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The impact of air pollution on residents' health in China: the mediating effect of population migration

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Abstract
At present, air pollution remains a serious environmental issue with extensive attention in China. It may not only cause population outflow but also poses significant threats to residents' health. Therefore, it has become an imperative initiative to explore the impact of air pollution on the residents' health. In this paper, we map the spatial distribution of air pollution, population migration, and residents' health between 2010 and 2020 based on panel data from 31 Chinese provinces. Theoretical analysis and empirical tests are then carried out to investigate the intrinsic logical relationships between the three. The research findings demonstrate the following: (1) Air pollution not only has a direct negative impact on residents' health, but it also has an indirect impact on residents' health through the mediating effect of population migration. (2) Air pollution has a significant negative spatial spillover effect on residents' health, and neighboring residents are at greater health risk of being exposed to air pollution than local residents. (3) Economic development, environmental regulation, and their interaction term exhibit a single threshold effect on the health risk of air pollution. (4) From the perspective of regional heterogeneity, we find that the health risk of air pollution is greater in northern China and the southeast of the Hu Line. This paper provides valuable insights for promoting the implementation of the grand strategies of "Beautiful China" and "Healthy China."

Keywords Air pollution · Population migration · Residents' health · Mediating effect · Spatial spillover effect · Threshold effect

Introduction

Since the reform and opening up, the development style of "pollution for growth" at the expense of the ecological environment has made China one of the most seriously polluted countries in terms of sulfur dioxide and particulate matter (Liu et al. 2021a; Qiu et al. 2020). According to the *Bulletin on the Ecological Environment of China in 2022*, 126 out of 339 prefectural-level and above cities in 2022 are still faced with air quality problems that do not meet the standards (MEE and PRC 2022). In fact, the National Population Development Plan (2016-2030) has highlighted the need to restrict population migration, promote ecological migration in an orderly manner, and strive for an optimal balance between population, resources, and the environment (SC, and PRC, National Population Development Plan 2017). Besides, as proposed in *Opinions on Implementing Actions for a Healthy China*, effective measures ought to be taken to improve the healthy environment and prevent and control diseases associated with environmental pollution. Additionally, it is projected that by the year 2030, the health literacy level of the national population will be no less than 30% (SC, and PRC, Opinions on Implementing Healthy China Action 2019). Therefore, it can be seen that the Chinese government has realized that it exists a certain relationship between air pollution, population migration, and residents' health. This suggests that it is of great theoretical and practical significance to investigate the intrinsic logical relationships among them.

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A great deal of effort has been made in the academic community to explore the relationship between air pollution, population migration, and residents' health. Generally, the existing research can be summarized as follows. On the one hand, some scholars studied the relationship between air pollution and population migration. They found that when there is a localized deterioration in air quality, residents will pay more attention to air pollution (Chen et al. 2020b; Ji et al. 2022), and then they have a stronger willingness to migrate (Zhao et al. 2021b), so as to reduce economic losses from air pollution (Chen and Chen 2021; Sun et al. 2021), and avoid health damage (Gao et al. 2022; Schraufnagel et al. 2019). As indicated in some literature, with the increasing frequency of Internet searches on migration (Pinchas-Mizrachi et al. 2020), people eventually shift from a willingness to migrate to an active flight (Guo et al. 2022) and often to more environmentally friendly regions (Chen et al. 2022). This is particularly true among high human capital groups (Liu et al. 2021b). On the other hand, the relationship between population migration and residents' health was discussed. Previous research in this field mainly focused on the "health paradox of immigrants" (Mazhin et al. 2020), which suggests that immigrants are generally healthier than the natives, although they have lower incomes. Some scholars also proposed the "healthy immigrant hypothesis," which indicates the deviation of survivors due to the fact that only healthy individuals choose to immigrate (Constant and Milewski 2021). In addition, some studies put forward the so-called "salmon bias hypothesis". They believed that unhealthy immigrants are more likely to return to their place of origin, resulting in an impression that "immigrants are healthier than natives" (Brown 2018). These research undoubtedly provide practical insights into the connections between air pollution, population migration, and residents' health.

The previous studies have laid the foundation for our research. However, most of the existing literature primarily focused on examining the pairwise relationship between air pollution, population migration, and residents' health while largely ignore the interactions and logical connections between the three. To the best of our knowledge, there is no literature that has explored the effects and transmission mechanisms of air pollution on the residents' health based on the suppressing effect of population migration. To address these gaps, this paper attempts to investigate their intrinsic logical relationships through an in-depth theoretical analysis and empirical test. By using the panel data from 31 Chinese provinces between 2010 and 2020, this article is dedicated to addressing the following three issues:

(1) To what extent does the increasing air pollution affect residents' health, and What role does population migration play in the health risk effects of air pollution?
(2) Is there spatial heterogeneity in the health risk effects of air pollution due to regional differences in air pollution and its natural properties of dispersion?
(3) Can economic development, environmental regulation, and their efforts improve the health risk*s* of air pollution?

Through a detailed theoretical derivation and empirical test, this paper not only testifies that air pollution has adverse and negative spatial spillover effects on residents' health but also finds that the health risk of air pollution exhibits a single threshold effect and regional heterogeneity. To this end, the main contributions of this work are as follows. Firstly, we explore the direct effects of air pollution on residents' health and the indirect effects of population migration on the relationship between air pollution and residents' health. Secondly, a spatial econometric analysis is conducted to examine the spillover effects of air pollution on residents' health. Thirdly, the differential impact of air pollution on health risk is analyzed from the perspective of regional heterogeneity. Lastly, we employ a threshold regression model to determine whether the health risk of air pollution exhibits a significant threshold effect.

