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SPATIOTEMPORAL DISTRIBUTION OF THE IMPACT OF URBAN DEVELOPMENT ON AIR POLLUTION

This study applies China's air pollution and urban development data from 2007 to 2021, and the temporally weighted regression (GTWR) model to analyze the spatiotemporal distribution characteristics of air pollution influencing factors. It was found that the temporal evolution of air pollution in different regions is highly consistent but its degree varies with the pollution severity. The impact of urban development on air pollution has significant spatiotemporal heterogeneity. Overall, urban green space area (UGSA), urban population density (UPD), and domestic waste removal volume (DWRV) have positive impacts, while urbanization rate (UR), per capita disposable income of urban residents (URI), and public vehicles per every 10 000 people (PTV) have negative impacts. The impact of USGA, UR, and URI is mainly visible in western provinces, the impact of UPD in northeast provinces, the impact of DWRV in eastern and central provinces, and the impact of PTV in eastern provinces.

1. INTRODUCTION

With the rapid development of urbanization, most cities in China have severe air pollution, with over 95% of cities exceeding the standard by over 30% [1]. The economic agglomeration and population growth within cities are closely related to severe air pollution. In recent years, the number of large cities and the incidence of air pollution have been continuously increasing. The relationship between urban development and air pollution is close and complex. Smoke and dust control has improved the quality of urban development in China, but sulfur dioxide control has led to a decline in the quality of urban development in China [2]. Population growth may lead to air pollution, and the

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expansion of urban scale is accompanied by changes in transportation modes and congestion. Whether the expansion of the urban scale will affect transportation and have a significant impact on air pollution is still unknown.

Urban development includes population, economy, industrial structure, environmental regulations, and public transportation. The adjustment of urban development is considered an effective strategy to improve air quality. However, research on how to alleviate air pollution through adjustments in urban development is still unclear. Faced with complex urban development factors and imbalanced regional development in China, it is important to determine the impact mechanism of air pollution and formulate air pollution control policies tailored to local conditions. This is an important issue currently faced by urban development in China and the starting point of this study.

Existing research mainly focuses on analyzing the relationship between air pollution and urban development in individual regions. This study introduces a geographically and temporally weighted regression (GTWR) model. GTWR model can simultaneously consider the spatiotemporal heterogeneity of influencing factors and obtain influence coefficients under different spatiotemporal conditions. This article also verifies that the GTWR model has high accuracy and applicability in the analysis of air pollution impact mechanisms. Therefore, this article considers the complex urban development situation in China and analyzes the spatiotemporal distribution characteristics of air pollution influencing factors in different regions. In the study of the relationship between urban development and air pollution, the STIRPAT model indicates that environmental pressure is mainly related to population, wealth level, and technology. This study analyzes the impact of urban development on air pollution from multiple perspectives, starting from the comprehensive development and actual situation of cities. In addition to common influencing factors, the selection of indicators also introduces urbanization level, urban greening, urban environmental regulation, and urban public transportation.

1.1. AIR POLLUTION

Air pollution is closely related to human health and social development. The reported studies mainly focus on the hazards of air pollution and the connection between air pollution and society. For example, air pollution, especially combustion-related fine particulate air pollution and ozone, leads to a variety of adverse health outcomes, including increased morbidity and mortality from respiratory and cardiovascular diseases and increased risk of lung cancer [3]. Air pollution significantly worsens income distribution in China [4]. Guo et al. [5] find that a sharp increase in air pollution leads to an immediate deterioration in the price parity of listed stocks in both regions, which is consistent with air pollution-induced depressive symptoms. A threshold must be reached for a period of heavy air pollution to trigger a reduction [6].

Air pollution acts on social development. For example, the relationship between air pollution and pro-social behaviors is limited and not all types of pro-social behaviors are affected by air pollution, probably because air pollution only affects specific psychological motives, and different types of pro-social behaviors have different motives [7]. Green technology innovation and industrial structure upgrading are important transmission mechanisms for environmental tax reform to improve air quality [8]. Nationally, government policies appear to have reduced air pollution but have not significantly affected industrial production [9]. Luthra et al. [10] show how the National Green Tribunal has targeted one source of air pollution by recommending waste-to-energy technologies that deprive scavengers of their livelihoods.

