Examining the driving factors of industrial CO2 emissions in Chinese cities using geographically weighted regression model

Huiping Wang (519636216@qq.com)
Xi'an University of Finance and Economics

Xueying Zhang
Xi'an University of Finance and Economics

Research Article

Keywords: Industrial CO2 Emissions, City-level, Geographically Weighted Regression, China

Posted Date: February 23rd, 2021

DOI: https://doi.org/10.21203/rs.3.rs-157696/v1

Version of Record: A version of this preprint was published at Clean Technologies and Environmental Policy on March 27th, 2021. See the published version at https://doi.org/10.1007/s10098-021-02073-4.

Examining the driving factors of industrial CO_2 emissions in Chinese cities using geographically weighted regression model

Huiping Wang*, Xueying Zhang
Western Collaborative Innovation Research Center for Energy Economy and Regional Development, Xi'an University of Finance and Economics, Xi'an 710100, China

Abstract: The industrial sector is the sector with the largest CO_2 emissions, and to reduce overall CO_2 emissions, analysis of the impact factors holds significance. Based on the 2015 industrial CO_2 emissions of 282 cities in China combined with economic and social data, and a geographically weighted regression (GWR) model, we analysed the characteristics of the spatial distribution of CO_2 emissions and the influencing factors of spatial heterogeneity. The results show that China's urban industrial CO_2 emissions present a significant spatial agglomeration state that includes Shandong, Beijing, Tianjin, Shanghai, Zhejiang, and Jiangsu, and the core of the coastal areas form a high-high (H-H) concentration; a low-low aggregation (L-L) is formed in less developed areas such as Guizhou, Yunnan, Sichuan and Guangxi. The influence of various factors on industrial CO_2 emissions has significant spatial heterogeneity. The Industrial scale, industry share of GDP, and share of the service industry in GDP are factors that promote industrial CO_2 emissions. The technological innovation, population density, and social investment in fixed assets are important factors that inhibit industrial CO_2 emissions, but their impact on industrial CO_2 emissions shows spatial differences. In contrast, the level of economic development, foreign direct investment, financial development and government intervention have a two-way impact on industrial CO_2 emissions.

Keywords: Industrial CO_2 Emissions; City-level; Geographically Weighted Regression; China

---

1. Introduction

Rising concentrations of greenhouse gases in the atmosphere are the main cause of global warming, and CO_2 is the greatest greenhouse gas emitted. According to data released by the International Energy Agency (IEA), the total global CO_2 emissions in 2018 amounted to approximately 33 billion tons, contributing up to 65% of the greenhouse effect. In particular, with the development of the global economy, the total amount of CO_2 emissions has been maintained at a high level. CO_2 emissions from the industrial sector are the major source of CO_2 emissions. Based on the estimation of IEA, in 2016, industrial CO_2 emissions (ICEs) accounted for 36% of energy CO_2 emissions globally, ranking first among all sectors and being far higher than construction (27%) and transportation (25%) (IEA 2018). At the same time, as China continues to industrialize, the industrial sector consistently ranks first among all sectors in China in terms of energy consumption and CO_2 emissions. According to

the National Bureau of Statistics, in 2017, China's industrial energy consumption reached 294,480,400 tons of standard coal equivalent, accounting for 65.7% of the country's total energy consumption, indicating that the industrial sector relies too much on energy consumption. However, China's industrialization is far from complete. Scholars believe that China's industrialization is, overall, in a transitional stage from the middle to the later stage, with approximately 80% of the industrialization level basically having been completed, and there is still nearly 20% room for growth. Based on the experience of the industrialization process and CO_2 emissions of developed countries, as well as the judgement on influencing factors such as China's industrialization and urbanization process, the emissions of the industrial sector will increase gradually and reach a peak around 2040. Even under a low-carbon scenario, China's total industrial sector emissions will peak as soon as around 2030

At present, the Chinese government is actively formulating and implementing various carbon emission reduction policies to deal with climate change and its impacts. Since 2013, seven regions, including Beijing, Shanghai, Tianjin, Hubei, Guangdong, Shenzhen and Chongqing, have established carbon markets and started substantial trading. Since its inception in 2013, the carbon markets have increasingly grown. By the end of August 2020, the cumulative turnover of the seven pilot carbon market quotas was 406 million tons, with a cumulative turnover of approximately 9.28 billion yuan. A total of 2,837 key emitters, 1,082 non-compliant organizations and 11,169 natural persons participated in the pilot carbon markets. In 2016, nearly 200 countries signed the Paris Agreement, and China promised to peak its CO_2 emissions around 2030 and to reduce its CO_2 emissions per unit of GDP by 60%-65% compared to the 2005 level (Feng and Chen 2018). In the face of such a tough emission reduction target, the industrial sector, as the largest carbon emitter, should assume the primary responsibility for CO_2 emission reduction. Only by reducing the CO_2 emissions of the industrial sector can the overall goal of CO_2 emission reduction be achieved. Cities are the core area of relatively complete basic space units and industrial development in China, and they are also the most important source of energy consumption and CO_2 emissions. Excessive energy consumption and serious CO_2 emissions have become important factors hindering urban development (Glaeser and Kahn 2010). Therefore, studying the characteristics of the spatial distribution and influencing factors of ICEs in Chinese cities holds great significance for reducing CO_2 emissions and realizing a low-carbon way of life.

In existing research, it is believed that the factors influencing CO_2 emissions mainly include the industrial structure, urbanization, energy structure, energy consumption, technological innovation and so on. Some scholars believe that economic growth is positively correlated with CO_2 emissions. For example, Al-Mulali (2012) discussed the influencing factors of CO_2 emissions in 12 Middle Eastern countries, and the research results showed that GDP and the total trade volume were the main reasons for CO_2 emissions. Mousavi et al. (2017) used the logarithmic mean Divisia index (LMDI) to study the relationship between energy consumption and CO_2 emissions in Iran, and they found that economic

activity was the largest driving force. Lin and Benjamin (2019) found that economic growth has a positive effect on CO_2 emissions in the long run. However, some scholars believe that economic growth can help reduce CO_2 emissions. For example, Qin et al. (2019) found that per capita GDP and the CO_2 emissions of northern China and the southeast coastal region present negative correlations, showing that a city's economic development has the potential to reduce carbon dioxide emissions. Some scholars used the environmental Kuznets curve (EKC) to analyse the relationship between economic growth and CO_2 emissions, arguing that CO_2 emissions show an inverted U-shaped relationship with per capita GDP (Ghazali and Ali 2019). For example, Liddle (2015) confirmed the inverted U-shaped relationship between CO_2 emissions and economic growth according to the EKC hypothesis. Other scholars believe that there is no connection between the two. For example, Freitas and Kaneko (2011) studied the relationship between CO_2 emissions and economic growth in the UK using a decoupling index of energy and environmental pressure, and they found that the relationship between the two was completely disconnected.

The impact of urbanization on CO_2 emissions is also a key research area (Knight et al. 2013; Pata 2018). Jorgenson and Clark (2010) and Knight et al. (2013) found that urbanization is the main driving force promoting the increase in CO_2 emissions. Zhang et al. (2018) argued that the population and industrial scale brought by urban expansion have expanded the consumption of fossil fuels and that urbanization and industrialization have staged effects on ICEs and the emission intensity. Lin and Benjamin (2019) found that urbanization accelerated CO_2 emissions in China and India. Wang et al. (2019) argued that different levels of urban development in China would obviously lead to different air quality pollution conditions. Su et al. (2020) found that the higher the level of urbanization, the greater the CO_2 emissions in the urban areas of Fujian. Energy structure is considered to be an important factor affecting CO_2 emissions (Zhang et al. 2018; Wen and Li 2020). Li and Moubarak (2014) argued that China, which has abundant natural resources, could increase its investment in clean energy and renewable energy (solar energy), optimize the energy structure, and thus promote carbon emission reduction. Moutinho et al. (2015) found that the optimization of the energy mix would lead to a significant reduction in CO_2 emissions in four regions of Europe. Zhang et al. (2018) found that the coal-based energy structure was the main cause of high ICEs and that adjustment of the energy structure was a powerful measure for reducing environmental pollution and promoting ICEs reduction. Wen and Li (2020) argued that the development of clean energy greatly improved the energy structure and reduced the consumption of fossil energy; additionally, adjustment of the energy structure could limit the increase in CO_2 emissions. In other words, adjusting the energy structure has a significant effect on reducing CO_2 emissions, which is of great significance for China's sustainable development strategy (Dong et al. 2018). Some scholars have found that CO_2 emissions are closely related to the industrial structure and have a long-term positive correlation with the proportion of the secondary industry because the secondary industry is considered to be a major user of energy and a major

contributor to global CO_2 emissions (Lin and Benjamin 2019). Griffin et al. (2016) found that 19% of the greenhouse gas emissions in the UK came from the steel industry, which had the second largest amount of emissions; the steel industry consumed more energy than the service industry and had a higher carbon emission level. Su et al. (2020) found that an increased proportion of the tertiary industry could significantly restrain CO_2 emissions. Most CO_2 emissions come from the secondary industry, and Kumbaroglu (2011) adopted the Shapely index decomposition method and found that the increase in CO_2 emissions mainly comes from the scale effect of electricity, manufacturing and transportation industries.

