Spatiotemporal Analysis of Carbon Emissions from Rural Residential Energy Consumption in China: Postprint

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Abstract

With the improvement of living standards, rural residential energy consumption in China has exhibited a trend of substantial growth, emerging as a new source of carbon emission increase. This study estimates rural residential energy carbon emissions across 30 provinces in China from 2001 to 2013, employs the carbon Gini coefficient and ArcGIS technology to analyze the spatiotemporal characteristics of rural residential energy carbon emissions at the provincial scale, and utilizes the STIRPAT model to identify the primary influencing factors. The results indicate that: (1) From 2001 to 2013, direct and indirect rural residential energy carbon emissions increased by 7.65% and 9.16%, respectively. (2) The carbon Gini coefficients in the eastern, central, and western regions exhibited a declining trend, suggesting that regional disparities in per capita rural residential energy carbon emissions have generally narrowed across all regions. (3) During 2001-2013, the spatial distribution pattern of regions with high per capita direct rural residential energy carbon emissions remained relatively stable, whereas for per capita indirect emissions, the spatial distribution pattern of regions with low emissions was more stable. (4) Rural population size, per capita net income of farmers, rural residential consumption expenditure, and the proportion of young and middle-aged population promote rural residential energy carbon emissions, while the energy consumption structure of rural residents mitigates them; furthermore, rural residential energy carbon emissions in northern China are significantly higher than those in the south. (5) From the perspective of the environmental Kuznets curve hypothesis, economic development is a crucial factor contributing to the existence of an inflection point in the Kuznets curve for China’ s rural residential energy carbon emissions.

Full Text

Preamble

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Analysis of Spatio-Temporal Patterns of Carbon Emission from Energy Consumption by Rural Residents in China

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Abstract

With improving living standards, energy consumption by rural residents in China has increased substantially, emerging as a new source of carbon emissions growth. This study estimates carbon emissions from rural residential energy consumption in China from 2001 to 2013, analyzes spatio-temporal patterns at the provincial scale using the carbon Gini coefficient and ArcGIS technology, and identifies key influencing factors through the STIRPAT model. Results show that direct and indirect carbon emissions from rural residential energy consumption increased by 7.65% and 9.16%, respectively. The carbon Gini coefficient analysis indicates that regional disparities in per capita carbon emissions among eastern, central, and western zones are narrowing overall. The spatial distribution of provincial per capita carbon emissions is not completely random. Areas with low direct carbon emissions are mainly distributed in eastern and western regions, while high-emission areas remain relatively stable, concentrated primarily in Sichuan, Hebei, and Anhui. Population size, affluence level, and age structure are the main driving factors of carbon emissions, while energy consumption structure has a mitigating effect. For per capita indirect emissions, low-level areas show stable spatial distribution patterns. Rural residents in northern China exhibit significantly higher carbon emissions than those in the south. Based on the Environmental Kuznets Curve hypothesis, economic development is an important factor driving the turning point in rural residential energy carbon emissions.

Keywords: rural residents; energy consumption; carbon emissions; spatio-temporal pattern; impact factors

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Introduction

Global climate change, characterized primarily by global warming, represents one of the most severe challenges facing human society and has become a focus of public concern. The international mainstream view, represented by the IPCC, holds that global average temperatures increased significantly during the 20th century, with human activities altering the Earth' s carbon cycle being the primary cause. Fossil fuel combustion is considered one of the most important contributors to global warming. Consequently, reducing carbon emissions and establishing a low-carbon society have become fundamental consensus responses to climate change.

During China' s transition period, carbon emissions from residential consumption have become another growth point exceeding the industrial sector. Rural residential energy consumption in particular has shown a substantial growth trend, increasingly becoming a new source of carbon emissions that will impose increasingly strong stress on the future environment. While existing research has focused on estimating carbon emissions from urban and rural residential energy consumption, studies specifically examining the spatial patterns and influencing factors of rural residential energy carbon emissions remain limited.

