k is the nitrous oxide carbon emission factor of livestock. C_{CH4} and C_{N2O} are standard carbon conversion coefficients, and their values are 6.82 and 81.27.

2. Carbon emissions from construction land

Major sources of carbon emissions on construction land are energy use and human breathing (Liu et al. 2018). In this research, industrial fossil energy consumption was adopted to indirectly estimate carbon emissions of energy use, mainly

Table 1 Grading index of land use degree

Land use type	Cultivated land	Forest land	Grassland	Water area	Construction land	Unused land
Grading index	3	2	2	2	4	1

considering 11 energy types including coal, coke, gasoline, kerosene, diesel, fuel oil, natural gas, liquefied natural gas, liquefied petroleum gas, electricity, and heat. Based on China Energy Statistical Yearbook and *IPCC Guidelines for National Greenhouse Gas Inventories*, the discounted conversion factors were converted from physical units to the coal equivalent and carbon emission coefficient in Henan Province (Table 3). Following is the calculating formula:

$$CE_{con} = C_e + C_p = \sum \left(Q_i \times E_i \times \delta_i \right) + P \times \varepsilon \tag{4}$$

where CE_{con}, C_e, and C_p denote carbon emissions of construction land, energy consumption, and human respiration, respectively. Q_i, E_i, and δ_i sequentially represent total energy consumption, conversion factors from physical units to the coal equivalent and carbon emission coefficient of the ith energy type. P is the resident population, ϵ is the average per capita carbon emission coefficient of 0.079 tC/a.

Carbon absorption accounting

According to the relevant studies (Ding et al. 2022; Lai et al. 2016) and the characteristics of land use carbon absorption in Henan Province, the direct carbon emission coefficient was used to measure the carbon absorption of cultivated land, forest land, grassland, water area, and unused land. Following is the calculating formula:

$$CS = \sum C_t = \sum S_t \times M_t \tag{5}$$

where CS is the total amount of carbon absorption, C_t is the carbon emission of land use category, S_t is land use t category area, and M_t is the carbon emission coefficient of land use category. The carbon emission coefficients of cultivated land, forest land, grassland, water area, and unused

Table 3 Carbon emission coefficient of energy categories

Item	Conversion factor	Carbon emission coefficient	Unit
Coal	0.7143	0.7559	tC/t
Coke	0.9714	0.8550	tC/t
Gasoline	1.4714	0.5538	tC/t
Kerosene	1.4714	0.5714	tC/t
Diesel oil	1.4571	0.5921	tC/t
Fuel oil	1.4286	0.6185	tC/t
Natural gas	1.3300	0.5390	tC/t
Liquefied natural gas	1.7572	0.3548	tC/10^4m^3
Liquefied petroleum gas	1.7143	0.8458	tC/10^4m^3
Electricity	0.1229	0.7330	kgC/kwh
Heat	0.0341	0.2600	kgC/kwh

land were 0.013, 0.581, 0.021, 0.0248, and 0.0005 t/ha, respectively.

Economic contribution coefficient of carbon emissions

The variability of regional carbon emissions in an economic perspective was measured using the economic contribution coefficient of carbon emissions, reflecting the magnitude of regional carbon productivity (Lu et al. 2012). Following is the calculating formula:

$$ECC = \frac{G_i}{G} \Big/ \frac{CE_i}{CE} \tag{6}$$

where G_i and G stand for the ith county's and Henan Province's GDP, and CE_i and CE are the total land use carbon emissions of the ith county and Henan Province. If $ECC>1$, it indicated that the economic contribution of the region was higher than the contribution of carbon emissions, and the region had higher carbon productivity and energy utilization efficiency. If $ECC<1$, it indicated that the region had low carbon productivity and energy utilization efficiency.

Ecological support coefficient of carbon absorption

The ecological support coefficient of carbon absorption can measure the equity of carbon ecological capability contribution from an ecological perspective and reflects the magnitude of regional carbon sink capacity (Li et al. 2023). Following is the calculating formula:

$$ESC = \frac{CS_i}{CS} \Big/ \frac{CE_i}{CE} \tag{7}$$

where CS_i and CS stand for the ith county's and Henan province's respective total carbon absorptions. If ESC > 1, it meant that carbon emissions were outpacing carbon absorption in the area, and the ecosystem had a high carbon absorption capacity. If $ESC < 1$, it meant that the carbon absorption capacity of this region was low.

Carbon footprint of land

The carbon footprint evolved out of the ecological footprint, which is employed to explain amounts of bio-productive land that is needed to absorb carbon dioxide produced by human economic activity. (Wu et al. 2014). It can reflect the impact of social production and the regional ecological support capacity of nature. In this paper, we use net ecosystem production (NEP) to represent the regional carbon absorption capability and to calculate the required land area for cultivated land, forest land and grassland ecosystems, namely the carbon footprint. Following is the calculating formula:

$$Cf = CE_i \times \left(\frac{P_r}{NEP_r} + \frac{P_f}{NEP_f} + \frac{P_g}{NEP_g} \right) \qquad (8)$$

$$Ec = CS_i \times \left(\frac{P_r}{NEP_r} + \frac{P_f}{NEP_f} + \frac{P_g}{NEP_g} \right) \qquad (9)$$

$$Ed = Cf - Ec \qquad (10)$$

where Cf is the carbon footprint, Ec is the ecological carrying capability, Ed is the ecological deficit. P_r, P_f, and P_g are the proportion of carbon absorption of cultivated land, forest land and grassland, respectively. NEP_r, NEP_f, and NEP_g are the carbon absorption capability of cultivated land, forest land, and grassland, respectively, with the coefficients of 4.05, 3.8096, and 0.9482 t/ha in order.

Entropy weight assignment method

The entropy value method is an objective assignment method, its principle is that in the process of index evaluation, the weight is determined according to the amount of information reflected by the variation degree of each index value, which can avoid the deviation caused by subjective factors (He et al. 2021). Following is the calculating formula:

$$e_j = -\frac{1}{\ln n} \sum x_{ij} \times \ln x_{ij} \qquad (11)$$

$$w_j = \frac{1 - e_j}{m - \sum e_j} \qquad (12)$$

$$D_j = \sum x_{ij} \times w_j \qquad (13)$$

where e_j is the information entropy of the jth indicator; w_j is the weight of the jth indicator; D_j is the comprehensive evaluation value of the jth region; x_{ij} is the standardized value of the indicator; m is the number of evaluation indicators; and n is the number of study areas.

Results

Overall evolution of carbon budget

Evolution of land use pattern

The primary land uses in Henan Province were cultivated land and forest land, which combined made up about 78% of the study area's total area (Table 4). Next came construction land, which made up about 12% of the study area, followed by grassland, water area, and unused land. In general, from 2000 to 2020, the trend in land use mainly showed a large rise in construction land and water, a large decline in cultivated land, and a slight reduction in forest land, grassland, and unused land (Table 5, Fig. 2). The amount of cultivated land having the property of double carbon decreased by 2678.05 km² over the past 20 years, and the reduction was the largest from 2000 to 2005, at 856.42 km². The amount of forest land and grassland, which were the most important carbon sinks, decreased by 53.82 km² and 63.24 km², respectively, and the decline rate was relatively stable. As the most important carbon source, the amount of construction land raised by 2354.43 km², with the largest increase from 2010 to 2015 reaching 1280.03 km². The evolution of land use patterns directly affected the regional combination of carbon sources/sinks, which leads to the change of total carbon emissions from land use. The comprehensive level of land use can reflect the degree of human interference with land resources (Zhu et al. 2019) and represents the potential of regional land resources. It was clear that the comprehensive level of land use increased during the study period since the value of the comprehensive degree of land use in 2020 (288.92) was greater than that in 2000 (287.68).