Technological innovation can improve energy utilization efficiency and reduce the energy intensity of China's industry, thus reducing the CO_2 emissions (Poumanyvong and Kaneko 2010; Wen and Li 2020). For example, Dauda et al. (2019) suggested that improving energy technology and related equipment could greatly improve energy efficiency, thereby reducing urban carbon dioxide emissions. Rahman et al. (2017) argued that improving clean energy technologies was crucial for reducing carbon dioxide emissions and that industrial technological innovation should be encouraged, especially to solve the carbon emission problem in carbon-intensive industrial sectors. Åhman et al. (2016) studied Belgium and Sweden and found that to significantly reduce greenhouse gas emissions after 2050, it is necessary to rely on disruptive technologies in the steel industry. Therefore, to reduce CO_2 emissions, it is necessary to promote the intensive development of industries with low energy consumption, promote the extensive application of advanced technologies, and eliminate energy-intensive industries (Lin and Benjamin 2019). Other scholars believe that factors such as the industrial scale, population density, social fixed asset investment and foreign direct investment (FDI) will have a certain impact on CO_2 emissions.

Taking 282 Chinese cities as samples, this paper uses exploratory spatial data analysis (ESDA) to analyse the characteristics of the spatial and temporal distribution of ICEs, and it uses a geographically weighted regression (GWR) model to study the spatial heterogeneity of the influencing factors of ICEs. This article makes three major contributions to the existing literature on ICEs. First, existing research basically takes a provincial- or national-level perspective to study ICEs, but data at the national and provincial scales fail to reveal the spatial differences at the city scale. The city is the main body of ICEs, and it is necessary to explore the relationship between ICEs and important measures of social and economic development. Therefore, this article discusses the differences in ICEs at the city level and compensates for the inadequacy of existing research at the ground level and above the city level. Second, the territory of China is vast in size, and cities are interconnected and influenced by each other in geographical space. However, the spatial correlation between cities has been ignored in most existing studies. This paper adopts ESDA to reveal the spatial clustering characteristics of urban ICEs. Third, the existing literature mostly adopts an ordinary least squares (OLS) panel regression model to analyse the influencing factors of ICEs. The model of the estimated coefficient can reflect the influence

extent as a whole and cannot reflect the differences in influence between cities. This paper introduces a GWR model to consider the parameters of local spatial heterogeneity and the industrial emissions of social and economic factors based on a more meticulous and comprehensive understanding of spatial scales.

2. Materials and Methods

2.1 Models

2.1.1 Global spatial autocorrelation

Spatial autocorrelation test can accurately reflect the characteristics of the spatial distribution and agglomeration of ICEs in Chinese cities. Global spatial autocorrelation can reflect the agglomeration characteristics of an economic variable in the whole space. It is represented by Moran's I, and the Z score is calculated to judge the significance of the result. Moran's I is used in this paper to describe the global spatial correlation of ICEs in Chinese cities. The formula is as follows:

$$I = \frac{n\sum_{i}^{n}\sum_{j\neq i}^{n} w_{ij}(x_i - \overline{x})(x_j - \overline{x})}{\sum_{i=1}^{n}(x_i - \overline{x})^2 \sum_{i=1}^{n}\sum_{j\neq i}^{n} w_{ij}} \tag{1}$$

$$Z(I) = \frac{[I - E(I)]}{\sqrt{Var(I)}} \tag{2}$$

where n is the number of cities, w_{ij} is the spatial weight matrix, x_i and x_j are the ICEs of cities i and j, respectively, and $\overline{x}$ is the average industrial emissions of each city. The value range of Moran's I is [-1,1]. When Moran's I >0, it represents positive spatial correlation. The greater the value is, the more obvious the spatial correlation is. When Moran's I <0, it represents negative spatial correlation. The smaller the value is, the greater the spatial difference. When Moran's I = 0, it represents the randomness of space.

2.1.2 Local spatial autocorrelation

Global spatial autocorrelation is a global indicator that measures spatial autocorrelation. It reflects only the differences in spatial mean values and may ignore the atypical characteristics of ICEs in some cities in local areas (Elhorst 2012). Local spatial autocorrelation test can be used to test the local agglomeration characteristics of ICEs. The formula is as follows:

$$I_i = \frac{n(x_i - \overline{x})}{\sum_{j=1}^{n}(x_i - \overline{x})^2} \sum_{j=1}^{n} W_{ij}(x_i - \overline{x}) \tag{3}$$

where I_i is the local Moran's I, i reflects the correlation between a city and its surrounding cities, and the other indicators have the same meaning as those in formula (1). When $I_i > 0$, it

represents a positive correlation between the ICEs of city i and those of its surrounding cities; that is, the CO_2 emissions present high-high (H-H) or low-low (L-L) agglomeration. When $I_i < 0$, it means that the ICEs of city i are negatively correlated with those of its surrounding cities; that is, CO_2 emissions present H-H or L-L agglomeration.

2.1.3 Geographically weighted regression model

In traditional regression analysis, the OLS method is commonly used, but the regression coefficient obtained by an OLS model is the average value of the whole study area, and local regional characteristics cannot be obtained. A GWR model is a local form of a linear regression model that is used to analyse spatial variation relationships. When analysing influencing factors, a GWR model sufficiently considers the spatial effects and can reflect the heterogeneity of the regression coefficients in different spaces. Due to the vast size of China, there are huge differences in industrial development and ICEs between cities. Therefore, a GWR model is adopted in this paper to analyse the influencing factors of ICEs. The formula is as follows:

$$Y_i = c\left(u_i, v_i\right) + \sum_j^m b_j\left(u_i, v_i\right) x_{ij} + \varepsilon_i \tag{4}$$

where Y_i represents the ICEs value of city i, (u_i, v_i) represents the latitude and longitude coordinates of city i, $c(u_i, v_i)$ represents the constant term, $b_j(u_i, v_i)$ represents the regression parameter of the influence of city j on city i, $c(u_i, v_i)$ and $b_j(u_i, v_i)$ are coordinate functions, and ε_i represents the residual term.

2.2 Description of the variables

2.2.1 Explained variable: Industrial CO_2 emissions (ICEs)

In this paper, data from the China High Resolution Emission Gridded Database (CHRED), composed of 76 units and 137 researchers, are used. Covering the enterprise, industry, and urban levels, these data on the levels of city greenhouse gas emissions from activities are collected, sorted and cleaned. At the same time, they are used to carry out a large number of cross-validation and data analyses. A dataset on the 2015 greenhouse gas emissions of Chinese cities is ultimately established. The CHRED references the international mainstream bottom-up spatial analysis method. It combines the actual situation in China and the characteristics of the data. The spatial analysis method is based on point emission sources from the bottom up (industrial enterprises, sewage treatment plants, landfills, livestock and poultry farms, coal mining, water transport ships, etc.) and other line source (traffic source) and non-point source (such as agriculture, life source) data, as well as other greenhouse emissions grid data at a 1 km resolution and methods of spatial data accuracy and uncertainty analysis. The spatial position accuracy of point source data is controlled by two methods: the longitude and latitude data on emission sources and spatial coordinates, and address matching verification is carried out based on application programming interface (API) geocoding technology. CHRED data highlight

the spatialization and spatial distribution pattern of emissions and emphasize the spatial accuracy of emissions data.

2.2.2 Explanatory variables

On the basis of previous studies, this study takes 10 indicators, i.e., the industrial scale (IS), the share of industry in GDP (IR), the share of the service industry in GDP (RGDP) (TR), the economic development level, technology innovation (TI), population density (PD), foreign direct investment (FDI), social investment in fixed assets (FA), government intervention (FE), and financial development (FD), as influencing factors of China's urban ICEs. These indicators and their impact on ICEs can be simply described as follows: Industrial scale is expressed by the total industrial output value of each city. In general, the larger the industrial scale is, the higher the level of industrial output will be, and the higher the ICEs will naturally be. The share of industry in GDP is expressed by the proportion of industrial added value in GDP, reflecting the impact of the industrial structure on ICEs. The higher the proportion of the secondary industry is, especially the higher the proportion of heavy industry, the higher the ICEs will be. The share of the service industry in GDP uses the proportion of the added value of the service industry to GDP, reflecting the effects of ICEs from the upgrading of the industrial structure of the industry, especially the modern service industry relative to traditional industry, The service sector is characterized by low energy consumption, low pollution, and the accelerated development of finance, tourism, education, culture and other industries that can reduce ICEs. Economic development (RGDP) is measured by per capita GDP. According to the EKC hypothesis, due to different levels of economic growth, economic growth may increase or reduce ICEs, and there may be an inverted U-shaped relationship between the two. Technology innovation (TI), represented by the number of patents granted per 10,000 people, improves energy efficiency and promotes the development of high-tech industries, thereby effectively reducing ICEs. Population density is represented by the number of people per square kilometre. Human activities will result in an increase in ICEs. In general, population density is positively correlated with ICEs, but population agglomeration can also bring energy-intensive use, thus reducing ICEs. FDI, expressed in terms of the actual use of foreign capital as a share of GDP, brings advanced production technologies and managerial expertise, promotes technological progress in host-country industries, and thus increases and reduces ICEs. Social fixed asset Investment is expressed by the per capita fixed asset investment of the whole society. When investment is inclined towards industrial upgrading, it can bring advanced production equipment and technology to enterprises, thus reducing ICEs. Government intervention is expressed by the proportion of fiscal expenditure in GDP, and it reflects the government's intervention in economic activities. The government uses fiscal allocations to encourage enterprises to increase their research and development (R&D) and innovation, improve their energy efficiency and reduce their ICEs. In addition, China's fiscal decentralization system enables local officials to control the power of fiscal expenditure and resource allocation. The existing performance appraisal mechanism, with GDP as the core, also enables

local governments to relax environmental regulations on ICEs and to even support high-pollution industries, leading to an increase in ICEs. Financial Development is expressed by the proportion of the total amount of deposits and loans in GDP. Efficient financial intermediaries are usually more conducive to the loan activities of consumers, making it easier for them to buy automobiles, refrigerators, air conditioners and other big-box goods and increasing the amount of ICEs. At the same time, the development of the financial market helps enterprises reduce their financing costs, increase their financing channels, and optimize the structure of their assets and liabilities to introduce new equipment, increase technological innovation, and thus reduce ICEs.

