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Original Research

Assessing the effectiveness of $PM_{2.5}$ pollution control from the perspective of interprovincial transport and $PM_{2.5}$ mitigation costs across China

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ABSTRACT

Due to the transboundary nature of air pollutants, a province's efforts to improve air quality can reduce $PM_{2.5}$ concentration in the surrounding area. The inter-provincial $PM_{2.5}$ pollution transport could bring great challenges to related environmental management work, such as financial fund allocation and subsidy policy formulation. Herein, we examined the transport characteristics of $PM_{2.5}$ pollution across provinces in 2013 and 2020 via chemical transport modeling and then monetized inter-provincial contributions of $PM_{2.5}$ improvement based on pollutant emission control costs. We found that approximately 60% of the $PM_{2.5}$ pollution was from local sources, while the remaining 40% originated from outside provinces. Furthermore, about 1011 billion RMB of provincial air pollutant abatement costs contributed to the $PM_{2.5}$ concentration decline in other provinces during 2013–2020, accounting for 41.2% of the total abatement costs. Provinces with lower unit improvement costs for $PM_{2.5}$, such as Jiangsu, Hebei, and Shandong, were major contributors, while Guangdong, Guangxi, and Fujian, bearing higher unit costs, were among the main beneficiaries. Our study identifies provinces that contribute to air quality improvement in other provinces, have high economic efficiency, and provide a quantitative framework for determining inter-provincial compensations. This study also reveals the uneven distribution of pollution abatement costs ($PM_{2.5}$ improvement/abatement costs) due to transboundary $PM_{2.5}$ transport, calling for adopting inter-provincial economic compensation policies. Such mechanisms ensure equitable cost-sharing and effective regional air quality management.

1. Introduction

Fine particulate matter ($PM_{2.5}$) pollution is a primary environmental concern in China [1,2], characterized by its long residence time in the atmosphere, long-distance reach, environmental disruption, impact on atmospheric visibility, and public health risks [3,4]. Given the severe air pollution over the past decades, the Chinese government launched the “Action Plan for Air Pollution Prevention and Control” in 2013 and the “Three-Year Action Plan for Winning the Blue Sky Protection Campaign” in 2018 [5,6], in which regional-level $PM_{2.5}$ mitigation was considered.

Owing to these stringent control policies, the $PM_{2.5}$ pollution has been greatly reduced from 2013 to 2020 [7,8]. Accordingly, the annual average $PM_{2.5}$ concentration in China decreased from 64 to 33 $\mu g\ m^{-3}$, with 93,271 premature deaths prevented [9,10]. The significant national $PM_{2.5}$ pollution mitigation is attributed to the great efforts exerted by provinces. For example, Shanxi province completed 543 emission-trading transactions in 2019, amounting to 330 million Chinese yuan (CNY). Liaoning Province completed an ultra-low-emission transformation for all coal-fired power plants.

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Anhui province phased out 18,974 environmentally unregulated enterprises and more than 66,000 old diesel trucks in 2020 [11]. However, only a few studies have assessed the interprovincial transport costs incurred by provinces to improve air quality.

The transboundary nature of $PM_{2.5}$ pollution across provinces in China, exacerbated by differences in emission patterns and meteorological conditions, poses significant challenges [12,13]. Variations in population spatial distribution further accentuate the divergence in emission reduction contributions and air quality enhancements among provinces [14,15]. This emphasizes the need to assess the impact of interprovincial transport on local $PM_{2.5}$ exposure risks, enabling the targeted allocation of $PM_{2.5}$ mitigation responsibilities to respective emitter provinces.

Numerous studies have focused on quantifying the cross-border transport of $PM_{2.5}$ pollution [16,17], using health risks and population monetization economies as indicators to assess the social, health, and environmental impacts of $PM_{2.5}$ pollution [18–20]. Emphasizing the impact of transboundary $PM_{2.5}$ pollution, Liu et al. indicated that nearly half of the deaths and costs attributable to $PM_{2.5}$ pollution in China each year can be traced to emissions originating outside the boundaries of the affected areas [21]. Similarly, Irene highlighted that the average incidence of premature deaths ranged from 41% to 53% regarding air quality caused by emissions from a certain state in the United States that spread outside that state's borders [19]. These findings prove the critical impact of cross-border transport on air quality and public health. In recent years, some studies on $PM_{2.5}$ transboundary assessment have shifted the research perspective from single-source or regional contributions to cross-cutting contributions from multiple sources and regions [21–23]. However, the vital questions are quantifying interprovincial transport contributions regarding pollutant control cost and allocating $PM_{2.5}$ abatement investment costs among provinces more efficient.

To assess the interprovincial transport of $PM_{2.5}$ abatement (referring to a decrease in $PM_{2.5}$ concentration) costs, we first reproduced the spatial distribution of $PM_{2.5}$ concentration across China (data from Hong Kong, Macau, and Taiwan is not available) in 2013 and 2020, using the Weather Research and Forecasting and Community Multiscale Air Quality (WRF-CMAQ) model. Second, we assessed the interprovincial transport characteristics of $PM_{2.5}$ exposure by employing the Integrated Source Apportionment Method (ISAM) module to track the emission sources of different $PM_{2.5}$ components in 31 provinces in China and coupling the simulation results with population distribution. Finally, we further computed the hidden transport of $PM_{2.5}$ abatement costs between provinces due to the transport nature of air pollutants by integrating provincial abatement costs between 2013 and 2020 and thereby developed a compensation framework. Our study reveals the dynamics of interprovincial transport of $PM_{2.5}$ pollution and abatement costs across 31 provinces, thus identifying priority provinces for regulation but also enhances the realism of pollution mitigation funding allocations and proposes a quantitative framework for interprovincial compensation policies. It also suggests how air quality management can be carried out more effectively and equitably.

2. Materials and methods

Our study is organized into three parts (Supplementary Material Text S1): ensuring $PM_{2.5}$ modeling accuracy, applying regional tracking markers to investigate interprovincial transport relationships, and integrating $PM_{2.5}$ abatement cost data to construct an interprovincial cost transport matrix.

2.1. Model configuration

We conducted simulations utilizing the WRF version 4.1.2 and CMAQ version 5.3.2 platforms. The simulation scope encompassed China (data from Hong Kong, Macau, and Taiwan is not available) and was established using a Lambert conformal projection centered at 103° E, 37° N, with two parallel latitudes situated at 25° N and 40° N. The CMAQ-ISAM model labeled 31 provinces and all PM components of each province (excluding secondary organic particles), totaling 2065 markers. The specific configuration parameters for the WRF-CMAQ coupling are enumerated in Tables S1, S2, and S4 (Supplementary Materials). Both anthropogenic and natural sources were considered in terms of emissions. We adopted the Multi-resolution Emission Inventory for China (MEIC) from Tsinghua University for anthropogenic emissions (http://www.meicmodel.org) [24,25]. Emissions from natural sources, specifically emissions of biogenic volatile organic compounds, were estimated using the Model of Emissions of Gases and Aerosols from Nature version 3.1 [26]. Table 1 outlines the various CMAQ simulation scenarios alongside their respective objectives. Comprehensive information about the modeling process and meteorological validation can be found in Figs. S4 and S5, and Table S5 (Supplementary Materials).

