Spatiotemporal Patterns and Driving Factors of Carbon Emissions from Fossil Energy Consumption in Hunan’ s Prefecture-Level Cities: A Postprint

Authors: Liu Xianzhao, Gao Changchun, Song Yan, Zhang Yong, Su Qing, Tian Yanlin

Date: 2017-04-18T00:00:00+00:00

Abstract

Studying the spatiotemporal evolution of carbon emission patterns and their influencing factors is of great significance for guiding carbon emission reduction efforts. Using terminal energy consumption data from industrial enterprises above designated size in 14 prefecture-level cities of Hunan Province from 2008 to 2013, and employing the reference method provided by the IPCC and the Logarithmic Mean Divisia Index (LMDI) decomposition model, this study investigates the spatiotemporal patterns of carbon emissions, per capita carbon emissions, and carbon emission intensity at the prefecture level in Hunan, as well as the factors influencing changes in carbon emissions. The results indicate that: 1) During 2008-2013, the temporal trends of carbon emissions across Hunan’ s prefecture-level regions varied, generally exhibiting three distinct patterns; the top three prefectures in cumulative carbon emissions were Loudi, Yueyang, and Xiangtan, whose combined emissions accounted for 48.92% of the provincial total, while the combined emissions of Jishou, Zhangjiajie, and Huaihua accounted for only 2.59% of the provincial total. 2) The spatial variation of energy consumption carbon emissions and per capita carbon emissions in Hunan’ s prefecture-level regions exhibited similar patterns, both showing a high-east-low-west configuration with strong correlation—prefectures with high carbon emissions also had high per capita emissions; during 2008-2013, carbon emission intensity in Hunan’ s prefecture-level regions showed a decreasing trend, with the number of low-intensity prefectures increasing from 4 in 2008 to 7 in 2013, and the spatial distribution of carbon emission intensity was related to the industrial structure of each prefecture. 3) Energy structure and energy intensity primarily exerted inhibitory effects on carbon emission growth, though the contribution of energy structure was minimal; the reduction in carbon emissions was mainly driven by energy intensity; economic development was the most significant factor driving carbon emission growth, with cumulative contribution values of 74.285 and 27.579 in the periods 2008-2010 and 2011-2013, respectively; population size had a relatively small driving effect on carbon emissions, with a cumulative contribution value of only 2.252 to emission increases during 2011-2013. The focus of current and future carbon emission reduction in Hunan should be on accelerating clean energy development while simultaneously improving energy efficiency, optimizing energy structure and promoting industrial upgrading, and strategically promoting coordinated development of Hunan' s "Four Major Regions" .

Full Text

Title and Authors

Temporal-Spatial Carbon Emission Patterns Caused by Fossil Energy Consumption at the City Level in Hunan Province, China and the Factors Driving Their Composition

Liu Xianzhao[1], Gao Changchun[1], Song Yan[2], Zhang Yong[1], Su Qing[1], Tian Yanlin[1] [1]College of Architecture and Urban Planning, Hunan University of Science and Technology, Xiangtan 411201, China [2]College of Life Sciences, Hunan University of Science and Technology, Xiangtan 411201, China

Abstract

Investigating the spatio-temporal evolution of carbon emissions and their influencing factors is crucial for guiding carbon emission reduction efforts. Using terminal energy consumption data from industrial enterprises above designated size across 14 cities in Hunan Province from 2008 to 2013, this study examined temporal-spatial patterns and influencing factors of carbon emissions, per capita carbon emissions, and carbon emission intensity at the city level. The IPCC reference approach and Logarithmic Mean Divisia Index (LMDI) decomposition model were employed for analysis. The results show: (1) From 2008 to 2013, cities exhibited divergent carbon emission trends, classifiable into three categories. The top three cities for cumulative carbon emissions were Loudi, Yueyang, and Xiangtan, accounting for 48.92% of the provincial total, while Jishou, Zhangjiajie, and Huaihua contributed only 2.59%. (2) City-level carbon emissions and per capita emissions displayed similar spatial patterns, characterized by higher values in eastern Hunan and lower values in western regions, with strong correlation between total and per capita emissions. Carbon emission intensity declined across all cities, with the number of low-intensity regions increasing from four in 2008 to seven in 2013. (3) Emission reductions were primarily driven by energy intensity improvements, while economic development was the strongest positive driver of emission growth. Energy structure effects contributed minimally, and population size had a small impact. The study concludes that Hunan' s carbon reduction strategy should prioritize accelerated

clean energy development alongside energy efficiency improvements, optimizing both energy and industrial structures to promote coordinated regional development.

