



OPEN ACCESS

EDITED BY

Mariarosaria Lombardi,
University of Foggia, Italy

REVIEWED BY

Adnan Abbas,
Nanjing University of Information Science and
Technology, China
Kai Zhang,
Shandong University of Finance and
Economics, China

*CORRESPONDENCE

Weichun Gao,
✉ gaoweichun123@163.com

RECEIVED 12 June 2024

ACCEPTED 03 October 2024

PUBLISHED 14 October 2024

CITATION

Gao W, He W, Zhang J, Chen Y and Wei Z (2024)
County-level carbon emissions in the
guanzhong area of Shaanxi province: towards
achieving China's dual carbon goals.
Front. Environ. Sci. 12:1447728.
doi: 10.3389/fenvs.2024.1447728

COPYRIGHT

© 2024 Gao, He, Zhang, Chen and Wei. This is
an open-access article distributed under the
terms of the [Creative Commons Attribution
License \(CC BY\)](#). The use, distribution or
reproduction in other forums is permitted,
provided the original author(s) and the
copyright owner(s) are credited and that the
original publication in this journal is cited, in
accordance with accepted academic practice.
No use, distribution or reproduction is
permitted which does not comply with these
terms.

County-level carbon emissions in the guanzhong area of Shaanxi province: towards achieving China's dual carbon goals

Weichun Gao^{1,2*}, Wei He^{1,2,3}, Jun Zhang^{1,2}, Yifei Chen^{1,2} and Zheng Wei^{1,2}

¹Shaanxi Dijian Guantian Investment and Construction Co., Ltd., Baoji, China, ²Shaanxi Provincial Land Engineering Construction Group Co., Ltd., Xi'an, China, ³School of Water Resources and Hydropower, Xi'an University of Technology, Xi'an, China

China's rapid urbanization has significantly impacted carbon emissions in rural areas, driving the need for region-specific carbon management strategies to achieve the country's dual carbon goals. However, previous research has primarily focused on large urban centers, leaving a gap in understanding the spatial and temporal patterns of carbon emissions at the county level in rural regions. This study focuses on the Guanzhong region of Shaanxi Province and develops a county-level carbon emission accounting system based on geographic, socio-economic, and land-use data. The carbon emissions are categorized into energy, industrial processes, agriculture, and waste management. Key findings indicate that industrial and residential sectors are the primary contributors to carbon emissions, with Xi'an being the largest emitter. Carbon emission intensity follows a ranking of Xi'an < Weinan < Baoji < Xianyang < Tongchuan. Spatial patterns show a "core-edge" distribution, with higher emissions in urban centers and lower emissions in rural areas. The study also highlights the carbon sink potential in the southern Qinling National Park. This research provides a valuable framework for rural low-carbon development and offers critical insights for policymakers aiming to balance carbon reduction and economic growth in rural China.

KEYWORDS

county scale, carbon emissions, carbon balance, influence factor, guanzhong urban agglomeration

1 Introduction

Greenhouse gases from agricultural, livestock and industrial sectors is the main reasons of climate change (Abbas et al., 2022b; Abbas et al., 2022a; Abbas et al., 2023; Ullah et al., 2022; Abam et al., 2023; Elahi et al., 2024a; Elahi et al., 2024b). Global climate change has always been one of the most pressing problems faced by the world (Sage, 2020). Controlling greenhouse gas emissions to slow down the pace of global warming has become a societal consensus. Climate change and sustainable development have become urgent and major issues requiring immediate attention (Ucal and Xydis, 2020; Zurek et al., 2022). As a result, governments and international organizations globally have proposed goals for carbon reduction and low-carbon development (Caetano et al., 2020; Wimbadi and Djalante, 2020; Li et al., 2022). China, the world's largest developing country, has committed to peaking carbon emissions by 2030 and striving to achieve carbon neutrality before 2060 (Sun et al.,

2022; Zhao, 2022). China's rapid urbanization process has led to a significant increase in carbon emissions in rural areas. Recent studies have shown that between 2000 and 2015, rural carbon emissions increased by 4.2% annually, primarily due to increased infrastructure development, modernization of agriculture, and the adoption of urban energy consumption patterns in rural communities (Zhu et al., 2021; Guo et al., 2023). The construction of rural residential buildings and the expansion of rural transportation networks further contributed to this rise in emissions (Zhang et al., 2020; Xu et al., 2024).

At present, extensive research has been conducted on low-carbon ecological rural areas (Song et al., 2020; Wang C. et al., 2020; Wang et al., 2021), primarily focusing on carbon emission accounting (Harris et al., 2020), carbon emission spatialization (Sun et al., 2024), carbon emission spatiotemporal patterns (Lin et al., 2021), and low-carbon ecological rural evaluation models (Yu et al., 2023). This is because through the systematic accounting and evaluation of carbon emissions in rural areas, the current status and trends can be precisely determined. Such data provides a basis for formulating scientific emission reduction measures and policies. Meanwhile, rural carbon emission accounting helps to identify key sources of carbon emissions and potential areas for emission reduction, optimize resource allocation, and improve energy efficiency (Zhang et al., 2014). In addition, establishing and improving a rural carbon emission accounting system can enable rural areas to participate in national and regional carbon trading markets, realize economic benefits through carbon trading, and promote the green and low-carbon transformation of rural areas.

Comprehensive research on regional carbon emissions, both domestically and internationally, mainly utilizes the emission factor method for calculation (Shan et al., 2017). Based on the scale differences of the research areas, it is observed that carbon emission accounting research mainly focuses on macro scales such as national and provincial regions, cities, or micro scales such as individual buildings. However, research on carbon emission accounting at the village scale is scarce (Lai et al., 2022). There are significant differences and interactions among regions regarding carbon emission intensity. In optimizing resource allocation, adjusting industrial structure, and promoting the application of clean energy, agriculture is an important area for carbon emission reduction, and regions must consider regional characteristics when formulating carbon emission reduction policies (Chen et al., 2020). In addition, the spatiotemporal pattern of carbon emissions helps identify hotspots of carbon emissions. It also provides a scientific basis for evaluating the effectiveness of carbon reduction policies and formulating more effective carbon reduction strategies (Wang Y. et al., 2020). The low-carbon ecological rural evaluation model can not only effectively reduce greenhouse gas emissions, but also promote sustainable development of the rural economy and improve the quality of life of rural residents (Zhang et al., 2021). Although numerous studies have achieved certain results, there are still problems in rural research, such as the synchronous growth of carbon emissions caused by infrastructure construction, the significant driving effect of rural industrial development on carbon emissions, and the serious lack of low-carbon management and research capabilities in rural areas, resulting in relatively weak green and low-carbon awareness (Zhou et al., 2020). Therefore, promoting agricultural and

rural emission reduction and carbon sequestration during the implementation of the rural revitalization strategy is a practical requirement and top priority for achieving the "dual carbon" goal.

However, existing research on quantitatively calculating greenhouse gas emissions in spatial regions mainly focuses on the national, provincial, and large city levels (Guo et al., 2023), or the individual building level. Research at the village level is scarce, which is not conducive to low-carbon rural development and planning. In addition, the Guanzhong region has actively responded to the national low-carbon development strategy in recent years (Guo, 2023), committing to rural low-carbon development and ecological civilization construction. Preliminary results have been achieved through measures such as promoting agricultural greening, optimizing the rural energy structure, and utilizing agricultural waste resources. There is relatively little research on the Guanzhong region. The Guanzhong region still faces challenges such as a single industrial structure, limited application of green and low-carbon technologies, and outdated rural energy facilities (Yu et al., 2022). In the context of accelerating urbanization, addressing the major challenge of achieving sustainable economic and social development while protecting the ecological environment is a prerequisite for promoting the low-carbon ecological rural evaluation system and planning strategies.

In order to address these issues, the Guanzhong region of Shaanxi Province is examined in this paper, and based on the analysis of its geography, natural conditions, land use status, and socio-economic conditions, a county-level carbon emission accounting system and carbon balance zoning evolution are meticulously constructed. This study offers theoretical and practical guidance for rural development in this region and similar areas under the dual carbon background, and also has important theoretical and practical value for promoting low-carbon development and ecological civilization construction in China and globally.