Table 4 Henan Province area and percentage of land use type from 2000 to 2020

Year		Cultivated land	Forest land	Grassland	Water area	Construction land	Unused land
2000	Area (km²)	105,898.38	27,048.50	8985.26	3795.56	19,556.73	52.27
	Proportion (%)	64.05	16.36	5.43	2.30	11.83	0.03
2005	Area (km²)	105,041.97	27,025.25	8935.91	4163.78	20,148.24	21.37
	Proportion (%)	63.53	16.35	5.40	2.52	12.19	0.01
2010	Area (km²)	104,784.96	27,015.31	8965.07	4678.82	19,870.87	21.37
	Proportion (%)	63.38	16.34	5.42	2.83	12.02	0.01
2015	Area (km²)	104,029.59	27,005.40	8929.22	4199.28	21,150.90	21.97
	Proportion (%)	62.92	16.33	5.40	2.54	12.79	0.01
2020	Area (km²)	103,220.33	26,993.68	8922.02	4267.21	21,911.16	21.97
	Proportion (%)	62.43	16.33	5.40	2.58	13.25	0.01

Table 5 Amplitude of change in land use of Henan Province from 2000 to 2020

Type of land use	2000—2005 year		2005—2010 year		2010—2015 year		2015—2020 year	
	Area (km^2)	Rate of change (%)	Area (km^2)	Rate of change (%)	Area (km^2)	Rate of change (%)	Area (km^2)	Rate of change (%)
Cultivated land	− 856.42	− 0.81	− 257.01	− 0.24	− 755.36	− 0.72	− 809.26	− 0.78
Forest land	− 23.24	− 0.09	− 9.94	− 0.04	− 9.91	− 0.04	− 11.72	− 0.04
Grassland	− 49.34	− 0.55	29.16	0.33	− 35.86	− 0.40	− 7.19	− 0.08
Water area	368.22	9.70	515.04	12.37	− 479.54	− 10.25	67.93	1.62
Construction land	591.52	3.02	− 277.37	− 1.38	1280.03	6.44	760.25	3.59
Unused land	− 30.90	− 59.12	0	0	0.60	2.80	0	0
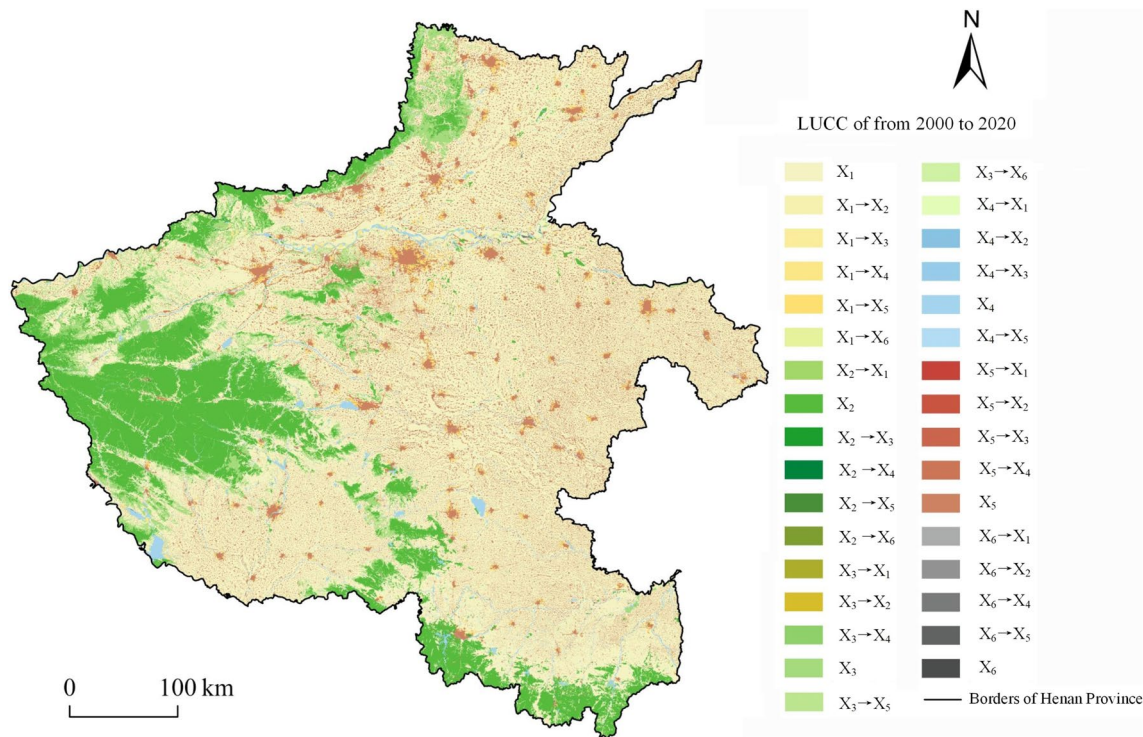
Fig. 2 Land use change of Henan Province from 2000 to 2020. X_1, cultivated land; X_2, forest land; X_3, grassland; X_4, water area; X_5, construction land; X_6, unused land

General characteristics of carbon budget

In Henan Province, the total carbon emissions raised quickly from 9343.47 to 96,463.7 t between 2000 and 2020 (Table 6). Construction land has always contributed more than 80% of carbon emissions, and it is expected to grow further. The total carbon absorption in Henan Province decreased slowly from 1737.47×10^4 to 1731.84×10^4 t in 2000–2020. Forest land has the strongest carbon sink effect and the carbon absorption was always above 1568×10^4 t, accounting for approximately 90% of the total. From 2000 to 2020, the net carbon emissions of Henan Province increased

from 7606×10^4 to 94731.88×10^4 t, and the overall change trend was consistent with carbon emissions. The primary carbon source and sink in the research area were, respectively, forest land and construction land, but the carbon emission from construction land far exceeded the carbon absorption of forest land. Moreover, the amount of construction land continued increasing, and that of forest land decreased significantly, which eventually result in the rapid rise in net carbon emissions of Henan Province. Additionally, the acceleration of industrialization and urbanization caused an increase in energy consumption by industrial

Table 6 Carbon emissions from different land categories of Henan Province from 2000 to 2020

Year	Carbon sources (10^4 t)			Carbon sinks (10^4 t)						Net carbon emission (10^4 t)
	Construction land	Cultivated land	Carbon emissions	Cultivated land	Forest land	Grass land	Water area	Unused land	Carbon absorption	
2000	7495.68	1847.80	9343.47	137.67	1571.52	18.87	9.41	0.003	1737.47	7606.00
2005	13,834.64	2085.66	15,920.30	136.55	1570.17	18.77	10.33	0.001	1735.81	14,184.49
2010	54,313.29	2265.14	56,578.43	136.22	1569.59	18.83	11.60	0.001	1736.24	54,842.19
2015	66,820.28	1876.23	68,696.51	135.24	1569.01	18.75	10.41	0.001	1733.42	66,963.09
2020	94,875.56	1588.16	96,463.72	134.19	1568.33	18.74	10.58	0.001	1731.84	94,731.88

enterprises, which was also a key factor in the Henan Province's significant increase in carbon emissions.

Spatial pattern changes of the carbon budget

Spatial and temporal patterns of carbon emissions

The areas with higher carbon emissions were mostly located in the center of Henan Province, especially in Zhengzhou and its surrounding areas (Fig. 3). In 2000, the biggest value area of carbon emissions in Henan Province was Gongyi (422.54×10^4 t), while the lowest value area was Longshi (3×10^4 t). Most areas were below 100×10^4 t. In 2010, carbon emissions had increased by 486.73% compared with 2000. The highest value area was still Gongyi (2369.99×10^4 t), and the lowest value area was Hubin (3.82×10^4 t). The areas with carbon emissions below 100×10^4 t was significantly reduced. In 2020, the number of areas with carbon emissions above 1000×10^4 t accounted for 20% in this research area, and the carbon emissions of each county had increased substantially. All the districts and counties in Henan Province showed different degrees of growth in carbon emissions during the 20 years. From 2000 to 2010, except for Fengquan, Runan, Xiangfu, Hubin, and Weibin, the carbon emissions of areas in Henan province displayed a rising tendency. From 2010 to 2020, the carbon emissions from the areas of the center and south grew further, with an increase of more than 8000×10^4 t in Guancheng.