This paper investigates the spatio-temporal evolution of rural residential energy carbon emissions in China based on per capita historical cumulative carbon emissions. Using the carbon Gini coefficient and other indicators, we reveal development trends from 2001 to 2013, analyze spatial characteristics through ArcGIS, and employ the STIRPAT model to examine key influencing factors. The findings aim to provide references for differentiated carbon reduction policies and low-carbon society construction.

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1. Data Sources

Rural residential energy in China primarily includes coal (sum of raw coal, washed coal, and briquettes), electricity, and heat. Indirect carbon emissions refer to emissions from clothing, daily necessities, household equipment, medical and health care, education, culture, and entertainment services. Data sources include the *IPCC Guidelines for National Greenhouse Gas Inventories*, *China Energy Statistical Yearbook*, and China' s regional input-output tables. The apparent consumption method is used to convert various energy consumption types into standard coal equivalent.

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2. Research Methods

2.1 Emission Calculation Method

This study uses the emission coefficient method, a baseline approach provided in the *IPCC Guidelines for National Greenhouse Gas Inventories*, to estimate direct carbon emissions from rural residential energy consumption based on fossil fuel consumption quantities. Indirect carbon emissions are calculated using a comprehensive input-output and consumer lifestyle approach.

The direct carbon emission formula is:

$$CE = \sum_j AC_j \times NCV_j \times CC_j \times O_j \times \frac{44}{12}$$

where CE represents direct carbon emissions from rural residential energy (tCO), AC_j is the physical consumption quantity of fossil fuel j, NCV_j is the low calorific value of each fuel (kJ/kg or kJ/m^3), CC_j is the carbon content of fuel j (kg/GJ), and O_j is the oxidation rate (assumed as 100% for complete combustion). Low calorific values are obtained from the *China Energy Statistical Yearbook*.

For indirect emissions:

$$E_d = \sum_j CEST_j \times \frac{CPIB_j}{CPIT_j} \times T_{ji} \times \frac{X_i}{AC_j \times NCV_j \times CC_j \times O_j} \times \frac{44}{12}$$

where E_d is indirect carbon emissions from rural residential energy (tCO), i represents industrial product or service categories, $CEST_j$ is consumption expenditure on product j in the target year, $CPIB_j$ and $CPIT_j$ represent consumer price indices for product j in the base and target years, T_{ji} is the transformation matrix converting expenditure on product j to industrial product/service category i, and X_i is household expenditure on category i.

2.2 Carbon Gini Coefficient

To analyze provincial disparities in rural residential energy carbon emissions, we employ the carbon Gini coefficient (GiNi) based on China’ s official east-central-west regional division. A higher GiNi value indicates greater regional disparity in carbon emissions.

Assuming region P has n sub-units, each with rural residential energy carbon emission y_i $(i = 1, 2, ..., n)$, and P is divided into k regions P_j $(j = 1, 2, ..., k)$, the carbon Gini coefficient can be decomposed into three components following Dagum’ s method: within-region disparity contribution (G_w), between-region net disparity contribution (G_b), and between-region transvariation density contribution (G_t):

$$G = G_w + G_b + G_t$$

The within-region carbon Gini coefficient for region P_j is:

$$G_{jj} = \frac{1}{2n_j^2\mu_j}\sum_{i=1}^{n_j}\sum_{r=1}^{n_j}|y_{ji} - y_{jr}|$$

The between-region carbon Gini coefficient between regions P_j and P_h is:

$$G_{jh} = \frac{1}{n_j n_h(\mu_j + \mu_h)}\sum_{i=1}^{n_j}\sum_{r=1}^{n_h}|y_{ji} - y_{hr}|$$

2.3 STIRPAT Model

The STIRPAT model, developed from the classic IPAT equation, is a stochastic regression model examining population, affluence, and technology impacts on environment. This study uses it to analyze key factors influencing rural residential energy carbon emissions:

$$I = aP^bA^cT^de$$

where I is environmental impact (carbon emissions), P is population, A is affluence, T is technology, a is the coefficient, and e is the error term. In logarithmic form:

$$\ln I = \ln a + b\ln P + c\ln A + d\ln T + \ln e$$

The estimated coefficients (b, c, d) represent elasticities, indicating the proportional change in carbon emissions relative to each factor.