Zhang. et al. [11] analyzed the impact of air pollution on labor mobility, Alyousifi et al. [12] proposed a new application of a Markov chain-based fuzzy state (MCFS) model that uses triangular fuzzy numbers to analyze the uncertainty of the occurrence of an air pollution event and to describe the transition behavior of air pollution. The level of awareness of air pollution among yurt residents is quite high and fully recognize the risks of air pollution [13], suggesting that air pollution in rural areas should receive more attention from the media, environmental organizations, and policy-makers [14].

1.2. IMPACT OF URBAN DEVELOPMENT ON AIR POLLUTION

There have been many achievements in research on the impact of urban development on air pollution. For example, in terms of public transportation, road traffic has become an important source of air pollution affecting Chinese cities. Guo et al. [15] analyzed the spatial spillover effects of urban transportation infrastructure on air pollution. Urban high-speed rail construction and tourism resources play an important moderating role in the relationship between tourism development and urban industrial SO_2 emissions [16]. Green transportation modes can reduce air pollution, while traffic congestion increases commuting time and thus air pollution [17].

In terms of urban scale and spatial structure, appropriate urban expansion has strong positive externalities in terms of direct and spillover effects on air pollution and eco-efficiency. However, excessive urban sprawl exacerbates air pollution in local cities but favors air improvement in neighboring cities [18]. Increasing industrial scale and diversity exacerbate air pollution, reflecting structural effects [19]. Reducing the density of urban public centers and developing a polycentric urban structure may help improve air quality in compact cities [20].

There are significant spatial correlations between green innovation and air pollution in both urban economy and green development [21]. The level of economic development, population density, degree of openness, geographic location, and wind direction relationship are important factors affecting the spatial correlation network of air pollution [22]. Land resource mismatch inhibits technological innovation, government science and technology investment, and foreign direct investment, and exacerbates local air pollution [23], and there is a strong spatiotemporal dependence effect between air pollution and technological innovation [24].

To summarize, the influencing factors of urban air pollution are complex and diverse [25], and regional pollution prevention and control measures should be taken to combat air pollution, and different measures should be developed for the different urban "actors" in the pollution network, to fundamentally solve the air pollution problems in the region [26]. Therefore, it is important to analyze the spatial and temporal distribution characteristics of the impacts of urban development on air pollution from multiple perspectives, taking into account the differences between regions and the comprehensive development of cities, and to give locally adapted prevention and control policies.

2. EXPERIMENTAL

Methods. This study used a geographically and temporally weighted regression (GTWR) model to analyze the spatiotemporal heterogeneity of the impact of urban development on air pollution. In existing research, geographically weighted regression (GWR) and temporally weighted regression (TWR) are commonly used to address the issues of spatial and temporal heterogeneity. Bai et al. [27] verified that GTWR is superior to GWR in regression analysis. By applying panel data regression, spatiotemporal heterogeneity can be analyzed simultaneously. The calculation formula for the GTWR method is:

$$y_i = \beta_0 (u_i, v_i, t_i) + \sum_{k=1}^{p} \beta_k (u_i, v_i, t_i) x_{ik} + \varepsilon_i \tag{1}$$

where y_i refers to the dependent variable, which represents the degree of air pollution, i.e., the concentration of sulfur dioxide, u_i and v_i are the longitude and latitude coordinates of the observation point; (u_i, v_i, t_i) are the space-time coordinates of the ith sample point, β_0 is the regression constant of sample point i, that is, the constant term of GTWR, β_k is the kth regression parameter of point i, and x_{ik} is the value of independent variable x_k at point i, that is, the value of each explanatory variable in the GTWR model.