Spatial and temporal patterns of carbon absorption

The regions with high carbon absorption in Henan Province were most located in the western Funiu Mountain, the southern Tongbai Mountain–Dabie Mountain and the northern Taihang Mountain regions (Fig. 4). From 2000 to 2020, the carbon absorption of all regions in Henan Province was less than 156×10^4 t, along with a generally stable changing trend. The areas with the largest carbon absorption were always Xixia, which is located in the Funiu Mountain area, followed by Lushi, Luanchuan, and Songxian. The areas with lower carbon absorption were the municipal districts with rapid urban expansion, such as Shilong in Pingdingshan, Weidu in Xuchang, and Chanhe in Luoyang.

Spatial and temporal patterns of net carbon emissions

According to data from 2000 to 2020, the net carbon emissions of land use in 158 counties (cities, districts) of Henan Province were calculated (Fig. 5). In 2000, the largest net carbon emission locations were mostly in Henan Province's central-eastern plain. From 2000 to 2010, the total net carbon emissions grew rapidly, and the high-value areas extended to the northwest. From 2010 to 2020, net carbon
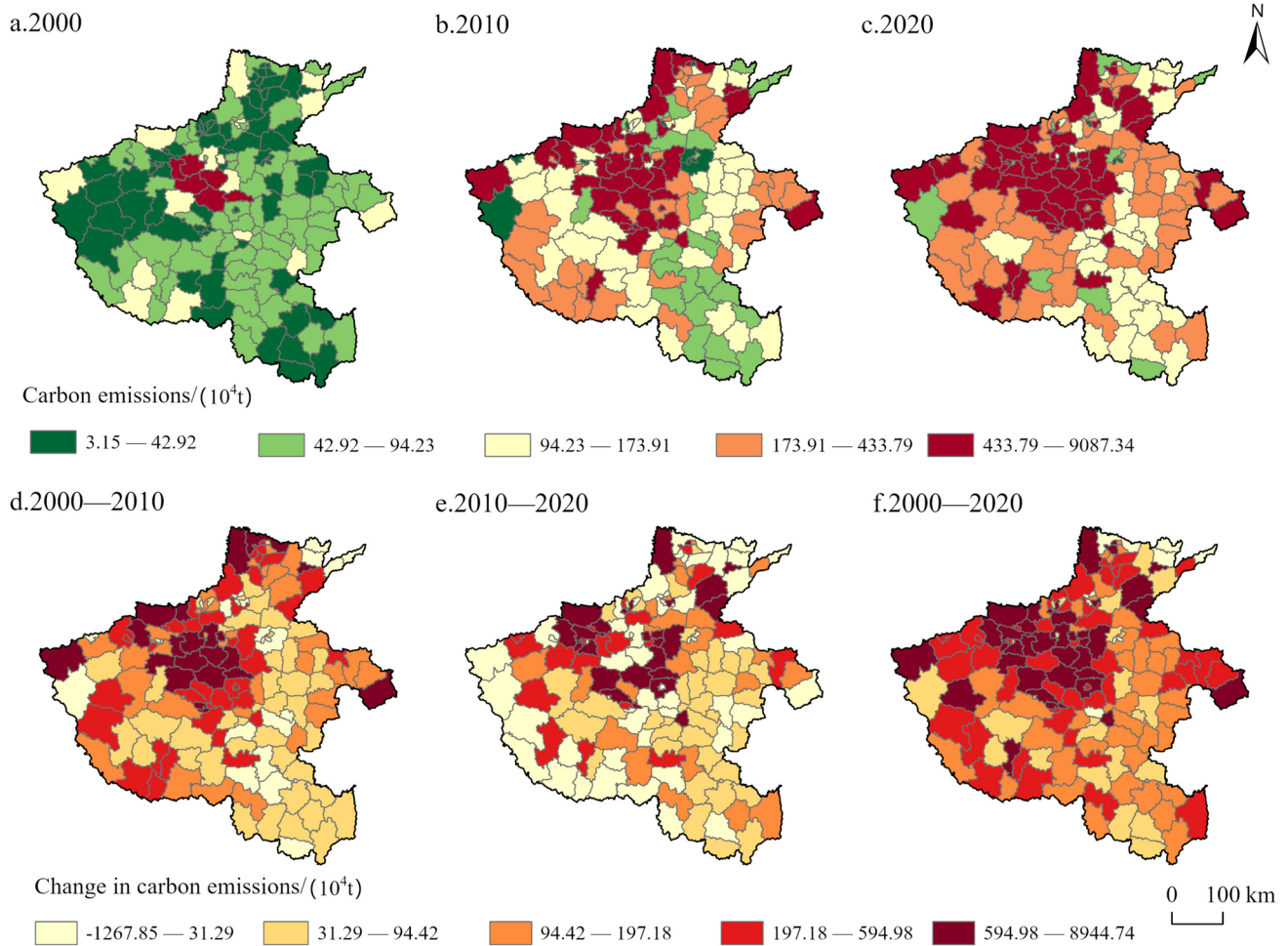
Fig. 3 Land use carbon emissions spatial pattern in Henan Province from 2000 to 2020

emissions further increased and exceeded 5000×10^4 t in Zhongmou, Xinzheng, Guancheng, and Jiyuan. Overall, the net carbon emissions of Henan Province increased rapidly while the internal differences gradually increased over the previous 20 years. The high-value areas spread from the periphery of Zhengzhou, to the north–central part of the province, and the net carbon emissions around Nanyang, sub-central city of the province, accelerated. In addition, the majority of areas in Henan Province have positive net carbon emissions, demonstrating that the overall land use carbon emissions in Henan Province were much higher than carbon absorption, and net carbon emissions had been steadily rising due to industrialization and urbanization. As a result, the internal carbon system mechanism was unable to maintain a carbon balance through its own carbon cycle.

Carbon balance zoning and spatial optimization

Selection and construction of the partitioning indicator system

The carbon budget of land use in Henan Province showed obvious geographical disparities, and there were also and there were also differences in the degree of regional economic growth and resource carrying capacity, which leads to a certain degree of economic-ecological imbalance in the region. Therefore, it is necessary to fully consider the difference of land use carbon budget and its reflected attribute characteristics in the carbon balance zoning, and make use of the regional characteristics according to local conditions, so as to achieve the coordination of ecological protection and economic development.

