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Will new-type urbanization restrain carbon emissions in rural China?

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KEYWORDS

Clean energy, moderating effect, new-type urbanization, rural carbon emissions, spatial Durbin model

HIGHLIGHTS

- From 2000–2021, carbon emissions in rural China showed an annual increasing trend with a growth rate of 28.93% and an average annual increase of 1.31%.
- New-type urbanization has a significant negative impact on rural carbon emissions.
- Clean energy, as a moderating variable, attenuates the negative impact of new-type urbanization on rural carbon emissions.

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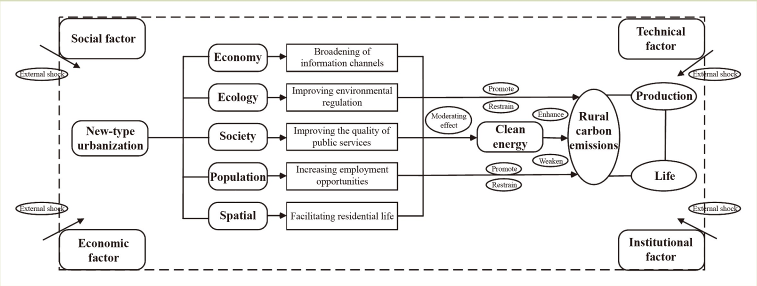
GRAPHICAL ABSTRACT



ABSTRACT

Investigating the potential impacts of new-type urbanization and clean energy adoption on rural carbon emissions is crucial for the advancement of urbanization and the realization of green agricultural development. Based on panel data from 30 provinces in rural China spanning the period from 2000 to 2021, this paper constructs a new-type urbanization evaluation system to assess its five dimensions: economic, ecological, social, demographic and spatial aspects. Subsequently, this paper estimates rural carbon emissions from the perspectives of production and household consumption, and uses the PVAR and spatial Durbin models to examine the interactive relationship between new-type urbanization and rural carbon emissions in China, as well as the moderating role of clean energy adoption. The study reveals firstly that, carbon emissions in rural China have a consistent upward trend from 2000 to 2021, with an overall growth rate of 28.93% and an average annual increase of 1.31%. Secondly, new-type urbanization exerts a significant negative effect on rural carbon emissions, whereas technological progress, industrialization, economic openness, agricultural marketization and agricultural mechanization have significant positive effects on rural carbon emissions. Significant heterogeneity exists in both the direction and magnitude of these impacts across different regions and categories. Thirdly, as a moderating variable, clean energy attenuates the negative effect of new-type urbanization on rural carbon emissions at the nationwide and in northeastern China, but exerts an opposite effect in eastern, and western China. Under the framework of the ecological civilization strategy, deepening the application of clean energy should be prioritized as a key initiative to advance the green development and low-carbon production, with the aim of achieving multiple objectives including carbon emission reduction, energy conservation, and pollutant emission mitigation in rural areas.

1 Introduction

The Chinese government has explicitly articulated its commitment to advancing people-centered new-type urbanization, actively promoting carbon peak and neutrality, and accelerating the development of a clean energy system, matters of significant theoretical and practical importance. Since 1978, China's urbanization rate has increased from 17.9% to 65.2%, reflecting an average annual growth rate of 1.1%. This remarkable progress represents a historic phase in the global urbanization process[1]. Urbanization, particularly the urbanization of the rural population, is vital for leveraging the advantages of the domestic market and unlocking the potential of domestic demand. It also holds significant strategic importance for advancing common prosperity among all people[2]. However, while benefiting from the influx of factor resources, such as agricultural products, labor and land flowing from rural to urban areas, rural areas are having serious environmental challenges, including rising carbon emissions and escalating water pollution[3]. It is clear that rapid urbanization has led to the transfer of surplus rural labor, resulting in a significant increase in demand for meat, milk, eggs, and other agricultural and livestock products. Simply increasing the use of production inputs such as pesticides, fertilizers and agricultural plastics to achieve high yields and substantial output growth in response to urban demand has simultaneously resulted in higher carbon dioxide emissions[4]. However, in recent years, household energy consumption in China has continued to rise, from 136 Gtce in 1995 to 463 Gtce in 2021, accompanied by significant changes in the consumption structure. The proportion of coal consumption decreased from 75.4% (1995) to 9.4% (2021), while electricity consumption increased from 9.2% in 1995 to 31.2% in 2021. To some extent, the continuous increase in carbon dioxide emissions from daily household activities poses a significant threat to the ecological environment of rural areas[5]. As China's economic development transitions from the phase of high-speed growth to that of high-quality growth, urbanization is also evolving from the previous focus on quantitative expansion to a new stage characterized by comprehensive quality improvement[6]. New-type urbanization will inevitably influence the process of reducing rural carbon emissions through the mobility and restructuring of production factors, including capital, labor, technology, land and public services[7]. However, it should not be overlooked that urbanization in China is being promoted under the national basic conditions of a large population base, low per capita resource availability and a relatively fragile ecological environment. As a result, the contradictions between urbanization and resources constraints as well as environmental pressures are particularly pronounced, primarily manifested in inefficient energy resource consumption and continuously rising carbon emissions[8]. What is more concerning is that, under the influence of urbanization and intensive human activities, rural production factors are flowing unidirectionally toward urban areas, resulting in increasingly prominent challenges in rural areas, including low energy use efficiency, deteriorating ecological and environmental conditions, and lagging socioeconomic development[9]. The phased, gradual and comprehensive realization of a green and low-carbon transition in production and development represents one of the central themes of future economic and social development. As one of the most deeply entrenched challenges associated with carbon peaking and carbon neutrality, the advancement of clean energy and the restructuring of the energy sector are poised to become a primary focus in achieving China's dual-carbon goal. Therefore, from the perspective of academic value, this paper conducts an in-depth analysis of the underlying mechanism through which new urbanization affects rural carbon emissions, thereby further expanding the research horizons on rural carbon emissions. From the perspective of practical application, based on the empirical findings regarding the moderating effect of clean energy, this study provides guidance for rural residents to continuously upgrade their energy consumption structure towards a green and low-carbon pathway, thereby offering targeted policy recommendations for achieving the goals of reducing carbon emission reductions, pollution control and expanded green coverage.

In recent years, national strategies, such as ecological civilization advancement, new-type urbanization, carbon peak and carbon neutrality, and rural revitalization, have spurred extensive theoretical research, empirical studies and policy development aimed at promoting carbon reduction and sequestration, accelerating the urbanization of the agricultural migrant population and improving rural ecosystem quality, yielding significant achievements[10–12]. The first of these is research on rural carbon emissions. Existing studies primarily focus on various aspects including emission measurement, empirical characteristics, efficiency evaluation, influencing factors, and pathways for emissions reduction[13–18]. The second is research on urbanization. Existing studies on urbanization have yielded substantial results, including but not limited to the measurement of urbanization levels, spatial and temporal heterogeneity, and the identification of driving factors[19–21]. The third is research on the relationship between urbanization and agricultural carbon emissions. This body of research has primarily focused on the mechanisms through which urbanization affects carbon emissions from agricultural production, yielding diverse conclusions. One identified pathway is carbon reduction. Urbanization leverages industrial upgrading, technology spillovers to generate economies of scale in pollution control, optimize the allocation of factor resources, improve the use efficiency of agricultural inputs, thereby helping to reduce agricultural carbon emissions[22]. The other pathway involves carbon increase. Urbanization further exacerbates rural aging, feminization and part-time employment in rural areas, necessitating that the remaining rural workforce to intensify the use of agricultural inputs and machinery to maintain agricultural production levels, thereby contributing to increased carbon emissions in agriculture[23].

The literature provides essential theoretical and empirical foundations for this study, however there remains significant room for advancement. First, carbon emissions from agricultural production are often examined in isolation, overlooking the continuous increase in residential energy consumption, which leads to inaccurate findings. Second, most of the existing studies adopt a traditional perspective that measures the urbanization level by using single indicators, such as land or population, from a quantitative standpoint, while largely neglecting the development requirements of new-type urbanization in economic, ecological, and social dimensions centered on supposed quality. Also, few studies have systematically established an indicator system to assess the level of new-type urbanization over the long term. Third, these studies have explored the impact of new-type urbanization on agricultural carbon emissions from various perspectives; however, they have given less consideration to the interaction between the two and have overlooked the moderating role of clean energy.

Thus, there were three potential marginal contributions of this paper. First, it provides a scientific and accurate measurement of carbon emissions from both agricultural production and residential consumption perspective, addressing the limitations of prior studies that focused exclusively on either production- or household-level emissions. This dual perspective enhances the comprehensiveness and accuracy of the research conclusions. Second, a comprehensive evaluation index system is presented based on five dimensions: economic, ecological, social, demographic and spatial urbanization, to assess the new-type urbanization level. Given this framework, the PVAR model was used to examine the dynamic interactive relationship between new-type urbanization and rural carbon emissions. Third, building on the theoretical framework using the spatial Durbin model to investigate the impact of new-type urbanization on rural carbon emissions, clean energy is introduced as a moderating variable to examine its potential moderating effect on the relationship between new-type urbanization and emissions. The paper also covers four key areas. (1) The logical mechanism through which new-type urbanization affects rural carbon emissions can be clarified. (2) Evaluation systems for rural carbon emission and new-type urbanization, which are separately presented being calculated based on the panel data from 30 provinces in China spanning the period 2000 to 2021, that enable a scientific assessment of carbon emission levels and new-type urbanization levels at both the national level and across the four major regions of China: eastern, central, western and northeastern. (3) The spatial Durbin model was used to empirically examine the direction and magnitude of the impact of new-type urbanization on rural carbon emissions at both the national level and across the four regions. (4) Clean energy is introduced as a moderating variable to examine its potential regulatory role, aiming to providing actionable policy recommendations for accelerating new-type urbanization and promoting the reduction of agricultural carbon emissions.

2 Logical mechanisms

In the context of promoting integrated urban-rural development and ecological civilization construction, new-type urbanization and rural carbon emissions have become increasingly interconnected due to the flow and allocation of factor resources, as well as the optimization and upgrading of industrial structures[24]. New-type urbanization reflects the ongoing transformation of spatial, social and economic structures. The migration of rural labor to cities and towns, the non-agricultural transformation of the industrial structure and the return of factors, such as capital and technology, to rural areas constitute effective pathways through which new-type urbanization influences rural development. Changes in rural carbon emissions are also closely associated with the effects resulting from the inflow of factors such as population, capital and technology into rural areas[25]. Therefore, the direction of the impact of new-type urbanization on rural carbon emissions remains uncertain. Compared with the rural carbon emission system, which comprises emissions from agricultural production and residential activities, the new-type urbanization system encompasses five dimensions: economic, ecological, social, demographic and spatial. The impacts of these urbanization dimensions on rural carbon emissions tend to vary and cannot be generalized[26]. Therefore, this paper analyzes the influencing mechanism of new-type urbanization on rural carbon emissions from the economic, ecological, social, demographic and spatial dimensions.