Variables and data sources. Sulfur dioxide is the main source of air pollution. This paper uses sulfur dioxide emissions (SDE) as a measure of air pollution, the higher the SDE, the more serious air pollution is. Referring to Guo et al. [15] and Wei and Li [22], and taking into account the level of urban development, this article selects urban green space area (UGSA), urbanization rate (UR), urban population density (UPD), domestic waste removal volume (DWRV), per capita disposable income of urban residents (URI), and the number of vehicles every Mt people have (PTV) as indicators for urban development. The data type used in this article is panel data, which includes the annual variable values of various provinces in China[3] from 2007 to 2021. The dependent variable is SDE and the urban development variables are independent ones. Data were taken from the *China Statistical Yearbook* and *China Urban Statistical Yearbook* published by China from 2007 to 2021. The definitions of the variables and descriptive statistics are shown in Tables 1 and 2. Table 2 shows the descriptive statistics of different variables at the national level from 2007 to 2021, and the data presented in the indicator values are per year. As shown in Table 2, the SDE took values ranging from 0.14 to 182.74, with a mean value of 48.25 Mt/year.

Table 1

Air pollution and urban development variables

Abbreviation	Variable
SDE	Sulfur dioxide emissions, Mt/year
UGSA	Urban green space area, Mha
UR	Urbanization rate, %
UPD	Urban population density, person/km^2
DWRV	Domestic waste removal volume, Mt/year
URI	Per capita disposable income of urban residents, Mt CNY
PTV	Number of public vehicles per every 10^4 people have

Table 2

Descriptive statistics of the initial indicators from 2007 to 2021

Variable	Min	Q_1	Median	Mean	Q_3	Max
SDE	0.14	12.93	36.33	48.25	71.94	182.74
UGSA	0.20	3.42	6.16	8.29	9.00	53.29
UR	21.45	46.54	55.10	56.05	63.37	89.58
UPD	515.00	1896.00	2637.00	2822.00	3536.00	5967.00
DWRV	16.30	298.20	504.60	617.60	790.30	3347.30
URI	1.04	1.80	2.66	2.88	3.55	8.24
PTV	5.63	9.75	11.54	12.01	13.52	26.55

3. RESULTS AND DISCUSSION

3.1. TEMPORAL AND SPATIAL DISTRIBUTION OF AIR POLLUTION

SDE data were collected from the *China Statistical Yearbook* from 2007 to 2021. The data presented in Fig. 1 are the annual average values of SDE in the regions of China. The nationwide refers to the annual average value of SDE for the whole country.

[3]According to the definition of the Bureau of Statistics, the 34 provinces of China can be divided into four large regions: easternernern, central, westernern, northeasternern as well as Hong Kong, Macao, and Taiwan. In the article, we consider data referring to provinces excluding those last three.

The temporal evolution of SDE in different regions is highly consistent, showing an overall downward trend, and the fastest decline rate was observed from 2015 to 2016. During the investigation period, the minimum and maximum values of SDE in different regions appeared in 2007 and 2021, respectively. Nationally, the SDE rises only slightly from 2010 to 2011, and the rest of the time the SDE is on a downward trend, reaching a minimum in 2021 (8.86). In eastern provinces, the SDE is lower than in all regions from 2017–2021. In the central, the SDE rises only slightly in 2010–2011 and is higher than all regions in 2007–2019. In western provinces, SDE has always been at an intermediate level. In the northeast, SDE shows an upward trend in 2010–2011 and a downward trend in all other times, but in 2020–2021, SDE in the northeast is higher than in all regions.