Keywords: fossil energy; carbon emission; temporal-spatial pattern; city level in Hunan Province

Introduction

Climate change represents not only an ecological and environmental challenge but also a severe threat to regional socioeconomic sustainability. According to the IPCC Fourth Assessment Report, rising global average temperatures are primarily caused by greenhouse gases such as CO , with over 90% of these emissions related to human activities. Traditional fossil energy consumption constitutes the main source of these emissions. China' s sustained rapid economic growth, accelerated urbanization, and industrialization have led to persistently high fossil energy consumption and rapidly increasing carbon emissions. Statistical data indicate that China' s energy-related CO emissions reached 60.37 billion tons in 2007. Although not listed among the first group of countries with mandatory emission reduction targets under the Kyoto Protocol, China' s carbon emissions have attracted global attention. As a responsible major country, China has committed to reducing carbon emissions per unit GDP by 40-45% by 2020 compared to 2005 levels, incorporating this as a binding target in its medium- and long-term national economic and social development plans.

Numerous scholars have conducted extensive research on regional disparities in energy-related carbon emissions, emission drivers, the relationship between economic development and emissions, and carbon reduction pathways. Studies have primarily focused on national, regional, and provincial scales, with limited analysis at the city level. For Hunan Province specifically, existing research on energy consumption and carbon emissions lacks depth, often relying on coarse provincial-scale data that cannot precisely reflect regional patterns. Given significant variations in resource endowments, population, and economic development levels within provinces, finer-scale analysis at the city level is essential for formulating differentiated and targeted emission reduction policies.

Hunan Province, located in south-central China (108°47 -114°5 E, 24°8 - 30°08 N), serves as an important destination for national industrial transfer and hosts the central region' s "Two-Oriented Society" (resource-saving and environment-friendly) comprehensive reform pilot zone. With accelerating industrialization and improving living standards, Hunan' s energy demand and associated carbon emissions are expected to increase significantly. However, the province faces coal, oil, and natural gas shortages, necessitating a low-carbon, efficient, and green development path. Substantial differences in economic development, industrial structure, and energy consumption across Hunan' s cities result in distinct carbon emission patterns. Against the backdrop of the "new normal" economy, there is an urgent need to identify emission patterns and drivers at the city level to propose targeted carbon reduction policies and low-carbon economic development measures.

Data and Methods

Carbon Emission Estimation

Carbon emissions were estimated using the reference approach provided in the *IPCC Guidelines for National Greenhouse Gas Inventories*. Based on actual fossil terminal energy consumption by industrial enterprises above designated size in each city, emissions were calculated for raw coal, cleaned coal, crude oil, gasoline, kerosene, diesel oil, fuel oil, and natural gas. Carbon emissions from thermal power generation during processing and conversion, as well as from residential energy consumption, were excluded. All subsequent references to carbon emissions pertain to industrial fossil energy consumption only.

The calculation formula is:

$$CE = \sum_{i=1}^{n} E_i \times e_i \times p_i$$

where CE represents carbon emissions from fossil energy consumption in each city; E_i is the consumption quantity of energy type i; e_i and p_i are the standard coal conversion coefficient and carbon emission coefficient for energy type i, respectively; and n is the number of energy types.

Calculation parameters of carbon emissions from 8 main fossil fuels

Data Sources and Processing

Data on fossil energy consumption, population, and socioeconomic indicators for each city were obtained from the *Hunan Statistical Yearbook* (2009-2014). City-level spatial data were sourced from the National Geomatics Center of China at a scale of 1:400,000. Economic data were calculated using constant 2000 prices to eliminate price factor effects.