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3. Results

3.1 Temporal Evolution Characteristics

From 2001 to 2013, China' s rural population decreased from 7.96×10 to 6.30×10 (annual growth rate of -1.93%). Direct carbon emissions from rural residential energy increased from 4.47 Gt to 11.77 Gt (7.65% annual growth rate), while per capita direct emissions rose from 0.22 t to 0.71 t (9.61% annual growth rate). Indirect carbon emissions grew from 1.71 Gt to 4.05 Gt (9.16% annual growth rate), with per capita indirect emissions increasing from 0.29 t to 1.16 t (11.14% annual growth rate). The growth rate of indirect emissions significantly exceeded that of direct emissions.

[Figure 1: see original paper] shows the trend of rural residential energy carbon emissions from 2001 to 2013. The period 2001-2002 saw relatively flat growth (4.39 Gt total emissions), while 2003-2013 experienced rapid increase (11.77 Gt total, 10.15% annual growth; per capita emissions reached 1.16 t, 11.46% annual growth). Direct emissions showed a declining trend after 2013, while indirect emissions continued increasing.

Regional analysis reveals that eastern China had the fastest growth in total and per capita emissions (7.65% and 10.61% respectively), followed by the central region (7.97% and 7.65%), while western China grew slowest (2.53% and 4.45%). The eastern region consistently ranked highest in total emissions, while the western region ranked lowest. Total emissions in the east increased from 0.83 Gt to 2.00 Gt, while the west grew from 0.63 Gt to 0.84 Gt. Per capita emissions in the east rose from 0.26 t to 0.86 t, in the central region from 0.22 t to 0.71 t, and in the west from 0.31 t to 0.53 t.

[Figure 2: see original paper] illustrates these trends for the three major regions. At the provincial level, Hebei had the highest total emissions throughout 2001-2013, while Hainan showed the largest increase. Guangdong' s per capita emissions decreased from 0.63 t to 0.34 t (-6.98% annual growth), whereas Guangxi showed the largest increase (17.13% annual growth).

3.2 Regional Disparities in Per Capita Emissions

The carbon Gini coefficient for per capita rural residential energy emissions showed a fluctuating decline from 0.15 to 0.14 between 2001-2013 (-0.01/10a), indicating narrowing regional disparities. All three economic zones exhibited declining Gini coefficients: eastern region from 0.18 to 0.16, central from 0.12 to 0.09, and western from 0.16 to 0.12, with reduction rates of 3.14%, 2.10%, and 3.02% respectively.

[Figure 4: see original paper] displays the carbon Gini coefficient trends. Decomposing the overall disparity reveals that between-region net disparity (G_b) contributed 71.25% to 85.47% of total inequality, while within-region disparity (G_w) contributed 7.01% to 1.40%, and transvariation density (G_t) contributed 21.75% to 13.13%. The dominance of between-region net disparity indicates that inter-regional differences are the primary source of overall inequality.

3.3 Spatial Patterns

Using ArcGIS natural breaks classification, provinces were categorized into high, relatively high, medium, relatively low, and low emission levels for 2001, 2005, 2009, and 2013.

For direct per capita emissions, high-level areas remained relatively stable, concentrated in Hebei (east), Hubei and Anhui (central), and Guizhou, Sichuan, and Inner Mongolia (west). Between 2001-2005, Beijing and Shanghai shifted from high to relatively high levels. Between 2005-2009, Hubei shifted downward while Hebei, Anhui, and Inner Mongolia moved upward. Between 2009-2013, Hubei shifted from high to relatively high, while Sichuan remained stable. Low-level areas were primarily in Hainan, Tianjin, and Fujian (east), Heilongjiang (central), and Ningxia (west). Hainan shifted upward from low to medium level, while Heilongjiang, Xinjiang, and Tianjin moved downward.

[Figure 6: see original paper] maps the spatial distribution of direct per capita emissions. The number of high-level provinces first increased then decreased, while low-level provinces showed an increasing trend overall. Central China' s urbanization and changing energy use patterns increased electricity, heat, and natural gas consumption, raising per capita emissions. Western regions, though less coal-dependent, are remote poverty-stricken areas with poor transportation, limiting renewable energy access.