2.1 Impact of new-type urbanization on rural carbon emissions

As shown in Fig. 1, from the economic dimension, promoting economic urbanization can provide sufficient funding, technology and advanced management models for green and low-carbon agricultural production, thereby contributing to the reduction of carbon emissions generated in the agricultural production process and supporting the low-carbon transformation of commercial agriculture[27]. However, economic urbanization has increased urban resident demand for both the quantity and quality of green agricultural products, which to some extent incentivizes farmers to optimize or shift away from high-input, high-pollution farmland management practices and business models, thus potentially curbing the growth of agricultural carbon emissions[28]. Second, from the ecological dimension, under the guidance and requirements of the ecological civilization strategy, environmental considerations, such as green development, low-carbon practices and sustainability, have been increasingly integrated into the performance evaluation system of local governments. To meet these assessment targets, governments at all levels are inclined to introduce and implement relevant environmental regulations and measures to protect the ecological environment of cities and towns[29]. Against the backdrop of urban-rural integration and rural revitalization, the relationship between urban and rural areas has becoming increasingly close, and the governance benefits of eco-urbanization are likely to spill over into the agricultural sector, promoting agricultural carbon reduction and sequestration through advances in agricultural technology and constraints on production practices[30]. Third, from the social dimension, a

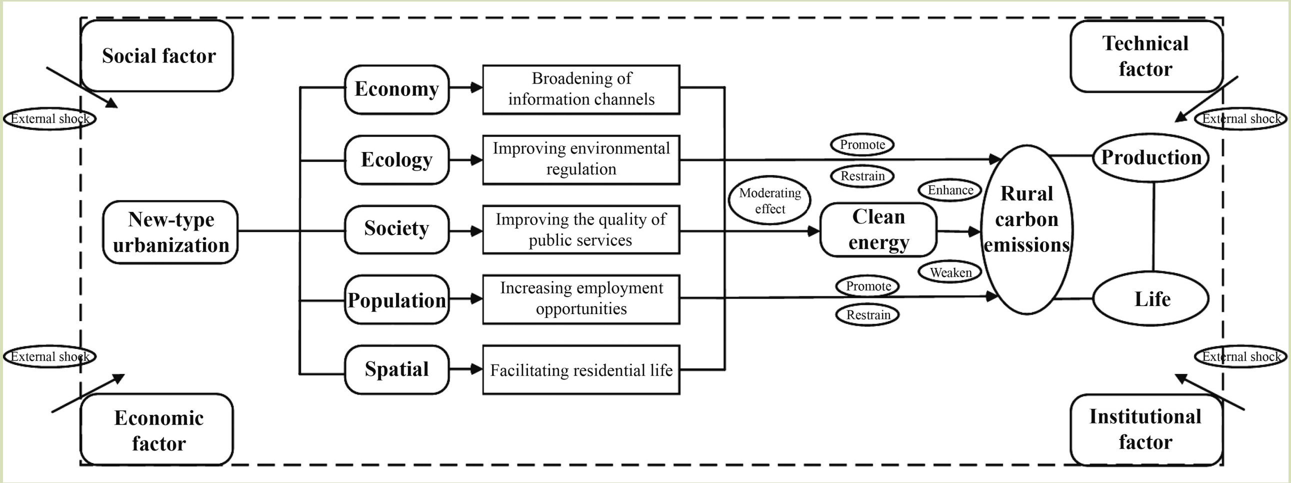


Fig. 1 The logical relationship between new-type urbanization and rural carbon emissions in China.

direct reflection of the significant increase in the social urbanization is the continuous rise in urban resident income, consumption and education levels. The growth in disposable income may lead to changes in dietary patterns among urban dwellers, increasing demand for meat, eggs, milk and other livestock products, thereby stimulating agricultural and livestock production, which in turn could contribute to some extent to higher agricultural carbon emissions[31]. Fourth, from the demographic dimension, the advancing population urbanization has significantly promoted to the transfer of surplus rural labor, alleviating the pressure of labor redundancy on agricultural production, improving the allocation efficiency of production factors, and effectively mitigating the contradiction between people and land. These changes create favorable conditions for scaling up, and specialization in agricultural production, as well as reducing the consumption of chemical fertilizers, pesticides and agricultural plastics, thereby potentially curbing the growth of agricultural carbon emissions[32]. In addition, the income earned by surplus rural laborers working in urban areas often raises the average household income, enabling rural family members left behind to afford improved breeding cultivars, adopt advanced agricultural carbon reduction and sequestration technologies, and participate in technical education and training, thereby helping to restrain the growth of agricultural carbon emissions[33]. Population urbanization has led to a continuous decline in the number of permanent rural residents and an increase in the per capita arable land area. To adapt to the changes in production patterns, the rural workforce has adjusted capital inputs and increased the purchase and use of large-scale agricultural machinery and equipment, resulting in higher consumption of diesel, petroleum and other fossil fuels, thereby potentially contributing to increased agricultural carbon emissions[34]. Finally, from the spatial dimension, the advancement of spatial urbanization inevitably affects the allocation of resources, such as land and agricultural inputs in rural areas, thereby influencing agricultural production and the rural ecological environment, and consequently rural carbon emissions[35].

2.2 Clean energy, new-type urbanization and rural carbon emissions

Under the backdrop of new-type urbanization, the role of clean energy in promoting carbon emission reduction in rural areas has become increasingly prominent[36]. From the perspective of population migration, new-type urbanization has prompted the migration of some rural residents to urban areas, potentially leading to changes in rural household income levels[37]. According to the theory of moderate-scale operation of agricultural land, the income level of rural residents left behind may increase with the expansion of per capita cultivated land area. This income growth has significantly lowered the threshold for clean energy adoption and alleviated concerns associated with its implementation. Economically well-off households are more inclined to adopt clean energy technologies and bear the corresponding maintenance and update costs, thereby contributing to reduced carbon emissions in rural areas[38]. From the perspective of consumption patterns, new-type urbanization has gradually transformed rural resident consumption behaviors and attitudes. The concepts of green, convenient and environmentally friendly consumption have become increasingly ingrained in public consciousness, enhancing the willingness to adopt clean energy, partially replaced standard fossil fuels, promoting the low-carbon transformation of the energy structure, and thereby contributing to reduced carbon emissions in rural areas[39]. From the perspective of industrial upgrading, new-type urbanization has facilitated the transition of rural industries from the existing profit-driven agriculture to ecological agriculture. The integration of rural clean energy development with agricultural waste resource utilization has established an emerging low-carbon industrial chain, promoted green industrial upgrading, optimized the industrial structure, and further reduced carbon emissions in rural areas[25]. From the perspective of technological progress, new-type urbanization has facilitated the continuous adoption of clean energy application and promotion technologies in rural areas. This has not only significantly improved energy use efficiency, but also enhanced the convenience of rural resident lives, making their energy consumption structure cleaner and thereby contributing to reduced carbon emissions in rural areas[40].

In summary, the factor mobility and restructuring induced by urbanization across demographic, spatial, economic, social and ecological dimensions have transformed the carbon emissions associated with rural production and daily life[41]. However, there remains a lack of clear theoretical explanations and robust scientific conclusions regarding to whether the changes brought about by new-type urbanization will promote or inhibit rural carbon emissions, making it difficult to provide targeted policy guidance for the synergistic development of urban and rural areas. Therefore, this paper seeks to expand existing research in the following aspects: identifying the impact of new-type urbanization on rural carbon emissions and elucidating the underlying transmission mechanism; assessing whether the regulatory role of clean energy is being effectively fulfilled. Progress on these would provide policy-relevant insights for China to advance new-type urbanization while simultaneously promoting rural carbon emission reduction.

3 Research and data methodology

3.1 Methodology

3.1.1 Carbon emissions from agricultural production

Following Tian and Lu[42], agricultural carbon emissions were divided into four categories: (1) carbon emissions from agricultural material input, including fertilizer, pesticide, plastic film, diesel and irrigation; (2) N_2O emissions resulting from the disturbance of the soil surface layer due to crop cultivation, including rice, spring wheat, winter wheat, soybean, maize and vegetables; (3) CH_4 emissions generated during rice growth and development; and (4) N_2O and CH_4 emissions arising from enteric fermentation and manure management associated with livestock (cow, non-cow, buffalo, donkey or mule, camel, horse, goat, sheep, poultry and pig). Their carbon emissions were calculated as[1]:

$$T = \sum T_i = \sum (M_i \cdot \delta_i) \tag{1}$$

where, T is the total carbon emissions from agricultural production, T_i is the carbon emissions from various sources, M_i is the amount of each source and δ_i is the emissions coefficient.

The specific carbon sources and their corresponding emissions coefficients are determined according to the four parts (agricultural materials, soil, rice and livestock breeding) delineated above. When calculating CH_4 emissions from livestock manure management, region-specific coefficients based on provincial temperature data were adopted to account for the influence of varying annual average temperatures on the emission coefficients, thereby improving the accuracy of estimated agricultural carbon emissions. Due to space constraints, only representative years are presented.

3.1.2 Carbon emissions from residential life

The estimation of carbon emissions from residential life primarily follows the *General Principles of Comprehensive Energy Calculation (GB/T 2589-2020)* and incorporates the carbon emission coefficients published by the National Development and Reform Commission for the corresponding calculations[43]. Residential energy consumption data from 2000 to 2021 were sourced from the energy balance tables (in standard coal equivalent) in the China Energy Statistical Yearbook. Following Cao et al.[39], energy consumption in rural areas is categorized into four main types: coal (including raw coal, washed coal, other washed coal, coal, coal gangue, coke, coke oven gas, blast furnace gas, converter gas, other gas and other coking products), petroleum (crude oil, gasoline, kerosene, diesel fuel, fuel oil, naphtha, lubricating oils, paraffin waxes, solvent oils, petroleum asphalt, petroleum coke, liquefied petroleum gas, dry gas from refineries and other petroleum products), natural gas (including liquefied natural gas) and electricity. Based on this classification, the carbon emissions for rural residential life were calculated as:

$$S = \sum S_i = \sum (N_i \cdot \gamma_i) \tag{2}$$

where, S is the total carbon emissions from residential life, S_i is the carbon emissions from each energy source, N_i is the consumption amount of each energy type and γ_i is the corresponding emission coefficient.

