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Examining the impact of inter-provincial migration on environmental health in China

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Abstract:

Background: China has a large volume of inter-provincial migrants, accounting for more than 11% of the total population. The economic benefits of inter-provincial migration have been well studied, whereas the health impacts related to environmental factors are generally ignored.

Methods: In this study, we use 1% national population sampling survey data from 2015 and daily PM_{2.5} (particles ≤ 2.5 μm in aerodynamic diameter) concentration data from 360 cities to analyze the health benefits associated with air pollution due to inter-provincial migration. The exposure-response function was used to estimate the economic value of these health benefits via the adjusted-human-capital and cost-of-illness methods.

Results: Considering a full-exposure scenario, inter-provincial migration resulted in a reduction in the PM_{2.5} exposure concentration of 3.94 $\mu\text{g}/\text{m}^3$ in 2015, corresponding to a reduction of 6114 premature deaths, 233.4 thousand hospitalization cases, and 1.5 million asthma attacks. The corresponding economic value of these health benefits was about 10.44 billion yuan (0.02% of the national GDP in 2015). A protection scenario, assuming that the migrants protected themselves from air pollution, showed very similar results to the full-exposure scenario (PM_{2.5} exposure reduced by 3.60 $\mu\text{g}/\text{m}^3$); hence, personal protection does not reduce significantly the health risks of air pollution.

Conclusions: At the national level, the labor force obtains both economic and health

benefits. However, a high number of migrants flow out of the central region of China result in a labor deficiency and social imbalance. Migration to large cities provides economic benefits at the expense of health. Environmental migration becomes an increasingly important motivation for inter-provincial migration, which places new pressure on policy makers to consider social welfare and environmental protection in the provinces.

Keywords: air pollution, population migration, health effects

1. Background

Rapid global industrialization contributed significantly to environmental pollution. The benefits of economic development are offset by the huge costs in health reduction. The World Health Organization [1] showed that around 3 million people die due to outdoor air pollution every year, because 92% of the global population lives in areas where the concentration of particulates exceeds the WHO threshold. The incidence of respiratory, cardiovascular, circulatory, and other diseases is related to air pollution. Many studies have confirmed that air pollution causes serious health loss [2-12].

In 2013, the central east regions of China suffered from continuous and serious air pollution, with the affected area accounting for almost one-quarter of the country, which is inhabited by 50% of the population. The PM_{2.5} annual average concentration in 74 key cities of China in 2013 was 72 $\mu\text{g}/\text{m}^3$, which was 6 times the National Ambient Air Quality Standard (NAAQS) formulated by the United States Environmental Protection

Agency (EPA), and 4.8 times China's National Primary Standard for Ambient Air Quality.

Air pollution has become the fourth in the list of factors contributing the most to disease in China [13,14].

Previous studies revealed the effect of air pollution on health from different perspectives. The disease risk of air pollution exposure has been well studied, and the exposure-response coefficients and relative risks of different air pollutants at the national, regional, and urban levels in China have been obtained [15-19]. To evaluate the direct economic cost of health loss due to air pollution, the human-capital, cost-of-illness, and willingness-to-pay methods are commonly used [20,21]. However, the direct loss is not a sufficient indicator for risk assessment and management, and indirect losses should also be considered. A few studies used the computable general equilibrium model and input-output model to evaluate the loss of working hours caused by air pollution and the indirect economic loss induced by industrial chains [22,23]. Some studies proposed that the increase in the clean energy use as a result of increasing urbanization can reduce the effect of indoor air pollution on human health, thus significantly reducing the mortality of diseases related to air pollution [24-28]. Studies of the effect of air pollution control policies confirmed the importance of emission control for protecting the health of residents, and affirmed China's great achievements in this regard [29-33].

Previous studies considered the effect of air pollution on all residents, without distinguishing between local residents and migrants. Under the Chinese Hukou registration system, migrants are defined as citizens who have resided away from their

registered address for more than six months [34]. The regional economic disparity has resulted in a large number of migrants in China, reaching 245 million in 2016 [35]. Inter-provincial migrants accounted for 63.5% of the migrants, and 11.25% of the total population.

Most of the current studies focus on the determinant factor to cause population migration. Generally, economic motivation is considered the most important factor driving migration. Todaro [36] considered that the number of migrants depends on the gap between the actual income before migration and the expected income after migration. Oded [37] proposed that the absolute income gap is not the main reason for migration, while the sense of loss caused by the relative income gap of similar groups is the real motivation. Many previous studies [38-42] showed that there is a significant positive correlation between population migration in China and regional income level, industrial structure, employment opportunities, and level of urbanization.