Decomposition Method for Carbon Emission Drivers

To analyze drivers of city-level carbon emissions in Hunan, the relationship between total carbon emissions and influencing factors was expressed using the following identity:

$$CO_2 = POP \times \frac{GDP}{POP} \times \frac{PE}{GDP} \times \frac{CO_2}{PE}$$

where POP, GDP, and PE represent total population, gross domestic product, and total energy consumption, respectively. This defines population size (POP), economic development level (GDP/POP), energy intensity (PE/GDP), and energy structure level (CO_2/PE).

The total change in carbon emissions from base year 0 to year t is defined as the total effect ($\Delta CO_{2,tot}$). Using the LMDI method without residual terms, the total effect can be decomposed into energy structure effect ($\Delta CO_{2,F}$), energy intensity effect ($\Delta CO_{2,T}$), economic development effect ($\Delta CO_{2,G}$), and population size effect ($\Delta CO_{2,P}$), calculated as follows:

$$\Delta CO_{2,F} = \sum (CO_2^t - CO_2^0) \times \ln\left(\frac{CO_2^t}{PE^t} / \frac{CO_2^0}{PE^0}\right) / \ln\left(\frac{CO_2^t}{CO_2^0}\right)$$

$$\Delta CO_{2,T} = \sum (CO_2^t - CO_2^0) \times \ln\left(\frac{PE^t}{GDP^t} / \frac{PE^0}{GDP^0}\right) / \ln\left(\frac{CO_2^t}{CO_2^0}\right)$$

$$\Delta CO_{2,G} = \sum (CO_2^t - CO_2^0) \times \ln\left(\frac{GDP^t}{POP^t} / \frac{GDP^0}{POP^0}\right) / \ln\left(\frac{CO_2^t}{CO_2^0}\right)$$

$$\Delta CO_{2,P} = \sum (CO_2^t - CO_2^0) \times \ln\left(\frac{POP^t}{POP^0}\right) / \ln\left(\frac{CO_2^t}{CO_2^0}\right)$$

Results

Temporal Patterns of City-Level Carbon Emissions in Hunan

From 2008 to 2013, carbon emissions from energy consumption across Hunan's cities exhibited divergent trends, which can be categorized into three types based on growth rates and emission changes:

1. **High-growth type**: Characterized by large initial emissions and growth rates significantly exceeding the provincial average, with clear heavy industrial economic structures. Representative cities: Yueyang (average annual growth rate 9.02%) and Loudi (22.48% of provincial emissions in 2008).

2. **Medium-decline type**: Emissions showed negative growth (average annual rate -4.67%), with representative city Huaihua.

3. **Rise-then-fall type**: With 2011 as the turning point, emissions increased before this year then decreased afterward. This type can be further divided into three subcategories based on initial emission levels: large initial emissions maintaining high levels after mid-term decline; medium initial emissions with mid-term low-speed increase then decline; and low initial emissions with medium-speed increase then decline maintaining low levels. Representative cities: Changsha, Zhuzhou, and Zhangjiajie.

In terms of cumulative emissions from 2008-2013, Loudi ranked highest (13,550.6×10 t), followed by Yueyang (12,951.1×10 t) and Xiangtan (7,853.9×10 t), together accounting for 48.92% of the provincial total. The lowest cumulative emissions were from Jishou, Zhangjiajie, and Huaihua, totaling only 335.1×10 t (2.59% of the provincial total). The high cumulative emissions in Loudi, Yueyang, and Xiangtan are closely related to their industrial structures dominated by energy-intensive industries such as steel and non-ferrous metallurgy, which led the province in energy consumption. In contrast, Jishou and Zhangjiajie, primarily tourism-oriented cities with tertiary industry dominance, showed low emissions due to minimal dependence on energy-intensive industries.