Based on this framework, specific energy consumption data and their respective emission coefficients are determined according to the four categories (coal, natural gas, oil and electricity) divided above.

3.1.3 Carbon emissions in rural China

Carbon emissions in rural areas were divided into two components: those from agricultural production and those from residential life, and calculated as:

$$CAR = T + S \tag{3}$$

where, CAR is the total carbon emissions from rural areas, T is the total carbon emissions from agricultural production activities, and S is the total carbon emissions from rural residential life.

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[1] To facilitate our summary and remain consistent with other studies on carbon emissions, several greenhouse gases were uniformly converted into standard carbon our actual calculation. According to IPCC 2021, the conversion coefficients of C, CO_2, CH_4, and N_2O are 12/44, 1, 27.2, and 273, respectively.

3.1.4 PVAR model

Following Charfeddine and Kahia[44], the panel vector autoregression (PVAR) model was used to examine the dynamic interaction between carbon emissions and new-type urbanization. The PVAR model combines the strengths of panel data and vector autoregression (VAR) approaches, incorporates lagged terms of all variables, effectively captures the interdependencies among variables, addresses issues of endogeneity and heteroskedasticity, and provides accurate insights into the impact of random disturbances on variable shocks. The model being:

$$y_{i,t} = \alpha_i + \beta_t + \sum\nolimits_{j=1} \beta_p y_{i,t-p} + \varepsilon_{i,t} \tag{4}$$

$$y_{it} = \{CAR, URB\} \tag{5}$$

where, y_{it} is the vector of explanatory variables, including CAR (carbon emission in rural China) and URB (new-type urbanization), i is the region, t is the year, p is the lag order, α_i is the region fixed effect, β_t is the time effect, β_p is the matrix of coefficients of 2 × 2 lagged variables and μ_{it} is the error term obeying the independent homogeneous distribution.

3.1.5 Spatial Durbin model

Following Sun and Guo[45], the spatial Durbin model under the geographic distance weight matrix was chosen to explore the impact of new-type urbanization on carbon emissions in rural China and to assess its spatial spillover effects. Specifically, carbon emission in rural China was used as the dependent variable, new-type urbanization as the core explanatory variable, and economic development, planting structure, technological progress, industrialization, openness to the world, environmental regulation, agricultural marketization and agricultural mechanization were included as control variables. The model being:

$$Y_{it} = \alpha_i + \rho \sum_{j=1}^{n} W_{ij} Y_{it} + \beta X_{it} + \varphi \sum_{j=1}^{n} W_{jt} X_{jt} + \mu_i + \delta_i + \varepsilon_{it} \tag{6}$$

where, where i and j are different prefecture-level provinces, t is the year, Y_{it} is the value of the explained variable in the i-th cell t period, specifically the level of rural carbon emissions (CAR) for each city, X_{it} is the value of the independent variable in the$i$ cell of t period, W_{ij} is the spatial weight matrix, ρ, β and φ are the regression coefficients, μ_i and δ_i are spatial and time fixed effects, respectively, and ε_{it} is the random error term.

3.2 Indicators

The explained variable: CAR denotes carbon emissions in rural China (10^8 t). This variable consists two components: carbon emissions from agricultural production and those from residential life. The specific calculation procedure is detailed in Eqs. (1)–(3).

The core explanatory variable URB denotes the level of new-type urbanization. The core concept of new-type urbanization lies in emphasizing intensiveness and intelligence development, promoting green and low-carbon growth, prioritizing people-centered principles, identifying county seats as key implementation platforms, and placing greater emphasis on the civic integration of agricultural migrant populations. Thus, drawing on the relevant discussions in the *National New-type urbanization Plan (2014–2020)* and the research findings of Tian and Lu[42], Xu and Wang[46], and Yin et al.[47], this study adhered to the principles of scientific rigor, rationality and data availability. In terms of economic, environmental, social, demographic and spatial dimensions, 32 refined indicators were selected to measure the development level of new-type urbanization in each province. In practice, to minimize the influence of subjective factors and ensure the objectivity of the weights of indicator weights, the principal component analysis method was used for weight assignment. Accordingly, the new-type urbanization evaluation index system and its corresponding weights are presented in Table 1.

To address the potential multicollinearity issue among indicators, this study used the variance inflation factor (VIF) method to test for multicollinearity, in accordance with the principle of indicator independence. The average VIF value across all indicators are 1.46, with a maximum of 1.65, both of which are substantially below the threshold of 10. This indicates that multicollinearity among the variables is not present.

Control variables included economic development, planting structure, technological progress, industrialization, openness to the world, environmental regulation, agricultural marketization and agricultural mechanization. Economic development was measured by regional per capita real GDP. Planting structure was defined as the proportion of grain sown area to total crop sown area. The level of technological progress

Table 1 New-type urbanization evaluation index system and weight

Component	Indicator	Variable	Weight
Economic Urbanization	Industry	Tertiary output/Total regional output	0.003
		Patent grant rate	0.008
	Economy	Fiscal revenue per capita	0.048
	Technology	Technology market turnover / Total GDP	0.090
		R&D output / Number of R&D	0.087
	Market level	Actual use of foreign investment per capita	0.050
		Total social retail sales per capita	0.004
Ecological urbanization	Natural habitat	Urban greening coverage	0.008
		Urban sewage treatment rate	0.019
		Domestic waste disposal rate	0.013
	Social amenity	Population density	0.007
		Number of health technicians per 1,000 population	0.020
		Number of public toilets for 10,000 people	0.025
Social urbanization	Education	Per capita expenditure on education and culture	0.030
	Public culture	Coverage of public cultural facilities	0.025
		Cable media coverage	0.021
	Development	Urban governance as a proportion of fiscal expenditure	0.002
	Infrastructure	Piped water coverage	0.029
		Per capita electricity consumption	0.012
		Communications coverage	0.016
	Informatization	Network coverage	0.038
Demographic urbanization	Income	Urban disposable income per capita	0.030
	Consumption	Urban per capita consumption level	0.009
	Employment	Proportion of non-agricultural employment	0.013
		Unemployment rate	0.003
	Quality of life	Urbanization rate	0.056
		Engel coefficient	0.000
		Housing area per capita	0.131
Spatial urbanization	Size of economy	Economic density in built-up areas	0.091
		Per capita investment in fixed assets	0.086
	Construction	Proportion of urban built-up area	0.012
		Transport network density	0.015

was measured by the intensity of regional R&D investment. The level of industrialization was measured by the proportion of regional industrial added value to GDP. The level of openness to the world was measured by the ratio of total import and export volume to regional GDP. The level of environmental regulation was measured by the proportion of regional investment in wastewater treatment to total investment in pollution control. The level of rural marketization was measured by the proportion of rural per capita net operating income to their total per capita net income in the region. The level of agricultural mechanization was calculated using the agricultural mechanization rate formula[2].

Moderating variables: ES is clean energy and was measured as the share of regional electricity generation from cleaner sources, such as wind, hydro and solar power, in total electricity production. The descriptive statistics of the main variables are shown in Table 2.

3.3 Data sources

This paper uses data from 30 provinces (the energy balance of Xizang could not be obtained, so it is excluded here) in rural China from 2000 to 2021 as study area. The 30 provinces in China were divided into the four major regions (eastern, central, western and northeastern) according to the unified national standard[3]. The research data were obtained from the *China Statistical Yearbook*, the *China Rural Statistical Yearbook*, the *China Agricultural Yearbook*, the *China Environmental Statistical Yearbook*, the *China Statistical Data Compilation in the 65th Year of the People's Republic of China*, the *China Finance Yearbook*, the *China Energy Statistics Yearbook* and statistical yearbooks of various provinces and cities. In addition, the output value indicators involved in this study were deflated using 2000 as the base year to eliminate the effects of price fluctuations.

4 Empirical results

4.1 Characterization of carbon emissions in rural China

As shown in Fig. 2, carbon emissions in rural China exhibited a year-on-year increasing trend from 2000 to 2021, rising from 280 Mt in 2000 to 361 Mt in 2021, an increase of 28.9%, with an average annual growth rate of 1.3%. Of the four regions, carbon emissions in the northeastern region increased from 19 Mt in 2000 to 32 Mt in 2021, representing a rise of 68.4%, with an average annual growth rate of 3.1%, the highest among the four regions. Carbon emissions in the central region increased from 83 Mt in 2000 to 108 Mt in 2021, representing a rise of 30.1%, slightly lower than that of the northeast region, and an average annual growth rate of 1.4%. Carbon emissions in the western region increased from 87 Mt in 2000 to 113 Mt in 2021, representing a rise of 29.9%, with an average annual growth rate of 1.4%. Carbon emissions in the eastern region increased from 89 Mt in 2000 to 105 Mt in 2021, representing a rise of

Table 2 Descriptive statistics of main variables

Variable	Sample size	Mean	Std. deviation	Minimum	Maximum
CAR (10^8 t)	660	0.11	0.06	0.01	0.26
URB	660	0.30	0.08	0.17	0.62
ECO (10^4 yuan)	660	0.83	0.73	0.08	4.78
STR (%)	660	65.21	13.04	32.82	97.08
TEC (%)	660	0.95	0.62	0.01	5.03
IND (%)	660	43.63	8.91	0.46	59.05
OPE (%)	660	29.63	35.83	0.77	168.08
ENV (%)	660	26.88	18.48	0.07	100.00
MAR (%)	660	47.77	17.13	4.22	90.16
MEC (%)	660	44.90	23.75	1.41	113.51
ES (%)	660	22.21	23.42	0.0295	96.48

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[2] Agricultural mechanization rate was calculated as (0.4 × machine-plowed area + 0.3 × machine-sown area + 0.3 × machine-harvested area) / (area sown to crops).

[3] The eastern region includes Beijing, Tianjin, Hebei, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Hainan; the central region includes Shanxi, Anhui, Jiangxi, Henan, Hubei, and Hunan; the western region includes Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang; and the northeastern region includes Liaoning, Jilin, and Heilongjiang.