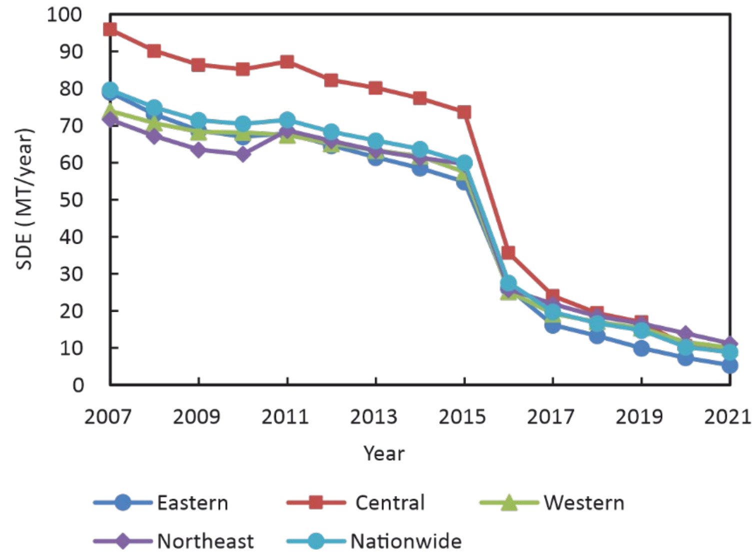

Fig. 1. Trends in SDE for different regions from 2007 to 2021

The evolution of SDE in different regions can be divided into five periods: 2007–2010, 2010–2011, 2011–2015, 2015–2016, 2016–2021. SDE in all regions showed a downward trend in the first phase. There is spatial heterogeneity in the changes in SDE in the second phase. Specifically, SDE in the western region continues its downward trend in the second phase, while the eastern, center, and northeast have risen by varying degrees. In the third phase, SDE continued to maintain a downward trend, with no significant change in the rate of decline. In the fourth phase, although SDE is still in a downward trend, the rate of decline reached its maximum during the inspection period. In the fifth phase, SDE continued to maintain a stable decline and reached its minimum value during the inspection period in 2021.

SDE distribution is spatially heterogeneous, and its characteristics vary from region to region. Figure 2 shows a box-line plot of the spatial distribution of SDEs. The degree of SDE discretization is not consistent across different regions. Specifically, the range in eastern provinces is the largest, with both the maximum (182.74 Mt) and minimum (0.14 Mt) SDE values in China, with the highest degree of dispersion. Central China has outliers, while the northeast has the smallest degree of dispersion and the most concentrated data distribution.

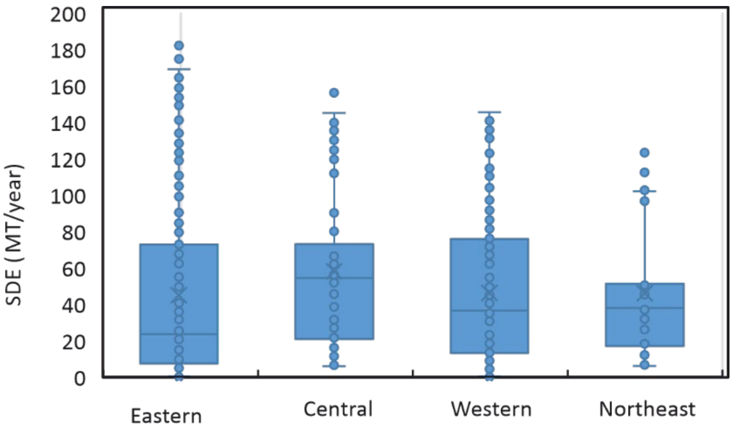

Fig. 2. Spatial distribution of SDE

In terms of air pollution severity, central provinces had the highest mean SDE (58.29 Mt) and central provinces had the most severe air pollution. This was followed by western (46.30 Mt/year) and then northeast provinces (46.10 Mt/year). Eastern provinces had the lowestern mean SDE (44.89 Mt/year) and the lowestern air pollution level.

3.2. GTWR MODEL EVALUATION

In the GTWR model, one can obtain regression coefficients of influencing factors under different time and space conditions. Considering the uneven urban development in China, the GTWR model is applied to explore the spatiotemporal distribution of the impact of urban development on air pollution. By comparing the fitting effects of ordinary least squares (OLS), TWR, and GWR, it is demonstrated that the GTWR model has high accuracy and applicability in analyzing the impact mechanism of air pollution in China. Specifically, the adjusted R-squared values for OLS, TWR, and GWR are 0.42, 0.62, and 0.80, respectively, while the adjusted R-squared values for GTWR are 0.94. In summary, the GTWR model outperforms other models in analyzing the influencing factors of spatiotemporal heterogeneity.

Figure 3 shows the evaluation plot of the GTWR model, where the mean value of the SDE is calculated in chronological order to visualize the fitted and observed values.