[Figure 1: see original paper] Variations in carbon emissions at the city-level in Hunan Province from 2008 to 2013

Spatial Patterns of City-Level Carbon Emissions in Hunan

Total Carbon Emissions Significant spatial disparities characterize Hunan' s city-level energy consumption carbon emissions, showing an overall east-high, west-low pattern. In 2008, Yueyang exhibited the highest emissions (3,492.3×10 t), followed by Loudi (3,390.0×10 t), both classified as super-heavy and heavy emission types. Xiangtan (1,959.6×10 t), Zhuzhou (1,849.6×10 t), and Changsha (1,804.3×10 t) showed medium emissions, while Yiyang and Zhangjiajie had light emissions significantly below the provincial average. Zhangjiajie recorded the lowest emissions (469.8×10 t).

By 2013, most cities saw emission increases except Zhangjiajie and Huaihua. Loudi transitioned from heavy to super-heavy emission type, while Chenzhou and Hengyang moved from medium to heavy emission types. The number of light-emission cities decreased from four to two, while heavy-emission and above cities increased from two to four. This pattern reflects excessive reliance on fossil energy consumption driven by oversized secondary industries and extensive economic growth models, indicating a challenging emission reduction outlook for Hunan.

[Figure 2: see original paper] Spatial carbon emission patterns caused by energy consumption at the city-level of Hunan Province in 2008 and 2013

Per Capita Carbon Emissions Per capita carbon emissions reflect population pressure on limited carbon space and embody equity in energy use and emissions. Hunan's per capita emissions show clear city-level differences, mirroring the spatial pattern of total emissions with an east-high, west-low distribution. In 2008, Loudi recorded the highest per capita emissions (8.10 t), followed by Xiangtan (6.67 t) and Yueyang (6.64 t), all significantly exceeding the provincial average (2.71 t) and constituting high-value zones. In contrast, Zhangjiajie, Huaihua, Shaoyang, and Yongzhou showed low per capita emissions (0.35-1.65 t), well below the provincial average, with the minimum in Jishou (0.35 t).

By 2013, the spatial pattern remained largely unchanged, but inter-city disparities widened significantly. Loudi' s per capita emissions increased from 8.1 t to 13.6 t, while Jishou' s decreased from 0.35 t to 0.32 t, making the highest value 42.5 times the lowest. The coefficient of variation for per capita emissions increased from 0.32 to 1.06, indicating intensifying spatial inequality.

[Figure 3: see original paper] Spatial patterns of per capita carbon emissions at the city-level in Hunan Province in 2008 and 2013

Carbon Emission Intensity Carbon emission intensity, defined as emissions per 10,000 yuan GDP, measures economic structure rationality and technological advancement, representing relative emission efficiency. Hunan' s emission intensity shows significant city-level variation but no clear pattern. In 2008, Loudi exhibited the highest intensity (6.42 t), followed by Xiangtan (3.28 t), Yueyang (3.28 t), Chenzhou (2.38 t), and Hengyang (1.80 t), constituting super-high and high-intensity zones. Zhangjiajie showed the lowest intensity (0.42 t), with other cities ranging 0.42-0.96 t, classified as low-intensity zones.

This spatial distribution correlates closely with industrial structure. Cities with super-high and high intensity in 2008—Loudi, Xiangtan, and Chenzhou—were dominated by traditional heavy industries such as metallurgy, petrochemicals, and building materials, resulting in persistently high emission intensities. Conversely, low-intensity cities like Huaihua and Zhangjiajie, primarily tourism-oriented, had minimal dependence on energy-intensive industries.

From 2008-2013, all cities experienced emission intensity declines. By 2013, the number of low-intensity cities increased from four to seven, demonstrating the positive impact of Hunan' s Two-Oriented Society construction on low-carbon development. However, spatial disparities intensified, with 娄底 remaining the only super-high intensity city while Yueyang entered the high-intensity category.

[Figure 4: see original paper] Spatial patterns of carbon emission intensity at the city-level in Hunan Province in 2008 and 2013

Carbon emission intensity at the city-level in Hunan Province in 2008 and 2013

Decomposition of Carbon Emission Drivers

Based on emission change characteristics, factor decomposition was conducted for two periods (2008-2010 and 2011-2013). shows the absolute and relative changes in decomposition components.