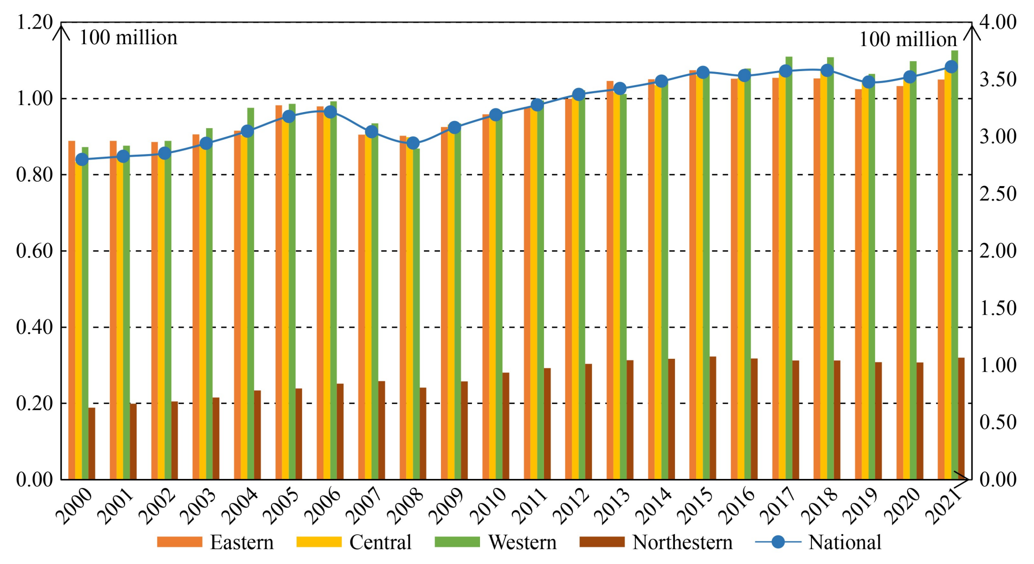

Fig. 2 Trend and structure of carbon emissions in rural China from 2000 to 2021.

18.0%, with an average annual growth rate of 0.8%, the lowest among the four regions. In terms of provinces, the calculation shows that the average level of carbon emissions from rural areas across 30 provinces from 2000 to 2021 was 11 Mt, with 15 provinces above the average and the remaining 15 provinces below it. Of these, the top five provinces in terms of the average emissions were Henan, Shandong, Hebei, Hunan and Sichuan, and the bottom five regions were Tianjin, Shanghai, Beijing, Ningxia and Hainan.

4.2 Characterization of carbon emissions from agricultural production and residential life

4.2.1 Characterization of carbon emissions from agricultural production

Figure 3 shows that from 2000 to 2021, carbon emissions from total agricultural production activities underwent four different phases: continuous increase, slight decrease, slow recovery and continuous decrease. Emissions rose from 236 Mt in 2000 to 257 Mt in 2021, representing an 8.9% increase, with an average annual growth rate of 0.4%. Structurally, carbon emissions from agricultural inputs and livestock were relatively similar, each accounting for 35%–40% of the total. Rice cultivation generated the next highest carbon emissions, contributing about 20%–25% of the total, and crop N_2O emissions were the lowest, representing less than 10%. Compared with the base period, carbon emissions from livestock decreased, while those from agricultural inputs slightly increased and emissions from rice cultivation and crop N_2O remained essentially unchanged.

4.2.2 Characterization of carbon emissions from residential life

As shown in Fig. 4, carbon emissions from residential life had a steady year-on-year increase from 2000 to 2021, rising from 45 to 104 Mt, an increase of 131%, with an average annual growth rate of 6.0%, significantly exceeding the growth rate of carbon emissions from agricultural production during the same period. Structurally, the proportion of carbon emissions from coal consumption in rural residential energy use declined steadily year by year, decreasing from 77.8% in 2000 to 26.0% in 2021, with an average annual reduction of 2.4%. The share of coal-fired power generation gradually decreased from 63.0% in 2019 to 58.4% in 2022, and the share of clean energy-based power generation steadily increased from 27.9% in 2019 to 36.2% in 2022. This decline in coal dependence and the corresponding rise in clean energy use represent core features of China’s power system transformation towards green and low-carbon development. Coal-fired power is gradually transitioning from a primary energy source to a regulating role, while new energy sources are becoming the main driver of power generation growth.

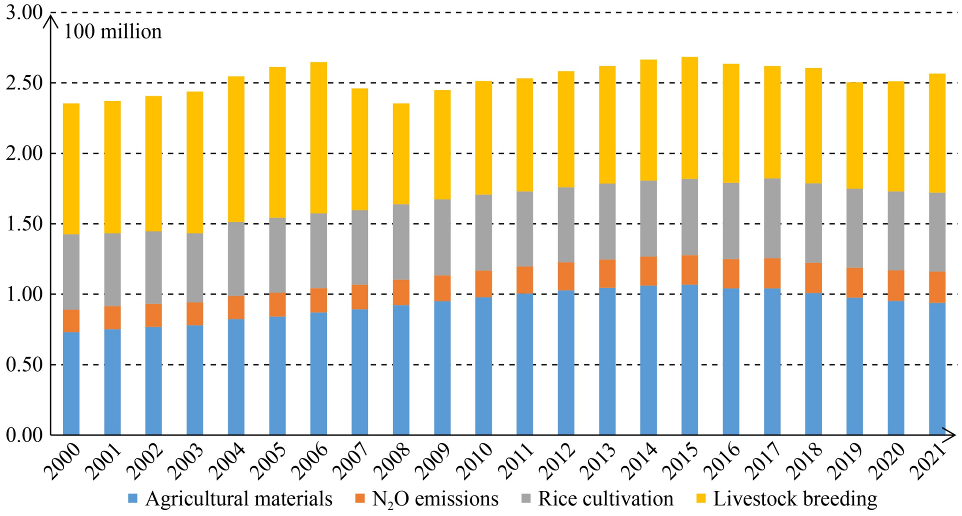

Fig. 3 Trend and structure of carbon emissions from agricultural production in China from 2000 to 2021.

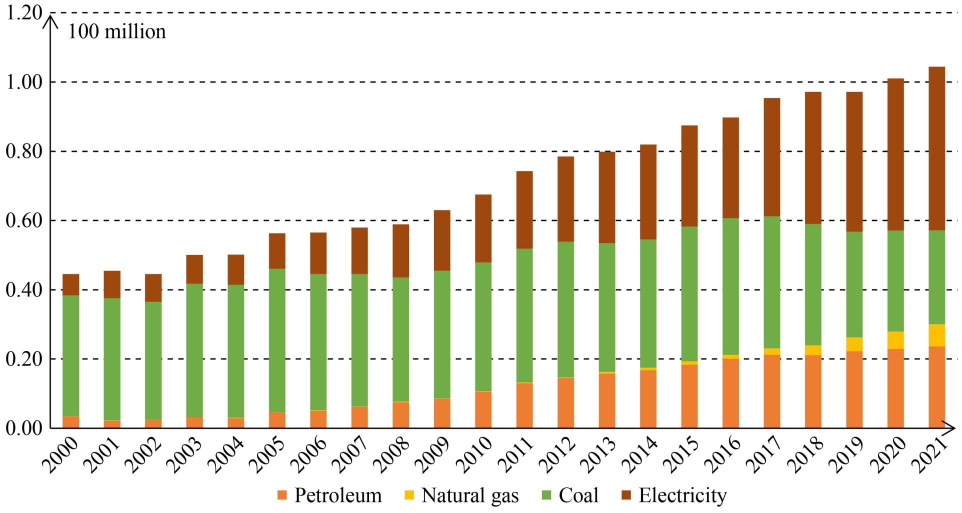

Fig. 4 Trend and structure of carbon emissions from residential life in China from 2000 to 2021.

4.3 Impact of new-type urbanization on carbon emissions in rural China

4.3.1 Interaction mechanisms between carbon emissions and new-type urbanization in rural China

4.3.1.1 Unit root test

Prior to conducting regression analysis, a unit root test was performed to assess the stationarity of the data. The ADF, HT and IPS tests were used to examine both the level series of the explanatory variables (CAR) and the core explanatory variables (URB), as well as their first-order differenced counterparts, D (CAR) and D (URB), respectively (Table 3). This comparison indicates that the original data are non-stationary, whereas the first-order differenced series D (CAR) and D (URB) are statistically significant at the 1% level, indicating that the variables become stationary after differencing.

Table 3 Unit root test

Variable	ADF test	HT test	IPS test
CAR	−0.1054**	0.8497	−1.2762
URB	−0.1645***	0.8122***	−1.9353**
D (CAR)	−1.1425***	−0.1162***	−4.400***
D (URB)	−1.2118***	−0.2000***	−5.2849***

Note: $^{***}P < 0.01$, $^{**}P < 0.05$

4.3.1.2 Determination of the optimal lag order

The lag order of the model critically influences the reliability of the test results; therefore, selecting the optimal lag order for the PVAR model based on information criteria ensures the validity and credibility of the estimation outcomes. The values of the MAIC, MBIC and MQIC criteria are presented in Table 4, and the optimal lag order is determined as the first order based on the criterion with the minimum value among the three.

4.3.1.3 Panel cointegration test

After determining the optimal lag order and ensuring data stationarity, a panel cointegration test was conducted on the first-order differenced data to examine the long-run equilibrium relationship between the variables (Table 5). Both D (CAR) and D (URB) are statistically significant at the 5% level, indicating a stable long-term relationship over time.

4.3.1.4 Granger causality test

The Granger causality test was used to examine whether a causal relationship exists between rural carbon emissions and new-type urbanization, with potential interactions and mutual influences. As shown in Table 6, the hypothesis that carbon emissions in rural areas are not a Granger cause for new-type urbanization fails to pass the significance test. Therefore, the null hypothesis cannot be rejected. The hypothesis that new-type urbanization is not a Granger cause of Carbon emissions in rural areas passes the significance test at the 1% level, and thus the null hypothesis can be rejected, indicating that new-type urbanization is a Granger cause of rural carbon emissions.