2.3 Data Sources

282 Chinese cities are selected as samples in this paper. The data are collected from the China City Statistical Yearbook, China Energy Statistical Yearbook, and Yearbook Of China Transportation & Communications, as well as provincial statistical yearbooks. The Statistical description of the variables are shown in Table 1.

Table. 1 Statistical description of variables.

	Description	Max	Min	Mean	Std. Dev.
ICEs	Industrial CO_2 emissions(10^4 ton)	16641.15	10.10	3110.74	3093.49
IS	Industrial scale (10^4 Yuan)	7991.77	46.33	1139.94	1301.91
IR	Share of industry in GDP（%）	71.45	15.17	46.71	9.47
TR	Share of service industry in GDP（%）	79.65	24.17	40.94	8.68
RGDP	Per capita GDP（Yuan）	207163.00	10987.00	51125.54	29543.82
TI	Number of patent authorization per 10^4 people（unit）	118225.00	73.00	6204.68	13576.52
PD	Population density（people/km^2）	2501.14	5.77	436.64	338.21
FDI	Share of FDI in GDP（%）	20.72	0.00	2.03	2.59
FA	total social fixed assets investment per capita (Yuan)	173987.40	6799.22	42814.45	26561.95
FE	Share of financial development in GDP (%)	84.56	2.27	20.72	10.09
FD	Share of total deposit and loan in GDP (%)	743.60	91.05	242.32	110.23

3. Empirical results and analysis

3.1 Spatial distribution pattern of ICEs

3.1.1 Characteristics of the spatial distribution

The spatial distribution of ICEs in Chinese cities is shown in Figure 1. Chongqing, Tianjin, Tangshan, Binzhou, Shanghai, Wuxi, Ningbo, Shijiazhuang, Handan, Linfen, Yinchuan, Ordos and Yulin are the cities with the highest ICEs. Cities with high ICEs are mainly located in Shandong, Inner Mongolia, Yunnan, Henan, Hubei, Shanxi, Jiangsu, Guangzhou and the Beijing-Tianjin-Hebei region.

Cities with low ICEs are mainly located in underdeveloped regions, such as Gansu, Ningxia, Qinghai, Heilongjiang, Jilin and other regions in Northwest and Northeast China. Therefore, the characteristics of the spatial distribution of ICEs are closely related to the level of regional economic development. The Beijing-Tianjin-Hebei region, Shanghai-Nanjing Hangzhou region, Suzhou-Xichang region and Pearl River Delta region are China's four major industrial bases. These four regions have high ICEs. Coastal areas have superior geographical environments, convenient traffic conditions, rapid economic development, and advanced levels of science and technology, which are conducive to industrial development. Shanxi, the western part of Inner Mongolia and the northern part of Shaanxi are the largest energy and chemical industry bases in China. The rich coal resources there provide abundant energy security for non-ferrous metal smelting, electric power, the chemical industry and other energy-intensive industries; thus, the ICEs are relatively high. Compared with Eastern China, Northwest China has a poor ecological environment, weak carrying capacity, and weak industrial base; it is unsuitable for large-scale industrialization. In Northeast China, although there are steel, heavy machinery, automobile, shipbuilding, aviation, and defence industries as well as other major industrial projects, since the 1990s, the industrial structure has been monolithic, with traditional products constituting the bulk. The institutional and structural contradictions are increasingly apparent. The old industrial base of enterprise equipment in Northeast China is ageing. The level of competitiveness is declining. There is an obvious contradiction in employment. Cities rich in resources and with leading industries are in recession. Economic development is still occurring at a slower pace. The gap between the regions and developed coastal areas is expanding.

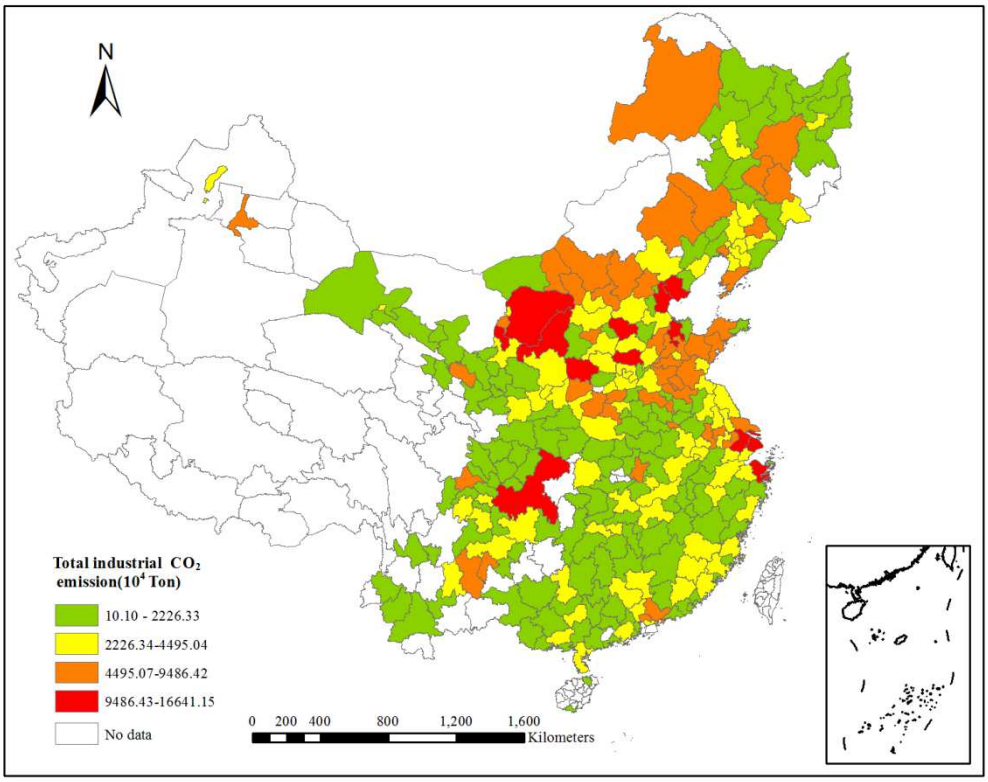


Fig. 1 Spatial distribution of ICEs

3.1.2 Global and local correlation

Based on the formulas (1) and (2), Moran's I is 0.24719, the P value is 0.000, and the Z score is 18.719. The results show that China's urban ICEs have significant spatial clustering characteristics and positive spatial autocorrelation. The global Moran's I reflects only the overall clustering characteristics of ICEs. This paper proceeds to use the local Moran's I to analyse the local characteristics of ICEs. Local indicators of spatial autocorrelation (LISA) agglomeration is shown in Figure 2. The results show that there are four types of spatial agglomeration, namely, H-H agglomeration (H-H), high-low (H-L) agglomeration (H-L), low-high (L-H) agglomeration and L-L agglomeration. The ICEs of high-agglomeration areas and peripheral cities are relatively high, and most of mainly distributed in the Beijing-Tianjin-Hebei region, the Yangtze River Delta region, Inner Mongolia, Shaanxi, Shanxi and other regions. This result may be due to the agglomeration of urban agglomerations and industrial zones in the Beijing-Tianjin-Hebei region and the Yangtze River Delta region, resulting in large ICEs. Inner Mongolia, Shaanxi and Shanxi are the largest energy and chemical bases in China. Local industries with high energy consumption, such as non-ferrous metal smelting, electric power and the energy and chemical industries, are relatively developed; thus, their ICEs are relatively high. The ICEs in H-L agglomeration areas are relatively high, while the ICEs in peripheral cities are relatively low, mainly distributed in cities such as Chongqing and Chengdu. L-H agglomeration areas have low ICEs, while the ICEs of peripheral cities are relatively high, mainly distributed in some cities in Hebei, Anhui and Sichuan. The ICEs of low-low-agglomeration areas and peripheral cities are relatively lower, mainly distributed in Guizhou, Yunnan and Guangxi, where the economy is less developed and the industrial base is weak; thus, the ICEs are also low.