2 Materials and methods

2.1 Overview of the study area

The object selected for this paper is located in the Guanzhong area of Shaanxi Province, positioned in the central part of Shaanxi Province and named after its location west of Hangu Pass. The geographical coordinates are approximately from 107° 40'E to 110° 10'E, and 33° 42'N to 35° 29'N. The Guanzhong Plain constitutes a part of the Loess Plateau in China. Due to the historical alluvial effect of the Yellow River, it has become a fertile plain area and is known as the "800 mile Qinchuan". The Guanzhong region is bordered by the Liupan Mountains to the north, the Qinling Mountains to the south, the Longdong Mountains to the west, and the Wei River to the east, making it a transportation hub connecting the three major geographical regions of east, west, and north. The geographical location of the Guanzhong region endows it with unique strategic and economic value. It has been a battleground for military strategists and a political center in Chinese history since ancient times. It is also a focus of economic and cultural development, having a profound impact on the development of ancient Chinese

civilization. Now, with the promotion of the national “Belt and Road” initiative (Zhu et al., 2024), the Guanzhong region has once again demonstrated its important strategic position, becoming an important transportation and economic corridor connecting China’s eastern coast and western inland, and even connecting Asia and Europe. Therefore, examining the Guanzhong region as the research object is both representative and highly significant.

2.2 Data sources

The data used in this paper include DEM, basic geographic information, land use status, and socio-economic data. Among them, DEM data come from the geospatial data cloud platform; basic geographic information data mainly include water systems, residential areas, roads, etc., sourced from the National Geographic Information Resource Catalog Service System. The data on the current state of land use are sourced from the land use change survey data of Huayi District for 2010, 2015, and 2020; socio-economic data include population density data, POI data, GDP data, and energy consumption data, which are sourced from data platforms such as WorldPop, the Resource and Environmental Science and Data Center, as well as statistical yearbooks.

2.3 Research methods

2.3.1 Carbon emission accounting checklist

The IPCC has published a series of technical guidelines for carbon emission accounting methodology based on relevant standards and guidelines (Amon et al., 2021). Based on two major categories of natural emission sources and socio-economic emission sources, carbon emission sources are subdivided into six sectors: energy, industrial processes, solvent and other product use, land use change and forest land, agriculture, and waste. Further detailed emission projects are provided for each sector. Subsequently, a new inventory guide was published, which merges carbon sources into four sectors: energy activities, industrial processes and product use, agriculture, forestry and other land use, and waste.

Energy: The main source of carbon emissions from human activities is energy activities, which account for 80% of the total greenhouse gas emissions from human activities (Zhong et al., 2021). According to the guidelines, energy activities are divided into four parts: fixed source combustion, mobile source combustion, fugitive emissions, and carbon dioxide transportation, injection, and geological storage. Energy activities specifically involve the energy industry, manufacturing, transportation, coal mining, oil and gas extraction and processing, and other aspects (Mehedi et al., 2022).

Industrial processes and product use: They mainly include carbon emissions from production processes in industries such as mining, chemical, metal, non-energy products, electronics, and other product manufacturing and use (Chen et al., 2024). The greenhouse gas emissions in product use mainly involve the use of ozone-depleting substances and fluoride substitutes.

Agriculture, forestry, and other land use: Land use change and management can affect ecosystem processes, biological processes, and physical processes, leading to carbon and nitrogen conversion,

which in turn affects greenhouse gas flows (Noda et al., 2024). Agriculture, forestry, and other land use mainly involves forest land, cultivated land, grassland, wetland, residential land, other land use, livestock and poultry manure management, and the application of lime and urea. Subsequently, estimation methods for greenhouse gas emissions and absorption in wetland drainage, wetland return, coastal wetlands, and constructed wetlands for sewage treatment were included.

Waste: Waste mainly includes urban solid waste, sludge, industrial waste, and other waste (Khan et al., 2022). During the waste disposal process, methane, carbon dioxide, non-methane volatile organic compounds, and relatively small amounts of nitrous oxide, nitrogen oxides, and carbon monoxide are produced.

The carbon emission accounting boundary of this study is limited to the administrative divisions within the study area, and the carbon exchange occurring within and outside the study area due to atmospheric activities falls outside the scope of this study’s accounting. Based on the energy activities of the Guanzhong Plain urban agglomeration and the availability of data, the carbon emission accounting system of this study is depicted in Figure 1.

2.3.2 Carbon emission accounting methods

This paper calculates carbon emissions using a carbon emission accounting checklist, incorporating the four aforementioned sectors. **Energy:** The calculation of carbon emissions from fossil fuels is shown in Equation 1 (Meng and Niu, 2011):

$$E_e = AC \times CF \times CC \times COF \quad (1)$$

where E_e is the carbon emissions from energy use, AC is the apparent consumption, CF is the conversion factor for converting fuel to energy units (TJ) based on net calorific value, CC is the carbon content, and COF is the carbon oxidation factor. $EF = CF \times CC \times COF$, and Equation 1 can be simplified to Equation 2 (Liu et al., 2024):

$$E_e = AC \times EF \quad (2)$$

where EF is the carbon emission factor.

Table 1 provides the default values for commonly used fossil fuel-related parameters. Industrial processes and product use: Carbon emissions accounting for industrial processes and product usage mainly focuses on industries such as cement, steel, raw aluminum, and flat glass. Among these, the carbon emissions from the production process of cement clinker represent the most significant part of the carbon emissions from industrial processes and product usage (Na et al., 2024). Table 2 presents carbon emission products and emission factors for industrial processes.

Agricultural carbon emissions: Using the carbon emission coefficient method released by the IPCC and combining existing research results to calculate agricultural carbon emissions, the calculation is shown in Equation 3 (Meng et al., 2024).

$$C = \sum C_i = \sum T_i \times \delta_i \quad (3)$$

where C is the total agricultural carbon emissions, C_i is the carbon emissions of each source category, T_i is the activity level of each source category, δ_i is the carbon emission coefficient for each source category.

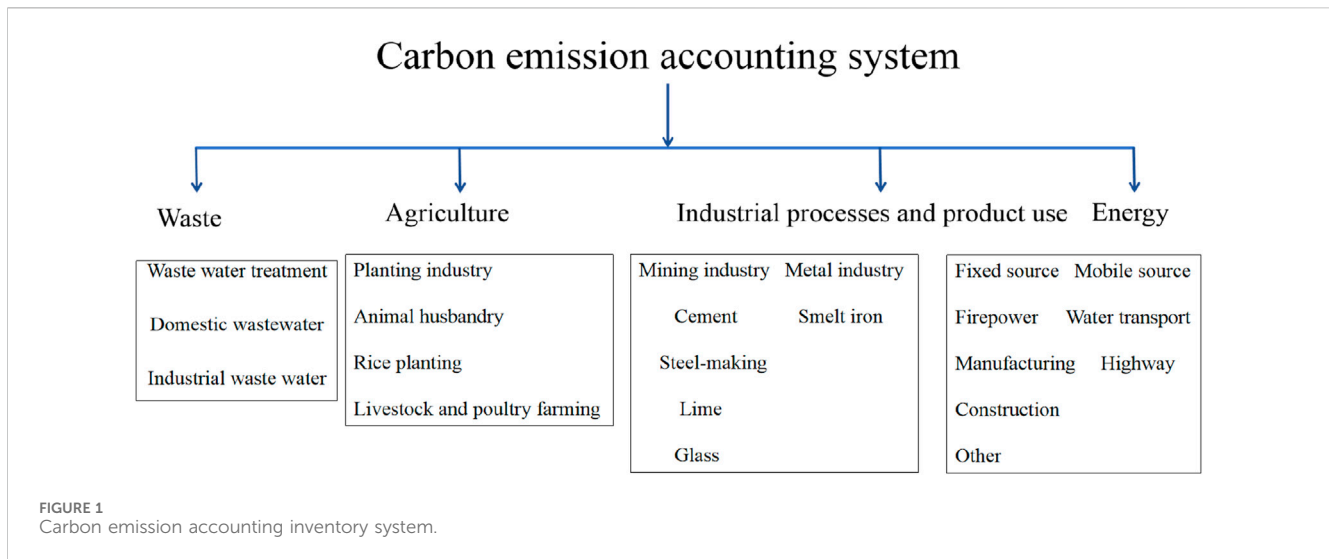


Table 3 presents the carbon emissions from the planting and livestock industries, while Table 4 presents the agricultural carbon emission factors. Waste: Due to the availability of waste data, this paper only covers carbon emissions during the treatment process of industrial and domestic sewage treatment plants (Lv et al., 2022). The production of methane depends on the amount of degradable organic matter in wastewater. The commonly used parameters for determining the organic components of wastewater are Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD). The reporting frequency of BOD in domestic wastewater is higher, while COD is mainly used for industrial wastewater. This paper calculates the carbon emissions related to sewage based on data from sewage treatment plants. The reduction of BOD (or COD) can be obtained by the concentration of BOD (or COD) in the inlet and outlet of the sewage treatment plant. The calculation of carbon emissions during sewage treatment and carbon emissions into the environment is shown in Equation 4 (Liu et al., 2023).

$$CE_w = TOW \times B_0 \times MCF \quad (4)$$

where CE_w is the carbon emissions from sewage treatment, TOW is the total amount of organic matter in the wastewater in the inventory year, B_0 is the maximum CH_4 production, MCF is the methane correction factor. The default values are shown in Table 5.