4.3.1.5 Impulse response analysis

Impulse response functions were used to examine the long-term dynamic relationships among variables. As shown in Fig. 5, carbon emissions in rural areas and new-type urbanization responded rapidly to internal shocks. Both variables had significantly positive responses in the current period, followed by a gradual convergence to zero, indicating a certain degree of self-persistence and short-term inertia in their dynamic adjustment processes. In response to a shock in rural carbon emissions, new-type urbanization remains initially

Table 4 Determination of the optimal lag order

Lag	MAIC	MBIC	MQIC
1	12.7115	−37.3707	−6.9760
2	1.6138	−31.7765	−11.5112
3	3.0660	−13.6291	−3.4965

Table 5 Panel cointegration test

Statistic	Gt	Ga	Pt	Pa
Value	−1.467	−5.149	−7.844	−4.741
Z-value	−5.149	−1.622	−4.325	−7.027
P-value	0.000	0.050	0.000	0.000

Table 6 Granger causality test

H_0	*F*-statistic	*P*-value	Yes or No
Carbon emissions are not the Granger reason for new-type urbanization	0.396	0.529	Yes
New-type urbanization is not the Granger cause of carbon emissions	7.992	0.005	No

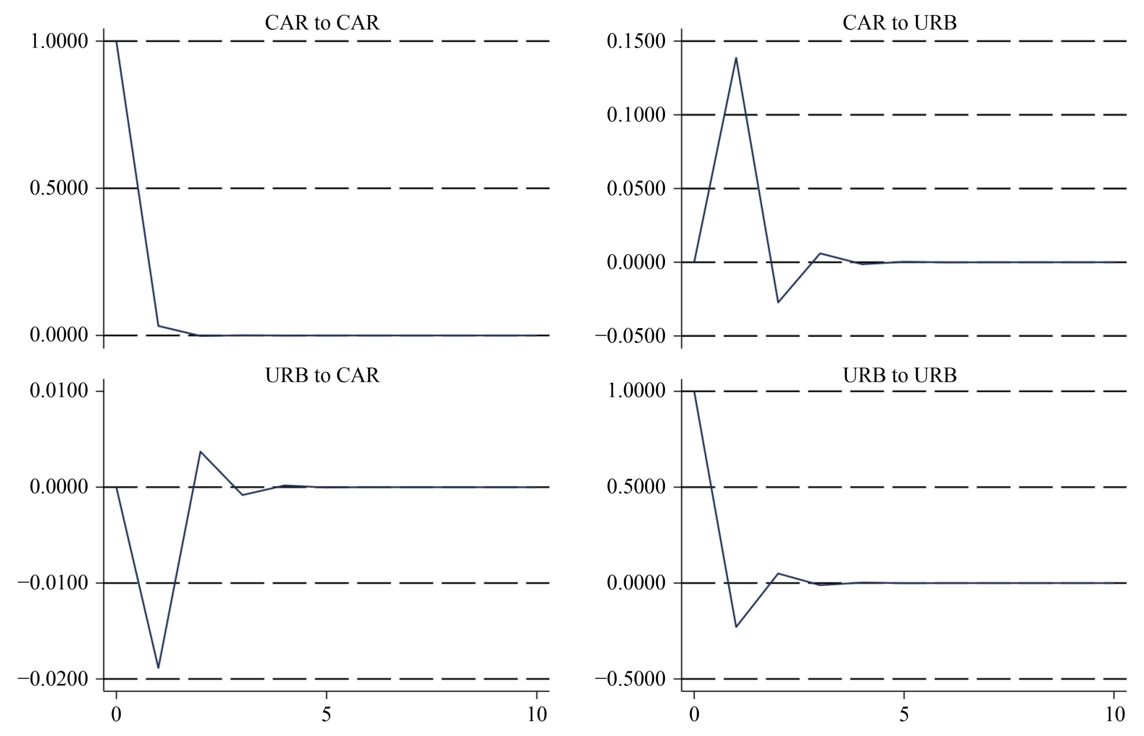

Fig. 5 Impulse response function.

unresponsive in the current period, but subsequently had a rapid positive response, peaking in the first period before gradually converging to zero. This indicates that rural carbon emissions have a delayed yet transient stimulating effect on the development of new-type urbanization. The impact of new-type urbanization on carbon emissions in rural areas had positive-negative fluctuations in the initial stage and gradually stabilized in the later stage, indicating that the lack of coordination between new-type urbanization and rural carbon emissions may hinder carbon emission reduction in rural areas.

4.3.2 Regression results of the entire sample

Table 7 presents the regression results of the impact of new-type urbanization on rural carbon emissions, carbon emissions from agricultural production and carbon emissions from rural residential life. Table 7 shows that, first, the Moran's I test of the three models were statistically significant at the 1% level, indicating the presence of significant spatial correlation among the variables included in the regression model. Therefore, a spatial econometric model is appropriate for the subsequent empirical testing and analysis. Second, the tests of LM, Robust LM, LR, Robust LR and Wald were statistically significant, indicating that the SDM model outperformed the OLS, SEM and SAR models. Finally, the Hausman tests consistently reject the null hypothesis of random effects at a statistically significant level, indicating that the spatial Durbin model with fixed effects was more appropriate. The results of this model are analyzed below.

Table 7 Regression results of the entire sample

Variable	CAR	PROD	LIFE
URB	-0.8464^{***}	-0.7507^{***}	-0.0834^{**}
ECO	–0.0006	0.0128^{*}	-0.0143^{***}
STR	–0.00001	3.21e^{-6}	–0.00002
TEC	0.0299^{***}	0.0228^{***}	0.0070^{***}
IND	0.0016^{***}	0.0011^{***}	0.0005^{***}
OPE	0.0004^{***}	0.0003^{***}	0.0001^{**}
ENV	0.00002	0.0001	–0.0001*
MAR	0.0005^{**}	0.0007^{***}	–0.0001
MEC	0.0004^{***}	0.0007^{***}	-0.0003^{***}
W×URB	–1.1197	-2.3391^{***}	1.3067^{***}
W×ECO	0.2103^{***}	0.2392^{***}	-0.0353^{**}
W×STR	0.0052^{***}	0.0014	0.0039^{***}
W×TEC	0.1612^{***}	0.1346^{***}	0.0259^{***}
W×IND	0.0108^{***}	0.0079^{***}	0.0029^{***}
W×OPE	-0.0021^{***}	–0.0008	-0.0014^{***}
W×ENV	–0.0006	–0.0002	-0.0006^{*}
W×MAR	-0.0090^{***}	-0.0066^{***}	-0.0025^{***}
W×MEC	-0.0063^{***}	-0.0044^{***}	-0.0019^{***}
Moran’s I	55.375^{***}	56.757^{***}	43.361^{***}
LM-lag	2540.411^{***}	2670.364^{***}	1546.938^{***}
RLM-lag	494.248^{***}	518.829^{***}	259.474^{***}
LM-error	2063.847^{***}	2169.698^{***}	1318.451^{***}
RLM-error	17.684^{***}	18.163^{***}	30.988^{***}
LR-lag	177.03^{***}	177.92^{***}	154.81^{***}
Wald-lag	34.99^{***}	44.64^{***}	26.85^{***}
LR-error	177.05^{***}	178.57^{***}	151.99^{***}
Wald-error	6.33	16.29^{*}	7.24
Hausman inspection	39.59^{***}	59.58^{***}	61.94^{***}
Fixed/Random effect	Fixed by time and individual	Fixed by time and individual	Fixed by time and individual
rho	-0.4952^{***}	-0.3661^{**}	-0.6856^{***}
Sigma2_e	0.0023^{***}	0.0015^{***}	0.0002^{***}
Adjusted R^2	0.1958	0.0779	0.2214
Sample	660	660	660

Note: $^{***}P < 0.01$, $^{**}P < 0.05$, and $^{*}P < 0.10$.

At the overall sample level, new-type urbanization exerted a negative effect on carbon emissions from rural areas and agricultural production at the 1% significance level, and on carbon emissions from residential life at the 5% significance level. This indicates that, at the national level, the increase in the level of new-type urbanization had exerted a negative effect on rural carbon emissions from both production and daily life. In addition, the lagged term coefficient of new-type urbanization on carbon emissions from agricultural production was negative and statistically significant at the 1% level, indicating that an increase in the level of new-type urbanization may have contributed to reduced carbon emissions in the neighboring regions. In contrast, the lagged term coefficient on carbon emissions from rural residential life was positive and significant at the 5% level.

Of the control variables, the level of economic development had a positive effect on carbon emissions from agricultural production at the 10% significant level and a negative effect on carbon emissions from residential life at the 1% significant level. This indicates that increasing levels of economic development had differential impacts on carbon emissions from production and those from daily life. An increase in the level of economic development implies a rise in rural per capita income. Clearly, the growth in disposable income has led to changes in dietary structure, increasing demand for meat, eggs, milk and other livestock products, thereby stimulating agricultural production and animal husbandry. However, the growth in disposable incomes may also have led to changes in energy consumption patterns and even consumer behavior, as clean energy technologies such as solar and bioenergy gradually penetrate rural households, displacing some existing fossil fuel use. The level of technological progress had a positive effect on carbon emissions from rural areas, agricultural production and residential life, respectively, at the 1% significance level. This indicates that the increase in the level of technological progress had not achieved the expected mitigation effect, but has instead contributed to a rise in rural carbon emissions. Although technological progress can improve energy use efficiency, thereby conserving energy and reducing greenhouse gas emissions, it also stimulates economic growth, which in turn increases energy consumption. As a result, the energy savings achieved through improved efficiency may be partially or even fully offset by rising demand, leading to higher carbon emissions from production and daily life, a phenomenon known as the rebound effect. The level of openness to the world had a positive effect on carbon emissions from rural areas and agricultural production at the 1% significance level, and on carbon emissions from residential life at the 5% significance level. This indicates that the increase in the level of openness to the world also failed to effectively reduce emissions. Increased openness to the world also implies an expanding scale of foreign investment in agriculture, leading to higher costs in agricultural production, storage and transportation, as well as an increased energy and resource consumption, which in turn contributes to rising carbon emissions from production and daily life in rural areas. The level of industrialization had a positive effect on carbon emissions from rural areas, agricultural production and residential life, respectively, at the 1% significant level. This indicates that there was an existing conflict between rising levels of industrialization and efforts toward carbon reduction and sequestration. Higher levels of industrialization imply a consequent increase in demand for various agricultural commodities, such as cotton, oilseeds, and sugar, needed for industrial production, thereby enhancing farmer incentives to produce. The pursuit of high yields has increased the input, use and consumption of production factors, such as fertilizers, pesticides and agricultural films, as well as chemical energy sources such as oil and coal, thereby contributing to higher carbon emissions from production and daily life. The level of environmental regulation negatively affects carbon emissions from residential life only at the 10% significant level. This indicates that, currently, environmental regulation policies are effective in curbing carbon emissions from residential life, whereas their inhibitory effect on emissions from agricultural production are not statistically significant. The limited effectiveness of these regulatory policies is closely linked to the inherent characteristics and challenges of agricultural environmental pollution, including its widespread occurrence, deep-seated contamination and prolonged treatment cycle. The level of rural marketization has a positive effect on carbon emissions in rural areas at the 5% significant level and on agricultural production at the 1% significance level. This indicates that the increase in the level of agricultural marketization has had a significant impact on rural areas as a whole and on agricultural production, but a negligible impact on the daily lives of residents. The increase in the level of rural marketization indicates that the proportion of farmer operating income in total income has been rising, reflecting an enhanced capacity for high-quality agricultural products from rural areas to reach urban markets such as shopping malls, bazaars and supermarkets. As a result, farmer production incentives are significantly enhanced, and the increase in carbon emissions is objectively greater. The degree of agricultural mechanization had a positive effect on carbon emissions from rural areas and agricultural production at the 1% significance level, while exerting a negative effect on carbon emissions from residential life at the same significant level. This indicates that increased levels of agricultural mechanization exert differential effects on carbon emissions from production and daily life. Mechanized equipment constitutes a form of productive public investment in agriculture and inefficient investment may hinder the replacement of machinery and irrigation systems, while obsoleted equipment exacerbates energy consumption to some extent, thereby objectively contributing to increased carbon emissions.