In this paper, according to the carbon balancing target and the variations in regional characteristics, the main factors affecting the carbon balance were categorized into four aspects: natural attributes, economic factors, ecological
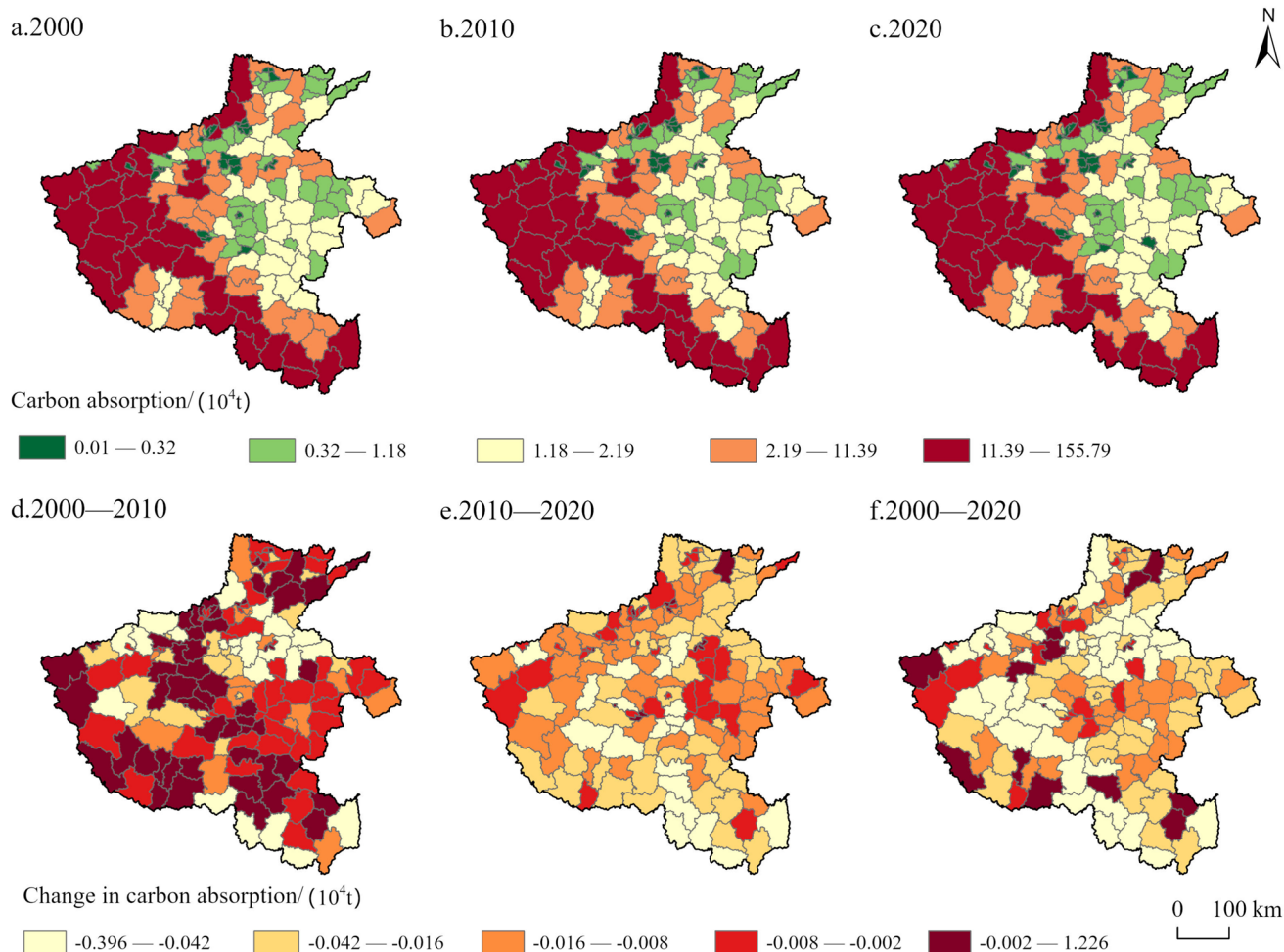
Fig. 4 Land use carbon absorption spatial pattern in Henan Province from 2000 to 2020

environment, and resource structure. The specific characterization indicators included (1) natural attributes, land use carbon budget is one of the important indicators reflecting the characteristics of regional carbon emissions, and different stages of industrialization and urbanization will be directly reflected in the changes of land use carbon budget. Thus, this paper selects land use carbon emissions (CE), carbon absorption (CS) and net carbon emissions (NCE) as indicators to reflect natural attributes. (2) economic factors, the economic contribution rate of carbon emissions (ECC) measure the productivity of regional land use carbon emissions from an economic perspective, which can characterize the economic attributes of carbon balance zoning. (3) ecological environment, carbon sink resources play a great role in maintaining the regional carbon balance. The ecological carrying coefficient of carbon absorption (ESC), land carbon footprint (Cf), ecological carrying capacity (Ec), and ecological deficit (Ed) can reflect the status of the regional carbon sinks to a certain extent, which can characterize the attributes of ecological environment. (4) Resource

structure, land use is one of the important factors affecting regional carbon emissions, and different land use degrees will also cause differences in the combination of regional carbon sources and sinks, and then affect the regional carbon balance. Therefore, this paper selects the composite index of land use degree (La) to characterize the attributes of resource structure.

On the basis of the analysis of the impact factors of carbon balance and the selection principle of the characterizing indicators, the average weight of each indicator over the study period was determined using the entropy weight approach and provided a comprehensive allocation to obtain the spatial distribution of natural, economic, ecological, and resource evaluation values (Table 7, Fig. 6). The evaluation value of natural attributes indirectly reflected the balance of the land use carbon budget, and the majority of the high-value regions were found in the west, north, and southeast of Henan Province. However, the evaluation value of the eastern region was low; thus, it is important to closely monitor the achievement of energy
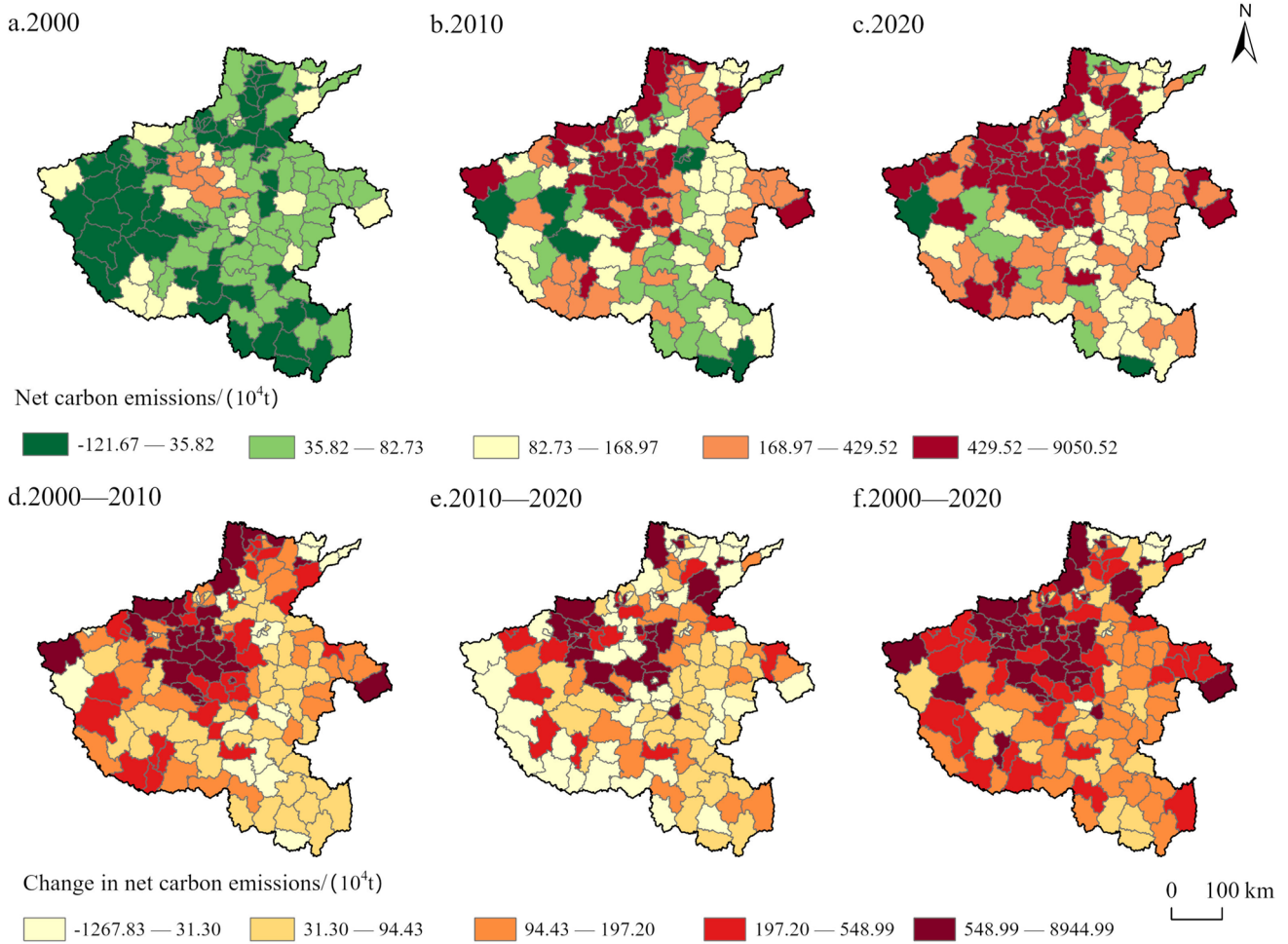
Fig. 5 Land use net carbon emissions spatial pattern in Henan Province from 2000 to 2020