3 Result and analysis

3.1 Carbon emission accounting and characteristics

The total carbon emissions of each city are shown in Table 6. Table 6 shows that the industrial and living sectors in each city exhibit high carbon emissions, while the agricultural sector demonstrates low carbon emissions. Xi'an has the highest total carbon emissions and is at a relatively high level in all sectors. The total carbon emissions are as follows: Xi'an (29.8978 million tons) > Baoji (9.837 million tons) > Weinan (7.2974 million tons) > Tongchuan (3.4849 million tons) > Xianyang (3.3163 million tons). Xi'an records the highest carbon emissions, especially in its domestic

and industrial sectors, which are 7.301 million tons and 13.4619 million tons, respectively. This is attributed to its population size and industrial activity intensity. The total carbon emissions of Xianyang and Baoji are relatively high, while the total carbon emissions of Tongchuan and Weinan are relatively low due to their smaller populations (Meng et al., 2023). The carbon emissions statistics for each city are shown in Figure 2.

As shown in the carbon emission structure in Figure 2, the agricultural carbon emissions of all cities are relatively low. Specifically, Tongchuan City has the lowest agricultural carbon emissions (259,000 tons), while Xianyang City has the highest agricultural carbon emissions (346,600 tons). The carbon emissions from daily life vary greatly among cities, with Xi'an having the highest carbon emissions (730.1 million tons), far higher than other cities. There are significant differences in industrial carbon emissions among cities, with Xi'an having the highest industrial carbon emissions (13.4619 million tons), followed by Xianyang (7.8736 million tons). The carbon emissions from waste in various cities are relatively low, with Xi'an having the highest (4.9785 million tons). In terms of carbon emissions from transportation, Xi'an has the highest (3.8923 million tons), followed by Xianyang (1.6865 million tons), and Tongchuan has the lowest (3.005 million tons). Further analysis of carbon emission intensity is presented in Table 7.

From the perspective of carbon emission intensity, the average carbon emission intensity of the Shaanxi section of the Guanzhong Plain urban agglomeration is 0.506 tons per 10,000 yuan. There are significant differences in carbon emission intensity among different cities, and the order of carbon emission intensity from low to high is: Xi'an < Weinan < Baoji < Xianyang < Tongchuan. The carbon emission intensity in Xi'an is the lowest, at 0.260 tons per 10,000 yuan, indicating that the amount of carbon dioxide emitted per unit of GDP in Xi'an is relatively low. The economic development is more focused on low-carbon industries and has higher energy utilization efficiency (Meng et al., 2023). Next is Weinan City, with a carbon emission intensity of 0.332 tons per 10,000 yuan. It has a relatively high carbon emission efficiency in economic development. Baoji City ranks third, with a carbon emission intensity of 0.359 tons per 10,000 yuan, slightly higher

TABLE 1 Default values for fossil fuels.

Type	Unit	Low calorific value CF(GJ/t)	Carbon content per unit calorific value CC (tC/GJ)	Carbon oxidation rate COF(%)
Anthracite	ton	20.304	27.49×10^{-3}	94
Bituminous coal	ton	19.570	26.18	93
Lignite	ton	14.080	28.00	96
Washed clean coal	ton	26.344	25.40	90
Other coal washing	ton	8.363	25.40	90
Briquette	ton	17.460	33.60	90
Other coal products	ton	17.460	33.60	90
Coke	ton	28.447	29.50	93
Crude oil	ton	41.816	20.10	98
Fuel oil	ton	41.816	21.10	98
Gasoline	ton	43.070	18.90	98
Diesel oil	ton	42.652	20.20	98
General kerosene	ton	44.750	19.60	98
Petroleum coke	ton	31.998	27.50	98
Other petroleum products	ton	41.031	20.00	98
Tar	ton	33.453	22.00	98
Crude benzene	ton	41.816	22.70	98
Liquefied natural gas	ton	41.868	17.20	98
Liquefied petroleum gas	ton	50.179	17.20	98
Coke oven gas	10,000 cubic meters	173.540	12.10	99
Blast furnace gas	10,000 cubic meters	33.000	70.80	99
Converter gas	10,000 cubic meters	84.000	49.60	99
Other gas	10,000 cubic meters	52.270	12.20	99
Natural gas	10,000 cubic meters	389.31	15.30	99
Refinery Gas	10,000 cubic meters	45.998	18.20	99
Closed calcium carbide furnace gas	10,000 cubic meters	111.190	39.51	99

TABLE 2 Carbon emission products and emission factors in industrial processes.

Product	Unit	EF (tC/t)
Cement clinker	ton	0.1417
Flat glass	10,000 weight box	29.4996
Lime	ton	0.2050
Pig iron	ton	0.0469
Crude steel	ton	0.0404

than Weinan City, but still at a relatively low level. Xianyang City ranks fourth, with a carbon emission intensity of 0.473 tons per 10,000 yuan. Although the carbon emission intensity of Xianyang City is lower than the average level of the Guanzhong Plain urban agglomeration, there is still room for improvement, and further optimization of the industrial structure is needed to improve energy efficiency. The carbon emission intensity in Tongchuan City is the highest, at 0.689 tons per 10,000 yuan. Tongchuan City emits the highest amount of carbon dioxide per unit of GDP, indicating that its industrial structure is biased, the energy structure is not clean enough, or its technological level needs to be improved.

TABLE 3 Agricultural carbon emission calculation indicators.

Index		Direct carbon emission coefficient	Indirect carbon emission coefficient	
Primary indicators	Secondary indicators	CO ₂	CH ₄	N ₂ O
Carbon emissions from agricultural materials (kg/kg ⁻¹)	chemical fertilizer	0.896	-	-
	pesticide	4.934	-	-
	Agricultural film	5.18	-	-
	diesel oil	0.5927	-	-
Carbon emissions from farmland soil (kg/hm ⁻¹)	wheat	2.5	-	-
	corn	2.532	-	-
	Oilseeds	0.95	-	-
	vegetable	4.21	-	-
	Melons and fruits	4.21	-	-
Carbon emissions from straw combustion (kg/kg ⁻¹)	wheat	13.557,852	-	-
	corn	32.7888	-	-
	rape	25.59384	-	-
Carbon emissions from livestock and poultry farming (kg/kg ⁻¹)	Large livestock	-	48.8	1.39
	Live pigs	-	4.5	0.53
	sheep	-	5.16	0.33
	rabbit	-	0.334	0.02
	poultry	-	0.02	0.02

TABLE 4 Agricultural carbon emission factor.

Straw burning	Combustion ratio	Grain grass ratio	Combustion efficiency	Carbon emission factor (CO ₂ kg/kg)
Wheat	13.4	1.1	0.63	1.46
Corn	22	1.2	0.92	1.35
Rape	14.4	1.5	0.82	1.445

TABLE 5 Default values for waste related emission factors.

B ₀		MCT	
(kg CH ₄ /kg BOD)	(kg CH ₄ /kg COD)	River and lake emissions	Concentrated oxygen consumption treatment plant
0.6	0.25	0.1	0.165

3.2 Overall carbon emission spatial pattern

The overall carbon emission distribution of the Guanzhong Plain urban agglomeration is shown in Figure 3.

Figure 3 shows that the spatial pattern of carbon emissions in the Shaanxi section of the Guanzhong Plain urban agglomeration exhibits “core-edge” and “layered agglomeration” characteristics, with significant differences in carbon emissions between urban and rural areas. Carbon emission cores are formed in the central areas of

cities such as Xi’an and Baoji. Weinan and Xianyang also exhibit higher carbon emissions, while the surrounding Guanzhong Plain is a region with lower carbon emissions. The southern Qinling National Park and the northern Loess Plateau are mainly rural areas, exhibiting the lowest total carbon emissions. This is because in the core areas, Xi’an and Baoji, as the core cities of the Guanzhong Plain urban agglomeration, have become the core areas of carbon emissions due to their dense population, concentrated industry, and frequent economic activities. The energy consumption,

TABLE 6 Total carbon emissions of each city.