Theoretical analysis and research hypothesis

This paper employs Grossman's health production function analysis framework and Cropper's research theory to develop a theoretical model that incorporates air pollution, population migration, and residents' health. Firstly, we make the following assumptions:

(1) There are n cities and L residents in a region, and residents can move freely between regions.
(2) Residents' utility is derived from the positive utility of common commodities, health capital, and the negative utility of air pollution.
(3) Air pollution in region i has a direct effect on population migration, which indicates that $\boldsymbol{\partial L_i/\partial Z_i \neq 0}$.

However, air pollution in region i is not relevant to population migration in region j, implying that $\partial L_i/\partial Z_i = 0$. Since we explore only the impact of local air pollution on the health of local residents, then we have $\partial Z_j/\partial Z_i = 0$. According to the above assumptions, the direct utility function of an individual resident is given by:

$$U_i = U\left(x_i, h_i, Z_i\right), i = 0, 1, \cdots \cdots, n \tag{1}$$

For Eq. (1), x_i represents a generic good, and h_i and Z_i represent health capital and air pollution, respectively. Thus, the budget constraint is

$$y = p_x \times x_i + p_h \times h_i \tag{2}$$

With respect to Eq. (2), y represents the residents' disposable income. According to Eqs. (1) and (2), the indirect utility function of the residents in region i can be obtained by solving the maximum utility problem of the residents under budget constraints:

$$V_i = V(x_i, h_i, Z_i) \tag{3}$$

In the equilibrium state, there is no difference in the indirect utility received by residents in any region, and the equilibrium condition can be expressed as

$$V(x_i, h_i, Z_i) = V(x_j, h_j, Z_j) \tag{4}$$

Air pollution, as suggested by Cropper, significantly reduces the level of health capital, and Grossman's theory suggests that residents' health improves when residents purchase health services. As a result, the demand function for residents' health services depends on disposable income, health capital, and air pollution levels. Hence, it can be represented by this function: $f_i = f_i(y, h_i, Z_i)$. Assuming that the total supply of health services in region i is $F_i(y, h_i, Z_i)$ and that the total demand for health services in this region is $L_i \times f_i$, we can conclude that the market equilibrium condition for health services in region i can be summarized as

$$F_i(y, h_i, Z_i) = L_i \times f_i(y, h_i, Z_i) \tag{5}$$

It can be seen that the residents' health capital function in region i is composed of various variables, including disposable income, air pollution, and migrating population. Specifically, it can be expressed as $h_i = h_i(y, Z_i, L_i)$; moreover, the regional migration population function is comprised of various variables, including disposable income and air pollution. It is expressed as $L_i = L_i(y, Z_i)$.

Since $\sum_{i=1}^{N} \mathrm{L_i} = \mathrm{L}$, Eq. (5) can be rewritten as

$$\sum_{i=1}^{N} \frac{F_i(y, h_i, Z_i)}{f_i(y, h_i, Z_i)} = L \tag{6}$$

By evaluating the partial derivative of Eq. (4) with respect to Z_i, we can derive

$$\frac{\partial V}{\partial h_i}\frac{\partial h_i}{\partial Z_i} + \frac{\partial V}{\partial Z_i} = \frac{\partial V}{\partial h_j}\frac{\partial h_j}{\partial Z_i} \tag{7}$$

The marginal rate of substitution (MRS) of air pollution in region i to disposable income per capita is described as $MRS_i = \frac{\partial V/\partial Z_i}{\partial V/\partial y}$. According to Roy's inequality, it can be concluded that $f_i = -\frac{\partial V}{\partial h_i}\frac{\partial h_i}{\partial Z_i}$ and $f_j = -\frac{\partial V}{\partial h_j}\frac{\partial h_j}{\partial Z_i}$, which can be incorporated into Eq. (7). Then we can derive the subsequent expressions as follows:

$$-h_i \times \frac{\partial h_i}{\partial Z_i} + h_j \times \frac{\partial h_i}{\partial Z_i} = -MRS_i \tag{8}$$

By evaluating the partial derivative of Eq. (6) with respect to Z_i, we can derive

$$\frac{\partial \frac{F_i}{f_i}}{\partial h_i}\frac{\partial h_i}{\partial Z_i} + \frac{\partial \frac{F_i}{f_i}}{\partial Z_i} + \sum_{j \neq i} \frac{\partial \frac{F_j}{f_j}}{\partial h_j}\frac{\partial h_j}{\partial Z_i} = 0 \tag{9}$$

We introduce the price elasticity of supply $\eta_i^S = \frac{\partial F_i}{\partial h_i} \times \frac{h_i}{F_i}$ and demand $\eta_i^D = \frac{\partial f_i}{\partial h_i} \times \frac{h_i}{f_i}$ for health services of residents, and then substitute them into Eq. (9). Thus, we have

$$\frac{L_i}{h_i} \times (\eta_i^S - \eta_i^D) \times \frac{\partial h_i}{\partial Z_i} + \sum_{j \neq i} \frac{L_j}{h_j} \times \left(\eta_j^S - \eta_j^D\right) \times \frac{\partial h_j}{\partial Z_i} + \frac{\partial L_i}{\partial Z_i} = 0 \tag{10}$$

By integrating Eqs. (8) and (10), the following result can be derived:

$$\frac{\partial h_i}{\partial Z_i} = \frac{\sum_{j \neq i} \left[(L_j/h_j) \times \left(\eta_j^S - \eta_j^D\right)/f_j\right] \times MRS_i - \partial L_i/\partial Z_i}{L_i \times (\eta_i^S - \eta_i^D)/h_i + \sum_{j \neq i} \left[(L_j/h_j) \times \left(\eta_j^S - \eta_j^D\right)/f_j\right] \times f_i} \tag{11}$$