Factor decomposition of carbon emission increment at the city-level in Hunan Province during 2008-2013

Energy Structure Effect Energy structure serves as an inhibiting factor for carbon emissions. During 2008-2013, the energy structure effect showed mixed influences across cities. Yongzhou and Huaihua shifted from positive to negative drivers, while Loudi transitioned from negative to positive. Most cities consistently exhibited negative driving effects. The cumulative contribution of energy structure was minimal: -1.111 for 2008-2010 and -0.340 for 2011-2013.

This limited impact likely stems from Hunan' s long-term reliance on fossil fuels, with raw coal accounting for an average of 63.78% of total energy consumption during 2008-2013, supplemented by clean and other energy sources. To enhance the emission reduction role of energy structure, cities must reduce dependence on traditional fossil fuels and accelerate new energy development.

Ratios of high-carbon energy in total energy consumption at the city-level in Hunan Province during 2008-2013

Energy Intensity Effect Energy intensity significantly inhibited carbon emission growth in most Hunan cities, with cumulative contributions of -65.699 for 2008-2010 and -37.493 for 2011-2013. This indicates energy intensity is a crucial factor affecting emission changes. The strong inhibitory effects in Changsha, Zhuzhou, and Xiangtan resulted from accelerated promotion of new industrialization and energy-saving technological transformations that improved industrial energy efficiency and reduced consumption growth.

Zhuzhou, located in the core Changsha-Zhuzhou-Xiangtan urban agglomeration, showed the strongest intensity effect due to vigorous implementation of energy conservation and consumption reduction technologies. Jishou and Yongzhou, focusing on tourism development with minimal energy-intensive industry dependence, also saw significant intensity declines. Chenzhou, along the Beijing-Guangzhou railway and expressway with relatively developed economy, shut down numerous high-energy-consuming and high-pollution enterprises, leading to substantial energy intensity reductions.

Economic Development Effect Economic development strongly drove carbon emission growth, representing the most important positive factor with cumulative contributions of 74.285 for 2008-2010 and 27.579 for 2011-2013. Rapid economic growth led to rapid increases in terminal energy consumption and consequent emission growth. Hunan' s large secondary industry share (43.5%-47.0% of GDP), combined with limited achievements in industrial structure adjustment and energy efficiency improvements, meant extensive economic growth relied heavily on fossil energy consumption, creating substantial positive effects in both periods.

Changsha and Zhuzhou, core cities in Hunan' s most economically dynamic Changsha-Zhuzhou-Xiangtan agglomeration, showed particularly strong economic development effects (30.999 and 9.460 respectively in 2008-2010), driven by the Xiangjiang New Area, Two-Oriented Society pilot zone, and national independent innovation demonstration zone. During 2011-2013, as China' s economic growth slowed due to macroeconomic adjustments, most cities saw enhanced economic development effects on emissions. Yueyang, part of the new Dongting Lake urban cluster, and Yongzhou, a central city in the southern Hunan industrial transfer demonstration zone, experienced rapid economic growth that accelerated energy consumption and emissions.

Population Size Effect Population size had minimal impact on carbon emissions, with inconsistent directionality. During 2008-2010, only Changsha showed positive population effects, while other cities exhibited negative effects. Changsha' s maximum contribution (2.252) resulted from rapid population growth due to rural labor transfer, with urbanization rate increasing nearly 7% while other cities saw minimal population growth. Rapid urbanization expanded city scale, directly increasing energy consumption and indirectly promoting consumption through changed production and lifestyle patterns.

During 2011-2013, all cities showed positive population effects, but contributions remained small (provincial cumulative value of 2.252), likely due to low annual population growth rates (<1%) across most cities.

Discussion and Conclusions

Current research on energy consumption carbon emissions has focused primarily on national, regional, and provincial scales, with limited city-level analysis. This study extends existing research by examining Hunan' s city-level emissions during rapid industrialization and urbanization using IPCC methods and LMDI decomposition.