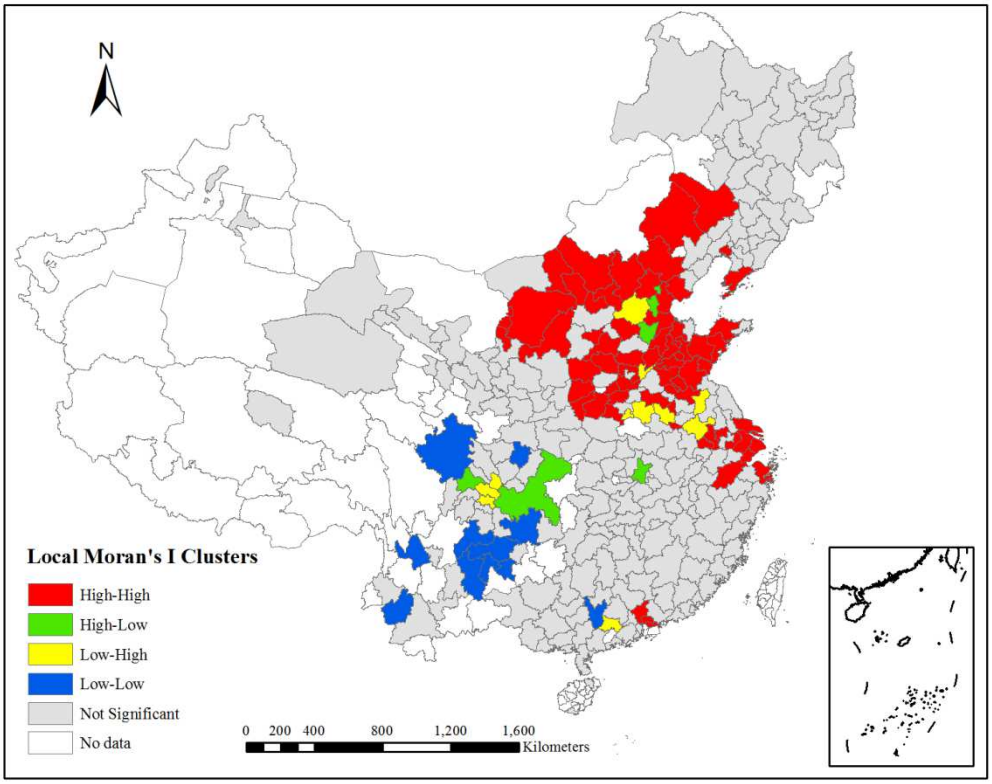


Fig. 2 Local Moran's I clusters of ICEs in China

3.2 Spatial heterogeneity of the influencing factors of ICEs

3.2.1 OLS regression results

Table 2 OLS regression results

	Coefficient	Std. Error	t-value	p-value	VIF
IS	0.661	0.125	5.30	0.000	5.24
IR	1.454	0.413	3.52	0.001	3.45
TR	1.858	0.497	3.74	0.000	3.64
RGDP	1.129	0.254	4.44	0.000	6.27
TI	-0.101	0.022	-4.64	0.000	4.65
PD	-0.251	0.086	-2.91	0.004	2.29
FDI	0.004	0.044	0.10	0.923	1.46
FA	-0.245	0.169	-1.45	0.147	3.80
FE	-0.383	0.204	-1.87	0.062	2.87
FD	-0.038	0.193	-0.20	0.844	2.01
Constant	4.554	2.781	1.64	0.103	

First, an OLS model was used for parameter estimation, and the results are shown in Table 2. The results of the ANOVA F test show that the model is strongly significant, and the variance inflation factor (VIF) values are less than 10, indicating that there is no serious collinearity problem in the model. The regression results show that the industrial scale, the share of industry in GDP, the share of service

industry in GDP and the level of economic development can significantly promote urban ICEs, and for each 1% increase in these four factors, the ICEs increase by 0.66%, 1.45%, 1.86% and 1.13%, respectively. At present, China's industrial output is as high as 39.0% of GDP, and industry is the sector with the largest CO_2 emissions. With the expansion of the industrial scale and the increase of the share of industry in GDP, the input of raw materials will increase, and in particular, energy consumption will greatly increase, which will naturally result in an increase in ICEs. The coefficient of the service industry is not consistent with expectations, which may be due to the high proportion of China's transportation industry in the service industry. In particular, in recent years, the rapid development of China's e-commerce and logistics industry has promoted the development of the transportation industry, which is the industry with the second largest ICEs after industry. With improved economic development, people will pursue better living standards, and the demand for household appliances, computers, automobiles and other industrial supplies will greatly increase, which will indirectly promote ICEs. At the same time, the figure shows that China is still on the left side of the EKC and has not reached the critical point of economic development to improve the environment. Technological innovation, population density, social fixed asset investment and government intervention are all important reasons for restraining ICEs; for every 1% rise in the four factors, accordingly the ICEs are reduced by 0.10%, 0.25%, 0.25% and 0.38%, respectively. Technological innovation, especially in energy conservation, environmental protection and low-carbon technologies, can improve energy efficiency and thus reduce carbon dioxide emissions. The higher the population density is, the more intensive the energy use, potentially reducing ICEs. Increased investment in fixed assets may promote the upgrading of production equipment and technology, which is conducive to reducing ICEs. An increase in government spending could encourage industrial enterprises to carry out technological innovations or to introduce advanced production lines to improve their energy efficiency and reduce their ICEs. The effects of FDI and on ICEs are not significant.

3.2.2 GWR regression results

In this paper, a GWR model is used to analyse the local heterogeneity of factors affecting ICEs. The R^2 values are shown in Figure 3. These values vary between 0.3731 and 0.8186, and there are significant differences in the fitting degree of different cities. The R^2 basically decreases from the marginal areas of Northeast China, Northwest China and the coast of Eastern China to Central China. The GWR model had the best fitting effect in Xinjiang, Gansu, Heilongjiang and Jilin, while the vast central region had the worst fitting effect. This result indicates that the relationship between the driving factors and ICEs is better reflected by the regression model in Xinjiang, Gansu, Heilongjiang and Jilin provinces.

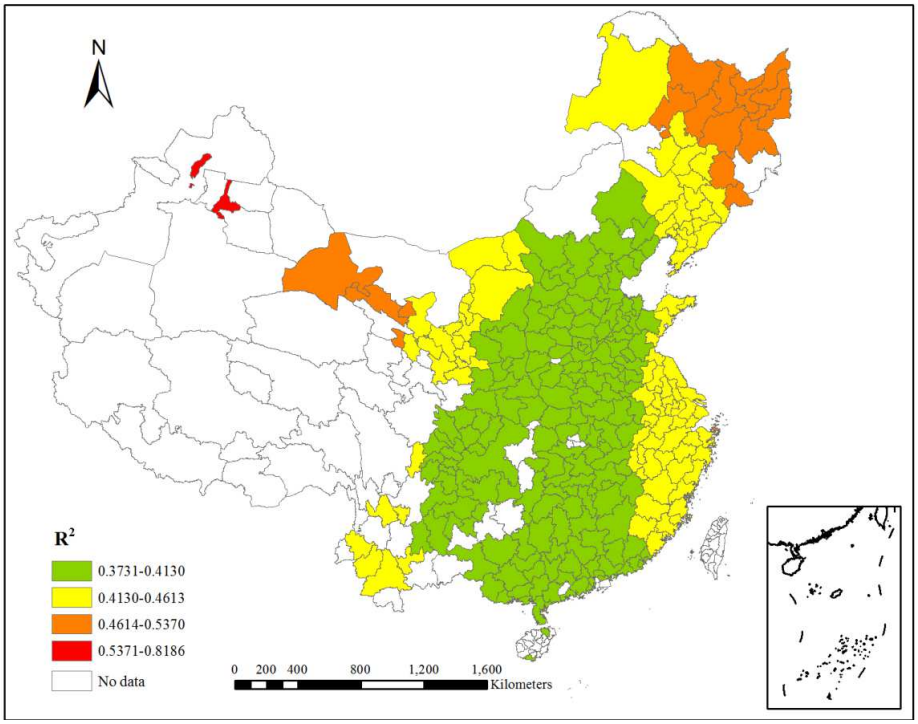


Fig. 3 Spatial distribution of R^2 values

The GWR model can calculate the coefficient of the influence of the explanatory variables on the explained variables in each city, making it possible to more clearly analyse the local characteristics of the coefficient of influence. The descriptive statistics of the coefficient of the influence for each variable on ICEs is shown in Table 3. The standard deviation of the estimated coefficient varies over a wide range, with the minimum (FD) value being 0.026 and the maximum (TI) value being 0.147. The greater the variation range of the coefficient is, the greater the spatial difference in the influence extent of various factors on ICEs, which better reflects the superiority of the GWR model. Table 3 also calculates the proportion of the number of cities with significant coefficients ($P < 0.10$) and the proportion of cities with positive and negative coefficients.

Table 3 Descriptive statistics of GWR regression coefficient

	Coefficients				Percent of cities by significance of T-test		
	max	Min	mean	Std. Dev.	P<0.1	+(%)	-(%)
IS	1.780	0.610	0.896	0.109	100	100	0
IR	0.515	0.178	0.321	0.087	86.01	100	0
TR	0.618	0.207	0.436	0.102	94.76	100	0
RGDP	0.225	-0.379	-0.215	0.142	53.5	0	100
TI	-0.115	-1.074	-0.403	0.147	93.36	0	100
PD	-0.033	-0.281	-0.088	0.036	9.79	0	100
FDI	0.147	-0.261	-0.003	0.067	19.23	50.91	49.09
FA	0.111	-0.227	0.008	0.077	5.24	0	100
FE	0.034	-0.109	-0.061	0.028	22.73	0	100
FD	-0.018	-0.128	-0.075	0.026	27.97	0	100

The article also describes the spatial characteristics of the estimated coefficients of each influencing factor, as shown in Figure 4. Cities whose estimated coefficients are significant at the 10% level are also marked with slashes. In all cities, the industrial scale, the share of industry in GDP and the share of service industry in GDP all promote ICEs, while technological innovation, population density and social fixed asset investment all restrain ICEs. In contrast, the level of economic development,FDI, financial development and government intervention have a two-way impact on ICEs, and there are significant differences in different cities. which is inconsistent with the results estimated by the OLS regression model. These results are different from those of OLS regression model. The specific analysis is as follows.

The coefficient of the IS is all positive and significant in 100% of the cities under study, indicating that industrial scale expansion significantly promotes ICEs, which is basically consistent with the OLS model estimation results. Among them, in cities such as Gansu and Xinjiang, the influence of the industrial scale on ICEs is the highest, while the influence on the ICEs of coastal areas such as Guangxi, Guangdong and Fujian is relatively low. Overall, the coefficient of influence for northern cities is obviously higher than that for southern cities. One possible reason for this result is that in recent years, with upgrading of industrial structure, energy-intensive enterprises in the eastern coastal areas have gradually moved to western regions. Gansu and Xinjiang are the two major energy and chemical bases in China, and the scale of energy-intensive industries continues to expand; thus, the impact on ICEs is higher than that in other regions.