City	Agriculture (10,000 tons)	Living (10,000 tons)	Industry (10,000 tons)	Waste (10,000 tons)	Traffic (10,000 tons)	Total
Tongchuan	25.90	62.32	167.14	63.08	30.05	348.49
Xianyang	28.45	216.16	787.36	131.01	168.65	1331.63
Weinan	31.72	75.58	359.35	172.83	90.26	729.74
Baoji	34.66	139.77	604.28	62.32	142.66	983.70
Xi'an	26.42	730.10	1346.19	497.85	389.23	2989.78

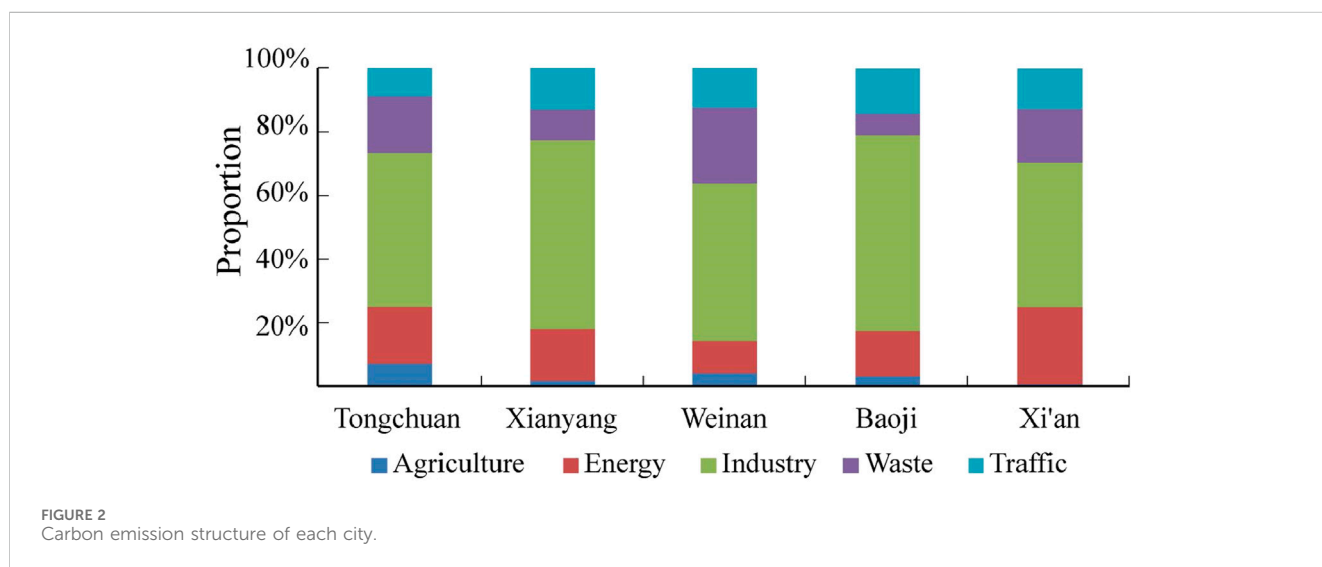


TABLE 7 Carbon emission intensity of each city.

City	Total carbon emissions (10,000 tons)	GDP (100 million yuan)	Carbon emission intensity (ton-10,000 yuan ⁻¹)
Tongchuan	348.49	505.55	0.689
Xianyang	1331.63	2817.55	0.473
Weinan	729.74	2201.13	0.332
Baoji	983.70	2743.1	0.359
Xi'an	2989.78	11,486.51	0.260

transportation, industrial production, and residential activities in these urban centers are the main sources of carbon emissions. In high-value areas, Weinan City and Xianyang City, as secondary cities, although their scale and economic activity intensity are not as high as Xi'an and Baoji, they still have high levels of carbon emissions. These cities play an important role in regional development, and their industrialization and urbanization processes have resulted in relatively high carbon emissions. In the lower value areas, the peripheral areas of the Guanzhong Plain have relatively low carbon emissions due to low population density and relatively fewer industrial activities. These regions may be predominantly agricultural, with relatively low energy consumption and carbon emission intensity. In the lowest value

areas, the Qinling National Park in the south and the Loess Plateau in the north have limited human activities due to the importance of natural protection and ecological restoration. These areas are mainly rural, resulting in the lowest total carbon emissions. However, when formulating regional carbon reduction strategies, it is important to consider this layered and clustered carbon emission spatial pattern, along with the development characteristics and carbon emission characteristics of different regions. To further analyze the carbon emission patterns of each sector, refer to Figure 4.

As shown in Figures 4, 4A shows a clustering distribution feature of high in the east and low in the west, with high agricultural carbon emissions in the Guanzhong Plain region. The spatial pattern of agricultural carbon emissions exhibits certain regional

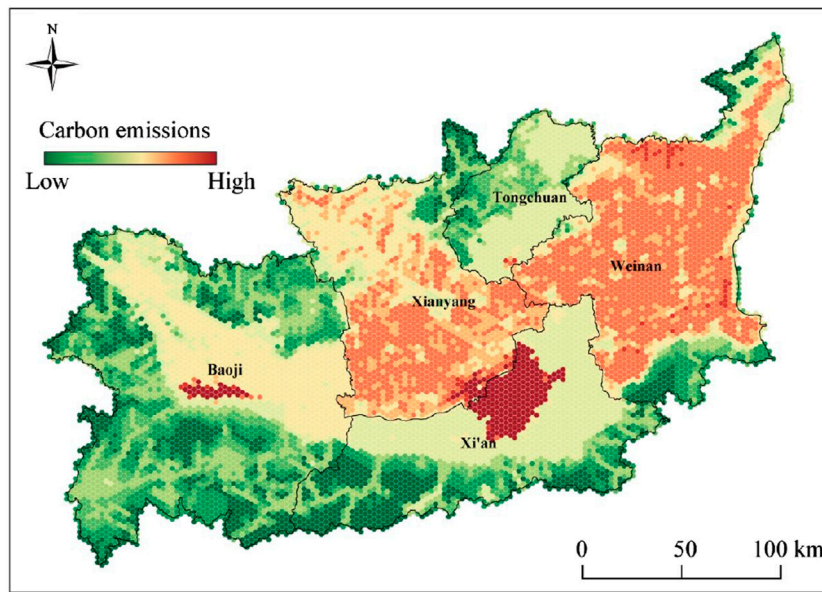


FIGURE 3 Overall carbon emission spatial pattern.