Key findings include:

(1) From 2008-2013, city-level energy consumption carbon emissions in Hunan showed divergent temporal trends classifiable into three types: high-growth, medium-decline, and rise-then-fall. The top three cumulative emitters—Loudi, Yueyang, and Xiangtan—accounted for 48.92% of provincial emissions, while the lowest three cities (Jishou, Zhangjiajie, Huaihua) contributed only 2.59%. Emission levels correlate closely with industrial structure, as high-emission cities feature energy-intensive industries (steel, petrochemicals, building materials) while low-emission cities are tourism-oriented with tertiary industry dominance.

(2) Significant spatial disparities exist, showing an east-high, west-low pattern. In 2008, Yueyang recorded the highest emissions ($3,492.3\times10$ t) and Zhangjiajie the lowest (469.8×10 t). By 2013, the number of light-emission cities decreased from four to two, while heavy-emission and above cities increased from two to four, reflecting excessive reliance on fossil energy due to oversized secondary industries. Per capita emissions mirror this spatial pattern, with Loudi reaching 13.6 t in 2013 while Jishou remained at 0.32 t, demonstrating strong correlation between total and per capita emissions in industrializing cities.

(3) Carbon emission intensity declined significantly, with low-intensity cities increasing from four to seven, indicating positive impacts from Two-Oriented Society construction. However, spatial disparities intensified. In 2008, intensity ranged from 6.42 t (Loudi) to 0.42 t (Zhangjiajie), correlating with industrial type—high-intensity cities relied on traditional

heavy industries while low-intensity cities were tourism-oriented.

(4) Decomposition analysis reveals that energy intensity and economic development effects are the primary negative and positive drivers, respectively. Energy structure effects contributed minimally (-1.111 and -0.340 across the two periods), while population effects were small (2.252). The dominance of economic development effects (74.285 and 27.579) highlights the challenge of coordinating economic growth with emission reduction. Energy intensity improvements were the main emission reduction driver, suggesting substantial potential for further reductions through industrial structure adjustment and efficiency gains.

Based on these findings, Hunan’ s carbon reduction strategy should: (1) Optimize urban functional zoning and energy consumption structure, accelerating clean energy development while improving efficiency; (2) Strictly control blind expansion of high-energy-consuming industries like chemicals and building materials; (3) Promote rapid development of tourism, new service industries, and strategic emerging industries to optimize industrial structure; and (4) Enhance coordinated development across Hunan’ s four regions to maximize emission reduction potential.

References

[1] Peng M, et al. Regional disparities and evolution characteristics of China’ s carbon emissions and factor decomposition. *Journal of Natural Resources*, 2014, 29(2): 189-200.

[2] IPCC (Intergovernmental Panel on Climate Change). *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK: Cambridge University Press, 2007: 44-45.

[3] IEA. *CO Emissions from Fuel Combustion.* Paris: International Energy Agency (IEA), 2012.

[4] Zhang M, Mu H L, Ning Y D. Accounting for energy-related CO emissions in China, 1991-2006. *Energy Policy*, 2009, 37(3): 767-773.

[5] Liu Y S, Yan B, Zhou Y. Urbanization, economic growth, and carbon dioxide emissions in China: A panel cointegration and causality analysis. *Journal of Geographical Sciences*, 2016, 26(2): 131-152.

[6] Su B, Ang B W. Input-output analysis of CO emissions embodied in trade: A multi-region model for China. *Applied Energy*, 2014, 114: 377-384.

[7] Zhao X T, Burnett J W, Fletcher J J. Spatial analysis of China province-level CO emission intensity. *Renewable and Sustainable Energy Reviews*, 2014, 33: 1-10.

[8] Luukkanen J, et al. Structural change in Chinese economy: Impacts on energy

use and CO emissions in the period 2013-2030. *Technological Forecasting and Social Change*, 2015, 94: 303-317.

[9] Guo B, et al. Uncovering China' s transport CO emission patterns at the regional level. *Energy Policy*, 2014, 74: 134-146.