The coefficient of the IR is positive and significant in 86.01% of the cities under study, and the influence extent gradually decreases from west to east. Among them, the share of industry in GDP has the highest influence on ICEs in Inner Mongolia, Gansu, Ningxia, Shanxi, Shaanxi and other western regions. This result may be because Western China is rich in energy resources, and the energy-intensive industries related to these resources, such as the energy and chemical industry, the equipment manufacturing industry and the non-ferrous metal smelting and processing industry, are relatively developed. Therefore, an increase in the share of industry in GDP will promote ICEs. In addition, to catch up and go beyond, western cities tend to weaken their environmental regulations when undertaking industrial transfer from eastern regions, and they introduce some high-energy-consuming enterprises into local areas. Therefore, with the development of industry, especially heavy industry, ICEs will inevitably increase.

The coefficient of the TR is positive and significant in 94.76% of cities, indicating that an increase in the share of the service industry in GDP will promote ICEs, and the influence extent successively decreases from west to east. In western cities such as those in Inner Mongolia, Gansu and Shaanxi, the share of the service industry in GDP has the highest impact on ICEs, while in eastern cities, the impact is much smaller. One possible reason is related to the internal structure of the service industry. In Western China, low-end service industries such as transportation, storage and logistics, accommodation

and catering account for a higher proportion. In Eastern China, financial, legal consulting, real estate and other services are more developed. Therefore, an increase in the share of the service industry in GDP in Western China will cause more ICEs compared to Eastern China.

The level of economic development has a two-way effect on ICEs. In Jiangsu, Zhejiang, Fujian, Guangdong, Hunan and other eastern coastal cities, the coefficient is significantly negative, showing that economic development can restrain ICEs, which conforms to the law described in the right part of the EKC. The main reason may be that the economic level of the eastern coastal areas has reached a certain degree and exceeded a certain critical point. Therefore, people will pursue better living standards and have a higher demand for green and low-carbon products, the government will have strong environmental regulations, and enterprises will tend to adopt green and low-carbon technologies; thus, ICEs can be restrained. The impact coefficient of RGDP in other cities is not significant, indicating that economic development in these cities has difficulty curbing ICEs.

The coefficient of TI is negative and significant in 93.36% of the cities under study, and the influence extent increases successively from east to west. In western regions such as Inner Mongolia, Gansu, Ningxia and Qinghai, technology innovation has the highest impact on ICEs, while its impact is relatively low in Heilongjiang, Hainan and other places. This result may be because of the rich resources in Western China; the high proportion of energy-intensive industries, such as flue gas enterprises; and the comprehensive utilization of solid waste, the energy savings and the reduced consumption in key areas, such as the independent development of new technologies, new processes, and new equipment, which promote the development of low-carbon technology, improve the efficiency of energy utilization, and curb ICEs.

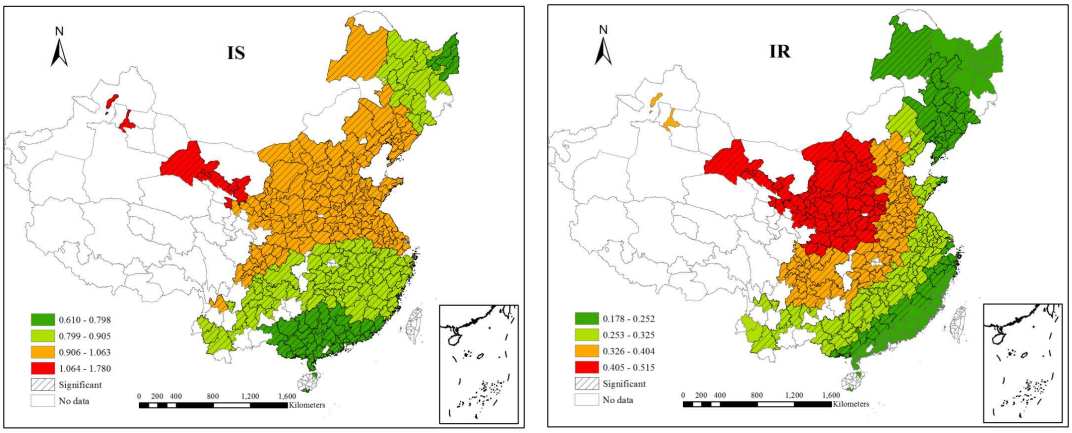
The impact coefficient of PD is negative and significant in only 9.79% of cities, indicating that PD can suppress ICEs in very few cities, which are mainly concentrated in western regions such as Ningxia, Gansu, Shaanxi and Inner Mongolia. One possible reason is that Western China is sparsely populated, with a low population density, and CO_2 emissions mainly come from the bioenergy in rural. With the advancement of urbanization and the increase in population density, energy is utilized intensively, and the utilization efficiency is greatly improved; thus, ICEs will also be reduced accordingly.

FDI has a two-way impact on ICEs. The impact is significantly positive in Hainan, Guangdong, Fujian and other south-eastern regions, indicating that FDI can promote ICEs. However, it is significantly negative in Heilongjiang, Jilin, Liaoning and other north-eastern regions, indicating that FDI can curb ICEs. This means that FDI has an impact on ICEs only in specific cities and that OLS models cannot reveal this feature. This may be because in the eastern coastal areas with developed industries, FDI inflows are mainly to industrial enterprises; thus, an increase in FDI will promote ICEs. In Northeast China, traditional industries, with high energy consumption and backward technology, are dominant. FDI inflow can bring advanced technology and management experience, promote the technological progress of local industrial enterprises, and thus reduce ICEs.

Social fixed asset investment has a two-way impact on ICEs. The coefficient of influence for Inner Mongolia, Ningxia, Gansu and other northwest regions is significantly negative, while in most other cities, it is not significant. This result shows that social fixed asset investment is an important factor in restraining ICEs in Northwest China, possibly because the industrial enterprises in Northwest China are at a critical stage of eliminating their backward production capacity and transforming and upgrading. A large amount of social fixed asset investment can bring advanced production equipment and technology to enterprises, which may increase their economic income and give them more funds for environmental governance, thereby reducing their ICEs.

The coefficient of FE is negative and significant only in 22.73% of the cities under study, which are mainly located in eastern regions such as Shanghai, Shandong, Zhejiang, Anhui, and Jiangsu. The impact of government intervention is not significant in most other cities. This result suggests that government intervention is currently able to curb ICEs in Eastern China. One possible reason is that the eastern region has a relatively developed economy, and local governments have relatively high financial revenues. They typically use tax incentives and subsidy policies to encourage enterprises to innovate. Under the encouragement of preferential policies from the government, enterprises will invest more money in scientific innovation and technological innovation and introduce green and low-carbon technologies to reduce their CO_2 emissions.

The influence of financial development on ICEs is negative and significant only in 27.97% of the cities under study. This result shows that financial development could inhibit ICEs. The cities in which financial development has an impact are mainly in Chongqing, Hunan, Guangdong, Guangxi, Yunnan, southern Sichuan, and Guizhou; the influence of financial development is not significant in most other cities. One possible reason is that the degree of regional financial development is higher, and therefore, financial institutions provide financial support for green credit business, technological transformation and innovation, especially in terms of green technology R&D and promotion. Financial institutions will give preferential access to credit, low interest rates and other support, improving the hatching rate and survival rate and improving technology innovation to reduce ICEs.