As shown in Fig. 3a, the observed data have a high degree of fit with the model fitting values, and except for a few ones, the accuracy of the model fitting is high. Figure 3b shows the model error diagram. The model fitting error is distributed around 0. Therefore, combined with the adjusted *R*-squared sum model effect map, the GTWR model achieved good results in its application in this study.

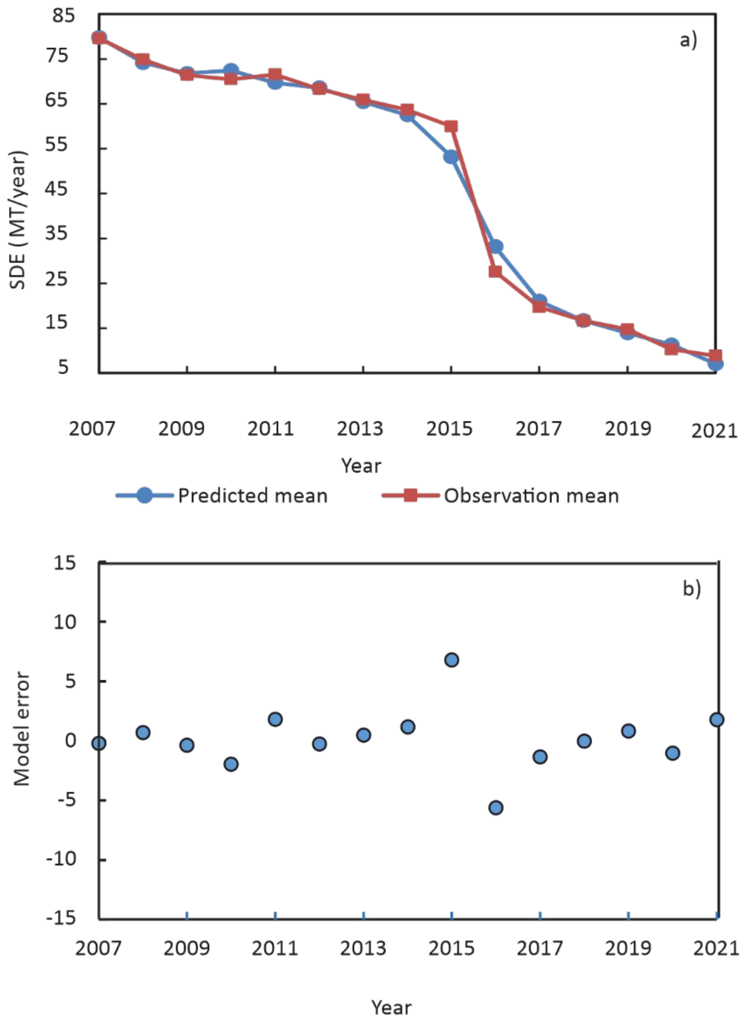

Fig. 3. Model evaluation: a) fitting effect, b) average residual

3.3. SPATIOTEMPORAL DISTRIBUTION OF FACTORS AFFECTING AIR POLLUTION

Table 3 presents descriptive statistics of the regression coefficient estimation results calculated by the GTWR. For example, from an average perspective, UGSA, UPD, and

DWRV have a positive impact on air pollution, while UR, URI, and PTV have a negative one. From the values of the regression coefficients, the minimum value of the coefficients for each variable is negative, and the maximum value is positive. Therefore, it is necessary to further investigate the spatiotemporal differences in the impact of urban development on SDE.

Table 3

Description statistics of GTWR results

Variable	Min	Q_1	Median	Mean	Q_3	Max
Intercept	–862.41	19.96	56.83	63.17	113.48	279.50
UGSA	–3018.33	–24.32	39.70	123.38	126.97	9257.43
UR	–13714.50	–89.84	–28.31	–94.82	18.87	910.96
UPD	–275.28	–30.11	0.98	5.06	36.30	800.60
DWRV	–910.24	–12.88	71.78	265.82	243.32	30401.30
URI	–1274.62	–179.54	–56.17	–60.06	–6.62	9248.33
PTV	–937.76	–79.31	–19.41	–43.20	5.81	804.94