2.2. Transport matrix setting

We simulated the $PM_{2.5}$ concentration in each province using the WRF-CMAQ model coupled with the MEIC inventory. To comprehensively evaluate the changes in $PM_{2.5}$ pollution for each province, considering the spatial differences in population distribution during 2013–2020, we used population-weighted $PM_{2.5}$ concentrations as an indicator to evaluate the effect of the emission reductions achieved by each province.

$$PPM_{2.5} = \frac{\sum_{i=1}^{n} C_i \times POP_i}{\sum_{i=1}^{n} POP_i} \tag{1}$$

where $PPM_{2.5}$ represents the population-weighted concentration of $PM_{2.5}$ (in $\mu g \cdot m^{-3}$), POP_i represents the grid population, and C_i represents the concentration of $PM_{2.5}$ in different grids (in $\mu g \cdot m^{-3}$).

Meanwhile, using the ISAM model, we obtained the $PM_{2.5}$ concentration generated by emissions from each province and then further obtained the transport matrix characterizing the interprovincial $PM_{2.5}$ transport relationship. In addition to focusing on the transport of $PM_{2.5}$ concentrations, our study also focused on the transport of $PM_{2.5}$ exposures (equation (2)), which requires processing $PM_{2.5}$ concentration transport data.

First, we obtained China's population point data from the LandScan global population dataset (https://landscan.ornl.gov). We processed it using ArcGIS (geoinformation processing tools) to obtain population data for the CMAQ grids, which consisted of 58,320 grids. The $PM_{2.5}$ concentration transport data included 58,320 grid points for $PM_{2.5}$ concentrations in 35 regions. We multiplied the acquired population grid data by the population grid data corresponding to each region.

$$EPM_{2.5} = \sum_{i=1}^{n} C_i \times POP_i \tag{2}$$

where $EPM_{2.5}$ represents $PM_{2.5}$ exposure (in $\mu g \cdot m^{-3} \cdot$100 million people), POP_i represents the grid population, and C_i represents $PM_{2.5}$ concentrations in different grids (in $\mu g \cdot m^{-3}$).

Table 1
CMAQ simulation scheme design.

Emission	Inventory Distribution	Meteorology	WRF Scheme	Module Design	Purpose
Year 2020	ISAT [27]	Year 2020	1–7	Regular	Comparison of different WRF schemes for $PM_{2.5}$ simulation
Year 2020	ISAT	Year 2020	2	Regular	Recreating the spatial distribution of $PM_{2.5}$ in 2020
Year 2020	ISAT	Year 2020	2	ISAM ($PM_{2.5}$)	Tracking the components of $PM_{2.5}$ in 2020
Year 2013	ISAT	Year 2013	2	ISAM ($PM_{2.5}$)	Tracking the components of $PM_{2.5}$ in 2013
Year 2013	ISAT	Year 2020	2	ISAM ($PM_{2.5}$)	Eliminating meteorological effects on $PM_{2.5}$ simulation results

We then used the ArcGIS' Spatial Join tool to merge the Chinese province layers with the CMAQ grid layers, assigning a unique province ID to each grid. Subsequently, we aggregated the $PM_{2.5}$ exposure for each province in the 35 regions by matching the grids with the corresponding province IDs obtained in the first step. The 35 regions represented 31 provinces, offshore regions, unmarked regions, and initial and boundary fields (Supplementary Material Text S2).

Finally, we summed the $PM_{2.5}$ exposure of a particular province across all regional grids to obtain the total $PM_{2.5}$ exposure for that province, which gives us the transport matrix of $PM_{2.5}$ exposure as follows:

$$\boldsymbol{A} = \begin{pmatrix} a_{1,1} & \cdots & a_{31,1} \\ \vdots & \ddots & \vdots \\ a_{1,31} & \cdots & a_{31,31} \end{pmatrix}_{31\times 31} \tag{3}$$

where $\boldsymbol{A}$ represents the $PM_{2.5}$ exposure transport matrix and $a_{\mathrm{i,j}}$ represents the absolute contribution of $PM_{2.5}$ exposure from province i(source) to province j(receptor).

Based on this method, we assessed the interprovincial transport matrix of $PM_{2.5}$ exposure for 2013 and 2020 in China. We obtained the matrix for differences in the transport of $PM_{2.5}$ exposure between provinces due to emission changes from 2013 to 2020. The calculation equations are as follows:

$$\boldsymbol{A}_{2013} - \boldsymbol{A}_{2020} = \boldsymbol{A}_{\mathrm{delta}}(\Delta\boldsymbol{A}) + \boldsymbol{A}_{\mathrm{deltaME}}(\Delta\boldsymbol{ME}) \tag{4}$$

$$\boldsymbol{A}_{20202013} - \boldsymbol{A}_{2020} = \Delta\boldsymbol{A} \tag{5}$$

$$\boldsymbol{A}_{2013} - \boldsymbol{A}_{20202013} = \Delta\boldsymbol{ME} \tag{6}$$

where $\boldsymbol{A}_{2013}$ represents the 2013 transport matrix, $\boldsymbol{A}_{2020}$ represents the 2020 transport matrix, $\boldsymbol{A}_{20202013}$ represents the transport matrix under 2013 emissions and 2020 meteorological conditions, $\boldsymbol{A}_{\mathrm{delta}}$ represents the transport matrix affected by emission (2013–2020), and $\boldsymbol{A}_{\mathrm{deltaME}}$ represents the transport matrix affected by meteorological conditions (2013–2020).

Our study solely considered the mutual contributions of the 31 provinces without considering contributions from outside China (Supplementary Material Text S2). Moreover, the ISAM within the CMAQ model did not trace all $PM_{2.5}$ components, excluding secondary organic aerosol and some primary organic aerosol components. Lastly, our focus was solely on pollutant transmission between Chinese provinces, disregarding contributions from outside China's borders, with a six-day spin-up time in our simulations to ensure result reliability.

2.3. Assessment of economic indicators and $PM_{2.5}$ abatement costs

To identify the economic efficiency of air pollution control for each province in China during 2013–2020, we used $PM_{2.5}$ exposure and the total pollutant control costs to develop two economic indicators (equation (7) and (8)), namely θ_i and γ_i, as follows:

$$\theta_i = \frac{\Delta EPM_i}{Cost_i} \tag{7}$$

where $Cost_i$ represents the total cost of air pollution control measures (pollutant control includes the emission reductions of primary $PM_{2.5}$, SO_2, NO_x, NH_3, and VOCs) for province i during 2013–2020, which was CNY 100 million, and the total cost of pollutant control measures is hereinafter uniformly referred to as the $PM_{2.5}$ abatement cost. ΔEPM_i represents the $PM_{2.5}$ exposure changes for province i during 2013–2020 ($\mu g\ m^{-3}\cdot 100$ million people). θ_i represents the improvement in $PM_{2.5}$ exposure achieved per unit cost spent for province i, $\mu g\cdot m^{-3}\cdot$people CNY^{-1}), and θ_{ave} represents the average value of θ for 31 provinces.

$$\gamma_i = \frac{\theta_i}{\theta_{\mathrm{ave}}} \tag{8}$$

where γ_i is derived by dividing the θ_i by the θ_{ave}, which considers the differences between provinces and characterizes the economic efficiency of the input costs of $PM_{2.5}$ abatement in each province.