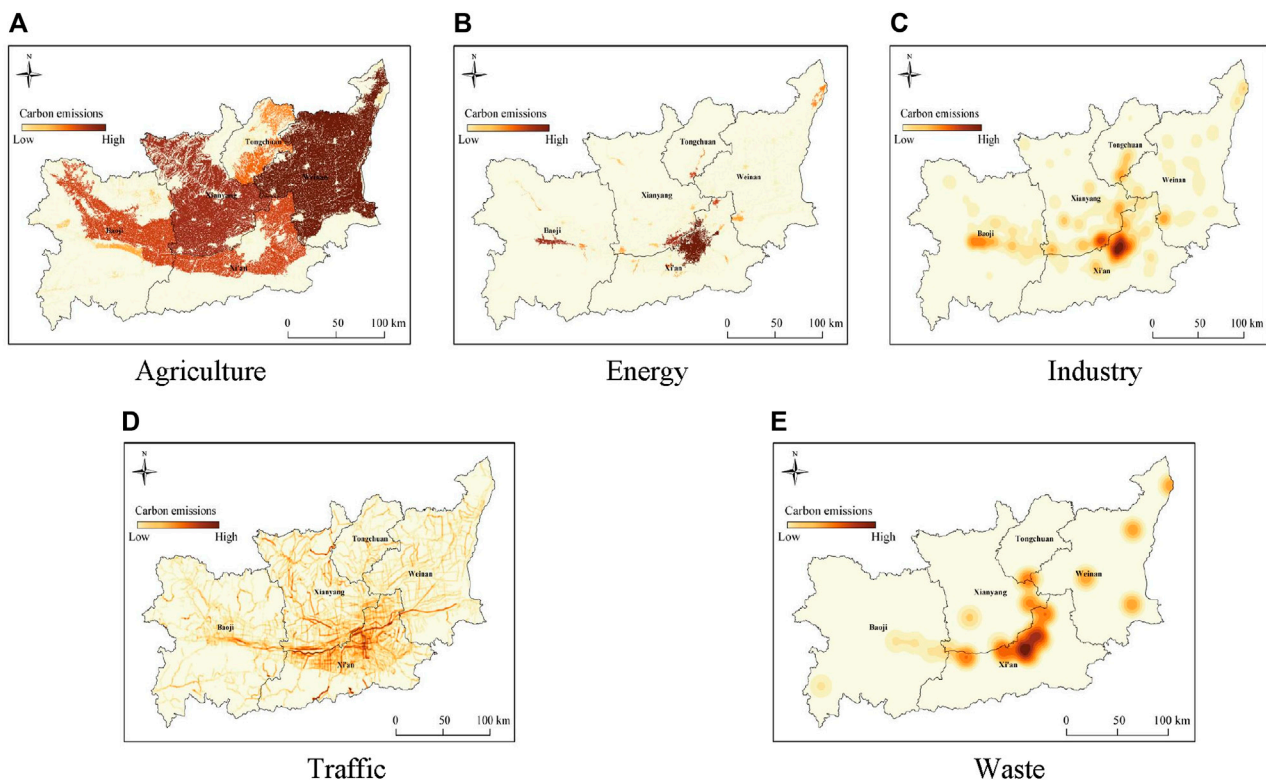


FIGURE 4 Carbon emission patterns of agriculture (A), energy (B), industry (C), traffic (D), waste (E) departments.

characteristics, which are influenced by various factors, including land use types, agricultural production methods, topography, *etc.* In the Guanzhong Plain region, due to its geographical location and natural conditions (Yan et al., 2023), agricultural activities are

relatively concentrated and arable land resources are abundant, resulting in relatively high agricultural carbon emissions. The Qinling National Park in the southern part of the Guanzhong Plain and the Loess Plateau area on the northern side have

limited arable land and relatively fewer agricultural activities due to terrain, topography, and soil conditions, resulting in lower agricultural carbon emissions. At the urban scale, the total agricultural carbon emissions in Weinan and Xianyang regions are relatively high, which may be related to their agricultural industry structure, agricultural technology level, and agricultural production scale. The relatively low agricultural carbon emissions in cities such as Tongchuan, Baoji, and Xi'an may be related to their higher proportion of non-agricultural industries, higher level of agricultural modernization, and possible carbon reduction measures.

Figure 4B shows that the spatial pattern of energy carbon emissions presents a “core periphery” feature. In the Guanzhong Plain region, the central urban areas of Xi'an and Baoji have formed the core areas of energy and carbon emissions due to their large urban scale and population density. The production activities and energy consumption of residents in the central areas of these cities are relatively concentrated, resulting in higher levels of energy and carbon emissions (Hu and Fan, 2020). At the same time, the central areas of peripheral districts and counties have formed a sub-core area of carbon emissions due to their relatively small scale and population. Although their energy carbon emissions are lower than those of the core areas, they are still higher than those of rural areas. Rural areas have relatively low energy consumption and carbon emissions due to sparse population distribution and relatively dispersed living and production activities. The formation of this spatial difference is closely related to the changes in land use patterns during the urbanization process. The construction land area in urban areas is relatively large, and with the concentration of population and intensive economic activities, energy demand and consumption have increased, especially in residential, commercial, and industrial construction land. On the other hand, rural areas are mainly occupied by agriculture and natural land, with relatively low energy consumption and correspondingly reduced carbon emissions.

Figure 4C shows that the spatial pattern of industrial carbon emissions presents a core-edge feature of “two centers and one belt,” forming a core area of industrial carbon emissions in the central urban areas of Xi'an and Baoji. The Guanzhong transportation corridor connecting Xi'an and Baoji forms a high-value industrial carbon emission belt, with secondary high industrial carbon emission centers in the central areas of peripheral districts and counties. Rural areas have almost no industrial carbon emissions. Xi'an and Baoji, as important cities in the region, have formed core areas for industrial carbon emissions due to their high level of industrialization and concentration of industrial enterprises. These cities have a relatively high proportion of manufacturing and heavy industry in terms of energy consumption and carbon emissions. The Guanzhong transportation corridor connecting Xi'an and Baoji serves as an important channel for regional transportation and logistics, with numerous industrial parks and bases distributed along the route. As a result, it forms a high-value zone for industrial carbon emissions (Chen et al., 2021). The frequent industrial activities and dense logistics transportation in this area have led to high energy consumption and carbon emissions. The central areas of peripheral districts and counties have formed secondary centers of industrial carbon emissions due to their relatively small industrial scale. Although the industrial carbon emissions in these regions are lower than those in the core areas, they are still an undeniable source of carbon emissions within the

region. In contrast, rural areas have almost no industrial carbon emissions due to their lower level of industrialization. Rural areas are mainly dominated by agricultural production with fewer industrial activities, resulting in relatively low carbon emissions.

Figure 4D shows obvious networked characteristics in the Guanzhong Plain region. The formation of this pattern is closely related to factors such as transportation infrastructure construction, urban development level, and population distribution within the region. Xi'an and Xianyang, as important cities in the Guanzhong Plain region, have dense road networks and highly developed transportation systems. These cities are not only transportation hubs within the region, but also centers of economic activity and population gathering, resulting in relatively high carbon emissions from transportation. The dense road network and frequent vehicle traffic have led to high energy consumption and carbon emissions, especially in the central urban areas and surrounding major transportation arteries. The Guanzhong transportation corridor connecting Baoji, Xianyang, Xi'an, and Weinan has formed a high-value zone of transportation carbon emissions due to the distribution of many high-grade roads, such as highways and national highways. These transportation arteries serve as the main channels for internal and external connections within the region, carrying a large amount of logistics and human flow, resulting in higher carbon emissions from transportation in the areas along them. In contrast, rural areas have lower traffic carbon emissions due to lower road network density, fewer roads, and relatively lower frequency and density of transportation. The main modes of transportation in rural areas may be non-motorized and low-speed motor vehicles, which have relatively low carbon emission intensity. In addition, the population distribution in rural areas is relatively scattered, and the demand for transportation is relatively small, which also leads to a reduction in transportation carbon emissions.

Figure 4E exhibits a “one core, multiple points” feature, with Xi'an as the regional center city, forming the core area of waste carbon emissions. The formation of this pattern is closely related to factors such as the population size, economic development level, industrial structure, and distribution of environmental protection facilities in cities. As the largest city in the Guanzhong Plain region, Xi'an has a large population, frequent economic activities, and a large amount of waste generated in daily life and industrial production. These wastes generate a certain amount of carbon emissions during the treatment process, especially in the sewage treatment process (Wang et al., 2023). Due to the fact that urban sewage treatment plants typically consume energy and may produce greenhouse gases such as methane during the treatment of sewage and industrial wastewater, these factors collectively contribute to Xi'an's core position in waste carbon emissions. Baoji, Xianyang, Tongchuan, Weinan, and other cities, as secondary cities in the region, have also formed their own waste carbon emission centers. Although the economic development level, industrial structure, and population size of these cities are not as high as Xi'an, they still have a certain amount of waste generation and carbon emissions, with a multi-point distribution feature in their spatial pattern. In addition, due to the fact that sewage treatment plants are often laid out along major rivers to facilitate the use of water resources and reduce transportation costs, this has led to the phenomenon of waste carbon emission centers being distributed in a strip pattern along major rivers. The distribution pattern along the river is conducive to the

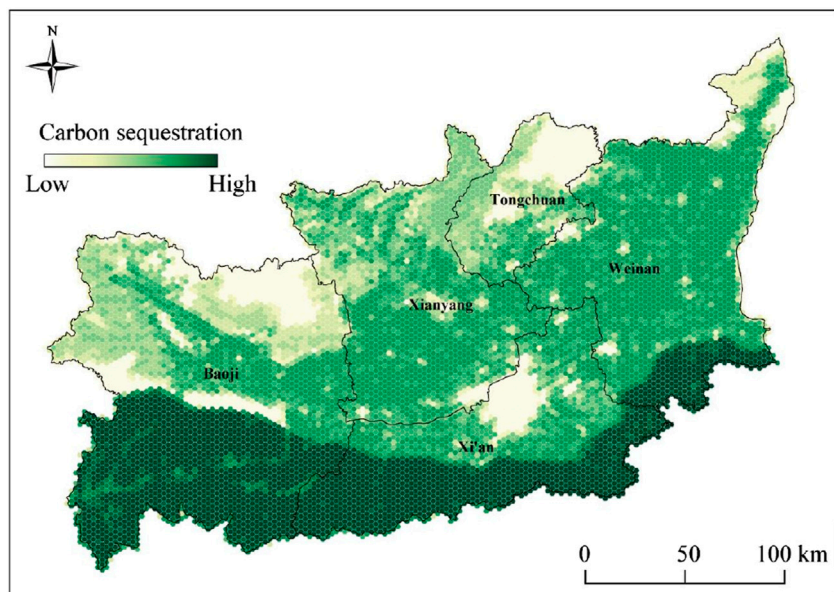


FIGURE 5
Carbon sink space.