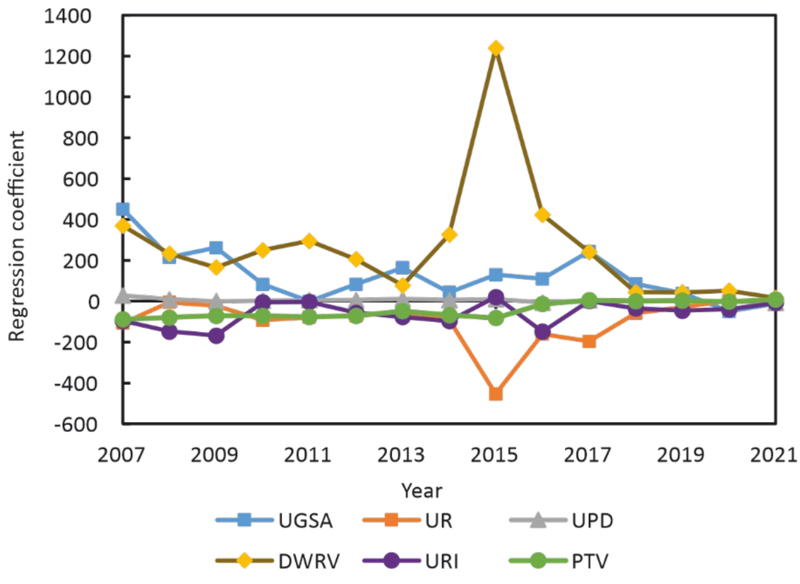

Fig. 4. Temporal evolution of the impact of urban development on SDE

Figure 4 shows the temporal evolution trend of the impact of urban development on air pollution. The vertical axis of Fig. 4 represents the regression coefficients, i.e., the direction and magnitude of the effect of each indicator on SDE. Overall, the impact of different urban development indicators fluctuates. Specifically, the larger fluctuations are in the DWRV, UR, and USGA, and the impact of the DWRV on the SDE is consistently positive, with the largest (1239.21) impact in 2015. The impact of UR on SDE in

2020 was positive (2.87), and the impact was negative for the rest of the time. On the contrary, USGA only hurt SDE in 2011 (–0.53) and 2020–2021 (–48.74, –11.10), with a positive impact at other times, and had the greatest (450.39) impact in 2007. The impact direction of UPD, URI, and PTV on SDE has changed multiple times, but their fluctuation amplitude is relatively small. Therefore, there is a strong temporal heterogeneity in the direction and magnitude of the impact of urban development on SDE.