4.3.3 Spatial effect decomposition

To better examine the spatial spillover effect of new-type urbanization on rural carbon emissions, this study uses the partial differential method to decompose the spatial spillover impact into direct and indirect effects. Table 8 shows that, first, from the regression results for rural carbon emissions, the direct effect coefficient was negative but not statistically significant, whereas the indirect effect coefficient was positive and significant at the 1% level. This indicates that an improvement in the level of new-type urbanization in a given region leads to increased rural carbon emissions in neighboring areas. This also indicates that the local inhibitory effect of new-type urbanization on rural carbon emissions has not yet manifested and the carbon emission reduction potential associated with local urbanization remains underutilized. However, through spillover effects arising from factor mobility, industrial transfer and related mechanisms, it has exerted a significant carbon-increasing impact on neighboring regions. Second, based on the regression results for carbon emissions from agricultural production, the direct effect coefficient is negative and statistically significant at the 1% level whereas the indirect effect coefficient is positive but not statistically significant. This indicates that, supported by driving factors such as technological progress and policy regulation, new-type urbanization in the local region has exerted a significant inhibitory effect on carbon emissions from agricultural production within the same region. However, due to external factors such as the low level of interregional agricultural connectivity in neighboring regions, the carbon emission-increasing effect of new-type urbanization from the local region on these areas is not pronounced and fails to achieve statistical significance. Finally, based on the regression results for carbon emissions from residential life, both the direct and indirect effect coefficients were positive, with the former being significant at the 5% level and the latter at the 1% level. This indicates that an improvement in the level of new-type urbanization in a given region will not only significantly increase carbon emissions from residential life within the region but also elevate emissions in neighboring areas. This indicates that new-type urbanization exerts a driving effect on carbon emissions from residential life in both local and neighboring regions. At the local level, urbanization leads to population agglomeration and consumption upgrading, thereby increasing energy demand in sectors such as household appliances and transportation, and directly contributing to higher carbon emissions. At the neighboring level, demand for consumer goods from local cities drives production and logistics activities in adjacent regions, leading to a significant increase in carbon emissions.

4.3.4 Heterogeneity analysis

Table 9 shows that, first, overall, only the level of new-type urbanization in the northeastern region exerted a negative effect on rural carbon emissions at the 5% significance level whereas the eastern, central and western regions had positive effects. Of these, the regression coefficient in the central region is statistically significant at the 1% level. Second, for production, the level of new-type urbanization in the eastern and western regions had a positive effect on carbon emissions from agricultural production. In contrast, the central and

Table 8 Results of effect decomposition

Variable	CAR	PROD	LIFE
Direct effect	–0.031	–0.095***	0.061**
Indirect effect	0.397***	0.079	0.271***
Total effect	0.366***	–0.016	0.331***
Control	Yes	Yes	Yes
Fixed by time	Yes	Yes	Yes
Fixed by individual	Yes	Yes	Yes

Note: ***$P < 0.01$, **$P < 0.05$, and *$P < 0.10$.

Table 9 Regression results of new-type urbanization on carbon emissions in different regions

Explanatory variable	Eastern	Central	Western	Northeastern
CAR	0.0196	0.2814***	0.2088	–0.1501**
PROD	0.0083	–0.1021	0.1199	–0.0853*
LIFE	0.1035***	–0.1591	0.0905***	0.0744
Control	Yes	Yes	Yes	Yes
Sample	220	132	242	66

Note: $^{***}P < 0.01$, $^{**}P < 0.05$, and $^{*}P < 0.10$.

northeastern regions had a negative effect, with the regression coefficients in the northeastern region being significant at the 10% level. Finally, with respect to the living dimension, the level of new-type urbanization in the central region had neither a positive or negative effect on residential carbon emissions. In contrast, the eastern, western and northeastern regions all had a negative effect, with the regression coefficients in both the eastern and western regions being significant at the 1% level.

In summary, the impact of new-type urbanization on rural carbon emissions exhibits regional heterogeneity; new-type urbanization in the northeastern region has an inhibitory effect on carbon emission, whereas the eastern, central and western regions show a facilitating effect.

4.3.5 Moderating effect analysis

Table 10 shows that, as previously analyzed, new-type urbanization may affect the energy structure through spillover effects arising from an increased proportion of electricity consumption, which in turn influences carbon emissions in rural areas. At the national level, clean energy as a moderating variable, attenuates the negative impact of new-type urbanization on rural carbon emissions and was statistically significant at the 1% level. In recent years, guided by the ecological civilization strategy, the energy consumption structure has been progressively shifting towards cleaner and greener sources, while sustainable development remains a core principle of new-type urbanization. Therefore, increasing the share of clean energy consumption had a positive reinforcing effect in promoting the development of new-type urbanization and curbing rural carbon emissions. On a regional basis, in the eastern and western regions, clean energy mitigates the positive impact of new-type urbanization on carbon emissions in rural areas. In the central region, the coefficient of the interaction term obtained was –0.0005, and the moderating effect was not statistically significant, indicating the absence of a meaningful moderating role of clean energy in this region. The promotion of clean energy reduces dependence on fossil fuels, optimizes the energy consumption structure, stimulates technological research and development as well as capital investment, significantly reduces carbon dioxide emissions, facilitates the modernization and renewal of related infrastructure, and positively contributes to the advancement of new-type urbanization, thereby helping to alleviate environmental problems caused by excessive carbon emissions. However, in the northeastern region, clean energy attenuated the negative impact of new-type urbanization on rural carbon emissions.

Table 10 Regression results under clean energy

Variable	All	Eastern	Central	Western	Northeastern
URB	–0.7085***	0.0443	0.2489***	0.3337**	–0.2389**
URB×ES	0.0011***	–0.0053***	–0.0005	–0.0008**	0.0098***
Control	Yes	Yes	Yes	Yes	Yes
Sigma2_e	0.0014***	0.0002***	6.54e^{-6***}	0.0003***	9.20e^{-7}
Adjusted R^2	0.0296	0.3753	0.0254	0.2934	0.0785

Note: $^{***}P < 0.01$, $^{**}P < 0.05$, and $^{*}P < 0.10$.

This indicates the presence of regional heterogeneity. Overall, clean energy has played a positive regulatory role, although in some regions did not reach statistical significance, indicating that the regulatory impact of clean energy may be subject to time lags.

4.3.6 Robustness test

To more comprehensively and accurately capture the impact of new-type urbanization on carbon emissions from rural China, encompassing both agricultural production and residential life, while minimizing potential biases arising from spatial weight matrix selection and mitigating the influence of outliers on model estimation, three robustness checks were used: alternative spatial weight matrix specification, 1% two-tailed winsorization of the sample data and exclusion of municipalities directly under the Central Government (Table 11). It was found that across the three scenarios, the signs and significance levels of the core explanatory variables as well as the control variables remained largely consistent with the baseline results, and the conclusions derived are broadly similar to those given above. Therefore, the regression results can be regarded as robust.

5 Discussion

First, this study comprehensively considered carbon sources from both agricultural production and residential life, and provides a scientific and comprehensive measurement of rural carbon emissions. Carbon emissions from agricultural production encompass four carbon sources: agricultural inputs, soil N$_2$O emissions, rice cultivation and livestock. Those from residential life include four energy sources: oil, natural gas, coal and electricity. Previous studies have typically assessed rural carbon emissions from a single perspective, either agricultural production or residential life, and few have provided an accurate, comprehensive and systematic measurement of rural carbon emissions that accounts for both production and living conditions. The present results indicate that carbon emissions

Table 11 Robustness test

Variable	Replacement matrix	1% Winsorization	Exclude samples
URB	−0.6692***	−0.8927***	−1.2032***
ECO	−0.0022	−0.0067	0.0359***
STR	0.00003	−0.00004	−0.0005*
TEC	0.0269***	0.0395***	0.0467***
IND	0.0013***	0.0014***	0.0015***
OPE	0.0002*	0.0004***	0.0005***
ENV	0.0001	5.42e^{-6}	−0.0001
MAR	0.0011***	0.0005**	−0.0003
MEC	0.0007***	0.0005***	0.0006***
W×URB	−0.5061**	−1.6583**	−0.5164
W×ECO	0.0886***	0.1845***	−0.2234**
W×STR	0.0001	0.0060***	0.0077***
W×TEC	0.0159*	0.2527***	0.2771***
W×IND	0.0032***	0.0092***	0.0020
W×OPE	−0.0013***	−0.0022***	−0.0005
W×ENV	0.0001	−0.0008	−0.0003
W×MAR	−0.0038***	−0.0102***	−0.0123***
W×MEC	−0.0010***	−0.0063***	−0.0039***
Sample size	660	660	572

Note: $^{***}P < 0.01$, $^{**}P < 0.05$, and $^{*}P < 0.10$.

in rural China have been increasing annually, with the rise in emissions from residential life exceeding that from agricultural production, indicating substantial potential for future growth in carbon emissions associated with rural resident energy consumption. The overall trend of carbon emissions from agricultural production was found to be consistent with that reported by Zhang et al.[48] and Chen et al.[49], however, the calculated results had slight differences, which may be attributed to variations in factors such as calculation methodologies and statistical scopes. The trend and calculated results of carbon emissions from residential life also had certain discrepancies compared to those reported by Wang et al.[16], which may be attributed to the differences in factors such as methodological perspectives and carbon source selection.