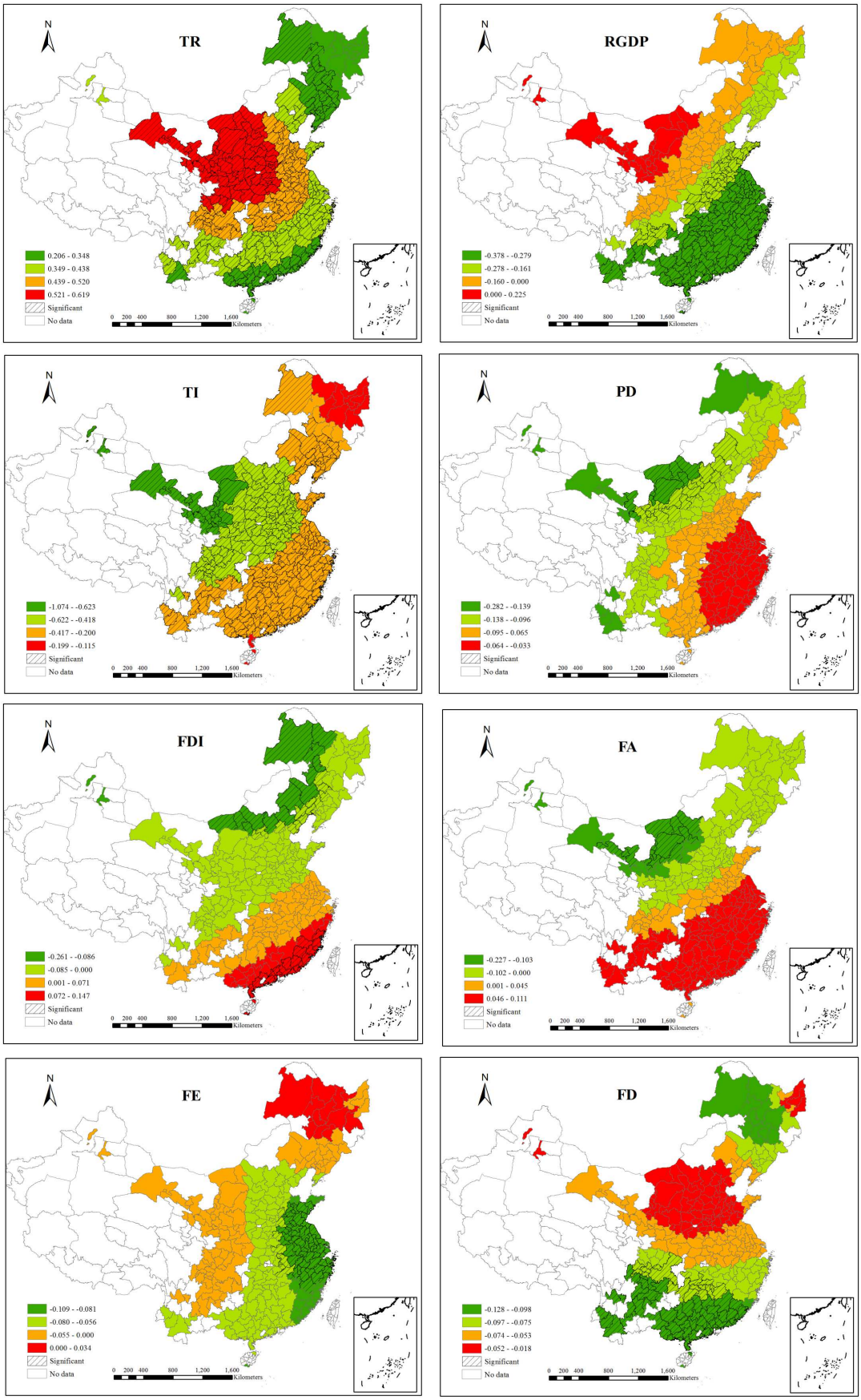


Fig. 4 Spatial distribution of regression coefficients

4. Conclusion and Policy Implications

4.1 Conclusion

In this paper, the spatial and temporal distribution characteristics of ICEs are discussed by ESDA method, and the spatial heterogeneity of influencing factors of ICEs is studied by GWR model. The main conclusions are as follows.

First, China's urban ICEs show significant spatial clustering characteristics. Areas with high ICEs are mainly concentrated in Chongqing, Tianjin, Shandong, Shanghai, Jiangsu, Zhejiang, Hebei, Shanxi, Yinchuan, Inner Mongolia, Shaanxi and other provinces, while low-emission areas are mainly distributed in less developed cities in Central and Western China, such as Sichuan, Gansu, Guizhou and Yunnan. Therefore, coordinated emission reduction policies should be formulated for areas with high ICEs.

Second, regarding ICEs, based on the influencing factors of the overall situation, industry scale, the share of industry in GDP, the share of service industry in GDP, and the level of economic development play a major role in promoting ICEs, while the technology innovation, population density, social fixed assets investment, government intervention play a major role in inhibiting ICEs. The influence of FDI and financial development on ICEs is not significant.

Third, the influencing factors of ICEs have spatial heterogeneity. The influence of the industrial scale on ICEs is always positive and significant in all cities evaluated, and the influence extent gradually decreases from north to south. The influence of the share of industry in GDP on ICEs is always positive and significant in 86.01% of the cities under study, and the influence extent gradually decreases from west to east. The coefficient of the share of service industry in GDP on ICEs is positive and significant in 94.76% of the cities, and the influence extent successively decreases from west to east. The economic development level has a two-way impact on ICEs. This impact is significant in 53.8% of the cities, and the inhibitory effect of the economic development level is the strongest in eastern coastal cities. The impact of technology innovation on ICEs is negative and significant in 93.36% of the cities, and the influence extent increases from east to west. The impact of population density on ICEs is negative and significant in only 9.79% of the cities, which were mainly concentrated in Ningxia, Gansu, Shaanxi, Shanxi, Hebei and other regions. FDI has a two-way impact on ICEs, and this impact is significantly positive in Hainan, Guangdong, Fujian and other south-eastern cities and significantly negative in Heilongjiang, Jilin, Liaoning, Hebei, Inner Mongolia and other north-eastern regions. Social fixed asset investment has a two-way impact on ICEs. This impact is significant in only 5.24% of the cities, which are mainly located in Inner Mongolia, Shaanxi, Ningxia and other north-western regions, while in most other cities, the impact of social fixed asset investment is not significant. Government intervention has a two-way impact on ICEs that is significant in only 22.73% of the cities, which are located in eastern regions such as Shanghai, Shandong, Zhejiang, Anhui, Jiangsu and Fujian. The impact of government intervention is not significant in most other cities.

Financial development has a negative impact on ICEs, and this impact is in 27.97% of the cities, which are located in southern regions such as Chongqing, Hunan, Guangdong, Guangxi, Yunnan, Sichuan and Guizhou.

4.2 Policy implications

According to the above conclusions, the influences of different factors on ICEs are spatially heterogeneous. Therefore, policies should be made according to the development characteristics of cities and according to local conditions. Therefore, the following suggestions are proposed: the industrial production scale and excessive proportion of industry are still one of the main sources of ICEs, and local governments should strictly control the industrial structure, especially the heavy industry output value, and maintain it within a reasonable scope. The choice of low-pollution, low-emission, and green industries should encourage enterprises in Central China to optimize and upgrade the industrial structure, reduce the proportion of the secondary industry in GDP, and actively develop the low-carbon economy. On the premise of encouraging industrial structure optimization, local governments should focus on developing high-end low-carbon service industries, such as finance, medical care, culture and entertainment, and information technology, while vigorously developing the service industry to avoid a shift in ICEs from industry to the service industry. As economic development has a significant restraining effect on ICEs, Central and Western China should vigorously develop their economy, improve people's living standards, alleviate the contradiction between people's growing demand for a better life and economic development, and promote people to cultivate green and low-carbon living habits. Technological innovation should be accelerated, with emphasis on the application of new energy technologies and low-carbon technologies, flue gas treatment and the comprehensive utilization of solid waste. Market mechanisms should be introduced to ensure the application of low-carbon technologies and to improve energy utilization efficiency. The government should encourage an appropriate increase in the population density of western cities and guide the population to flow into Western China through industrial transfer, talent introduction and other measures because this change in the population structure can not only relieve the environmental pressure brought by the population in Eastern China but also promote the balanced development of urbanization in Central and Western China. For the eastern coastal areas, foreign capital should be encouraged. When introducing foreign capital, attention should be paid to the investment structure of foreign investors, and they should be guided to flow to high-tech industries and service industries. For less developed regions such as Northeast China and Northwest China, the business environment should be further optimized to attract high-tech foreign-funded enterprises, and local enterprises should be encouraged to actively introduce advanced foreign technologies and conduct cooperations and collaborative innovation with foreign high-tech enterprises. Western China should increase the scale of social fixed asset investment, pay attention to optimizing the investment structure, accelerate the

transformation and upgrading of traditional industries in industrial investment, and encourage enterprises to introduce advanced production equipment and technological transformation. We will quickly promote investment in medium- and high-end manufacturing, reduce overcapacity and high energy consumption, and improve the quality of industrial investment. In Central and Western China, we should increase government financial expenditure, especially on science and technology and environmental governance. We should also set up innovation funds, use tax and fiscal subsidy policies, guide and encourage enterprises to adopt green and low-carbon technologies, and increase R&D. We should strengthen the financial development in the northern cities of China, give full play to the role of financial capital in allocating resources by means of the market, encourage financial institutions to provide financial support for innovative and green enterprises, and even offer certain preferential interest rates to alleviate the financing pressure of enterprises. For zombie enterprises with an excessive production capacity and severe pollution, loans should be prohibited.

Funding This research was funded by the National Natural Science Foundation of China for Young Scholars(No.71603202), the Shaanxi Soft Science Foundation (No.2019KRM129), the Shaanxi Province Education Department Philosophy and Social Science Key Institute Base Project (No. 19JZ048), the Xi'an Soft Science Foundation (No. 2019111813RKX002SF006-6) and the Scientific Research Project of China (Xi'an) Institute for Silk Road Research (No. 2019YA08).

Compliance with ethical standards

Conflict of interest The authors declare no confict of interest.

References

Al-mulali U (2012) Factors affecting CO_2 emission in the Middle East: A panel data analysis. Energy 44:564-569.

Åhman M, Nilsson LJ, Johansson B (2016) Global climate policy and deep decarbonization of energy-intensive industries. Climate Policy 17:634-49.

Dauda L , Long X , Mensah C N , Salman M (2019) The effects of economic growth and innovation on CO2 emissions in different regions. Environ Sci Pollut Res 26(15):15028-15038.

Dong F, Gao XQ, Li JY, Zhang YQ, Li YJ (2018) Drivers of China's Industrial Carbon Emissions: Evidence from Joint PDA and LMDI Approaches. Int J Environ Res Public Health 15:2712.

Elhorst JP (2012) Matlab software for spatial panels. Int Reg Sci Rev 37:389-405.

Feng Z, Chen W (2018) Environmental regulation, green innovation, and industrial green development: An empirical analysis based on the Spatial Durbin Model. Sustainability 10:223.

Freitas LC, Kaneko S (2011) Decomposing the decoupling of CO_2 emissions and economic growth in Brazil. Ecol Econ 70:1459-1469.

Ghazali A, Ali G (2019) Investigation of key contributors of CO_2 emissions in extended STIRPAT

model for newly industrialized countries: A dynamic common correlated estimator (DCCE) approach. Energy Rep 5: 242-252.