The $PM_{2.5}$ abatement cost data in our study were divided into two parts: (1) $PM_{2.5}$ abatement cost data from 2013 to 2017 were evaluated based on the abatement cost paid during the implementation Action Plan for the Prevention and Control of Air Pollution [28,29]. (2) The $PM_{2.5}$ abatement cost data from 2018 to 2020 were assessed based on the abatement costs paid during the Three-Year Action Plan on Defending the Blue Sky [29]. Detailed information on the costs for each province and each measure can be found in Tables S6 and S7 (Supplementary Materials).

Based on the above, we can obtain the cost of abating one unit of $PM_{2.5}$ exposure in each province ($1/\theta_i$, hereinafter referred to as the unit abatement cost of $EPM_{2.5}$), with one unit meaning 1 $\mu g\ m^{-3}\cdot$people, to construct the unit abatement cost matrix of $EPM_{2.5}$ for 31 provinces.

$$\boldsymbol{C} = \begin{pmatrix} c_1 & \cdots & c_{31} \\ \vdots & \ddots & \vdots \\ c_1 & \cdots & c_{31} \end{pmatrix}_{31\times 31} \tag{9}$$

where $\boldsymbol{C}$ represents the matrix of the unit abatement cost of $EPM_{2.5}$ in the 31 provinces, and c_i represents the unit abatement cost of $EPM_{2.5}$ in province i.

The interprovincial transport matrix of $PM_{2.5}$ abatement costs was calculated based on the following equation:

$$\Delta\boldsymbol{E} = \Delta\boldsymbol{A} \bullet \Delta\boldsymbol{C} \tag{10}$$

where $\Delta\boldsymbol{E}$ represents the interprovincial transport matrix of $PM_{2.5}$ abatement costs for the 31 provinces during 2013–2020, $\Delta\boldsymbol{A}$ represents the interprovincial transport matrix for $\varDelta EPM_{2.5}$ ($EPM_{2.5}$ interprovincial transport matrix for 2013 minus $EPM_{2.5}$ interprovincial transport matrix for 2020), and $\Delta\boldsymbol{C}$ ($\boldsymbol{C}$, same as $\Delta\boldsymbol{C}$) represents the matrix of unit cost for $EPM_{2.5}$ reduction in 31 provinces.

3. Results and discussion

3.1. $PM_{2.5}$ variations from 2013 to 2020

Figs. S10a–b (Supplementary Material) displays the CMAQ simulation results of the spatial distributions of the annual $PM_{2.5}$ concentrations in China in 2013 and 2020. $PM_{2.5}$ pollution exhibited significant spatial heterogeneity, as high concentrations were observed in the northern and central regions of China owing to high emission intensities [24,30]. The overall meteorological conditions in 2013 were less favorable for the dispersion of pollution in the northern regions, which led to less notable regional $PM_{2.5}$ transport compared with that in 2020 (Supplementary Material Fig. S10c). Except for the western areas, $PM_{2.5}$ concentrations considerably decreased in most regions because of the emission reduction of air pollutants during 2013–2020 (Supplementary Material Fig. S10d). The most noticeable decrease in $PM_{2.5}$ concentration was observed in Beijing–Tianjin–Hebei and its surrounding areas (including Henan, Shanxi, and Shandong), with an average decrease of 44.8 μg m^{-3}.

Based on our simulation, from 2013 to 2020, the national annual average population-weighted concentration of $PM_{2.5}$ ($PPM_{2.5}$) decreased from 59.3 to 35.7 μg m^{-3}, with a reduction of 39.8%, which was in general agreement with the simulation results of the mainstream international teams (e.g., Zhang et al., from 61.8 to 42.0 μg m^{-3}; Geng et al., from 60.7 to 34.5 μg m^{-3}) [10,31]. The major contribution to $PM_{2.5}$ declines was anthropogenic emission reductions (90.9%) [32], while the meteorological influence was relatively slight (9.1%; Supplementary Material Text S1). In addition, China's annual average $PM_{2.5}$ concentrations from monitoring and simulation in 2020 (2013) were close to 36.2 and 35.7 μg m^{-3} in 2020 and 60.6 and 59.3 μg m^{-3} in 2013 [33]. The correlation between the simulation results and the monitoring values reached 0.83 for 74 cities in 2013 (NMB = −10.9%, NME = 19.2%). The correlation between the simulation results and the monitored values in 2020 reached 0.84 (NMB = 2.8%, NME = 8.1%) and 0.60 (NMB = 48.6%, NME = 49.4%) for the east and west (total 1736 monitoring stations, 337 cities), respectively (Supplementary Material Figs. S4 and S5).

To better differentiate regional differences and to support subsequent analyses, we divided the provinces into eight key regions (Fig. 1a), designated as BTH (Beijing, Tianjin, and Hebei), YRD (Yangtze River Delta and its surrounding areas), MID (Middle region), NOR (Northern region), PRD (Pearl River Delta and its surrounding areas), SCY (Sichuan, Chongqing, Yunnan, and Guizhou), WES (Western region), and INM (Nei Mongol) (Supplementary Material Text S2, Fig. S15a). $\Delta PM_{2.5}$ represents the difference in $PPM_{2.5}$ concentrations between 2013 and 2020. The decline in simulated $PPM_{2.5}$ values for all eight regions ranged from 29.3% to 48.6%. The YRD region had the largest decline in $PPM_{2.5}$ (Fig. 1c), with a decrease of 48.6% ($\Delta PM_{2.5}$ = 34.0 μg m^{-3}), followed by the BTH and SCY regions (Fig. 1b–g), with a decrease of 48.5% ($\Delta PM_{2.5}$ = 44.8 μg m^{-3}) and 48.0% ($\Delta PM_{2.5}$ = 33.3 μg m^{-3}), respectively.