efficiency and emission reducing actions to maintain a carbon balance. The high-value regions of economic factor attributes were mostly distributed in the east and southeast of Henan Province, where the economic efficiency and energy utilization efficiency were relatively high. However, the western and central regions were relatively low, indicating that the model of economic development has problems such as excessive consumption of resources, and that measures such as industrial transformation and upgrading were needed to improve the efficiency of

resource utilization. The high-value regions of ecological attributes were concentrated in the western and southern mountainous areas of Henan Province, which has rich forest resources and superior ecological conditions; thus, the regional carbon absorption capacity was high. The resource structure attribute indirectly reflected the degree of human exploitation of land resources, and the high-value locations were primarily found in Henan Province's eastern region, where production activities were intense, the land resources were strongly disturbed, and the carbon sink resources were relatively scarce.

Table 7 Attributes and weights of carbon balance partition indicators

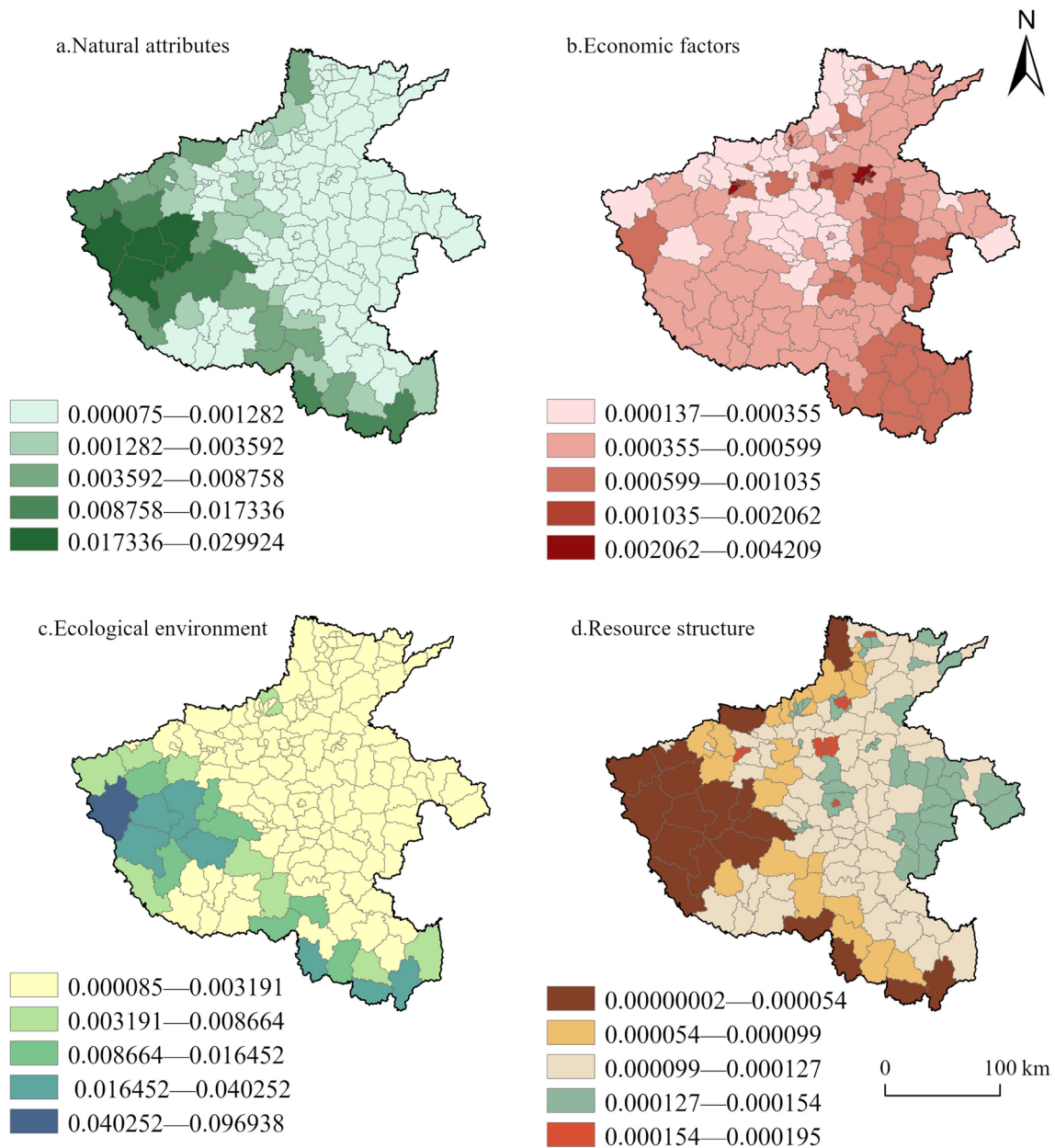| Category	Natural attribute			Economic factor	Ecological environment				Resource structure
Indicator	CE	CS	NCE	ECC	ESC	Cf	Ec	Ed	La
Attribute	-	+	-	+	+	-	+	-	+
Weighted average	0.005	0.333	0.005	0.095	0.447	0.005	0.088	0.005	0.018

Fig. 6 Spatial distribution of natural, economic, ecological, and resource evaluation values in Henan Province from 2000 to 2020
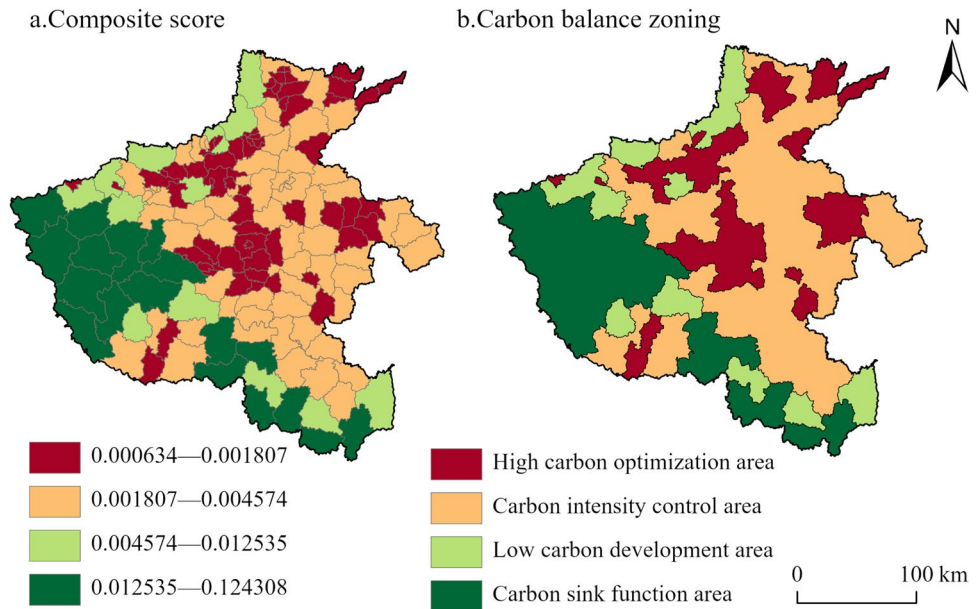
Carbon balance zoning and optimization ideas

According to the evaluation values of natural attributes, economic factors, the ecological environment, and the resource structure, nine indicators including carbon emissions, carbon absorption, net carbon emissions, carbon emission economic contribution coefficient, carbon absorption ecological carrying coefficient, carbon footprint, ecological carrying capacity, ecological deficit, and comprehensive land use index were considered comprehensively. From the perspective of regional carbon balance and low-carbon coordinated development, the final

score of the carbon balance zone was obtained using the comprehensive index method, which was divided into carbon sink functional areas, low-carbon development areas, carbon intensity control areas, and high-carbon optimization areas (Table 8, Fig. 7). Carbon balance zoning takes regional low-carbon development as the goal orientation, the comprehensive evaluation of carbon balance as the basis for delineation, and regional advantages as the role positioning, and then proposes the optimal development direction of each region in the future, so as to give full play to its maximum potential for economic development, agricultural production and ecological protection.