Glaeser EL, Kahn ME (2010) The greenness of cities: Carbon dioxide emissions and urban development. J Urban Econ 67:404-418.

Griffin PW, Hammond GP, Norman JB (2016) Industrial energy use and carbon emissions reduction: A UK perspective. Energy Environ 216:684-714.

International Energy Agency. CO_2 emissions from fuel combustion. https://webstore.iea.org/ CO_2-emissions-from- fuel-combustion-2018-highlights.

Jorgenson AK, Clark B (2010) Assessing the temporal stability of the population/ environment relationship in comparative perspective: a cross-national panel study of carbon dioxide emissions, 1960–2005. Popul Environ 32:27-41.

Knight KW, Rosa EA, Schor JB (2013) Could working less reduce pressures on the Environment ? A cross-national panel analysis of OECD countries, 1970–2007. Global Environ Change 23: 691-700.

Kumbaroglu G (2011) A sectoral decomposition analysis of Turkish CO_2 emissions over 1990-2007. Energy 36:2419-2433.

Liddle B (2015) What are the carbon emissions elasticities for income and population? Bridging STIRPAT and EKC via robust heterogeneous panel estimates. Glob Environ Change 31:62-73.

Lin BQ, Benjamin BI (2019) Determinants of industrial carbon dioxide emissions growth in Shanghai: A quantile analysis. J Clean Prod 217:776-78.

Lin B, Moubarak M (2014) Mitigation potential of carbon dioxide emissions in the Chinese textile industry. Appl Energy 113:781-787.

Mousavi B, Lopez NSA, Biona JBM, Chiu ASF, Blesl M (2017) Driving forces of Iran's CO_2 emissions from energy consumption: An LMDI decomposition approach. Appl Energy 206: 804-814.

Moutinho V, Moreira AC, Silva PM (2015) The driving forces of change in energyrelated CO_2 emissions in Eastern, Western, Northern and Southern Europe: The LMDI approach to decomposition analysis. Renew Sust Energ Rev 50:1485-1499.

Pata UK (2018) The effect of urbanization and industrialization on carbon emissions in Turkey: Evidence from ARDL bounds testing procedure. Environ Sci Pollut Res 25:7740-7747.

Poumanyvong P, Kaneko S (2020) Does urbanization lead to less energy use and lower CO_2 emissions? A cross-country analysis. Ecol Econ 70:434-444.

Qin HT, Huang QH, Zhang ZW, Lu Y, Li MC, Xu L, Chen ZJ (2019) Carbon dioxide emission driving factors analysis and policy implications of Chinese cities: Combining geographically weighted regression with two-step cluster. Sci Total Environ 684:413-424.

Rahman MS, Shahari F, Rahman M, Noman AHM (2017) The interdependent relationship between sectoral productivity and disaggregated energy consumption in Malaysia: Markov Switching approach. Renew Sustain Energy Rev 67:752-759.

Su K, Wei DZ, Lin WX (2020) Inflfluencing factors and spatial patterns of energy-related carbon emissions at the city-scale in Fujian province, Southeastern China. J Clean Prod 244:118-840.

Wang JY, Wang SJ, Li SJ (2019) Examining the spatially varying effects of factors on $PM_{2.5}$ concentrations in Chinese cities using geographically weighted regression modeling. Environ Pollut 248:792-803.

Wen L, Li ZK (2020) Provincial-level industrial CO_2 emission drivers and emission reduction

strategies in China: Combining two-layer LMDI method with spectral clustering. Sci Total Environ 700:134374.

Zhang L, Rong P, Qin Y (2018) Does Industrial Agglomeration Mitigate Fossil CO_2 Emissions?An Empirical Study with Spatial Panel Regression Model. Energy Procedia 152: 731-737.

Figures

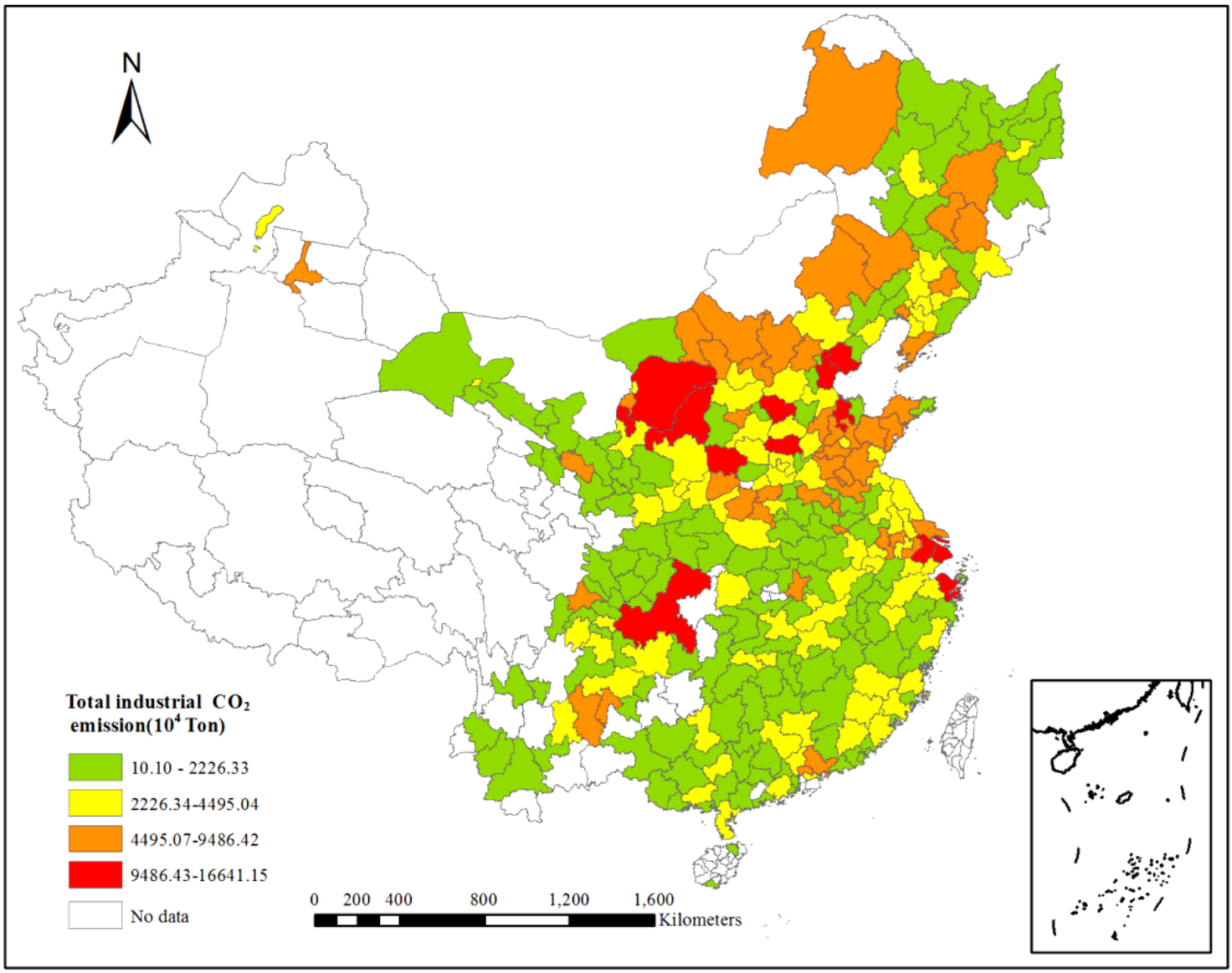


Figure 1

Spatial distribution of ICEs. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