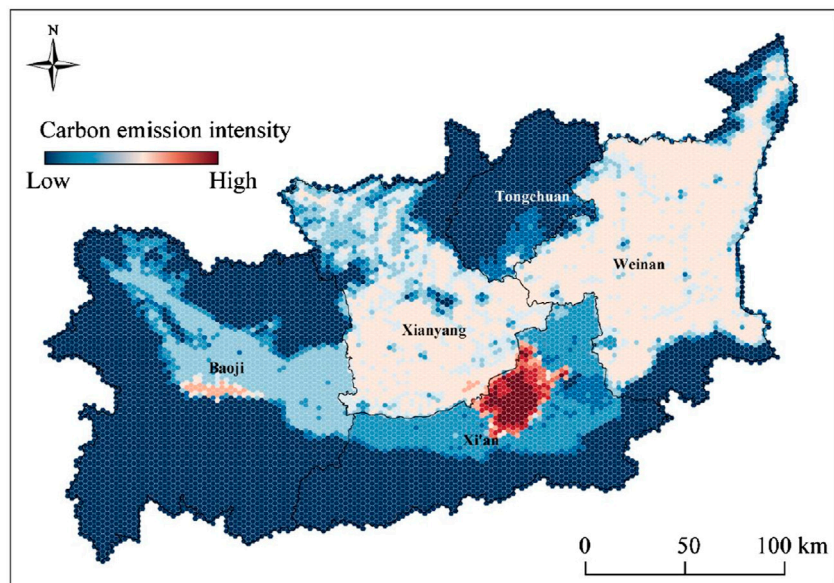


FIGURE 6
Carbon emission intensity.

construction and operation of sewage treatment stations, and also facilitates the discharge or reuse of wastewater.

3.3 Carbon sink distribution and carbon intensity distribution

The distribution of carbon sinks in the Guanzhong Plain region is shown in Figure 5, and the distribution of carbon intensity is

shown in Figure 6. Figure 5 shows that the distribution characteristics of carbon sinks in the Guanzhong Plain region exhibit a spatial pattern of “high in the south and low in the north,” which is closely related to factors such as natural geographical conditions, vegetation types, and land use patterns. The southern Qinling Mountains, as the geographical boundary between North and South China, have rich biodiversity and high vegetation coverage. This area is mainly dominated by tree forests, and the carbon sequestration capacity of forest ecosystems is strong,

resulting in high carbon sequestration. The central Guanzhong Plain region is mainly dominated by modern agriculture. Crops such as wheat and rapeseed have a good protective effect on the soil and absorb carbon dioxide through vegetation growth, contributing to a high carbon sink (Liu et al., 2016). In addition, agricultural measures such as organic matter management and straw returning in farmland can also help improve soil carbon storage capacity. Due to natural limitations, the vegetation coverage in the northern Loess Plateau region is relatively low, mainly consisting of shrubs and grasslands. The carbon sequestration capacity of vegetation types in these regions is relatively weak, resulting in lower carbon sinks. Moreover, soil erosion and land degradation issues may also affect the carbon sequestration capacity of the region. In addition, urban areas have the lowest carbon sequestration due to their large amount of construction land and dense population, resulting in less natural vegetation coverage. The carbon sink in urban areas mainly comes from parks, green spaces, roadside trees, and rooftop greenery. Compared to natural ecosystems, the carbon sink capacity of cities is relatively weak.

As shown in Figure 6, the carbon emission intensity exhibits a layered agglomeration feature. As the core of the Guanzhong Plain urban agglomeration, the central urban area of Xi'an has a dense population and frequent economic activities, including industrial production, transportation, construction industry, and residential life. These activities have led to significant energy consumption, especially the use of fossil fuels, resulting in higher carbon emission intensity. In addition, the expansion of construction land and infrastructure construction in the process of urbanization is also an important source of carbon emissions. As an important industrial city in the region, Baoji City has numerous industrial enterprises, especially in heavy industry and manufacturing. The production and operation activities of these industrial enterprises require a large amount of energy input, often accompanied by high carbon emissions. Therefore, the carbon emission intensity in the central urban area of Baoji is relatively high, second only to the central urban area of Xi'an. Weinan City and Xianyang City have a relatively large population and a considerable number of enterprises, including industrial and service industries. The economic and population activities in these cities are relatively concentrated, resulting in higher carbon emission intensity. Meanwhile, Weinan and Xianyang are also important agricultural areas, and agricultural production activities also contribute to carbon emission intensity. The carbon emission intensity in rural areas of the Guanzhong Plain is relatively low, mainly due to agriculture and sparse population distribution. Although agricultural production activities generate certain carbon emissions, such as fertilizer use and agricultural machinery operations, their carbon emission intensity is lower compared to urban and industrial activities. Qinling National Park and the northern Loess Plateau have sparse populations and relatively low human activities, mainly relying on natural ecosystems and agricultural production. The carbon emission intensity in these areas is relatively low.

3.4 Carbon balance zoning

The carbon sink zoning in the Guanzhong Plain region is shown in Figure 7. Figure 7 shows that the carbon sequestration functional

areas of the Guanzhong Plain urban agglomeration are mainly distributed in the southern Qinling National Park and northern Tongchuan City. These regions have a relatively large proportion of ecological land and good carbon sequestration capacity. As an important nature reserve, Qinling National Park has high vegetation coverage and strong carbon sequestration capacity of forest ecosystems, making it an important carbon sink area in the region (Gogoi et al., 2022). Due to its specific natural conditions and ecological protection measures, Tongchuan City also exhibits strong carbon sequestration potential. These regions are dominated by agriculture, and overall carbon sinks exceed carbon emissions. The carbon balance zone is mainly located in rural areas of the Guanzhong Plain. These areas have relatively dense villages, mainly focused on agriculture, with strong carbon sequestration capabilities. Due to agricultural production activities generating certain carbon emissions, such as fertilizer use and agricultural machinery operations, overall carbon emissions and carbon sinks are essentially balanced (Huang et al., 2024). The low-carbon optimization zone is mainly located in rural areas of Xianyang City and Weinan City. Agricultural carbon emissions in these regions are relatively high, and measures such as promoting low-carbon agricultural technology and optimizing land use structure are needed to further reduce carbon emissions. The carbon intensity control zone is mainly distributed in the central urban areas of cities such as Xi'an and Baoji. These regions have a high population density and a large number of industrial enterprises, resulting in much higher energy consumption and carbon emissions than carbon sinks. The human activity intensity in the central urban area of Xi'an is high, with the highest carbon emission intensity, while there are many industrial enterprises in Baoji City, resulting in high carbon emission intensity. These urban centers need to take measures such as promoting green and low-carbon development, optimizing energy structure, and improving energy efficiency to reduce carbon emissions and enhance carbon sequestration capacity.

4 Conclusion

This study presents a comprehensive analysis of county-level carbon emissions in the Guanzhong area of Shaanxi Province, using a detailed carbon emission accounting system that reflects the unique geographic, socio-economic, and land-use characteristics of the region. The innovative aspect of this research lies in its focus on rural county-level emissions, which are often underrepresented in existing literature that primarily focuses on urban areas or national-level studies. By adopting a granular, county-level approach, this study fills a critical gap in understanding rural emissions and offers a replicable model for similar regions across China.

In terms of carbon neutrality, the study reveals that industrial and residential sectors are the largest contributors to carbon emissions, while agricultural emissions remain relatively low. The findings indicate that achieving carbon neutrality at the county level will require a targeted approach, focusing on optimizing industrial energy use, promoting renewable energy, and enhancing energy efficiency in residential areas. The study also underscores the importance of integrating low-carbon agricultural practices and land-use management to further balance carbon emissions.