Let $\Omega = \sum_{j \neq i} (L_j/h_j) \times \left(\eta_j^S - \eta_j^D\right)/f_j$, since $\eta_j^S > 0$, $\eta_j^D < 0$, $L_j > 0$, $f_j > 0$, $h_j > 0$, then we have $\Omega > 0$, $L_i \times \left(\eta_i^S - \eta_i^D\right)/h_i + \Omega \times f_i > 0$. Accordingly, the following conclusion can be summarized if there exists $\partial L_i/\partial Z_i > \Omega \times MRS_i$, and we can derive the result as follows:

$$\frac{\partial h_i}{\partial Z_i} = \frac{\Omega \times MRS_i - \partial L_i/\partial Z_i}{L_i \times \left(\eta_i^S - \eta_i^D\right)/h_i + \Omega \times f_i} < 0 \tag{12}$$

This suggests that air pollution has a negative impact on residents' health when it is a relatively large driver of population migration.

In addition, by solving the partial derivative of Eq. (4) with respect to L_i, the following results can be obtained:

$$\frac{\partial V}{\partial h_i}\frac{\partial h_i}{\partial L_i} + \frac{\partial V}{\partial Z_i}\frac{\partial Z_i}{\partial L_i} = \frac{\partial V}{\partial \mathrm{h}}\frac{\partial h_j}{\partial L_i} \tag{13}$$

Following the conceptual framework of the Marginal Rate of Substitution (MRS) and Roy's Inequality, Eq. (13) can be simplified as

$$\left[-f_i \times \frac{\partial h_i}{\partial L_i} + f_j \times \frac{\partial h_j}{\partial L_i}\right] \times \frac{\partial L_i}{\partial Z_i} = -MRS_i \tag{14}$$

We can obtain the following result by solving the partial derivative of Eq. (4) with respect to L_i:

$$\frac{\partial \frac{F_i}{f_i}}{\partial h_i}\frac{\partial h_i}{\partial L_i} + \frac{\partial \frac{F_i}{f_i}}{\partial Z_i}\frac{\partial Z_i}{\partial L_i} + \sum_{j \neq i} \frac{\partial \frac{F_j}{f_j}}{\partial h_j}\frac{\partial h_j}{\partial L_i} = 0 \quad (15)$$

According to the definition of price elasticity of supply and demand related to health services for residents, we can derive a conclusion from Eq. (15):

$$\frac{L_i}{h_i} \times \left(\eta_i^S - \eta_i^D\right) \times \frac{\partial h_i}{\partial L_i} + \sum_{j \neq i} \frac{L_j}{h_j} \times \left(\eta_j^S - \eta_j^D\right) \times \frac{\partial h_j}{\partial L_i} + 1 = 0 \quad (16)$$

By integrating Eqs. (14) and (16), the following results can be derived:

If there exists $\partial L_i/\partial Z_i > \Omega \times MRS_i$, we have

$$\frac{\partial h_i}{\partial L_i} = \frac{\Omega \times MRS_i / \left(\partial L_i/\partial Z_i\right) - 1}{L_i \times \left(\eta_i^S - \eta_i^D\right)/h_i + \Omega \times f_i} < 0 \quad (17)$$

This suggests that when air pollution induces population migration, resulting in a decline in residents' overall health conditions. We propose *hypothesis 1: Air pollution adversely impacts residents' health. In addition, population migration has a suppressing effect and increases the health risk of air pollution.*

Due to its diffusive nature, air pollution can move across regions via a process known as advection transportation. This movement is largely influenced by the direction and speed of prevailing winds (Brattich et al. 2020; Lin et al. 2021). As a result, the surrounding region is expected to experience a deterioration in air quality (Shah et al. 2019; Song et al. 2022). In addition, air pollution may be spread through transmission resulting from the production activities of the "three-high" industries (Tan et al. 2022). Accordingly, we propose *hypothesis 2: The adverse impact of air pollution on residents' health has a spatial spillover effect.*

Given the different regional disparities in economic development and environmental regulation across Chinese provinces, air pollution will inevitably affect residents' health to varying degrees (Feng et al. 2020; Xiao et al. 2022). The "Inverted U" hypothesis of the Environmental Kuznets Curve suggests that we are currently standing at a stage of economic development that precedes the turning point, which means that the extensive overuse of the city's central region has significantly disrupted the urban ecological balance (Gan et al. 2021), the increase in air pollution contributes significantly to the increased health risk of residents (Liu and Pei 2019; Yuan et al. 2015). Meanwhile, residents' current environmental consciousness is insufficiently robust, and this lack of awareness often results in diminishing enthusiasm to engage in environmental conservation efforts. In some unfortunate cases, some residents may even inadvertently cause environmental degradation, thereby undermining the potential health benefits derived from environmental regulations (Kuang et al. 2022; Wang et al. 2021b; Zhao et al. 2021a). Accordingly, we propose *hypothesis 3: Economic development, environmental regulation, and their interaction term serve as critical thresholds for assessing the severity of the adverse effects of air pollution on residents' health.*

Material and methods

Exploratory spatial analysis method

To intuitively capture the temporal and spatial distribution characteristics of air pollution, population migration, and residents' health, we divide the distribution areas into five grades according to Jenks, which include the lowest distribution area, the lower distribution area, the middle distribution area, the higher distribution area, and the highest distribution area. Then, we utilize ArcGIS software to create a map that depicts both temporal and spatial distribution characteristics of air pollution, population migration, and residents' health, as shown in Fig. 1:

As indicated in Fig. 1(a) and (b), the temporal distribution of severe air pollution in 2010 and 2020 was mainly concentrated in Xinjiang, Shandong, Henan, and Bohai Economic Circle. In contrast, Tibet and Qinghai are the least polluted regions during this period (Han et al. 2023; Zhou et al. 2021), which is basically consistent with the conclusions presented in the World Air Quality Report 2020.