3.2. Interprovincial transport of $PM_{2.5}$

Significant interprovincial $PM_{2.5}$ transport characteristics existed between the provinces (Fig. 2a–c). Based on our simulation, the average contribution of local emissions to local $PPM_{2.5}$ in 31 provinces was 57.5% in 2013 and 60.2% in 2020, indicating a considerable contribution (approximately 40% on average) from emissions outside the province border to local $PM_{2.5}$ pollution for the provinces in China. The contribution of the emission sources outside local provinces (external emission sources) to the $PPM_{2.5}$ for each province varied greatly owing to the differences in emissions, spatial distribution, meteorological conditions, topography, and other factors [34]. In 18 provinces, external emissions contributed more than 40% to the local $PPM_{2.5}$ in 2013 and 2020. In 2020, the most significant phenomena for the external transport of $PM_{2.5}$ pollution occurred in Ningxia and Hainan, with external emission contributions accounting for 68.6% and 58.8% of the total $PPM_{2.5}$, respectively. Conversely, Xinjiang has minimal interaction with external emissions, with local emissions contributing 99.5% of $PPM_{2.5}$. Between 2013 and 2020, significant improvements in $PPM_{2.5}$ were observed across all provinces in China except Xizang. On average, the local emission reduction contributed 61.1% to the decrease in local $PPM_{2.5}$ for the 31 provinces in China (Fig. 2e).

The analysis of $EPM_{2.5}$ transport in the 31 provinces (Fig. 2b–d, f) revealed greater interprovincial variations in $EPM_{2.5}$ concentration than in $PPM_{2.5}$ concentration. Owing to the uneven population distribution, the $EPM_{2.5}$ concentration contributed by the emissions in the WES region is generally lower, displaying significant differences from those in populous provinces. Shandong, Hebei, Jiangsu, and Henan had the highest $EPM_{2.5}$ concentrations in 2020, at 53.5, 50.9, 39.5, and 36.7 μg $m^{-3}\cdot$100 million people. Nei Mongol and Jiangsu contributed significantly more to the $EPM_{2.5}$ exposure of other provinces than their $EPM_{2.5}$ exposure. The distribution of the $EPM_{2.5}$ values in 2013 was essentially consistent with the distribution in 2020. Between 2013 and 2020, the emission reductions in Shandong, Hebei, and Jiangsu contributed most to the decrease in $PM_{2.5}$ exposure ($\Delta EPM_{2.5}$), with decline values of 43.2, 39.9, and 32.5 μg m^{-3} per 100 million people, respectively (Fig. 2f).

3.3. Comparison of the transport of $PM_{2.5}$ exposure from the “source” and “receptor” perspectives

To better highlight the relationship between $EPM_{2.5}$ transport among the provinces and support the subsequent analysis, we defined $EPM_{2.5}$ input as the impact of emissions from all other provinces on the $PM_{2.5}$ exposure within a given province (receptor) and $EPM_{2.5}$ output as the total impact of emissions from that province (source) on the $PM_{2.5}$ exposure across all other provinces. Moreover, we defined the $EPM_{2.5}$ output minus the $EPM_{2.5}$ input as the $EPM_{2.5}$ net output, characterizing the “net effect” of $EPM_{2.5}$ on the interprovincial transport in each province. We defined the sum of the $EPM_{2.5}$ output and input as $EPM_{2.5}$ transport flux to reflect the overall level of interprovincial transport of $PM_{2.5}$ pollution for a given province.

Fig. 3a–c illustrates the $EPM_{2.5}$ output and input across the 31 provinces. In 2020, 13 provinces exhibited higher $EPM_{2.5}$ output than input, 15 provinces exhibited lower $EPM_{2.5}$ output than input, and three provinces exhibited equivalent output and input. Hebei, Jiangsu, and Shandong led in $EPM_{2.5}$ output, with 24.2, 24.2, and 23.8 μg $m^{-3}\cdot$100 million people, respectively (Fig. 3a). Both in 2020 and 2013, the $EPM_{2.5}$ output was much larger than the $EPM_{2.5}$ input in Nei Mongol and Shanxi, and the $EPM_{2.5}$ input was much larger than the $EPM_{2.5}$ output in Sichuan, Guangdong, and Hunan (Fig. 3a and b). Fig. 3d–f shows the $EPM_{2.5}$ net output across the 31 provinces in 2020 and 2013. Hebei, Shandong, Jiangsu, Shanxi, and Nei Mongol had the highest net $EPM_{2.5}$ outputs, while Hunan, Sichuan, and Guangdong had the lowest net $EPM_{2.5}$ outputs. Moreover, the net $EPM_{2.5}$ outputs were almost zero in the western and northeastern regions. Between 2013 and 2020, Nei Mongol demonstrated the highest net $\Delta EPM_{2.5}$ (2013 $EPM_{2.5}$ − 2020 $EPM_{2.5}$) output at 9.4 μg $m^{-3}\cdot$100 million people, indicating that it contributed significantly to the decrease in $PM_{2.5}$ exposure in the other provinces (Fig. 3f).

In 2020, BTH, YRD, MID, and INM were the dominant regions for $EPM_{2.5}$ output, contributing 115.9 μg $m^{-3}\cdot$100 million people,