[10] Clarke-Sather A, et al. Carbon inequality at the sub-national scale: A case study of provincial-level inequality in CO emissions in China 1997-2007. *Energy Policy*, 2011, 39(9): 5420-5428.

[11] Dhakal S. Urban energy use and carbon emissions from cities in China and policy implications. *Energy Policy*, 2009, 37(11): 4208-4219.

[12] Li G Z, et al. Analysis of regional disparities in China' s energy carbon emissions and influencing factors. *Urban Development Studies*, 2010, 17(7): 6-11, 44.

[13] Yuan Y, et al. Impact of industrial structure on regional carbon emissions: An empirical analysis based on multi-country data. *China Environmental Science*, 2013, 33(9): 1705-1713.

[14] Tan D, et al. Analysis of carbon emission differences in eastern, central, and western China using grey relational analysis. *Resources and Environment*, 2010, 20(5): 22-27.

[15] Li W B, et al. Driving factors of carbon emissions in China's eastern, central, and western regions based on STIRPAT model. *Journal of Huazhong University of Science and Technology (Social Science Edition)*, 2011, 25(3): 111-116.

[16] Jiang J H. Analysis of key drivers on China' s carbon emissions and policy rethinking based on LMDI: 1995-2010. *Journal of Resources and Ecology*, 2013, 4(4): 304-310.

[17] Zhao X C, et al. Spatio-temporal analysis of carbon emissions and absorption in Hunan Province from a carbon balance perspective. *Journal of Soil and Water Conservation*, 2012, 26(6): 158-163, 170.

[18] Huang C, Chen X H. Driving factors and decoupling effects of carbon emissions in Hunan under Two-Oriented Society construction. *Journal of Hunan University of Technology (Social Science Edition)*, 2014, 19(3): 10-15.

[19] Yin X F. Impact of age structure and industrial structure on Hunan' s carbon emissions based on STIRPAT model. *Hunan Normal University*, 2011.

[20] Zhao Y, et al. Factor decomposition of carbon emissions from energy consumption in Shaanxi Province. *Arid Zone Resources and Environment*, 2013, 27(9): 26-31.

[21] Ang B W. CO emissions, research and technology transfer in China. *Ecological Economics*, 2009, 68(10): 2658-2665.

[22] Vinuya F, DiFurio F, Sandoval E. A decomposition analysis of CO emissions in the United States. *Applied Economics Letters*, 2010, 17(10): 925-931.

[23] Ferdinand. Factor decomposition analysis of carbon emission changes in China (2001-2009). *East China Economic Management*, 2013, 27(4): 36-40, 97.

[24] Zhao X C, et al. Analysis of influencing factors of carbon emissions in Xinjiang based on extended STIRPAT model. *Acta Ecologica Sinica*, 2016, 36(8).

[25] Li G Z, et al. Temporal and spatial patterns of China' s carbon emissions and carbon footprint (1999-2007). *Resources and Environment*, 2010, 19(1): 18-23.

[26] Zhang M, et al. Spatial evolution characteristics of China' s energy consumption carbon emission intensity (2001-2009). *Resources and Environment*, 2011, 30(1): 19-24.

[27] Du Q, Wang N, Che L. Forecasting China' s per capita carbon emissions under a new three-step economic development strategy. *Journal of Resources and Ecology*, 2015, 6(5): 318-323.

[28] Hunan Provincial Bureau of Statistics. (2015-07-14) [2016-04-16]. http://www.hunan.gov.cn/sj/sjfx/201507/t20150714_1796307.html.

[29] Hunan Provincial Bureau of Statistics. Hunan economic structure research: Overall thinking and target positioning for industrial development from the perspective of central China rise. (2015-06-11) [2016-04-16]. http://www.hntj.gov.cn/fxbg/2015fxbg/2015jczx/201506/t20150611_117178.htm.

[30] Regional development layout: One core, three poles, four belts, multiple points. (2015-12-30) [2016-04-16]. http://www.hn.xinhuanet.com/2016-03/08/c_1118265594.htm.

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