According to Fig. 1(c) and (d), we find that Beijing, Shanghai, Guangzhou, and other coastal cities experienced significant population inflows during the same period. On the contrary, the overall inflow to the Central and Western regions of China decreased, indicating a more significant population decline. This is mainly due to the unbalanced economic development of different regions and economies in China, as the eastern coastal cities exert a significant population siphon effect. These cities have a large number of employment opportunities and promising development prospects and are known for their rich educational resources and well-developed infrastructure (Lyu and Jiang 2022).

Correspondingly, residents' health, as illustrated in Fig. 1(e) and (f), reflects the distribution pattern of population migration. The highest level of health is observed along the east coast of China compared to the west coast. This discrepancy can be attributed to the dense concentration of medical and healthcare resources in the eastern coast region, which facilitates superior provision of healthcare services to residents (Wu and Yang 2019).

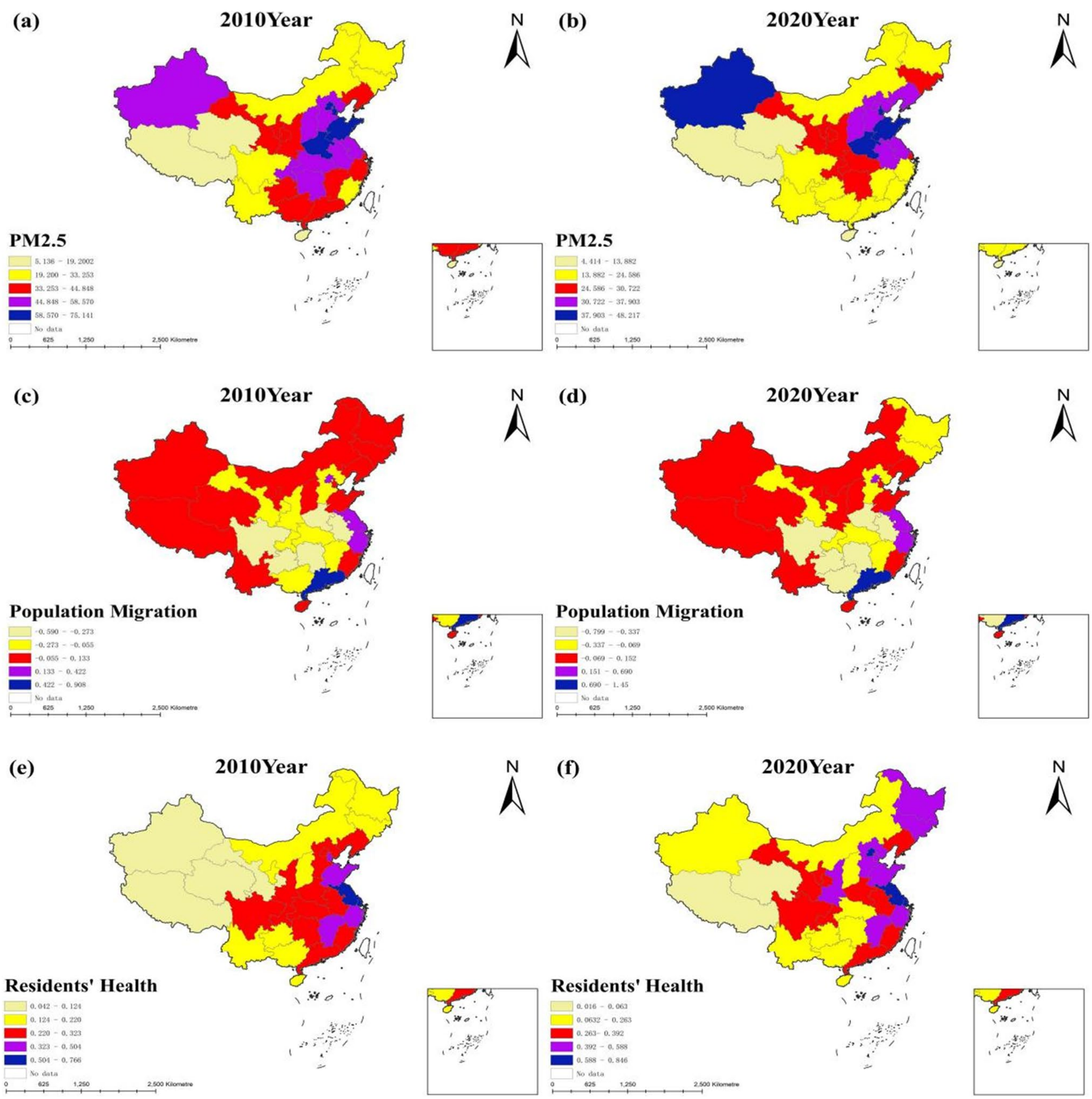

Fig. 1 **a**–**f** Spatial distribution of air pollution, population migration, and residents' health in China in 2010 and 2020. *Note: Those maps are based on the standard map with the approval number of GS (2019) 1822 downloaded from the standard map service website of the Ministry of Natural Resources, and the base maps have not been modified*