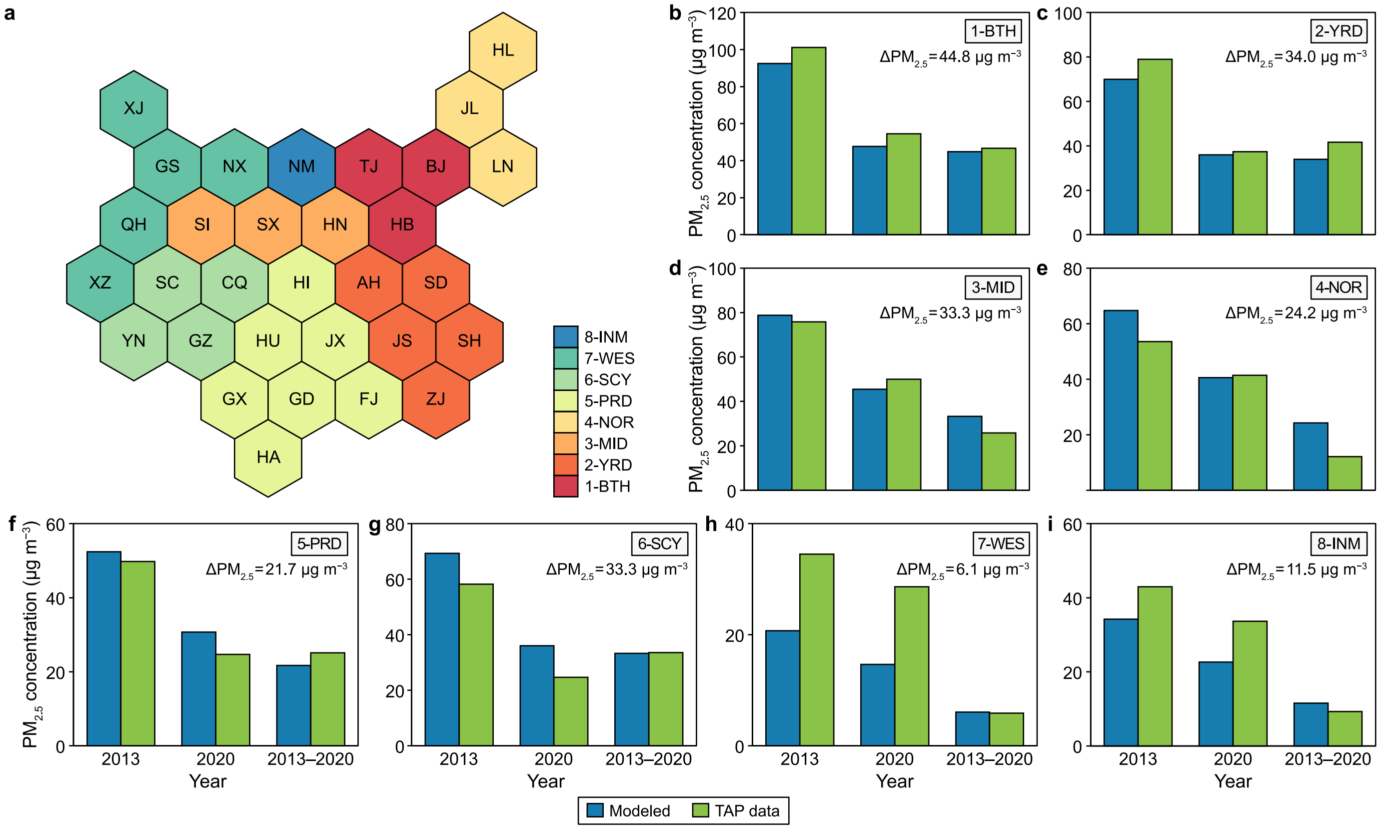

Fig. 1. **a**, Honeycomb map of China's 31 provinces (divided into eight regions). **b**–**i**, Improvement in $PM_{2.5}$ in the eight key regions: BTH (**b**), YRD (**c**), MID (**d**), NOR (**e**), PRD (**f**), SCY (**g**), WES (**h**), and INM (**i**). $\Delta PM_{2.5}$ represents $PPM_{2.5}$ in 2013 minus $PPM_{2.5}$ in 2020. The $PM_{2.5}$ concentration in the figure represents the population-weighted $PM_{2.5}$ concentration, wherein the simulated effects caused by meteorology were not subtracted to determine the effectiveness of $PM_{2.5}$ mitigation between 2013 and 2020. The blue bars represent simulated data, and the green bars represent TAP data.

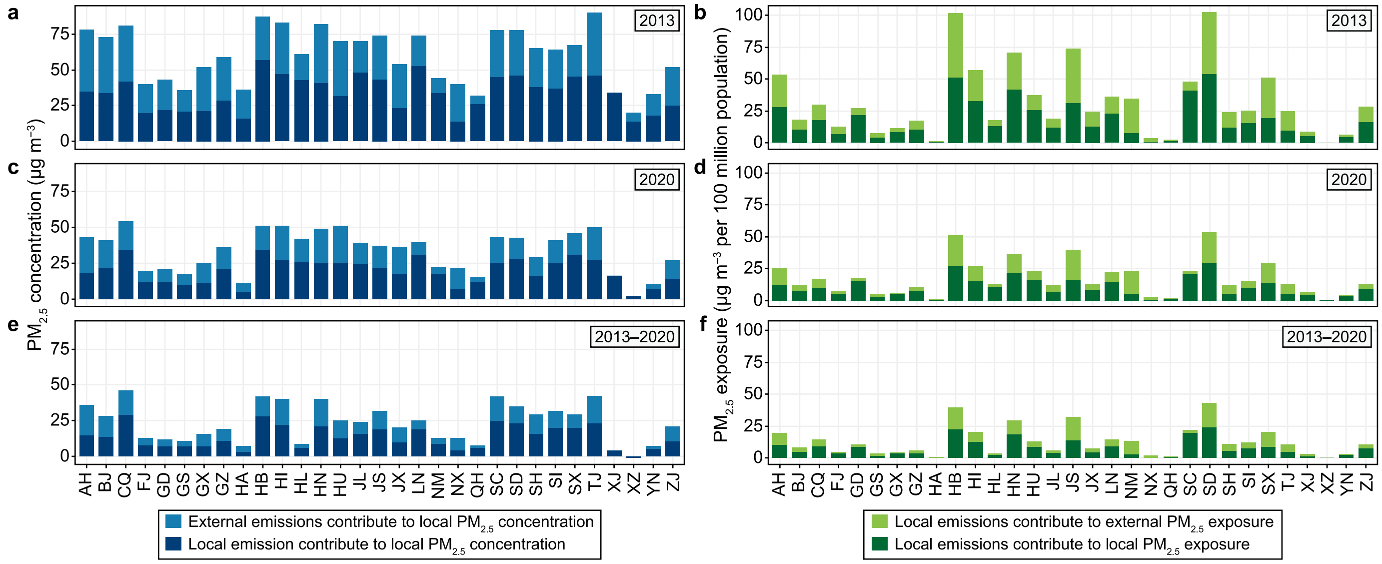

Fig. 2. **a**, **c**, **e**, Contributions to $PPM_{2.5}$ from local and external emissions based on the $PPM_{2.5}$ receptor side in the 31 provinces: 2013 (**a**), 2020 (**c**), 2013–2020 (**e**). The bottom and top bars represent local and external source contributions, respectively. The period 2013–2020 represents 2013 minus 2020 and the effects of meteorological conditions. **b**, **d**, **f**, Local emissions contribute to local and external $PM_{2.5}$ exposures across the 31 provinces based on the $EPM_{2.5}$ source side: 2013 (**b**), 2020 (**d**), 2013–2020 (**f**). The lower and upper bars represent the contributions of local emissions to the local and external areas, respectively.

constituting 81.6% of the national $EPM_{2.5}$ output. Concurrently, PRD and SCY were the major receptor regions, receiving $EPM_{2.5}$ at 61.9 μg m^{-3}·100 million people, which accounts for 43.6% of the national $EPM_{2.5}$ input. SCY, NOR, and WES exhibited low $EPM_{2.5}$ transport flux (Fig. 3g). The $EPM_{2.5}$ transport trend in 2013 converged with that in 2020 (Fig. 3h). The BTH, YRD, MID, and INM