For indirect per capita emissions, low-level areas remained stable, mainly in eastern and southern economic zones. High-level areas changed significantly, initially concentrated in Xinjiang (2001), then shifting to Shaanxi and Heilongjiang (2005), and later to Xinjiang, Heilongjiang, and Guangxi (2013). The overall trend shows movement toward eastern and middle Yellow River regions.

[Figure 7: see original paper] shows the spatial patterns of indirect per capita emissions. For rural residents, the largest emission increase came from housing, followed by transportation and communication, while medical care emissions fluctuated and food-related emissions declined. Housing, household equipment, and food are the three dominant factors driving energy consumption and carbon emissions.

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4. Influencing Factors

To identify key drivers, we estimated a STIRPAT model incorporating rural population size, per capita net income, living expenditure, energy consumption structure (coal share), age structure (proportion aged 15-65), and regional dummy variables.

presents the OLS estimation results. Model (1) achieves an R^2 of 0.517 (F=19.939, p<0.001), indicating that population, income, expenditure, energy structure, and age structure explain 51.7% of emission variation. Model (2) adds a quadratic income term, improving R^2 to 0.521 (F=17.700, p<0.001).

Key findings: - **Population size** and **living expenditure** have non-standardized coefficients >1 (1.177 and 1.837 in Model 1; 1.207 and 1.738 in Model 2), indicating that emission growth exceeds the rate of change in these factors (elasticity >1). - **Energy structure** coefficients are negative (-0.014 and -0.022), showing that reducing coal use mitigates emissions. - **Income** shows an inverted-U relationship: the linear term is positive (0.378) while the quadratic term is negative (-0.239), supporting the Environmental Kuznets Curve hypothesis. The turning point occurs at a specific income level, suggesting economic development can eventually reduce emissions. - **Regional effects** are significant, with northern China showing higher emissions than southern China.

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5. Conclusions

Rural residential energy carbon emissions have become a frontier research topic in energy consumption and emission studies. This paper defines rural residential carbon emissions as those generated from both direct energy use and all products/services consumed during production and living processes. China' s rural indirect emissions exceed direct emissions, contrasting with some previous studies.

The main conclusions are:

1. **Temporal trends**: From 2001-2013, direct and indirect carbon emissions increased by 7.65% and 9.16% annually. Indirect emissions grew faster than direct emissions.
2. **Regional disparities**: The carbon Gini coefficient declined, indicating narrowing regional differences. All three economic zones showed decreasing within-zone disparities.
3. **Spatial patterns**: High direct-emission areas remained stable in Hebei, Hubei, Anhui, Guizhou, Sichuan, and Inner Mongolia. Low-level areas were stable in eastern and southern regions. Northern emissions consistently exceeded southern emissions.
4. **Driving factors**: Population size, per capita income, and living expenditure accelerate emissions (elasticity >1), while energy structure optimization mitigates them. Age structure also significantly influences emissions.
5. **Environmental Kuznets Curve**: The significant negative quadratic income term supports the EKC hypothesis, indicating that economic development is a crucial factor in reaching the emission turning point.

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6. Recommendations

Based on these findings, we propose:

1. **Promote low-carbon consumption**: Advocate moderate consumption and low-carbon lifestyles, especially as rural-to-urban migration continues and household sizes shrink, increasing per capita expenditure and emissions.
2. **Optimize energy structure**: Northern provinces with high per capita emissions, particularly those over-reliant on coal, must improve energy

mix by increasing clean energy utilization. Northwest poverty regions should develop distributed renewable energy systems (biomass, solar) with national support to address energy shortages and reduce emissions.

3. **Regional differentiation**: Policy design should account for spatial patterns and regional differences, implementing targeted measures for high-emission zones while supporting low-emission areas.
4. **Integrated planning**: Combine national energy planning with scientific rural energy development strategies to improve living conditions and environments, providing strong support for building resource-saving and environmentally friendly rural societies.

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Note: Figure translations are in progress. See original paper for figures.