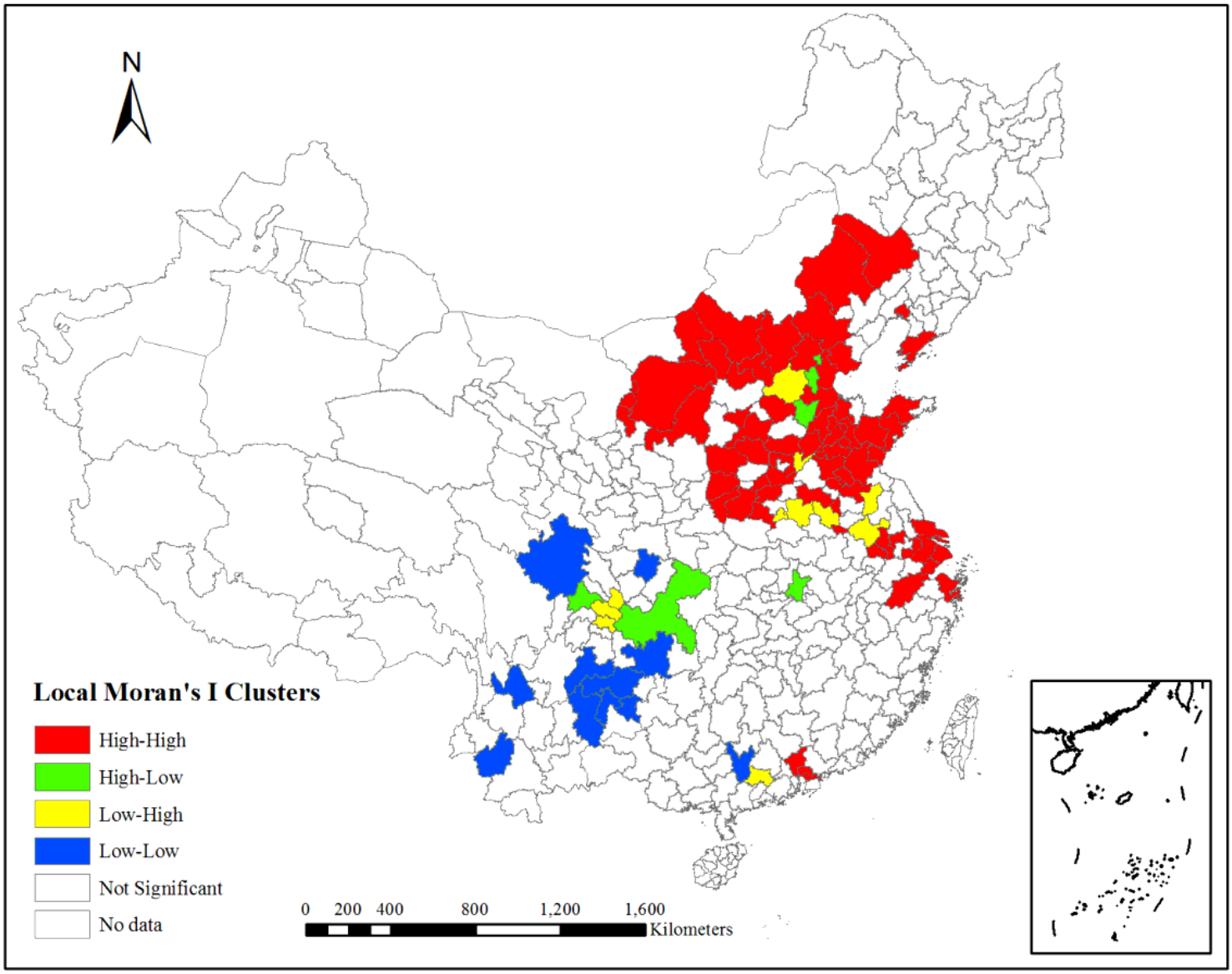


Figure 2

Local Moran's I clusters of ICEs in China. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

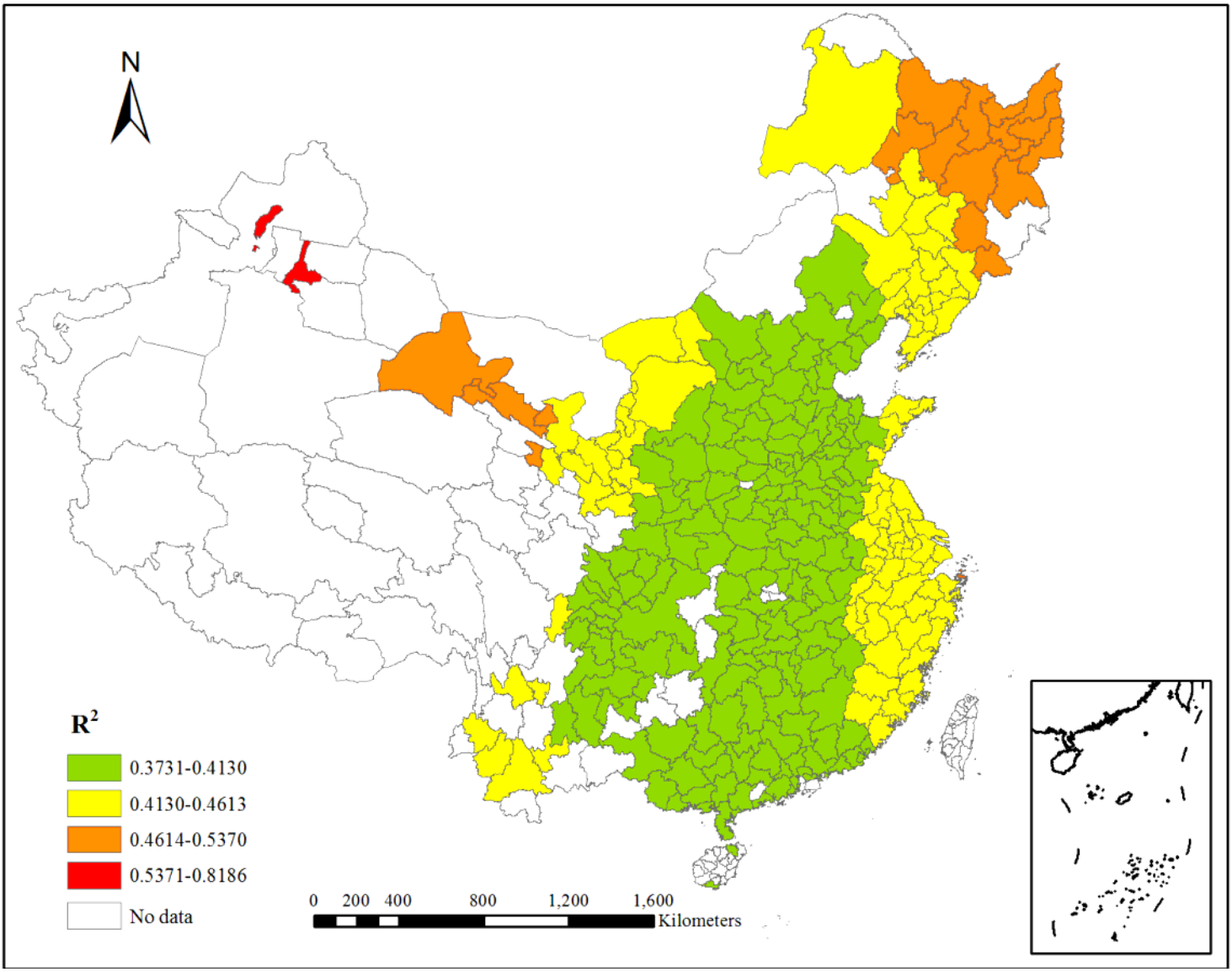


Figure 3

Spatial distribution of R2 values. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

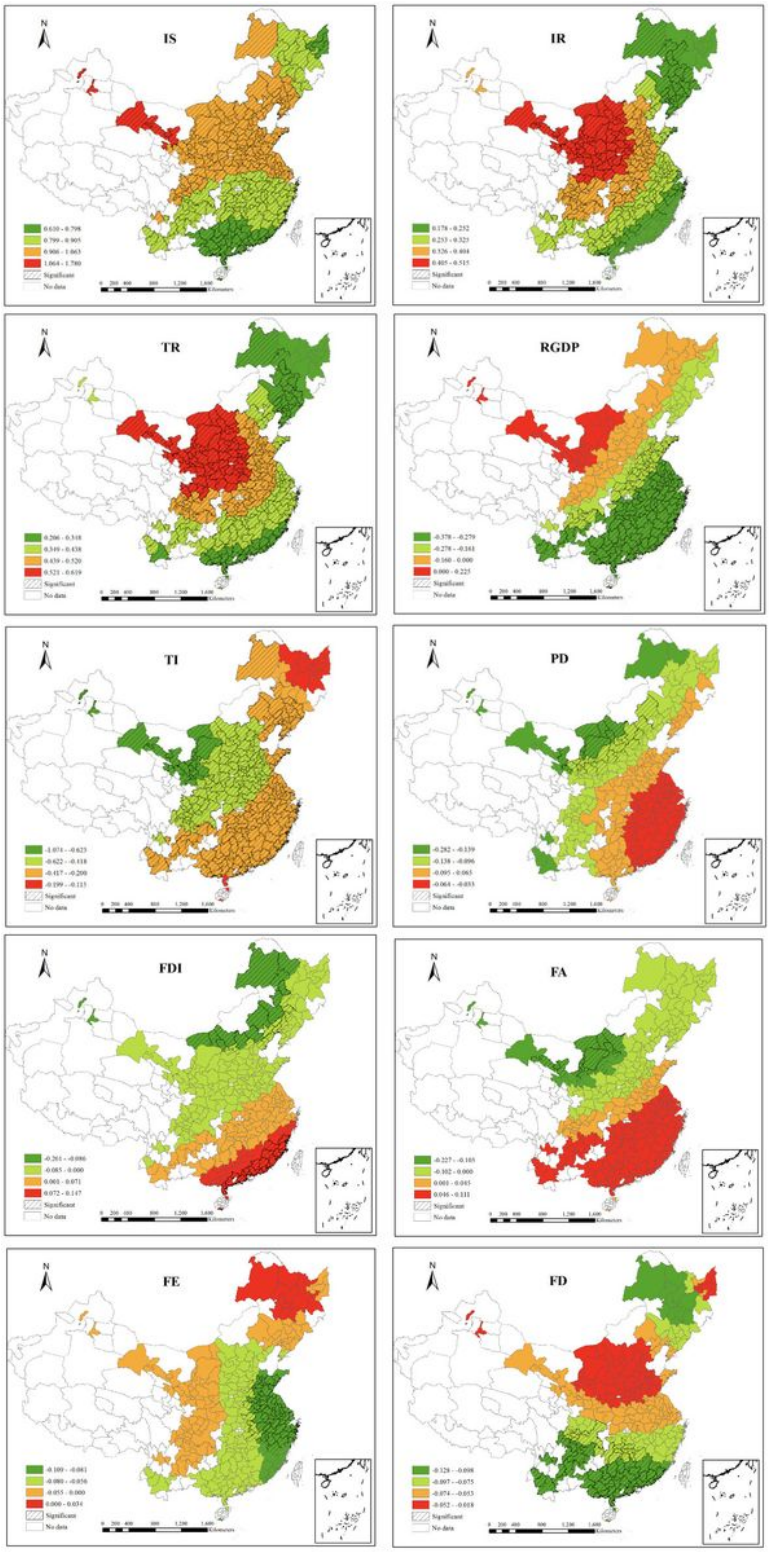


Figure 4

Spatial distribution of regression coefficients. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- GraphicalAbstract.tif