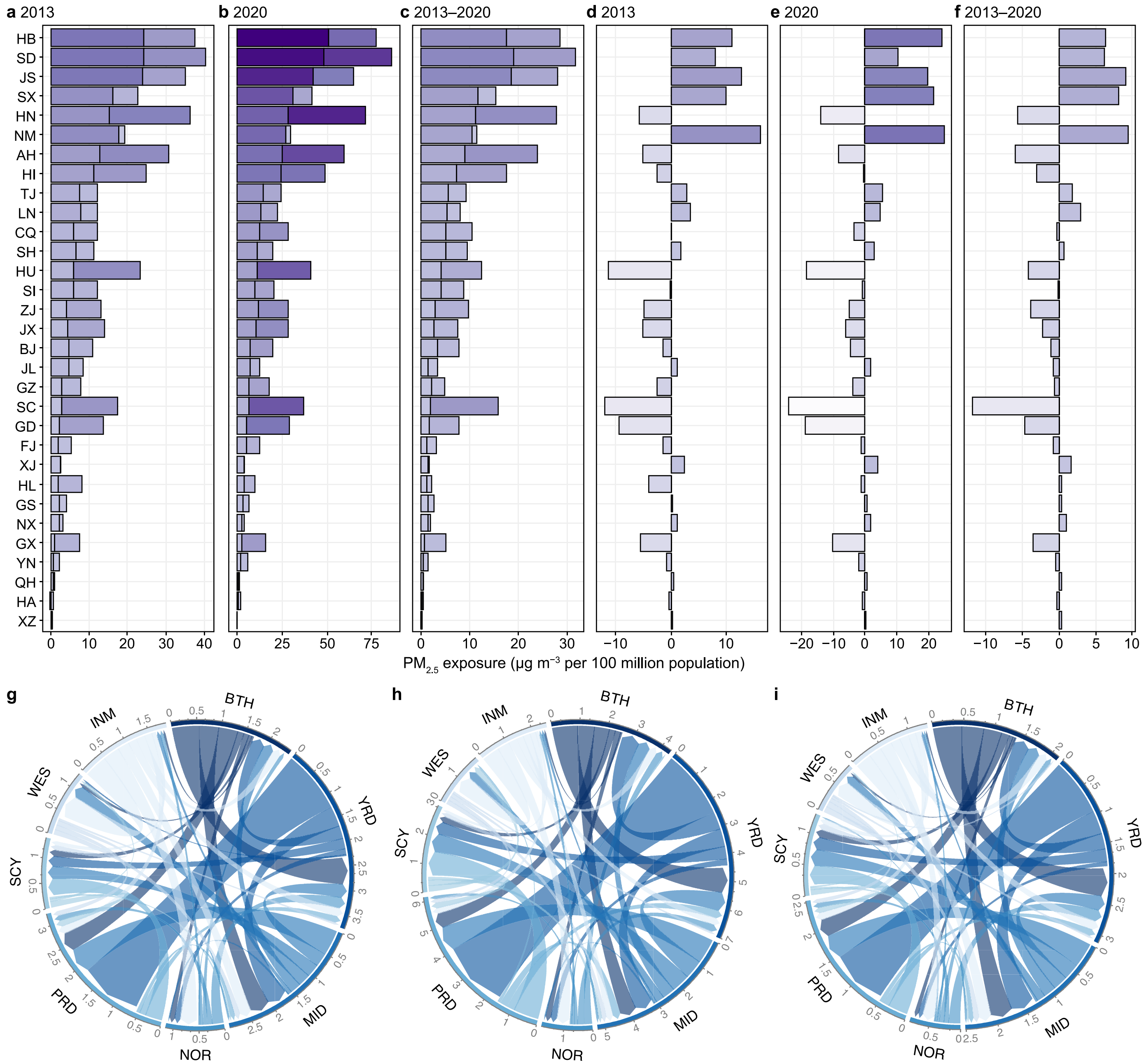

Fig. 3. **a**–**c**, Transport flux of EPM$_{2.5}$: 2013 (**a**), 2020 (**b**), 2013–2020 (**c**). The lower and upper bars represent the EPM$_{2.5}$ output and input, respectively. The color mapping represents the magnitude of the output and input at transport. **d**–**f**, Net EPM$_{2.5}$ output: 2013 (**d**), 2020 (**e**), 2013–2020 (**f**). In panels **a**–**f**, the purple shade represents the value's size. **g**–**i**, Input and output of EPM$_{2.5}$in eight regions: 2020 (**g**), 2013 (**h**), 2013-2020 (**i**). The local emission contributions of EPM$_{2.5}$ are hidden; thereby, the relationship between the EPM$_{2.5}$ and EPM$_{2.5}$ input of the eight key regions is represented. The arrow indicates the input with the same units as above.

regions also dominated in ΔEPM$_{2.5}$ output, contributing 81.1 μg m^{-3}·100 million people, which is equivalent to 80.1% of the national ΔEPM$_{2.5}$ output (Fig. 3i), indicating the high contributions of these regions to the decrease in PM$_{2.5}$ exposure nationwide. In addition, YRD to PRD and BTH to YRD were the most prominent ΔEPM$_{2.5}$ transport paths, contributing ΔEPM$_{2.5}$ at 12.7 and 8.3 μg m^{-3}·100 million people, respectively (Fig. 3i). Generally speaking, the regional transport of EPM$_{2.5}$ demonstrated a north-to-south and east-to-west pattern, with the transport influence gradually diminishing over longer interregional distances.

3.4. *Transport of PM$_{2.5}$ abatement costs*

We integrated the ΔEPM$_{2.5}$ matrix (Δ***A***) derived from the ISAM results with the unit abatement cost matrix of EPM$_{2.5}$ (Δ***C***) for each province to derive the transport matrix (Δ***E***) of the PM$_{2.5}$ abatement costs, as shown in Fig. S16 (Supplementary Material). Based on the assessment, in the 31 provinces, 58.8% of the PM$_{2.5}$ abatement costs contributed to the mitigation of PM$_{2.5}$ exposure in local areas, while 41.2% contributed to external areas on average, with a total flow of CNY 1011 billion of PM$_{2.5}$ abatement costs transferred between provinces. BTH, YRD, MID, and INM contributed a total cost output of CNY 742.8 billion, encompassing 73.5% of the national $PM_{2.5}$ abatement cost output. The BTH and YRD regions were the primary contributors to the $PM_{2.5}$ abatement cost output, accounting for 16.6% (CNY 166.4 billion) and 27.3% (CNY 276.3 billion) of the national $PM_{2.5}$ abatement cost output, respectively, with Hebei in the BTH accounting for 10.4% (CNY 105.1 billion). By contrast, the PRD and SCY regions were the largest $PM_{2.5}$ abatement cost input regions, receiving 240.5 (24.2%) and CNY 128.4 billion (12.8%) of $PM_{2.5}$ abatement cost inputs. In addition, the YRD, as the largest output region for $PM_{2.5}$ abatement costs, provided CNY 74.5 and 11.2 billion of hidden $PM_{2.5}$ abatement costs to PRD and SCY owing to the transport of $PM_{2.5}$ pollution during 2013–2020.