Table 8 Carbon balance partition results

Classification	Region
Carbon sink function area	Lushi, Xixia, Songxian, Xinxian, Luanchuan, Nanzhao, Shihe, Shangcheng, Luoning, Neixiang, Lushan, Tongbai, Ruyang, Luoshan, Xichuan, Lingbao, Queshan, Biyang
Low carbon development area	Shanzhou, Fangcheng, Guangshan, Jiyuan, Gushi, Yiyang, Mianchi, Linzhou, Xiuwu, Huixian, Gongyi, Pingqiao, Zhenping
Carbon intensity control area	Xigong, Longting, Yicheng, Weihui, Wugang, Jianxi, Dengfeng, Gulou, Tanghe, Xin 'an, Suiping, Zhengyang, Ruzhou, Zhongmu, Shunhe, Huangchuan, Xixian, Zhongzhan, Yexian, Neihuang, Huaibin, Fugou, Dengzhou, Boai, Yuzhou, Sheqi, Xiangfu, Taikang, Minquan, Runan, Xihua, Xiping, Fengqiu, Jiefang, Yuanyang, Yuwangtai, Shangshui, Xincai, Kixian, Huaxian , ShangCai, QinYang, Dangcheng, Anyang, jinshui, Pingyu, lankao, Yanjin, Huaiyang, Qixian, Chanhe, Wolong, Yucheng, Yongcheng, Laocheng, Xiayi, Luyi, Luolong, Shenqiu, Yichuan, Weishi, Xinmi, Erqi, Puyang, Tongxu
High carbon optimization area	Zhecheng, Jiaxian, Xiangcheng, Qingfeng, Xiangcheng, Ningling, Xinye, Qibin, Wuyang, Suixian, Yanling, Junxian, Changyuan, Yanshi, Suiyang, Wancheng, Chuanhui, Baofeng , Nanle, Beiguan, Taiqian, Huiji, Xingyang, Jian'an, Yuanhui, Hubin, Heshan, Weibin, Mengjin, Huojia, Wuzhi, Tangyin, Linying, Jili, Liangyuan, Yancheng, Wen Feng, Fanxian, Guancheng, Mengzhou, Xinzheng, Wenxian, Zhaoling, Weidu, Hualong, Weidong, Fengquan, Hongqi, Yindu, Xinxiang, Changge, Zhongyuan, Macun, Shanyang, Longan , Shangjie, Xinhua, Shancheng, Muye, Zhanhe, Shilong, Yima

Fig. 7 Carbon balance partition results

a.Composite score

- 0.000634—0.001807
- 0.001807—0.004574
- 0.004574—0.012535
- 0.012535—0.124308

b.Carbon balance zoning

- High carbon optimization area
- Carbon intensity control area
- Low carbon development area
- Carbon sink function area

0 　　 100 km

1. The carbon sink functional areas showed concentrated and contiguous distribution, primarily found in the hilly region of the Tongbai-Dabie Mountains and the western Henan Mountains, including 18 counties such as Lushi, Xixia, Songxian, Xinxian, and Luanchuan. These areas had a large extent of forest land and grassland, a high ecological carrying capacity, low ecological pressure, and an outstanding carbon sink function. Moreover, they had an absorption effect on the carbon spillover from other regions, which could be beneficial in lowering the province's overall carbon emissions. In the process of future development, we should focus on the conservation and increase of forest and grassland extent, and environmental protection should be prioritized to strengthen the

carbon absorption ability of the ecological land. What is more, special attention is needed for ecological protection, to avoid problems such as ecological deterioration brought by over-development by restraining and regulating human production activities and achieving harmony between humans and nature. For example, as an important part of the ecological functional area of biodiversity protection, water-holding, and soil-water conservation in the Dabie Mountains, Luoshan has a unique natural endowment and green development foundation. In the future, on the one hand, Luoshan should insists on ecological priority and green development, improve the mechanism of natural forest protection and ecological public welfare forest construction, and implements eco-

logical protection to the end. On the other hand, it needs to strictly control the ecological red line in the process of development, relying on the rich local resources to develop eco-industry.

2. The northern portion of Taihang Mountain and the southern portion of Dabie Mountain were the key distribution sites for low-carbon development, including 13 counties such as Shanzhou, Fangcheng, Guangshan, Jiyuan, and Gushi. The land cover of this type of area was mainly cultivated land and forest land, with good natural conditions, a more adequate foundation for green development, and a balance between the economic contribution rate and ecological carrying capacity. Future construction should fully utilize the assets of the location to create low-carbon industries. Firstly, we should aim to strengthen the construction of agricultural infrastructure, develop agriculture with regional characteristics, and improve the level of agricultural production. Secondly, we should strengthen the protection of forest resources, water conservation and soil conservation, and actively develop low-carbon tourism. Furthermore, economic forests can be planted to improve farmers' income, transform regional ecological advantages into economic advantages, and achieve harmonious progress between ecological benefits and economic development. For example, Xiuwu is not only a high grain-producing area in the country, but also rich in ecological culture and tourism resources, in recent years, the residential accommodation industry has a good development momentum. In the future, it should use residential accommodation industry to drive characteristic agriculture, combine green ecology with rural tourism, and ultimately achieve low-carbon and green development through excellent ecological environment.

3. The central region in this research region and the Nanyang basin were the main distribution locations for the carbon intensity control areas, including 65 counties such as Xigong, Longting, Yicheng, Weihui, and Wugang. This type of region had a good foundation for economic development, the land cover was mainly cultivated land and construction land, a concentration of energy companies, and large carbon emissions from industrial energy. However, the carbon sink resources were insufficient, and the carbon absorption capacity of regional ecosystems was weak. In the course of future development, it is essential not only to enhance the comprehensive management of land use and control development intensity, but also to guide the deep processing of agricultural products and improve the unit production capacity and industrial added value of crops. Meanwhile, future development should be oriented to green production and environmental protection, controlling the growth speed of high emission industries, adjusting the energy consumption structure, and attaining energy consumption efficiency improvements and functionally intensive production to optimize and upgrade the industrial structure. For example, as a typical resource-oriented city, Gongyi has the inherent advantage of developing green and low-carbon energy industry. The future should take the green development of industrial transformation as the guide, promote industrial energy saving and carbon reduction, actively introduce new energy enterprises, inject "green kinetic energy" into the development of manufacturing industry, and realize the green development of energy.