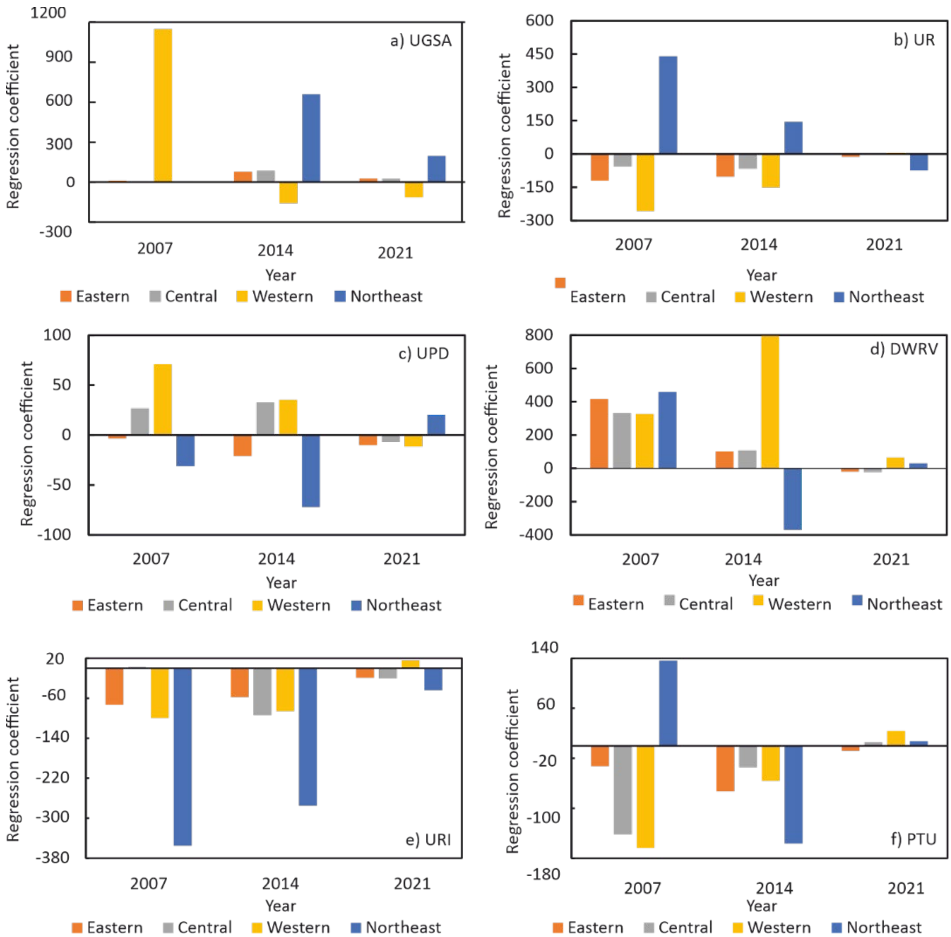

Fig. 5. The impact of urban development on SDE

The regression coefficients in Fig. 5 reflect the magnitude and direction of the impact of urban development variables on SDE in 2007, 2014, and 2021. As shown in Fig. 5a, USGA had a positive impact on SDE in different regions in 2007, while exhibiting regional heterogeneity in 2014 and 2021. For eastern, central, and northeast provinces, the impact of USGA on SDE has always been positive, being relatively small in 2007.

In western provinces, the impact of USGA on SDE turned negative in 2014 and remained small but negative in 2021. It shows that in eastern, central, and northeast provinces, reducing air pollution by increasing the area of urban greening is no longer the main means, while for western provinces, increasing urban greening can effectively improve air quality.

The effect of USGA on SDE is spatially heterogeneous. One possible explanation is the diversification of urban landscapes and the inconsistent process of urban greening construction in different regions of China. The urban greening area in the western region is insufficient, and the air cannot be effectively purified. Therefore, strengthening urban greening in the western region can effectively reduce air pollution.

As shown in Fig. 5b, the impact of UR on air pollution exhibits strong spatial heterogeneity. For example, in eastern and central provinces, the effect of UR on SDE is consistently negative and becomes smaller. In western and northeast provinces, the direction of UR impacts on SDE changes in 2021. Specifically, in 2007 and 2014, the impact of UR on SDE was negative in western provinces and positive in northeast provinces. In 2021, the impact of UR on SDE turned positive in the western and negative in the northeast provinces.

UR reflects the level of urbanization, which is often promoted at the expense of ecological damage. However, the higher the level of urbanization, to a certain extent, means that the entire urban management system is more perfect and standardized. In eastern, central, and northeast provinces, attention should be paid to changes in air quality in the promotion of urbanization, to avoid exacerbating air pollution as a result of increased levels of urbanization. In western provinces, in the process of promoting urbanization, attention should be paid to air quality, and supporting policies for air pollution control should be formulated to balance the relationship between urbanization and air quality.

In eastern provinces, the impact of UPD on SDE is always negative (Fig. 5c). In central, and western provinces, the impact of UPD on SDE was positive in 2007 and 2014 and turned negative in 2021. Conversely, in the northeast, the impacts are negative in 2007 and 2014 and turn positive in 2021.

UPD reflects urban population density. In northeast provinces, increased population density exacerbates air pollution. Considering the link between population and air, it has been demonstrated in the previous literature that an increase in population will bring about a certain amount of environmental stress. The results indicate that eastern, central, and western provinces are better at preventing air pollution accordingly, despite the increase in population. Therefore, northeast provinces should formulate policies for people's lives, balance the relationship between people’s lives and the ecological environment, and combat air pollution while the population grows.