We derived the net output of $PM_{2.5}$ abatement costs (Fig. 4a) for each province based on the transport matrix of the $PM_{2.5}$ abatement costs (Supplementary Material Fig. S16), where we denoted

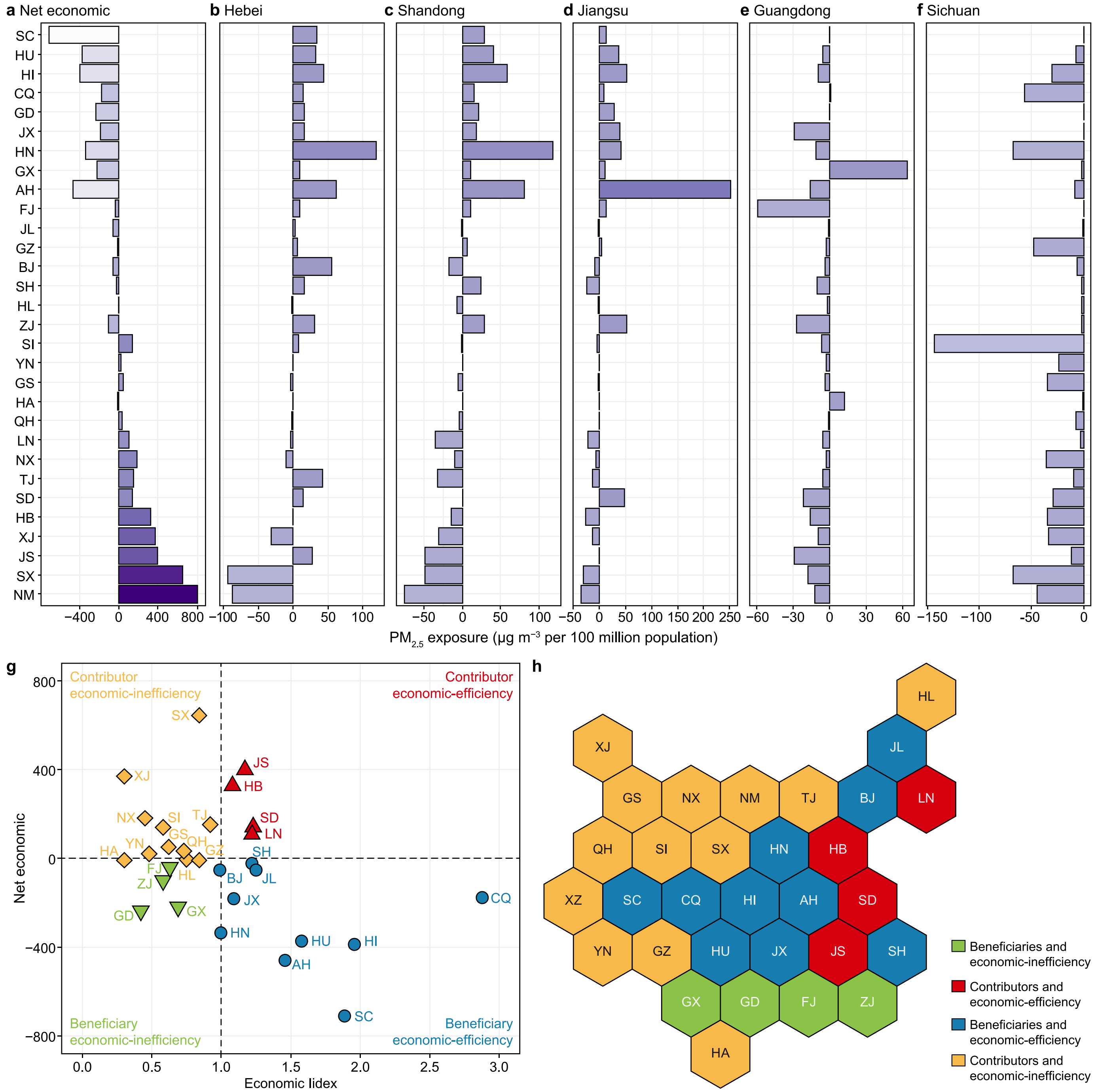

Fig. 4. **a**, The net output of the $PM_{2.5}$ abatement costs by province. **b**–**f**, The net output of $PM_{2.5}$ abatement costs in 31 provinces from major contributing and beneficiary provinces: Hebei (**b**), Shandong (**c**), Jiangsu (**d**), Guangdong (**e**), and Sichuan (**f**). Color mapping represents the magnitude of $PM_{2.5}$ abatement costs. In panels **a**–**f**, the purple shade represents the value's size. **g**, The division of the 31 provinces is divided into four categories, with different colors and shapes representing each category, with 1 and 0 as the dividing lines in the horizontal and vertical coordinates, respectively. "Contribution" represents provinces with a positive net output effect on $EPM_{2.5}$ transport, and "economic" represents provinces with high economic efficiency. **h**, The results of the classification of the 31 provinces in map format.

provinces with a positive net output of $PM_{2.5}$ abatement costs as "contributing provinces" and negative values as "beneficiary provinces." Among the 31 provinces were 14 contributing and 17 beneficiary provinces between 2013 and 2020, underscoring the existing inequality in distributing funds for pollution control across the Chinese provinces. We developed an economic compensation plan for the different provinces to mitigate this imbalance based on their performance on $PM_{2.5}$ exposure transport and related abatement costs. We determined the amount of compensation between the provinces by obtaining the transport matrix of the net output of the $PM_{2.5}$ abatement costs, where each matrix value represents the net output of the $PM_{2.5}$ abatement cost from the source province to the receptor province and the compensation that should be paid by the receptor province to the source province (Supplementary Material Fig. S17). Fig. 4b–f graphically represents the transport of the net output of the $PM_{2.5}$ abatement costs across the key provinces.

Based on the compensation plan we proposed, ten provinces must receive compensation, 12 provinces must provide compensation, and nine provinces must neither provide nor receive compensation (Fig. 4a). Hebei, Shandong, and Jiangsu were major contributing provinces and should be compensated mainly by the provinces in and around the YRD (Fig. 4b–d), with Anhui needing to compensate them CNY 25.1, 7.8, and 6.6 billion, respectively. Guangdong and Sichuan were identified as important beneficiary provinces that must compensate others (Fig. 4e and f). Some provinces in China have already begun implementing an ecological compensation policy whereby higher-level (provincial) government units generally provide financial compensation to lower-level (municipal) government units with significant air quality improvements [35]. However, no compensation policy has been established for inequalities arising from interprovincial air pollution transport, and our study provides a quantitative framework for mitigating such disparities.

3.5. Economic assessment

We classified the provinces according to the economic indicator γ_i (as explained in Section 2.3), and the net output of $PM_{2.5}$ abatement cost (Fig. 4g). An economic indicator exceeding 1.00 means that a province's unit cost for every unit of decrease in $EPM_{2.5}$ is lower than the average unit cost among all provinces. The contributing provinces, such as Hebei, Shandong, Jiangsu, and Liaoning, exhibited high γ_i values, indicating a low unit cost for every unit decrease in $EPM_{2.5}$. Meanwhile, the impact of emission reductions in these provinces on $PM_{2.5}$ exposure in other provinces is greater than the impact of emission reductions in other provinces on their $PM_{2.5}$ exposure levels. Conversely, the beneficiary provinces, such as Guangdong, Guangxi, Zhejiang, and Fujian, displayed lower γ_i values and needed to be compensated by other provinces (Fig. 4h).