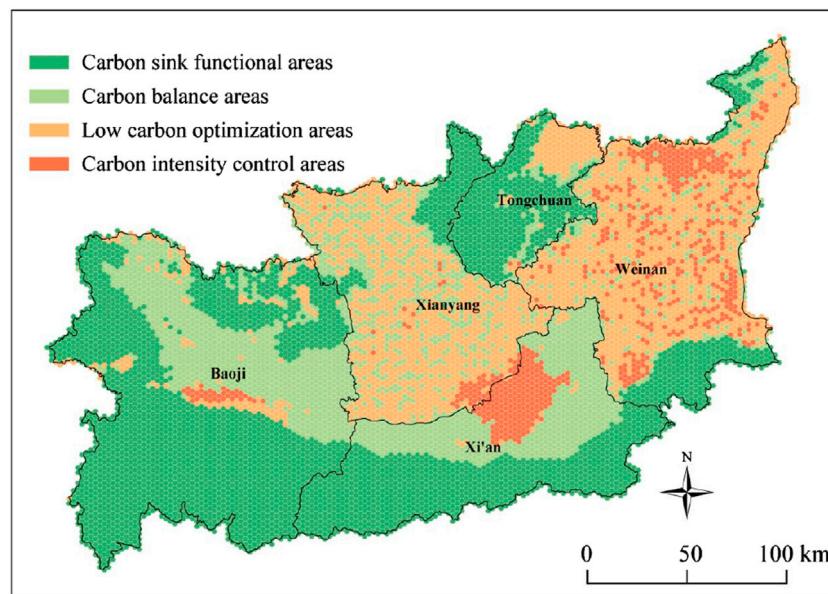


FIGURE 7
Results of carbon sink spaceCarbon balance zoning.

The unique contribution of this research is its practical framework for understanding and managing carbon emissions in rural regions, providing policymakers with critical insights on how to balance economic development and environmental sustainability. By focusing on county-level emissions, the study provides a crucial foundation for China's broader efforts to achieve its dual carbon goals, demonstrating that effective carbon management strategies must extend beyond urban areas to include the rural sectors that are essential to the country's overall carbon neutrality objectives.

5 Policy suggestion

Firstly, focus on optimizing industrial and energy structures. The study reveals that the industrial and energy sectors contribute significantly to carbon emissions in the Guanzhong region. To address this, policymakers should prioritize the optimization of industrial structures by promoting low-carbon industries and technologies. This includes supporting the development of renewable energy sources, such as solar and wind power, and incentivizing the adoption of clean energy in industrial processes. Additionally, the implementation of energy efficiency standards and regulations can help reduce energy consumption and carbon emissions across various sectors.

Secondly, enhance agricultural carbon management and land use practices. While agricultural carbon emissions are relatively low compared to industrial and energy sectors, there is still potential for improvement. Policymakers should encourage farmers to adopt low-carbon agricultural practices, such as precision agriculture, organic farming, and straw returning. These practices can help reduce chemical fertilizer and pesticide usage, decrease greenhouse gas emissions, and improve soil carbon sequestration. Furthermore, optimizing land use patterns, such as restoring

degraded land and promoting afforestation, can significantly enhance the carbon sink capacity of the region.

Third, establish a comprehensive carbon management and trading system. To effectively reduce carbon emissions and promote low-carbon development, it is crucial to establish a comprehensive carbon management system. This includes developing clear carbon emission reduction targets and implementing effective monitoring and reporting mechanisms. Additionally, policymakers should explore the feasibility of establishing a regional carbon trading market, which can incentivize emitters to reduce their carbon footprint and reward those who sequester carbon. This approach can not only help achieve carbon reduction goals but also stimulate economic growth and innovation in low-carbon technologies.

Finally, the policy recommendations derived from this study are not only pertinent to the Guanzhong region but also offer valuable insights for other rural areas across China. For instance, agricultural carbon management practices in northeastern China could inform efforts in other western and central regions, while the optimization of rural energy structures in eastern coastal regions provides valuable lessons for inland areas like the Guanzhong Plain. As such, it is recommended that the national government support the dissemination and implementation of county-level carbon emission accounting systems across the country. Tailored carbon emission reduction strategies, based on local characteristics, will be crucial to achieving China's broader rural carbon neutrality goals.

Data availability statement

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

Author contributions

WG: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing—original draft, Writing—review and editing. WH: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing—original draft, Writing—review and editing. JZ: Conceptualization, Data curation, Formal Analysis, Methodology, Writing—original draft, Writing—review and editing. YC: Software, Supervision, Validation, Visualization, Writing—original draft, Writing—review and editing. ZW: Data curation, Funding acquisition, Investigation, Validation, Writing—original draft, Writing—review and editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. This paper was granted by Technology Innovation Center for Land Engineering

References

- Abam, F. I., Inah, O. I., Ekwe, E. B., Igbong, D. I., Effiom, S. O., Ovat, F. A., et al. (2023). CO₂ emissions decoupling from added value growth in the chemical and pharmaceutical (CHPH) industry in Nigeria. *Green Low-Carbon Econ.* 1, 52–59. doi:10.47852/bonviewGLCE3202622
- Abbas, A., Mushtaq, Z., Ikram, A., Yousaf, K., and Zhao, C. (2023). Assessing the factors of economic and environmental inefficiency of sunflower production in Pakistan: an epsilon-based measure model. *Front. Environ. Sci.* 11. doi:10.3389/fenvs.2023.1186328
- Abbas, A., Waseem, M., Ahmad, R., Khan, K. A., Zhao, C., and Zhu, J. (2022a). Sensitivity analysis of greenhouse gas emissions at farm level: case study of grain and cash crops. *Environ. Sci. Pollut. Res.* 29, 82559–82573. doi:10.1007/s11356-022-21560-9
- Abbas, A., Zhao, C., Waseem, M., Ahmed Khan, K., and Ahmad, R. (2022b). Analysis of energy input–output of farms and assessment of greenhouse gas emissions: a case study of cotton growers. *Front. Environ. Sci.* 9. doi:10.3389/fenvs.2021.826838
- Amon, B., Çinar, G., Anderl, M., Dragoni, F., Kleinberger-Pierer, M., and Hörtenhuber, S. (2021). Inventory reporting of livestock emissions: the impact of the IPCC 1996 and 2006 Guidelines. *Environ. Res. Lett.* 16, 075001. doi:10.1088/1748-9326/ac0848
- Caetano, T., Winkler, H., and Depledge, J. (2020). Towards zero carbon and zero poverty: integrating national climate change mitigation and sustainable development goals. *Clim. Policy* 20, 773–778. doi:10.1080/14693062.2020.1791404
- Chen, L., Xu, L., Cai, Y., and Yang, Z. (2021). Spatiotemporal patterns of industrial carbon emissions at the city level. *Resour. Conservation Recycl.* 169, 105499. doi:10.1016/j.resconrec.2021.105499
- Chen, S., Shi, A., and Wang, X. (2020). Carbon emission curbing effects and influencing mechanisms of China's Emission Trading Scheme: the mediating roles of technique effect, composition effect and allocation effect. *J. Clean. Prod.* 264, 121700. doi:10.1016/j.jclepro.2020.121700
- Chen, Y., Billings, B. W., and Powell, K. M. (2024). Industrial processes and the smart grid: overcoming the variability of renewables by using built-in process storage and intelligent control strategies. *Int. J. Prod. Res.* 62, 1686–1698. doi:10.1080/00207543.2023.2199436
- Elahi, E., Li, G., Han, X., Zhu, W., Liu, Y., Cheng, A., et al. (2024a). Decoupling livestock and poultry pollution emissions from industrial development: a step towards reducing environmental emissions. *J. Environ. Manag.* 350, 119654. doi:10.1016/j.jenvman.2023.119654
- Elahi, E., Zhu, M., Khalid, Z., and Wei, K. (2024b). An empirical analysis of carbon emission efficiency in food production across the Yangtze River basin: towards sustainable agricultural development and carbon neutrality. *Agric. Syst.* 218, 103994. doi:10.1016/j.agsy.2024.103994
- and Human Settlements, Shaanxi Land Engineering Construction Group Co., Ltd and Xi'an Jiaotong University (Grant No. 2024WHZ0234), 2023 Annual Shaanxi Province State Capital Operation Budget Science and Technology Innovation Special Fund Project “Guanzhong Area Green Farmland Construction Key Technology Research and Demonstration Promotion Project”.

Conflict of interest

Authors WG, WH, JZ, YC, and ZW were employed by Shaanxi Dijian Guantian Investment and Construction Co., Ltd.