Model development

In this paper, the comprehensive multimetric models are constructed and delineated as follows:

$$H_{it} = \alpha_0 + \alpha_1 \ln PM_{2.5it} + \alpha_2 Controls + \lambda_i + \delta_t + \varepsilon_{it} \tag{18}$$

$$L_{it} = \beta_0 + \beta_1 \ln PM_{2.5it} + \beta_2 Controls + \lambda_i + \delta_t + \varepsilon_{it} \tag{19}$$

$$H_{it} = \gamma_0 + \gamma_1 \ln PM_{2.5it} + \gamma_2 L_{it} + \gamma_3 Controls + \lambda_i + \delta_t + \varepsilon_{it} \tag{20}$$

$$H_{it} = \rho_0 + \rho_1 W_1 H_{it} + \rho_2 \ln PM_{2.5it} + \rho_3 \sum_{j=1}^{N} W_{jt} \ln PM_{2.5it} + \rho_4 Controls + \lambda_i + \delta_t + \varepsilon_{it} \tag{21}$$

$$H_{it} = \delta_0 + \delta_1 \ln PM_{2.5it} \times I(q_{i,t} \le T) + \delta_2 \ln PM_{2.5it} \times I(q_{i,t} > T) + \delta_3 Controls + \lambda_i + \delta_t + \varepsilon_{it} \tag{22}$$

The mediating model is constructed based on Eqs. (18), (19), and (20), which correspond to Model 1, Model 2, and Model 3 in Table 2, respectively. In addition, Eq. (18) represents the two-way fixed effect, and Eq. (21) describes the spatial econometric model. The corresponding regression result is Model 12 in Table 5. Equation (22) represents the threshold model, and its regression result is Model 13 in Table 6. In the above comprehensive multimetric models, i represents a province, t represents a year, the explained variable H_{it} represents residents' health, and the explanatory variable $lnPM_{2.5}$ represents air pollution, *Controls* represents a set of control variables, λ_i represents the regional fixed effect, δ_t represents the time-fixed effect, and ε_{it} represents the random disturbance term.

Variables setting and data sources

In this section, we describe the explained variable, explanatory variable, mediating variable, threshold variables, control variables, and their data source for the models proposed in this paper, as shown in Table 1.

Table 2 The direct effect of air pollution on residents' health and the mediating effect of population migration

Variables	Model 1 H Coefficient(Se)	Model 2 L Coefficient(Se)	Model 3 H Coefficient(Se)
$\ln PM_{2.5}$	-0.184^{***}(0.047)	0.028^{*}(0.016)	-0.174^{***}(0.047)
L			-0.376^{**}(0.169)
Constant	4.219^{***}(1.240)	−0.308(0.425)	4.104^{***}(1.233)
Control Variables	Yes	Yes	Yes
Province	Yes	Yes	Yes
Year	Yes	Yes	Yes
Observation	341	341	341

Note: Standard errors are presented in parentheses, and significance levels are indicated as follows: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. The same is true below

Result

Benchmark regression and mediating mechanism test

The direct impact of air pollution on residents' health is assessed according to Eq. (18), and the regression results are presented in Table 2. Model 1 demonstrates the coefficient value of $lnPM_{2.5}$ is significantly negative at a level of 10%; with each unit increase in $lnPM_{2.5}$, H_{it} decreases by 0.184 units.

Equations (18), (19), and (20) are employed to assess the indirect impact of population migration on the health risks of air pollution, serving as a mediating variable. Based on

Table 1 Description of all variables

Variable type	Variable	Sign	Data source
Explained variable	Residents' health	H	China Health Statistics Yearbook
Explanatory variable	Air pollution	$\ln PM_{2.5}$	Columbia University International Geoscience Information Network Center
Mediating variable	Population migration	L	China statistical yearbook
Threshold variables	Actual GDP	lnActgdp	China Statistical Yearbook; China Environmental Statistics Yearbook
	Environmental Regulation	Er	
	Interaction	lnActgdp*Er	
Control variables	Human Capital Stock	Peredu	China Educational Statistics Yearbook; China Statistical Yearbook; China Health Statistics Yearbook
	Education input	Czedczb	
	Social medical coverage	Medinsurezb	
	Internet penetration rate	Internet	
	Unemployment rate	Unemploy	
	Actual GDP per capita	lnActpergdp	

Note: The explanatory variable is residents' health, which is calculated using the entropy weighting method based on the inverse of maternal mortality, perinatal mortality, and the incidence of infectious diseases the results derived from Model 2, the coefficient value of air pollution is 0.028, which passes the test at a level of 10%. It demonstrates that as air pollution increases in a certain region, residents increasingly prioritize seeking healthier living conditions to mitigate the health risk of air pollution. Consequently, air pollution emerges as a significant driving factor for population migration.

In Model 3, the coefficients γ_1 and γ_2 correspond to air pollution and population migration respectively, their coefficient values are −0.174 and −0.376, which have passed the significance test at a level of 5%. It suggests that air pollution affects residents' health through the mediating variable of population migration, which only partially contributes to the mediating effect, accounting for 6% of the total effect. Consequently, the hypothesis 1 proposed in this paper is empirically supported.

Robustness test

To ascertain the validity of the above estimation results, this paper employs the System GMM and substitution of key variables estimation method for the robustness test, as depicted in Table 3.

(1) *System GMM*. To address the issue of endogeneity, we employed System GMM for regression estimation, the corresponding results can be found in Table 3: The results derived from the Arellano-Bond dynamic panel data test highlight a significant p-value relative to the *AR(1)* series, while exhibiting an insignificant p-value in response to the *AR(2)* series. This implies the absence of second-order autocorrelation within the stochastic disturbance term. In addition, the p-value of *Sagan* test is greater than 0.1, confirming the validity of the instrumental variables chosen in this paper. The coefficient value of $lnPM_{2.5}$ is −0.147, which successfully meets the criterion under the 5% significance level test. This result from Model 4 is in line with the results obtained from the benchmark regression estimation.

(2) *Substitution of key variables*. Given the wide range of pollutants that can be utilized to access air quality, including but not limited to $PM_{2.5}$, PM_{10}, SO_2, and NO_2 (Chen et al. 2023). In this paper, $lnPM_{10}$, $lnSO_2$, and $lnNO_2$ are used as explanatory factors for air pollution, replacing the variable $lnPM_{2.5}$, and the Principal Component Analysis is adopted to estimate the residents' health (*Hpca*), which acts as the explained variable in this paper. The empirical findings derived from Models 5–7 remain valid according to the current analysis.