4. The high carbon optimization regions were primarily located in the municipal districts of the province and their surrounding areas, including 62 districts such as Zhecheng, Jiaxian, Xiangcheng, Qingfeng, and Xiangcheng. This type of region had rapid economic development, a dense population, and a high degree of industrialization and urbanization, leading to high total carbon emissions and a large regional land carbon footprint. The local carbon sink resources were far from offsetting the carbon emissions, resulting in a serious ecological deficit. In the process of future development, we should control the process of urbanization expansion, focus on urban greening, and strengthen the comprehensive management of the ecological environment. The area's dominant position in the regional economy should be fully used, make use of its own radiation capacity to carry out the transfer and division of high-carbon industries and drive the industrial development of the surrounding areas, while enhancing its economic contribution to carbon emissions. Finally, we should invest more in scientific research and implement eco-friendly, low-carbon technologies, and effectively protect carbon sink resources including effective protection of carbon sink resources such as woodlands and grasslands. In addition, the construction of urban green space should be strengthened to reduce regional net carbon emissions and form a carbon compensation mechanism with carbon sink areas to alleviate the pressure of carbon sources in the province. For example, as the core area of Zhengzhou's economic and social development, Jinshui is rich in talent and innovation resources, and a high proportion of modern service industries. In the future, it should focus on low-carbon technology, low-carbon industry and low-carbon community, innovate emission reduction mechanisms and systems, integrate the concept of green development into the whole process of economic and social development, and systematically push forward the green and low-carbon transformation in all fields.

Conclusions and discussion

Conclusions

In this research, 158 counties (cities and districts) in Henan Province were used as research units to analyze the overall spatiotemporal evolution of the land use carbon budget. Carbon balance zoning was carried out by considering the differences in regional attribute characteristics, and a differentiated regional optimization scheme was proposed. The conclusions of this research were as below:

1. From 2000 to 2020, the carbon emissions from land use in Henan Province demonstrated a growing tendency, rising from 9343.47×10^4 to 96463.72×10^4 t, with the highest proportion from carbon emissions of construction land. The carbon absorption of land use was steady, remaining at approximately 1735×10^4 t over the years. The share of forest land carbon absorption was always the highest. The total carbon emissions of Henan Province were always higher than the total carbon absorption, the net carbon emissions grew rapidly; therefore, the province experienced a carbon deficit. Overall, there was a serious carbon imbalance.

2. The carbon budget of land use in Henan Province showed obvious spatial differentiation, and the spatial distribution of the carbon emissions indicated high values in the center and low values in the surrounding areas. The central region, represented by Zhengzhou and its surrounding areas, had a dense population, and a relatively large construction land area, and thus it had a high carbon emission capacity. The distribution of high values in the west and low values in the east was evident in the spatial distribution of carbon absorption. The western and southern mountainous areas were dominated by forest land, with sufficient ecological capacity, high vegetation coverage, rich carbon sink resources, and high carbon absorption capacity. In general, the net carbon emissions were mostly positive and increasing in all regions of Henan Province, with high-value areas located in the central part and low-value regions located in the southwest.

3. From the land use carbon budget accounting, combined with nine index attributes including regional carbon emissions, carbon absorption, net carbon emissions, carbon source economic contribution and carbon sink ecological role, a comprehensive evaluation of Henan Province was established in this study. The counties of Henan Province were divided into carbon sink functional areas, low-carbon development areas, carbon intensity control areas, and high carbon optimization areas. According to the characteristics of each district, an optimization plan

in terms of ecology, economy, resources, and environment was proposed for each county. Under the current situation, Henan Province should reasonably allocate land resources and strengthen forest land protection to enhance the regional carbon sink capacity, while taking measures to save energy and reduce emissions, adjust the structure of the three major industries, and gradually approach the strategic goal of low-carbon and sustainable development.

Discussion

Based on the socio-economic and land use data of Henan Province from 2000 to 2020, this study analyzed spatiotemporal characteristics of the carbon budget in Henan Province. The research found that the carbon emissions generated from areas with concentrated carbon sources tended to rise continuously as the construction land area in Henan Province continued to grow. The growth rate of forest land, which was the important carbon sink resource in the province, could not keep the regional carbon cycle in a stable balance. As a result, for a very long period, Henan Province has been experiencing a carbon deficit, which is consistent with previous research conclusions in the same region (Wang et al. 2016). In terms of carbon balance zoning, the zoning standards of previous studies (Wei and Chen 2021; Xu et al. 2022) were often based on the economic contributive coefficient of carbon emissions and the ecological support coefficient of carbon absorption. However, in this study a more comprehensive consideration of zoning results was undertaken by constructing a zoning index system, spatially dividing counties in Henan Province based on differences in regional attributes, and selecting more diverse indicators. With the fast increase of industrialization and urbanization in Henan Province, this study found that the regional low-carbon development goal faces important challenges. The proposed carbon balance zoning and optimization scheme explored controlling carbon emissions, carbon spillover, and carbon dissipation, which can be coordinated with the overall optimization orientation and municipal units optimization strategy of Henan Province to formulate a more comprehensive regional high-quality development strategy, and also provides ideas for related research.

However, there were some shortcomings in this study. Because the current technical standards of carbon emission accounting are still not fully unified, this paper adjusted some of the carbon emission coefficients on the basis of the other studies to fit the actual situation of the carbon cycle system in Henan Province. However, owing to the differences in surface vegetation cover and energy use intensity within different regions, there were some errors in the calculation of land use carbon emissions. In

addition, because of the influence of adjustments to the county administrative divisions, the statistical approach of indicators in the statistical yearbook had some changes, which led to deficiencies in the quality of county data used in this study.

Declarations

Ethics approval Not applicable.

Consent to participate All authors agree to participate.

Consent for publication All authors agree to publish.

Competing interests The authors declare no competing interests.

References

Cai Z, Cheng L, Li T, Zheng X, Wang L, Han S, Wang K, Qu X, Jiang F, Zhang Y, Zhu J, Long S, Sun Y, Jia B, Yuan W, Zhang T, Zhang Q, Xie J, Zhu J et al (2021) Key scientific and technical issues in Earth system science towards achieving carbon neutrality in China. Bull Chin Acad Sci 36(5):602–613. https://doi.org/10.16418/j.issn.1000-3045.20210402002

Chen Y, Qiao Y, Lu H, Xia J (2022) Variation characteristics of water-carbon-ecological footprint in urban agglomerations in the middle reaches of the Yangtze River and their equilibrium analysis. Acta Ecol Sin 42(4):1368–1380. https://doi.org/10.5846/stxb202010182654

China Energy Editorial Department (ceed) (2020) Strive to peak carbon dioxide emissions by 2030 and strive to achieve carbon neutrality by 2060. Energy China 42(10):1

Dai X, Shen R, Wang J, Wang J, Zhou J (2021) Change detection of land use in Henan Province based on GEE remote sensing cloud platform. J Geomat Sci Techn 38(03):287–294. https://doi.org/10.3969/j.issn.1673-6338.2021.03.011

Ding M, Yang X, Zhao R, Zhang Z, Xiao L, Xie Z (2022) Spatial pattern optimization of national territory under carbon neutrality target: theoretical framework and practical strategies. J Nat Resour 37(5):1137–1147. https://doi.org/10.31497/zrzyxb.20220503

Fang J, Guo Z, Piao S, Chen N (2007) Estimation of carbon sinks of terrestrial vegetation in China from 1981 to 2000. Sci China (6):804–812

Hang Y, Huang J, Liu D (2020) Linking climate change and socioeconomic development to urban land use simulation: analysis of their concurrent effects on carbon storage. Appl Geogr 115(C). https://doi.org/10.1016/j.apgeog.2019.102135

Hao Q, Huang M, Bao G (2011) An overview and comparative study of carbon emission accounting methods. Chinese. J Environ Manag (4):51–55. https://doi.org/10.16868/j.cnki.1674-6252.2011.04.011

He D, Hou K, Wen J, Wu S, Wu Z (2021) A coupled study of ecological security and land use change based on GIS and entropy method—a typical region in Northwest China, Lanzhou. Environ Sci Pollut Res 29:6347–6359. https://doi.org/10.1007/s11356-021-16080-x