Authors WG, WH, JZ, YC, and ZW were employed by Shaanxi Provincial Land Engineering Construction Group Co., Ltd.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

- Lv, Z., Shan, X., Xiao, X., Cai, R., Zhang, Y., and Jiao, N. (2022). Excessive greenhouse gas emissions from wastewater treatment plants by using the chemical oxygen demand standard. *Sci. China Earth Sci.* 65, 87–95. doi:10.1007/s11430-021-9837-5
- Mehedi, T. H., Gemechu, E., and Kumar, A. (2022). Life cycle greenhouse gas emissions and energy footprints of utility-scale solar energy systems. *Appl. Energy* 314, 118918. doi:10.1016/j.apenergy.2022.118918
- Meng, B., Zhang, J., and Zhang, X. (2023). Detecting the spatial network structure of the Guanzhong Plain urban agglomeration, China: a multi-dimensional element flow perspective. *Land* 12, 563. doi:10.3390/land12030563
- Meng, F., Chen, H., Tan, Y., and Xiong, W. (2024). Changes in crop mix and the effects on agricultural carbon emissions in China. *Int. J. Agric. Sustain.* 22, 2335141. doi:10.1080/14735903.2024.2335141
- Meng, M., and Niu, D. (2011). Modeling CO₂ emissions from fossil fuel combustion using the logistic equation. *Energy* 36, 3355–3359. doi:10.1016/j.energy.2011.03.032
- Na, H., Yuan, Y., Du, T., Zhang, T., Zhao, X., Sun, J., et al. (2024). Multi-process production occurs in the iron and steel industry, supporting 'dual carbon' target: an in-depth study of CO₂ emissions from different processes. *J. Environ. Sci.* 140, 46–58. doi:10.1016/j.jes.2023.03.031
- Noda, I., Asada, M., and Nagao, H. (2024). Elucidation of the mechanism of greenhouse gas generation by abiotic transformation of nutrient ions flowing into closed water areas with little phytoplankton. *ACS ES&T Water* 4, 436–443. doi:10.1021/acestwater.3c00455
- Sage, R. F. (2020). Global change biology: a primer. *Glob. Change Biol.* 26, 3–30. doi:10.1111/gcb.14893
- Shan, Y., Guan, D., Liu, J., Mi, Z., Liu, Z., Liu, J., et al. (2017). Methodology and applications of city level CO₂ emission accounts in China. *J. Clean. Prod.* 161, 1215–1225. doi:10.1016/j.jclepro.2017.06.075
- Song, M., Zhao, X., and Shang, Y. (2020). The impact of low-carbon city construction on ecological efficiency: empirical evidence from quasi-natural experiments. *Resour. Conservation Recycl.* 157, 104777. doi:10.1016/j.resconrec.2020.104777
- Sun, J., Qi, Y., Guo, J., Zheng, J., Zhang, L., and Yang, X. (2024). Impact of nighttime light data saturation correction on the application of carbon emissions spatialization: a comparative study of the correction effect and application effect based on five methods in China. *J. Clean. Prod.* 438, 140815. doi:10.1016/j.jclepro.2024.140815
- Sun, L.-L., Cui, H.-J., and Ge, Q.-S. (2022). Will China achieve its 2060 carbon neutral commitment from the provincial perspective? *Adv. Clim. Change Res.* 13, 169–178. doi:10.1016/j.accre.2022.02.002
- Ucal, M., and Xydis, G. (2020). Multidirectional relationship between energy resources, climate changes and sustainable development: technoeconomic analysis. *Sustain. Cities Soc.* 60, 102210. doi:10.1016/j.scs.2020.102210
- Ullah, S., You, Q., Wang, G., Ullah, W., Sachindra, D. A., Yan, Y., et al. (2022). Characteristics of human thermal stress in South Asia during 1981–2019. *Environ. Res. Lett.* 17, 104018. doi:10.1088/1748-9326/ac8fa6
- Wang, C., Zhan, J., and Xin, Z. (2020a). Comparative analysis of urban ecological management models incorporating low-carbon transformation. *Technol. Forecast. Soc. Change* 159, 120190. doi:10.1016/j.techfore.2020.120190
- Wang, Q., Li, X., Liu, W., Zhai, S., Xu, Q., Nie, S., et al. (2023). Carbon source recovery from waste sludge reduces greenhouse gas emissions in a pilot-scale industrial wastewater treatment plant. *Environ. Sci. Ecotechnology* 14, 100235. doi:10.1016/j.ese.2022.100235
- Wang, Y., Fang, X., Yin, S., and Chen, W. (2021). Low-carbon development quality of cities in China: evaluation and obstacle analysis. *Sustain. Cities Soc.* 64, 102553. doi:10.1016/j.scs.2020.102553
- Wang, Y., Yang, H., and Sun, R. (2020b). Effectiveness of China's provincial industrial carbon emission reduction and optimization of carbon emission reduction paths in "lagging regions": efficiency-cost analysis. *J. Environ. Manag.* 275, 111221. doi:10.1016/j.jenvman.2020.111221
- Wimbadi, R. W., and Djalante, R. (2020). From decarbonization to low carbon development and transition: a systematic literature review of the conceptualization of moving toward net-zero carbon dioxide emission (1995–2019). *J. Clean. Prod.* 256, 120307. doi:10.1016/j.jclepro.2020.120307
- Xu, Y., Li, H., Zhang, R., Wang, T., Sui, P., Sheng, J., et al. (2024). Balancing the development and carbon emissions in rural areas of China. *J. Clean. Prod.* 454, 142338. doi:10.1016/j.jclepro.2024.142338
- Yan, Z., Li, Z., Li, P., Zhao, C., Xu, Y., Cui, Z., et al. (2023). Spatial and temporal variation of NDVI and its driving factors based on geographical detector: a case study of Guanzhong plain urban agglomeration. *Remote Sens. Appl. Soc. Environ.* 32, 101030. doi:10.1016/j.rsase.2023.101030
- Yu, Y., Yin, S., and Zhang, A. (2022). Clean energy-based rural low carbon transformation considering the supply and demand of new energy under government participation: a three-participants game model. *Energy Rep.* 8, 12011–12025. doi:10.1016/j.egy.2022.09.037
- Yu, Z., Wang, Y., Zhao, B., Li, Z., and Hao, Q. (2023). Research on carbon emission structure and model in low-carbon rural areas: bibliometric analysis. *Sustainability* 15, 12353. doi:10.3390/su151612353
- Zhang, L. X., Wang, C. B., and Bahaj, A. S. (2014). Carbon emissions by rural energy in China. *Renew. Energy* 66, 641–649. doi:10.1016/j.renene.2014.01.005
- Zhang, W., Zhang, M., Wu, S., and Liu, F. (2021). A complex path model for low-carbon sustainable development of enterprise based on system dynamics. *J. Clean. Prod.* 321, 128934. doi:10.1016/j.jclepro.2021.128934
- Zhang, Y., Wang, W., Liang, L., Wang, D., Cui, X., and Wei, W. (2020). Spatial-temporal pattern evolution and driving factors of China's energy efficiency under low-carbon economy. *Sci. Total Environ.* 739, 140197. doi:10.1016/j.scitotenv.2020.140197
- Zhao, W. (2022). China's goal of achieving carbon neutrality before 2060: experts explain how. *Natl. Sci. Rev.* 9, nwac115. doi:10.1093/nsr/nwac115
- Zhong, X., Hu, M., Deetman, S., Steubing, B., Lin, H. X., Hernandez, G. A., et al. (2021). Global greenhouse gas emissions from residential and commercial building materials and mitigation strategies to 2060. *Nat. Commun.* 12, 6126. doi:10.1038/s41467-021-26212-z
- Zhou, Z., Nie, L., Ji, H., Zeng, H., and Chen, X. (2020). Does a firm's low-carbon awareness promote low-carbon behaviors? Empirical evidence from China. *J. Clean. Prod.* 244, 118903. doi:10.1016/j.jclepro.2019.118903
- Zhu, H., Chen, S., Irfan, M., Hu, M., and Hu, J. (2024). Exploring the role of the belt and road initiative in promoting sustainable and inclusive development. *Sustain. Dev.* 32, 712–723. doi:10.1002/sd.2705
- Zhu, X., Zou, X., Lu, E., Deng, Y., Luo, Y., Chen, H., et al. (2021). Litterfall biomass and nutrient cycling in karst and nearby non-karst forests in tropical China: a 10-year comparison. *Sci. Total Environ.* 758, 143619. doi:10.1016/j.scitotenv.2020.143619
- Zurek, M., Hebinck, A., and Selomane, O. (2022). Climate change and the urgency to transform food systems. *Science* 376, 1416–1421. doi:10.1126/science.abo2364