Heterogeneity analysis

In this paper, we conduct regional heterogeneity analysis based on the division of regions along southern and northern China and the Hu lines. Table 4 shows that there is a significant difference in air pollution levels between the two regions. In Model 8, the coefficient value of air pollution

Table 3 Results of robustness analysis

Variables	Model 4 H Coefficient(Se)	Model 5 Hpca Coefficient(Se)	Model 6 Hpca Coefficient(Se)	Model 7 Hpca Coefficient(Se)
L.H	0.951^{***}(0.050)			
$lnPM_{2.5}$	-0.147^{**}(0.061)			
$lnPM_{10}$		-1.239^{**}(0.560)		
$lnSO_2$			-0.408^{***}(0.061)	
$lnNO_2$				-0.589^{***}(0.150)
Constant	0.463^{*}(0.239)	14.030^{**}(6.629)	16.603^{***}(5.993)	20.418^{***}(6.296)
Sargan *P* value	0.304			
AR(1) *P* value	0.010			
AR(2) *P* value	0.841			
Control Variables	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
Observation	341	341	341	341

Note: Standard errors are presented in parentheses, and significance levels are indicated as follows: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Hpca is a proxy variable for residents' health, which is calculated using the principal component analysis method based on the inverse of maternal mortality, perinatal mortality, and the incidence of infectious diseases

Table 4 Results of regional heterogeneity analysis

Variables	Model 8	Model 9	Model 10	Model 11
	H	H	H	H
	Coefficient(Se)	Coefficient(Se)	Coefficient(Se)	Coefficient(Se)
$\ln PM_{2.5}$	-0.227^{***}(0.065)	-0.218^{***} (0.068)	-0.209^{***} (0.060)	−0.050(0.101)
Constant	0.775 (1.963)	2.351 (1.973)	4.231^{**}(1.406)	6.333^{**}(2.750)
Control Variables	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
Observation	143	198	275	66

Note: Standard errors are presented in parentheses, and significance levels are indicated as follows: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

for northern China is -0.227, and it is −0.218 for southern China in Model 9. Both of them pass the significance test at a level of 10%. This phenomenon might be attributed to the fact that northern China is more densely industrialized than the south. Besides, the cold winter in northern China relies heavily on coal-fired heating, which leads to large amounts of air pollutant emissions (Zhang et al. 2021).

Considering the regional disparities observed on both sides of the Hu Line, the coefficient value of air pollution on the southeast side of the Hu Line in Model 10 is -0.209, passing the significance test at a level of 1%. However, the coefficient value of air pollution on the northwest side of the Hu Line is −0.050 in Model 11, failing to pass the significance test. In essence, the southeast side of the Hu Line, unlike the northwest side, represents a densely populated region in China, accounting for more than 90% of the total population. Higher population density naturally leads to increased traffic, energy demand, productivity, and daily activities. Together, these factors contribute to energy consumption and an escalation in air pollution, thereby exacerbating air quality degradation (Chen et al. 2020a).

Spatial spillover effect

After successfully passing the spatial correlation test, a two-way fixed spatial durbin model was established on

Table 5 Results of spatial dobbin model regression

Variables	Model 12			
	SDM	LR_Direct	LR_Indirect	LR_Total
	H	H	H	H
	Coefficient(Se)	Coefficient(Se)	Coefficient(Se)	Coefficient(Se)
$\ln PM_{2.5}$	-0.204^{***}(0.043)	-0.206^{***}(0.044)	-0.312^{***}(0.115)	-0.518^{***}(0.116)
$W^*\ln PM_{2.5}$	-0.176^{*}(0.102)			
rho	0.253^{**}(0.128)			
sigma2_e	0.004^{***}(0.000)			
LM (lag) test	60.871^{***}			
Robust LM (lag) test	15.191^{***}			
LM (error) test	75.211^{***}			
Robust LM (error) test	29.532^{***}			
Hausman	-9.41^{***}			
Log-likelihood	460.630			
AIC	−889.26			
BIC	−827.9499			
Control Variables	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
Observation	341	341	341	341

Note: Standard errors are presented in parentheses, and significance levels are indicated as follows: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

the basis of criteria such as the Akaike Information Criterion (AIC), Bayesian Information Criterion (BIC), Likelihood Ratio (LR) test, Lagrange Multiplier (LM) test, and the Hausman test. An estimation is then carried out, the results of which are presented in Table 5. It should be noted that Eq. (21) signifies Model 13, and the spatial autoregressive coefficient *rho* is −0.204, which passes the significance test at a level of 5%. This indicates that the health risks of air pollution have a spatial spillover effect. This means that the impact of air pollution extends beyond the local boundaries. It not only affects local residents' health, but also has significant impacts on neighboring residents' health.

Regarding the impact of air pollution on residents' health from the perspective of the decomposition effect, we find that the coefficient value of air pollution on the local residents' health is −0.206. Meanwhile, the coefficient value of air pollution on the neighboring residents' health is −0.312, and both of them have passed the significance test at a level of 1%.

The observation reveals that neighboring residents' health tends to be more adversely impacted by air pollution than local residents' health. It remains plausible that local residents have developed a heightened awareness of the prevalent problem of air pollution. Consequently, this increased awareness could stimulate an increase in the purchase of face masks and air purifiers (Sun et al. 2017; Zhang and Mu 2018), and domestic corporations are also encouraged by the local authorities to escalate their research and development of environment-friendly technologies (Sun et al. 2022). The above evidence supports hypothesis 2 of this paper.