Second, most previous studies adopted a standard perspective on urbanization measurement, relying on single indicator, such as land or population growth, to reflect quantitative aspects, while paying insufficient attention to the qualitative dimensions of new-type urbanization in economic, ecological and social development. Few studies have established an indicator system to examine the level of new-type urbanization in China in a long-term and systematic manner. There is limited research on the development of an indicator system for conducting long-term and systematic assessments of new-type urbanization levels in China. This paper establishes a new-type urbanization evaluation system encompassing five dimensions: economic, ecological, social, demographic and spatial. This framework not only addresses the limitations of previous studies that rely on single indicators, such as population size, land area and urbanization rate, to measure urbanization levels, but also enables a scientific, rigorous and comprehensive assessment of new-type urbanization through the incorporation of additional indicators. The results indicate that the level of new-type urbanization in China has been increasing steadily on an annual basis.

Third, this study empirically examined the impact of new-type urbanization on carbon emissions in rural China, as well as the moderating effect of clean energy. The results indicate that, at the national level, new-type urbanization exerts a significant suppressive effect on carbon emissions. In rural areas, a key driver of the rise in new-type urbanization level is the growing population urbanization rate. The rising level of population urbanization implies a continued migration of rural populations to urban areas. As a result, the per capita arable land available to remaining rural residents increases and the structure of cultivated land gradually shifts from fragmented and decentralized patterns toward intensive and large-scale operations. This transformation helps reduce agricultural production costs and mitigates non-point source pollution in agriculture, thereby contributing to a certain extent to the suppression of carbon emissions from agricultural activities. However, the rising level of new-type urbanization has accelerated the dissemination and flow of factors such as information, knowledge and capital between urban and rural areas. This has facilitated the introduction of clean energy sources, such as solar and bioenergy, into the rural energy consumption market and reduced rural resident reliance on fossil fuels, thereby contributing to a certain extent to the mitigation of carbon emissions from rural household activities. In addition, at the national level, clean energy acts as a moderating variable that weakens the negative impact of new-type urbanization on carbon emissions in rural areas and remains statistically significance at the 1% level. By region, in the eastern and western regions, clean energy has mitigated the positive impact of new-type urbanization on rural carbon emissions, whereas in the northeastern region, it has alleviated the negative impact of new-type urbanization on rural carbon emissions, indicating a certain degree of regional heterogeneity. The reason for this is that between 2000 and 2021, the share of clean energy, defined as electricity generated from sources, such as wind, hydro and solar power, in total electricity generation increased only from 25% to 35%, reflecting a limited rate of change. This shows that the regulatory potential has not yet been fully realized, indicating that significant efforts remain necessary for the future application and promotion of clean energy. For the clean energy scenario, the adjusted R^2 of the regression model was 0.0296, which is relatively low. The model results reflect the combined effects of multiple dimensions of variables, such as economic growth, industrial structure, technological progress, energy prices and environmental regulations, rather than isolating the specific impact of clean energy on rural carbon emissions. Also, for the limited explanatory power of the model in the clean energy scenario, the low adjusted R^2 does not undermine the reliability of the core findings. Rather, this indicates that the moderating influence of clean energy on rural carbon emissions remains marginal and gradual. In terms of clean energy application, the proportion of installed clean energy capacity in certain regions remains below 5%, indicating that its impact on rural carbon emissions is still in the initial stage. The technology has not yet achieved large-scale deployment or widespread adoption, and therefore cannot exert a dominant influence. This weak marginal effect is inherently limited in its ability to explain a substantial proportion of the variation in the dependent variable. Finally, there are regional heterogeneities in the sample, including variations in clean energy use efficiency and regional resource endowments. These minor disparities further reduce the explanatory power of clean energy, thereby contributing to a low adjusted R^2. Therefore, future research will build upon these issues by constructing a more comprehensive and systematic set of moderating variables from multiple dimensions, such as clean energy, industrial structure, technological progress, economic growth and environmental regulations, with the aim of further enhancing the explanatory power of the model. This approach not only enhances the objectivity of the research but also offers a feasible pathway for future studies in this field.

Finally, against the background of a rapidly growing digital economy, the in-depth application of digital technologies has significantly enhanced rural resident willingness to adopt clean energy by raising environmental awareness, optimizing resource allocation, innovating service models and promoting green innovation[50]. It has effectively facilitated the promotion and widespread adoption of clean energy, exemplified by photovoltaic power generation, and improved energy efficiency[9]. However, a limitation of this study is the failure to account for the potential impacts of digital technologies on the promotion and application of clean energy. Therefore, future research will focus on elements such as digital technologies in rural areas, establish corresponding indicator systems and further explore the potential relationships and impacts among digital technologies, clean energy and carbon reduction in rural regions. In addition, in light of the limitations associated with the absence of phase differentiation and methodological constraints, future research will adjust the analytical approach based on phase-specific results by adopting a threshold regression model with the clean energy adoption rate as the threshold variable. This approach aims to identify variations in impact coefficients across different phases and thereby minimize the extent to which long-term cumulative effects obscure inter-phase differences. With respect to the observation that new-type urbanization is associated with increased rural carbon emissions in certain regions, this phenomenon can be attributed to two interrelated factors. First, due to the time lag effect of policy implementation, the emission reduction impacts of energy conservation and environmental protection initiatives under new-type urbanization require a certain period to materialize, and the current research timeframe may not fully capture the phase during which these policies become effective. Second, while new-type urbanization promotes the upgrading of rural industries, in the short term, this transformation may lead to higher carbon emissions as a result of equipment modernization and rising energy demand, whereas the long-term emission reduction trend has not yet emerged.

6 Conclusions and implications

6.1 Conclusions

First, it is essential to scientifically and accurately measure carbon emissions from agricultural production and residential living activities. Carbon emissions in rural areas have increased annually, rising from 280 Mt at the beginning of the study period (2000) to 361 Mt by the end of the period (2021), a 28.9% increase, equivalent to an average annual growth rate of 1.3%. Notably, the growth rate of carbon emissions from daily life of rural residents exceeds that from agricultural production. In terms of regional differences, carbon emissions in the northeastern region increased the most, from 19 Mt in 2000 to 32 Mt in 2021, an increase of 68.4%, with an average annual growth rate of 3.1%. In contrast, the eastern region experienced the smallest increase, with emissions growing from 89 to 105 Mt over the same period, representing a 18.0% rise and an average annual growth rate of 0.8%.

Second, new-type urbanization has a significant negative effect on rural carbon emissions. Technological progress, industrialization, openness to the world, agricultural marketization and agricultural mechanization has significant positive impacts on rural carbon emissions. However, economic development and planting structure exert negative yet statistically insignificant effects on carbon emissions in rural China. Significant regional heterogeneity exists across different regions.

Third, at the national level, clean energy acts as a moderating variable that attenuates the negative impact of new-type urbanization on rural carbon emissions. Regionally, in the eastern and western regions, clean energy attenuates the positive impact of new-type urbanization on rural carbon emissions. In the northeastern region, clean energy attenuates the negative impact of new-type urbanization on rural carbon emissions. This indicates significant heterogeneity across different regions.

6.2 Implications

6.2.1 Managerial implications

Based on the above analysis, it is evident that new-type urbanization does not necessarily exert a negative impact on rural carbon emission reduction. Therefore, within the context of new-type urbanization, this study offers novel managerial insights into leveraging clean energy to promote green and low-carbon transformation in rural areas. Specifically, clean energy consumption is primarily influenced by factors including market demand, technological innovation and capital investment. Policy and strategic interventions should therefore focus on enhancing these drivers to promote sustainable adoption. Regarding market demand, it is essential to actively explore the implementation of a clean energy consumption compensation mechanism, provide consumers with high-quality services such as energy-saving consultation and price electricity prices, and reduce the costs associated with clean energy use. With regard to technological innovation, efforts should focus on advancing the research, development and application of clean energy technologies, promoting localized production and consumption, and enhancing their efficient use.

6.2.2 Social implications

Notably, rural household energy consumption remains predominantly reliant on coal. Therefore, promoting the diversification and greening of rural household energy structures holds significant social and practical importance. Specifically, first, village-based photovoltaic power plants and photovoltaic villages can be actively established to promote the adoption of clean energy. Second, efforts should be directed toward strengthening the construction and upgrading of rural electricity grids, as well as promoting the development of renewable energy local area networks. Third, existing, unattainable energy systems can be transitioned toward the development of centralized biogas, thereby alleviating pressure on energy demand and reducing environmental pollution.

However, in light of the heterogeneous characteristics of urbanization development across regions, a differentiated development strategy should be implemented to promote coordinated regional development. The eastern region, characterized by a higher level of development, should plan and layout its future urbanization according to urban environmental carrying capacity, rationally transfer surplus rural labor, prioritize resource integration and efficient use, and expand green development space and potential. For less developed regions such as the central, western and northeastern regions, it is essential to actively draw on the advanced experiences of more developed areas, promote the coordinated development of new-type industrialization and urbanization, fully leverage their respective resource advantages and expand opportunities green development.