Hu X, Wang J (2010) Estimation of greenhouse gas emissions from livestock and poultry in China. Trans Chin Soc Agric Eng 26(10):247–252. https://doi.org/10.3969/j.issn.1002-6819.2010.10.042

Huang D, Yan H, Chi H, Geng X, Shao Q (2020) Temporal and spatial variation characteristics of NPP in farmland ecosystems in Jianghan Plain, 2000-2015. J Nat Resour 35(4):845–856. https://doi.org/10.31497/zrzyxb.20200408

Lai L, Huang X, Yang H, Chuai X, Zhang M, Zhong T, Thompson JR (2016) Carbon emissions from land-use change and management in China between 1990 and 2010. Sci Adv 2(11). https://doi.org/10.1126/sciadv.1601063

Li J, Huang X, Wu C, Zhou Y, Xu G (2015) Spatial heterogeneity analysis of influencing factors of carbon emissions in China. Econ Geogr 35(11):21–28. https://doi.org/10.15957/j.cnki.jjdl.2015.11.004

Li L, Xia Q, Dong J, Zhang B (2023) County-level carbon ecological compensation of Wuhan Urban Agglomeration under carbon neutrality target: based on the difference in land use carbon budget. Acta Ecol Sin 43(7). https://doi.org/10.5846/stxb202204130976

Liu M, Meng J, Liu B (2014) Research progress on carbon emission accounting methods at home and abroad. Trop Geogr 34(2):248–258. https://doi.org/10.13284/j.cnki.rddl.002502

Liu Q, Wang S, Zhang W, Li J, Kong Y (2019) Examining the effects of income inequality On CO_2 emissions: evidence from non-spatial and spatial perspectives. Appl Energy 236:163–171. https://doi.org/10.1016/j.apenergy.2018.11.082

Liu Y, Zhang Z, Zhou Y (2018) Efficiency of construction land allocation in China: an econometric analysis of panel data. Land Use Policy 74. https://doi.org/10.1016/j.landusepol.2017.03.030

Liu Z, Huang X, Lu X, Li S, Qi X (2022) China's carbon neutrality path prediction under the shared social economic paths. Acta Geograph Sin 77(9):2189–2201. https://doi.org/10.11821/dlxb202209004

Lu J, Huang X, Dai L, Chen Z, Li Y (2012) Fairness analysis of carbon emissions from provincial energy consumption in China based on spatio-temporal scale. J Nat Resour 27(12):2006–2017

Lv Q, Liu H (2019) Spatio-temporal evolution characteristics of carbon emissions at the county level in Beijing-Tianjin-Hebei: Based on DMSP/OLS night lighting data. J Beijing Inst Technol 21(6):41–50. https://doi.org/10.15918/j.jbitss1009-3370.2019.7493

Mo H, Wang S (2021) Spatial-temporal pattern evolution and spatial effect mechanism of county carbon emissions in the Yellow River Basin. Sci Geogr Sin 41(8):1324–1335. https://doi.org/10.13249/j.cnki.sgs.2021.08.003

Peng W, Zhou J, Xu X, Luo H, Zhao J, Yang C (2016) Carbon emissions and carbon footprint effects in Sichuan Province based on land use change. Acta Ecol Sin 36(22):7244–7259. https://doi.org/10.5846/stxb201506111188

Piao S, He Y, Wang X, Chen F (2022) Estimation of China's terrestrial ecosystem carbon sink: methods, progress and prospects. Sci China Earth Sci 65(4). https://doi.org/10.1007/S11430-021-9892-6

Wang S, Xie Z, Wang Z (2021) Spatio-temporal evolution and influencing factors of county-level carbon emissions in China. Acta Geograph Sin 76(12):3103–3118. https://doi.org/10.11821/dlxb202112016

Wang X, Lu F, Qin Y, Sun Y (2016) Spatial-temporal variation of carbon sources and carbon sinks in Henan Province. Prog Geogr 35(8):941–951

Wei Y, Chen S (2021) Spatial correlation and carbon neutrality of land use carbon emissions in Fujian Province. Acta Ecol Sin 41(14):5814–5824. https://doi.org/10.5846/stxb202006301705

Wen S, Hu Y, Liu H (2022) Measurement and spatial–temporal characteristics of agricultural carbon emission in China: an internal structural perspective. Agriculture 12(11). https://doi.org/10.3390/AGRICULTURE12111749

Wu L, Tian Q (2022) A study on carbon ecological security and ecological compensation in China under the goal of carbon neutrality. Geogr Res 41(1):149–166. https://doi.org/10.11821/dlyj020210778

Wu L, Zhou J, Xie B et al (2022) Spatiotemporal differences of land use pattern between mountainous areas and basin areas at township scale: a case study of Yuxi City. Front Environ Sci 10:1029917. https://doi.org/10.3389/fenvs.2022.1029917

Wu W, Jiang J, Gao Q, Jiang H (2014) Spatio-temporal pattern of China's carbon emissions and carbon footprint from 2001 to 2009. Acta Ecol Sin 34(22):6722–6733. https://doi.org/10.5846/stxb201302100259

Xia C, Chen B (2020) Urban land-carbon nexus based on ecological network analysis. Appl Energy 276. https://doi.org/10.1016/j.apenergy.2020.115465

Xu Y, Guo N, Ru K, Fan W (2022) Spatial zoning characteristics and optimization strategies of Fujian province from the perspective of carbon neutrality. Chin J Appl Ecol 33(2):500–508. https://doi.org/10.13287/j.1001-9332.202201.016

Yang Y, Shi Y, Sun W, Chang J, Zhu J, Chen L, Fang J (2022) Terrestrial carbon sinks in China and around the world and their contribution to carbon neutrality. Sci China Life Sci. https://doi.org/10.1007/S11427-021-2045-5

Yi B, Han J, Zhou X, Yang F, Meng X, Cao W, Huang L, Xiang W (2015) Spatial-temporal pattern of regional carbon source carbon sinks: a case study of the Yangtze River Delta region. Chin J Appl Ecol 26(4):973–980. https://doi.org/10.13287/j.1001-9332.2015.0011

Yue T, Li M, Chen H, Long R, Wang Y (2022) Hot spots and evolution trends of carbon neutral research: based on scientific knowledge graph. Resour Sci 44(4):701–715. https://doi.org/10.18402/resci.2022.04.05

Zhang X, Ma D, Wang T (2020) Carbon emission efficiency and influencing factors of animal husbandry in Heilongjiang Province. Heilongjiang Anim Husb Sci Vet Med (4) 7-12+147. https://doi.org/10.13881/j.cnki.hljxmsy.2019.07.0017

Zhang Y, Chen X (2022) Spatial and nonlinear effects of new-type urbanization and technological innovation on industrial carbon dioxide emission in the Yangtze River Delta. Environ Sci Pollut Res Int 30(11). https://doi.org/10.1007/S11356-022-24113-2

Zhao Q, Zhou Y, Fang Q, Yi M (2023) Spatial-temporal evolution of carbon emissions and its influencing factors in China central region. Acta Sci Circumst 43(02):354–364. https://doi.org/10.13671/j.hjkxxb.2022.0252

Zhao R, Huang X, Peng B (2012) Carbon cycle and carbon balance analysis of Nanjing urban system. Acta Geograph Sin 67(6):758–770

Zhao R, Liu Y (2015) Theoretical and empirical study on regional carbon revenue and expenditure accounting. Science Press, Beijing (chapter 1)

Zhu W, Li S, Zhu L (2019) Provincial ecosystem service footprint flow and its influencing factors in China. Geogr Res 38(2):337–347. https://doi.org/10.11821/dlyj020171049

Zhuang D, Liu J (1997) Modeling of regional differentiation of land-use degree in China. Chin Geogr Sci 7(4):302–309. https://doi.org/10.1007/s11769-997-0002-4