Threshold effect

Having successfully passed the threshold effect test, the estimations presented in Table 6 are then obtained by using Eq. (22). In terms of economic development, the coefficient value of $lnPM_{2.5}$ is −0.186 when $lnActgdp \leq 11.165$, and when $lnActgdp > 11.165$, the coefficient value of $lnPM_{2.5}$ is −0.232. Both of those coefficients are significant at the 1% level. As the Chinese economy develops, it is expected that energy consumption will escalate and exceed the carrying capacity of the regional environment. Consequently, this could lead to increased levels of air pollution, posing significant health risks to the population (Feng and Wang 2021).

In terms of environmental regulation, it can be observed that when $Er \leq 0.476$, the coefficient value of $lnPM_{2.5}$ is −0.081 when $Er > 0.476$, the coefficient value of $lnPM_{2.5}$ is -0.149, both of those coefficients are significant at the 10% level. This result may be attributed to the insufficient proactive engagement of local residents or social groups in cultivating environmental awareness. Their behavior, which sometimes extends to environmental degradation, undermines the potential health and welfare benefits from environmental regulation (Feng et al. 2023).

Regarding the complex interaction between economic growth and environmental regulation, it can be observed that when $lnPgdp{*}Er \leq 0.002$, the coefficient value of $lnPM_{2.5}$ is -0.091, and when $lnPgdp{*}Er > 0.002$, the coefficient value of $lnPM_{2.5}$ is −0.149, both of those coefficients are significant at the 10% level. This suggests that some polluting enterprises may engage in irresponsible environmental practices and circumvent environmental regulations to pursue economic interests as a result of local governments

Table 6 Results of threshold effect regression

Variables	Model 13		
	H	H	H
	Coefficient(Se)	Coefficient(Se)	Coefficient(Se)
$lnPM_{2.5}$ (lnActgdp≤11.165)	−0.186***(0.043)		
$lnPM_{2.5}$ (lnActgdp>11.165)	−0.232***(0.043)		
$lnPM_{2.5}$ (Er≤0.476)		−0.081*(0.046)	
$lnPM_{2.5}$ (Er>0.476)		−0.149***(0.044)	
$lnPM_{2.5}$ (lnActgdp*Er≤0.002)			−0.091*(0.049)
$lnPM_{2.5}$ (lnActgdp*Er>0.002)			−0.149***(0.046)
Constant	4.169***(1.139)	3.419***(1.164)	3.710***(1.202)
Control Variables	Yes	Yes	Yes
Province	Yes	Yes	Yes
Year	Yes	Yes	Yes
Observation	341	341	341

Note: Standard errors are presented in parentheses, and significance levels are indicated as follows: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

relaxing environmental protection requirements in order to attract investment and foster economic development. Such actions ultimately undermine the effectiveness of environmental regulations (Wang et al. 2021a). The above conclusion is consistent with hypothesis 3.

Discussion

To explore the mechanism of the impact of air pollution on residents' health, this paper not only analyses the direct impact of air pollution on residents' health from the perspective of epidemiology but also explores the indirect impact of air pollution on residents' health through the mediating perspective of population migration. Our findings confirm the existing literature by demonstrating a consistent decline in residents' health of 0.184% for every 1% increase in air pollution (Palma et al. 2022; Schraufnagel et al. 2019; Usmani et al. 2020). This is because air pollution contributes to increased health risks, particularly cardiovascular and respiratory diseases, and even prolonged exposure to polluted air significantly increases the likelihood of illness and mortality. Furthermore, air pollution also has an indirect impact on residents' health through population migration, accounting for approximately 6% of the total effect. Our findings are inconsistent with existing research that suggests that air pollution directly causes deterioration in the health of the population, which thereby triggers population migration (Chen et al. 2022; Guo et al. 2022; Ma et al. 2023). This is because residents living in heavily polluted areas are exposed to higher health risks, which may prompt them to choose to relocate to areas with better air quality for the sake of their own and their families' health. For areas undergoing out-migration, this can alter the distribution of health services and resources, leaving residents with less access to health services and resulting in poorer health outcomes. For areas undergoing in-migration, the substantial arrival of people may surpass the capacity of current public services and infrastructure in the receiving area, resulting in insufficient resources and overburdened facilities. Furthermore, the influx can introduce novel viruses and pathways for disease transmission, thereby endangering public health.

To explore the potential impact of air pollution on the health of residents in neighbouring regions, this paper investigates the spatial spillover effects of air pollution on residents' health from the perspective of air pollution mobility. Our findings reveal that local air pollution not only detrimentally affects residents' health but also exerts a greater negative impact on residents' health in the neighborhood. These findings are generally consistent with the existing literature (Feng et al. 2019; Peng et al. 2021; Zhang et al. 2022). This phenomenon is due to the fact that air pollutants can be transported from source areas to neighborhoods through diffusion and transport processes. This process is influenced by a number of factors, including meteorological conditions, topography and human activities. Certain air pollutants undergo chemical reactions when they are released into the atmosphere, giving rise to what is referred to as secondary pollutants. The formation mechanisms of these secondary pollutants are complex and diverse, often involving photochemical reactions, redox reactions, and free radical reactions, which ultimately contribute to the formation of secondary air pollutants. In addition to the natural attributes of air pollution dispersion pathways, such as atmospheric circulation, the residents' health in the neighborhood can also be adversely affected by the relocation of polluting industries to adjacent areas. In addition, local residents and governments may be more sensitive to local pollution problems and take various measures to deal with them, such as indoor air purification, personal protective measures (e.g., wearing masks), and upgrading medical and health facilities. In contrast, the residents neighboring areas may be less aware of the protective measures against such pollution and are, therefore, more affected.