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Compliance with ethics guidelines

Dequan Hao, Jinjin Chen, Qing Ding, and Wenxin Liu declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

REFERENCES

1. Li L B, Gao X L, Huang J L. Prospects for major issues of China’s new urbanization development during the “14th Five-Year Plan” period. *Journal of Management World*, 2020, **36**(11): 7–21 (in Chinese)

2. Tian Y, Zhang H J. Spatial-temporal pattern and spatial differentiation mechanism of agricultural carbon emission efficiency in China. *Social Science Journal*, 2024, (2): 172–182 (in Chinese)
3. Hao D Q, Xu R F, Du B P, Yang J, Liu W X. Does carbon reduction and sequestration conflict with food security in rural China?—*What, why and how?*. *Science of the Total Environment*, 2024, **947**: 173871
4. Crippa M, Solazzo E, Guizzardi D, Monforti-Ferrario F, Tubiello F N, Leip A. Food systems are responsible for a third of global anthropogenic GHG emissions. *Nature Food*, 2021, **2**(3): 198–209
5. Zhuang R L, Yang J, Mi K N, Zhang C Y, Zhi M L. Spatiotemporal characteristics, influencing factors, and trend prediction of household energy consumption in China. *Progress in Geography*, 2024, **43**(5): 870–887 (in Chinese)
6. Tang L Z, Shi J X, Li Y J. Two-way correlation mechanism and measurement between new urbanization and clean energy consumption. *Nanjing Journal of Social Sciences*, 2022, (8): 27–36 (in Chinese)
7. Liu C F, Zhang Z Y. From town-country integration to urban-rural integration: new thinking on the relationship between urban and rural areas. *Scientia Geographica Sinica*, 2018, **38**(10): 1624–1633 (in Chinese)
8. Chen M X, Ye C, Lu D D, Sui Y W, Guo S S. Cognition and construction of the theoretical connotations of new urbanization with Chinese characteristics. *Journal of Geographical Sciences*, 2019, **29**(10): 1681–1698
9. Yin S, Wang Y R, Liu Y J, Wang S. Exploring drivers of behavioral willingness to use clean energy to reduce environmental emissions in rural China: an extension of the UTAUT2 model. *Journal of Renewable and Sustainable Energy*, 2024, **16**(4): 045903
10. Zhang J, Wang X J. The impact of ecological civilization construction on urban carbon emission: quasi natural experiment based on ecological civilization demonstration area. *Ecological Economy*, 2024, **40**(5): 214–222 (in Chinese)
11. Chen Z G, Xu M. Meeting low-carbon and food security objectives of China agri-food system under the greater food approach: status quo, challenges, and pathways. *Issues in Agricultural Economy*, 2023, (6): 77–85 (in Chinese)
12. Li R Z, Huang X L, Liu Y B. Spatio-temporal differentiation and influencing factors of China's urbanization from 2010 to 2020. *Acta Geographica Sinica*, 2023, **78**(4): 777–791 (in Chinese)
13. Li B, Zhang J B, Li H P. Research on spatial-temporal characteristics and affecting factors decomposition of agricultural carbon emission in China. *China Population, Resources and Environment*, 2011, **21**(8): 80–86 (in Chinese)
14. Wang X, Ma S T, Pu C, Zhao X, Wang Y Q, Zhang H L. Trends and influencing factors of agricultural carbon emissions in the Southwest China. *China Population, Resources and Environment*, 2017, **27**(S2): 231–234 (in Chinese)
15. Guo S D, Qian Y B, Zhao R. Analysis of agricultural carbon emission efficiency and convergence in western China—based on SBM-undesirable model. *Rural Economy*, 2018, (11): 80–87 (in Chinese)
16. Wang Y, Li F, Sun X. Progress of research on carbon emissions of urban household consumption. *Resources Science*, 2019, **41**(7): 1201–1212 (in Chinese)
17. He Y Q, Chen R, Zhu S Y, Xia S J, Wang F. Regional correlation of agricultural carbon emission reduction from the perspective of strategic interaction and technology spillover. *China Population, Resources and Environment*, 2021, **31**(6): 102–112 (in Chinese)
18. Shang J, Ji X Q, Shi R, Zhu M R. Structure and driving factors of spatial correlation network of agricultural carbon emission efficiency in China. *Chinese Journal of Eco-Agriculture*, 2022, **30**(4): 543–557 (in Chinese)
19. Cai Z B, Deng Z L. An analysis of China's spatial urbanization level and its influencing factors: based on geographically weighted regression model of Chinese provinces. *Journal of Zhengzhou University*, 2020, **53**(2): 48–54, 127 (in Chinese)
20. Yin J F, Shi P J, Huang W Z, Shi Z H, Li Y L. Spatiotemporal differentiation characteristics and influencing factors of coupling coordinated development of rural revitalization and new urbanization at the county level in Gansu Province. *Journal of Natural Resources*, 2023, **38**(8): 2148–2168 (in Chinese)
21. Xu W X, Wang M J, Zheng J H, Liu C J. Spatio-temporal evolution characteristics and driving factors of coupling and coordination of urbanization and greenization in Yangtze River economic belt. *Resources and Environment in the Yangtze Basin*, 2023, **32**(8): 1561–1572 (in Chinese)
22. Lu M, Feng H. Agglomeration and emission reduction: an empirical study on the influence of urban scale gap on industrial pollution intensity. *The Journal of World Economy*, 2014, **37**(7): 86–114 (in Chinese)
23. Cheng L L, Zhang J B, He K. The direct influence and indirect spillover effect of urbanization on agricultural carbon productivity base on the spatial Durbin model. *Chinese Journal of Agricultural Resources and Regional Planning*, 2019, **40**(11): 48–56 (in Chinese)
24. Li Z, Yao L, Wang M M, Wei G E, Sun P J. Does the digital economy catalyze the emergence of urban shrinkage? —Empirical evidence from Chinese prefecture-level cities. *Cities*, 2024, **154**: 105363
25. Jiang Y H, Sun P J. Does shrinkage have an impact on urban livability? An empirical analysis from Northeast China. *Sustainable Cities and Society*, 2024, **113**: 105725
26. Wu H T, Gai Z Q, Guo Y X, Li Y W, Hao Y, Lu Z N. Does environmental pollution inhibit urbanization in China? A new

perspective through residents' medical and health costs. *Environmental Research*, 2020, **182**: 109128

27. Guo Z D, Zhang X N. Carbon reduction effect of agricultural green production technology: a new evidence from China. *Science of the Total Environment*, 2023, **874**: 162483
28. Cao N G, Sun P J, Luo H, Gao X T. The impact of urban shrinkage on agricultural production efficiency—a case study of the lower Yellow River region in China. *Journal of Rural Studies*, 2025, **119**: 103755
29. Fu J, Ding R, Zhu Y Q, Du L Y, Shen S W, Peng L N, Zou J, Hong Y X, Liang J, Wang K X, Xiao W Q. Analysis of the spatial-temporal evolution of Green and low carbon utilization efficiency of agricultural land in China and its influencing factors under the goal of carbon neutralization. *Environmental Research*, 2023, **237**(Pt 1): 116881
30. Wei X H, Zeng C Y, Wang J N, Chen Y. The road to green development for national-level poverty-stricken counties: does poverty alleviation help reduce carbon emissions?. *Energy Economics*, 2024, **138**: 107817
31. Du R R, He T, Khan A, Zhao M J. Carbon emissions changes of animal husbandry in China: trends, attributions, and solutions: a spatial shift-share analysis. *Science of the Total Environment*, 2024, **929**: 172490
32. Yu B Y, Wei Y M, Gomi K, Matsuoka Y. Future scenarios for energy consumption and carbon emissions due to demographic transitions in Chinese households. *Nature Energy*, 2018, **3**(2): 109–118
33. Tian Y, He Y C. Does rural labor migration promote agricultural carbon reduction?—a panel data test based on 30 provinces. *Journal of China University of Geosciences: Social Sciences Edition*, 2023, **23**(5): 61–73 (in Chinese)
34. Ma Z Y, Xiao H, Li J, Chen H T, Chen W H. Study on how the digital economy affects urban carbon emissions. *Renewable and Sustainable Energy Reviews*, 2025, **207**: 114910
35. Xu G, Zheng M C, Wang Y X, Li J. The urbanization of population and land in China: temporal trends, regional disparities, size effect and comparisons of measurements. *China Land Science*, 2022, **36**(5): 80–90 (in Chinese)
36. Zhu Y H, Zheng Y, Ren Z Y. Household welfare loss from energy price crisis: evidence from China. *Energy Economics*, 2024, **138**: 107836
37. Zhang W W, Zhou Y. The impact of migrant workers' transfer of employment on rural residents' income and its spatial spillover effect. *Chinese Journal of Agricultural Resources and Regional Planning*, 2024, **45**(4): 131–142 (in Chinese)
38. Du X, Zhang G Y. The impact of land transfer on income distribution in Rural China: an empirical analysis based on rural household survey data collected in 10 provinces in 2020. *Chinese Rural Economy*, 2022, (5): 107–126 (in Chinese)
39. Cao X, Gao Y, Liu Z Q. The impact of urbanization of rural residents on carbon emissions from household energy consumption. *Chinese Rural Economy*, 2021, (10): 64–83 (in Chinese)
40. Jiang L, Yu L, Xue B, Chen X P. Regional characteristics of household energy consumption structure in Qinghai Province. *Economic Geography*, 2019, **39**(8): 146–152, 176 (in Chinese)
41. Gao F. The inflection point of China's urban and rural consumption and its economic growth effect. *Statistical Research*, 2014, **31**(12): 41–46 (in Chinese)
42. Tian Y, Lu Y H. Coupling coordination between new-type urbanization and agricultural carbon emission efficiency in China's Provinces. *Journal of Huazhong Agricultural University: Social Sciences Edition*, 2023, (4): 33–46 (in Chinese)
43. Tang Y Y, Li S, Xia Q. Analysis on influence factors of domestic energy carbon emissions in China: based on STIRPAT model. *Ecological Economy*, 2017, **33**(5): 42–47 (in Chinese)
44. Charfeddine L, Kahia M. Impact of renewable energy consumption and financial development on CO_2 emissions and economic growth in the MENA region: a panel vector autoregressive (PVAR) analysis. *Renewable Energy*, 2019, **139**: 198–213
45. Sun H, Guo J G. The influence and mechanism of environmental regulation and industrial agglomeration on energy efficiency: a spatial effects-based perspective. *Journal of Natural Resources*, 2022, **37**(12): 3234–3251 (in Chinese)
46. Xu X, Wang Y Y. Research on the logical mechanism, multidimensional measurement and regional coordinated development of urban-rural integration: from the perspective of coordinated promotion of new urbanization and rural vitalization. *Issues in Agricultural Economy*, 2023, (11): 49–62 (in Chinese)
47. Yin S, Wang Y L, Zhang Q Y. Mechanisms and implementation pathways for distributed photovoltaic grid integration in rural power systems: a study based on multi-agent game theory approach. *Energy Strategy Reviews*, 2025, **60**: 101801
48. Zhang S H, Wen X W, Sun Y, Xiong Y L. Impact of agricultural product brands and agricultural industry agglomeration on agricultural carbon emissions. *Journal of Environmental Management*, 2024, **369**: 122238
49. Chen M H, Xiao H Y, Zhao H, Liu L N. The power of attention: government climate-risk attention and agricultural-land carbon emissions. *Environmental Research*, 2024, **251** (Pt 2): 118661
50. Yin S, Zhao Y D, Hussain A, Ullah K. Comprehensive evaluation of rural regional integrated clean energy systems considering multi-subject interest coordination with Pythagorean fuzzy information. *Engineering Applications of Artificial Intelligence*, 2024, **138**: 109342