Among particular significance, the provinces of Sichuan, Anhui, Hunan, and Hubei are the main beneficiaries of $PM_{2.5}$ abatement while investing less in $PM_{2.5}$ abatement costs. This suggests these provinces have made reasonable and fair investments in air pollution control. However, for specific provinces in YRD and PRD, such as Guangdong, Guangxi, and Zhejiang, high investment in $PM_{2.5}$ abatement costs in the past had a limited effect on decreasing $PM_{2.5}$ exposure. Consequently, given these differences in the economic effectiveness of $PM_{2.5}$ pollution control among the different provinces [36,37], a comprehensive evaluation is warranted to ensure the rationale behind the allocation of $PM_{2.5}$ abatement costs. Our novel economic indicators diverge from previous studies, as they were developed based on past $PM_{2.5}$ abatement cost data and the effect of the decrease in $EPM_{2.5}$, reflecting the unit cost of a decline in $PM_{2.5}$ exposure. By contrast, Zhou et al. focused on the health benefits derived from $PM_{2.5}$ enhancement [38], assessing their economics within that context, while Zhao et al. adopted a holistic perspective that encompassed both costs and benefits to evaluate economics, factoring in environmental and health benefits [39]. Thus, discrepancies may arise between our findings and theirs.

3.6. Uncertainty and prospects

Our study has limitations. First, in terms of economic assessment, the results of the economic indicators in the different provinces may contain some uncertainty. For example, while $PM_{2.5}$ pollution is effectively mitigated in the YRD and PRD, O_3 concentrations increased instead of decreased. The considerable investment in VOC mitigation in these regions (Supplementary Material Table S7) may not significantly improve $PM_{2.5}$ pollution and could underestimate their economic indicators [40,41]. In addition, the different provinces had different initial pollutant emissions and $PM_{2.5}$ concentrations, resulting in varying costs of $PM_{2.5}$ mitigation in the initial stage. In addition, economic growth can lead to a greater burden of emission reduction, but the pollution effects caused by economic growth in terms of gross domestic product cannot be fully evaluated, potentially leading to an underestimation of the economic indicators in certain provinces. Moreover, the cost estimation and mitigation scopes of the three-year action plan and air plan for air pollution control were not completely unified (Supplementary Material Text S4–S5). For example, the three-year action plan considers the investment cost of VOC control in key industries, which is not considered in the air plan. Furthermore, the calculation methodology itself has limitations. While the present study validated its results with previous research [42], there is uncertainty in the γ_i values due to the uncertainty in the costs in each province.

In addition, we selected the meteorological conditions of 2020 as the simulation conditions. However, meteorological conditions can significantly impact interprovincial transport, and different meteorological conditions may result in different transport outcomes. This can lead to significant variations in transport results for certain provinces, particularly those with flat terrain, such as Anhui, Jiangsu, and Henan, which are more susceptible to meteorological influences [43,44]. Lastly, as mentioned earlier, the receptor points selected for the regional analysis in the present study were based on the full grids of each province, including fragmented grids. This may lead to differences in transport results for certain provinces compared with previous research findings.

Future research should focus on refining the cost calculation process for $PM_{2.5}$ mitigation by considering factors beyond existing policies, such as the economic impacts of technological advancement, industry restructuring, and variations in costs due to economic growth. In conclusion, despite the uncertainties and limitations, our study provides valuable insights into the economic assessment of $PM_{2.5}$ abatement costs in China. It serves as a basis for formulating effective pollution control policies and promoting interprovincial compensation mechanisms to achieve improved air quality and sustainable development.

4. Conclusions and recommendations

The findings of this study show significant contributions from all provinces to the decline of $PM_{2.5}$ concentration in China from 2013 to 2020, with especially notable contributions from Hebei, Shandong, Nei Mongol, and Jiangsu. This is particularly evident when considering the cross-border nature of $PM_{2.5}$ pollution, where pollution reduction efforts in these provinces benefit themselves and their neighbors. Our analysis revealed the substantial economic flow of $PM_{2.5}$ abatement costs between provinces. On average, roughly 40% of $PM_{2.5}$ abatement costs in a province contributed to the decrease of $PM_{2.5}$ exposure in other provinces, underscoring the complexities of air pollution control and allocation of corresponding expenses due to the interprovincial transport of air pollutants. This interprovincial transport dynamics of $PM_{2.5}$ abatement costs has significant implications for policymaking, especially regarding cost allocation and investment strategies in pollution control.

Moreover, previous policies and studies predominantly emphasized the BTH and YRD as key regions for air pollution control [45–48]. Our research further underscores the economic rationale for enhancing investments in pollution control measures within these regions. Meanwhile, based on our findings, it may be beneficial for policymakers to consider the following three points:

(1) Unify the management of the BTH, YRD, MID, and INM regions to establish a mega-control region. BTH, YRD, MID, INM, SCY, and YRD are key provinces with concentrated emissions of air pollutants, among which BTH, YRD, MID, and INM, being geographically close to each other, contribute to more than 80% of the total national $EPM_{2.5}$ output (output of $PM_{2.5}$ exposure). Jointly setting $PM_{2.5}$ abatement targets and implementing coordinated prevention and control measures could help optimize total pollution control costs and mitigate the impacts caused by $PM_{2.5}$ pollution transport from the mega-control area to other provinces, enabling more health, environmental, and social benefits.

(2) Establishing rules for economic compensation regarding the interprovincial transport of air pollution is crucial, as the transport of $PM_{2.5}$ pollution led to unfair allocation of pollution abatement responsibilities, which further led to inequality in abatement investments and air quality improvement effects across provinces. To address this issue, China can draw insights from existing ecological compensation policies in other countries [35], such as the US EPA (Environmental Protection Agency)'s cross-state air pollution rules (https://www.epa.gov/csapr) and the European Union's ecological compensation policy [49]. Our findings in this study could provide useful suggestions for identifying the contribution and benefit of provinces and thus for determining appropriate amounts of economic compensation among provinces.

(3) Optimize fund allocation to favor provinces with higher economic efficiency and greater net output of $PM_{2.5}$ abatement costs, such as Hebei, Shandong, and Jiangsu. Conversely, provinces such as Guangdong, Fujian, Zhejiang, and Guangxi faced relatively high $PM_{2.5}$ abatement unit costs, resulting in a heavier pollution reduction burden [50]. However, as beneficiaries, these provinces have the potential to achieve economic and efficient $PM_{2.5}$ abatement by realigning their investment strategy, such as by transferring $PM_{2.5}$ abatement investments to provinces that have contributed more to their air quality improvement [21]. This strategic reallocation can significantly enhance the rationality of $PM_{2.5}$ abatement cost allocation and effectively control the overall $PM_{2.5}$ pollution in China.

CRediT authorship contribution statement

Yihao Wang: Conceptualization, Formal Analysis, Methodology, Software, Validation, Visualization, Writing - Original Draft. **Xuying Wang:** Conceptualization, Methodology, Writing - Review & Editing. **Zeyuan Liu:** Data Curation, Writing - Review & Editing. **Shaoliang Chao:** Data Curation. **Jing Zhang:** Resources. **Yixuan Zheng:** Conceptualization. **Yu Zhang:** Methodology. **Wenbo Xue:** Resources. **Jinnan Wang:** Supervision. **Yu Lei:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing - Review & Editing.

Declaration of competing interest

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Appendix A. Supplementary data

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