To explore whether there are differences in the health risk effects of air pollution in different regions, this paper analyses the health risk effects of air pollution in northern and southern China as well as on both sides of the Hu Line, aiming to identify regional heterogeneity. Our findings reveal that air pollution in northern China and on both sides of the Hu Line has a greater impact on residents' health (Chang and Zou 2022; Xu et al. 2022a; Zhou et al. 2021; Zhu et al. 2022). This phenomenon can be attributed to geographical and climatic factors. In northern China, where low winter temperatures prevail, coal-fired central heating is commonly used, leading to the generation of substantial quantities of detrimental pollutants, including particulate matter (e.g., PM2.5 and PM10) and sulfur oxides, and because of the inversions that often occur in winter, pollutants accumulate in the lower atmosphere and are difficult to diffuse, thus exacerbating the level of air pollution. In contrast to the southern region, the industrial structure in northern China is more reliant on heavy industry, including high-emission industries like iron and steel, building materials, chemicals and coal-fired power plants. Emissions from these industries seriously impact air quality, and the northern provinces are also China's main energy suppliers, with the coal-fired industries in particular having a significant impact on local air quality. In addition, the southeastern side of the Hu Line is located in densely populated areas of China, where high population density leads to increased motor vehicle density, demand for energy consumption, and industrial production activities, which generate large amounts of pollutants.

Overurbanization in these areas has contributed to air pollution, including increased motor vehicle emissions due to the expansion of transport networks and increased dust pollutants in the atmosphere caused due to large-scale construction. In addition, the reduction of ecosystem services, such as the reduction of urban green spaces, further weakens the ability of the urban environment to cleanse itself of pollutants.

To explore the various influences on the health risk effects of air pollution, this paper analyses the threshold effect of air pollution on residents' health from the perspective of economic development and environmental regulation. We find that economic development and environmental regulation in China exacerbate the health risks of air pollution. This view is contrary to existing research (Feng et al. 2020; Wang et al. 2022; Xu et al. 2022b; Yang et al. 2022). This phenomenon can be attributed to the concurrent industrialization that typically accompanies economic growth, leading to increased emissions of pollutants from factories. Moreover, the expanding economy drives heightened demand for private cars, particularly in areas that lack efficient public transport systems. The growth in traffic not only leads to congestion but also increases tailpipe emissions. These emissions contain a wide range of harmful substances, posing a significant threat to both climate stability and public health. Furthermore, the government may take measures to relax environmental regulations in order to promote the economic development of less developed regions and to facilitate the transfer of polluting enterprises. Faced with strict regional environmental regulations, polluting enterprises may choose to relocate their production to regions with comparatively lax regulations or invest in pollution transfer technologies rather than clean-up technologies. These strategic decisions could consequently contribute to an overall deterioration in environmental quality. Since there may be information asymmetry between polluting enterprises and residents on environmental issues, i.e., residents do not accurately know the actual emissions of polluting enterprises, and the necessary transparency to ensure the accuracy of environmental information is often lacking in participatory environmental regulation, this may lead to an underestimation of the severity of the air pollution issue.

Conclusions and policy recommendations

Conclusions

In the context of promoting the implementation of the grand strategies of "Beautiful China" and "Healthy China," this paper employs spatial exploratory analysis to examine the spatial and temporal distribution maps of air pollution, population migration, and residents' health. Then, we explore the spatial and temporal evolution characteristics and conduct a comprehensive theoretical analysis and empirical estimation of the relationship between the three. The main conclusions can be summarized as follows.

Firstly, it is important to acknowledge that air pollution can directly and detrimentally impact the health of the population. Additionally, population migration serves as a mediating variable, exerting an indirect effect on the health risk of air pollution. Secondly, the adverse effects of air pollution on residents' health exhibit significant spatial spillover effects, and the spillover effect of health risk between regions is much greater than that within regions. Thirdly, there is a single threshold effect of economic development, environmental regulation, and their interaction term on the health risk of air pollution, which manifests itself at different thresholds. Finally, the negative impact of air pollution on residents' health shows regional heterogeneity. Compared with southern China and the northwest side of the Hu Line, higher health risks can be observed in northern China and the southeast side of the Hu Line.

Policy recommendations

Based on the results and conclusions of our research, we put forward the following recommendations: Firstly, local authorities should prioritize tackling the sources of air pollution to control air pollutant emissions effectively and regulate pollutant discharges. In addition, it is imperative to improve population management and regulation by implementing settlement systems, rationally controlling population flow, and mitigating the negative impact of population agglomeration on the urban environment.

Secondly, it is necessary for local authorities to strengthen regional collaborative efforts in the prevention and control of environmental issues. This can be achieved by breaking down administrative monopolies, catalyzing cross-regional environmental protection initiatives, encouraging the sharing of clean energy resources, promoting green technical assistance, and facilitating information exchange on environmental protection practices. Such concerted efforts are essential in our ongoing battle to preserve and protect our blue skies.

Thirdly, local authorities should take advantage of their distinctive comparative advantages originating from regional resource endowments. This can be achieved by developing a circular economy and setting environmental regulatory standards in line with regional economic development. It is crucial to avoid relaxing environmental standards for the sake of political performance. Furthermore, empowering informal environmental protection organizations to actively engage the public can help curb the waste of resources and reduce air pollution. Ultimately, this is expected to achieve a win-win result for both economic development and environmental protection.

Fourthly, local authorities should establish an air quality monitoring system to maintain constant vigilance over air pollution levels. The system regularly collects and analyzes extensive air quality data. These data not only help to assess the extent of variations in air quality but also contribute to identifying the primary sources of pollution in different regions. Based on the results of the assessment, tailored environmental protection measures can be equational in line with the specific circumstances of each location.

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Data availability The datasets generated during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethical approval Not applicable

Consent to participate Not applicable

Consent to publish Not applicable

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