The effect of DWRV on air pollution is reduced but there is spatiotemporal heterogeneity in the direction of the effect of DWRV on air pollution (Fig. 5d). In 2007, the impact of DWRV on SDE was all positive. In 2014, it turned negative in northeast provinces and remained positive in other regions. In 2021, the impact of DWRV on SDE turned negative in the eastern and central provinces, and positive in the western and northeast, and both impacts are reduced. The results show that in western and northeast provinces, disposal of domestic waste is no longer the main means of controlling pollution.

DWRV belongs to one of the governmental tools of environmental regulation. In eastern and central provinces, more household waste removal is effective in reducing air pollution. Therefore, for the eastern and central, it is recommended that government departments should make greater efforts to deal with domestic waste and increase the rate of harmless treatment of domestic waste, reducing the air pollution caused by domestic waste.

In 2007, the impact of URI on SDE was positive in the central with the smallest impact (2.66), and the impact of URI on SDE was negative in eastern, western, and northeast provinces (Fig. 5e). In 2014, the impact of URI on SDE was negative in all regions, in 2021, it turned positive in western provinces, and the impact remained negative in other regions.

URI can reflect the economic level of the region. The increase in per capita income can effectively reduce air pollution, and a higher level of regional economic development will lead to better means and management of air pollution control. In western provinces, however, URI has a positive effect on SDE in 2021, implying that increases in per capita income exacerbate air pollution. To some extent economic development needs to be at the expense of the ecological environment, the possible reason is that the western region has not synchronized its economic development with appropriate air pollution control measures. Therefore, the relationship between economic development and environmental protection should be balanced in western provinces.

As shown in Fig. 5f, the effect of PTV on SDE decreases with time, but there is spatial heterogeneity in the direction of the effect. Specifically, in eastern provinces, the impact of PTV on SDE has been negative. In central, and western provinces, the impact of PTV on SDE was negative in 2007 and 2014, became smaller in 2021, and the direction of the impact shifted to positive. In the northeast, there is a change in the impact of PTV on SDE, with a negative impact in 2014 and positive impacts in 2007 and 2021.

There is a strong link between transportation and air pollution [20–22]. PTV reflects the condition of urban public transportation, and green travel can effectively reduce air pollution. In central, western, and northeast provinces, PTV has a positive effect on SDE, indicating that combating air pollution by improving public transportation conditions is no longer the main means of combating air pollution. However, in the eastern, increasing public transportation facilities can effectively reduce air pollution. Therefore, it is important to pay attention to air pollution caused by transportation trips in the eastern region and promote green travel.

4, CONCLUSION

This study uses data from 31 provinces in China from 2007 to 2021 to analyze the impact of urban development on air pollution. The main conclusions are as follows. First, the SDE in different regions are highly consistent in time evolution and generally show a decreasing trend. However, the air pollution levels in the regions are different, and the air pollution severity is in the order of central, western, northeast, and eastern according to the order of the mean value of SDE. Second, urban development factors affect air pollution differently, with variables showing different effects at different times. For example, the larger fluctuations are in DWRV, UR, and USGA, where the effect of DWRV on SDE is always positive. the effect of UPD, URI, and PTV on SDE changes direction several times, but their fluctuations are all smaller. Third, there is strong spatial heterogeneity in the impact of urban development factors on air pollution. Specifically, the effects of USGA, UR and URI are mainly in the western, UPD in the northeast, DWRV in the eastern and central, and PTV in the east.

Based on this, the following practical recommendations are made for the different regions. In the eastern provinces, efforts should be stepped up to deal with domestic waste, improve transportation and travel conditions, and promote green travel. In the central provinces, effective treatment of domestic waste and improvement of the rate of harmless treatment of domestic waste. In the western provinces, in addition to upgrading the level of urban greening and increasing the area of urban green space. Moreover, in the course of economic development and urbanization, attention is paid to the protection of the ecological environment and to balancing the relationship between urban development and environmental protection. In the northeast, it is important to combat air pollution as the population grows while ensuring the livelihood of the people.

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