In addition to large economic disparities, there are significant differences in regional air pollution in China. Hence, this study investigates the effect of air pollution on the health of migrants who relocate to obtain economic benefits. In addition, we analyze whether environmental health benefits can be significantly improved if personal protective measures are taken to avoid exposure to air pollution. Unlike previous studies, this work investigates the environmental health benefits for inter-provincial migrants, and contributes the following innovations: a) focus on the health effects of air pollution on inter-provincial migrants, instead of local residents; b) discussion of the effects on inter-

provincial migrants at the regional level in terms of environment and health, not just economic factors; c) discussion of the effect of personal protective measures.

2. Methods

Here, the change in health effects from air pollution caused by inter-provincial migration is determined using an exposure-response function, and the economic value of health effects is evaluated using the adjusted-human-capital and cost-of-illness method.

2.1 Exposure-response function

The exposure-response function describes the relationship between environmental pollution and the health of the residents in the area. It is widely used in environmental epidemiological studies, such as the causal relationship between air pollution or noise pollution and human health [43-47]. Here, the risk of premature death and disease caused by PM_{2.5} exposure was calculated using this model, which describes the relationship between the change in ambient air quality and the health endpoint of the residents. The expected duration of migrants in their new destination has increased from 5.4 years in 2000, to 7.9 years in 2005, and further to 10.8 years in 2010 [48]. Therefore, the high concentration of PM_{2.5} in the destination had an impact on the health of migrants. The exposure-response relationship used here refers to the epidemiological studies in China, as shown in Table 2 [18,21,29,44]. The health endpoints include respiratory disease mortality (RM), cardiovascular disease mortality (CM), respiratory disease hospital admission (RHA), cardiovascular disease hospital admission (CHA), and asthma attack (AA).

2.1.1 Daily average exposure of PM2.5

Two scenarios were investigated here. First, a full-exposure scenario assuming the PM2.5 daily concentration in each province as the daily average exposure for subsequent calculations; and second, the exposure scenario assuming that the migrants used personal protective measures. In general, people use air purifiers and other protective measures under relatively serious pollution level, which is equivalent to reducing the exposure time. Hence, in the protected scenario, we reduced the daily average exposure time by certain proportions for different pollution conditions. The proportion of exposure time used here refers to our national household haze protection survey from 2019, which included urban and rural households. We used the results from 1129 questionnaires to calculate the duration of use of protective measures (including air purifier and ventilation system) under different pollution conditions. The exposure duration was calculated by deducting the duration of use of protective measures from the average daily exposure. It was assumed that when the air quality was good or moderate, no protective measures were used, and the exposure time ratio was 1.

Table 1. Duration and ratio of PM2.5 exposure under different pollution levels

Pollution level	Duration (ratio)
Good	24 h (1)
Moderate	24 h (1)
Lightly polluted	20.83 h (0.87)

Moderately polluted	18.67 h (0.78)
Heavily polluted	16.57 h (0.69)
Severely polluted	15.56 h (0.65)

As shown in Table 1, the daily average exposure in the scenario considering protective measures was calculated as follows:

$$ADE_{city} = (\sum TR * C_{city})/D \quad (1)$$

ADE_{city} is the daily average exposure dose of PM2.5 in each city; TR is the ratio of exposure duration; C is the daily concentration of PM2.5 in each city; and D is the number of days of exposure. The exposure dose of each province was calculated as the average exposure dose of each city in the province.

2.1.2 PM2.5 population-weighted exposure

By calculating the change in PM2.5 exposure after migration, we determined whether the inter-provincial migrants benefited from improved air quality or suffered from more air pollution. After migration, the population-weighted exposure (PWE) of inter-provincial migrants is:

$$PWE_{P,N} = \frac{1}{P} \sum_{i,j} (P_{i,j} * C_j) \quad (2)$$

where, P is the number of inter-provincial migrants; i is the migration origin; j is the migration destination; and C_j is the PM2.5 daily average exposure of the migration destination in 2015. $PWE_{P,N}$ is the population-weighted exposure of the inter-provincial migrants in the current residential area in 2015.

The PWE before migration ($PWE_{P,B}$) was obtained by the counterfactual assumption that the inter-provincial migrants lived in the original location in 2015, using Eq. (3), where C_i is the PM2.5 daily average exposure of the migration origin in 2015.

$$PWE_{P,B} = \frac{1}{P} \sum_{i,j} (P_{i,j} * C_i) \quad (3)$$

$$\Delta PWE_p = PWE_{P,N} - PWE_{P,B} \quad (4)$$

Here, ΔPWE_p is the change of population-weighted exposure after migration.

2.1.3 Health benefits

Many medical studies have confirmed that exposure to particulate matter has adverse health effects on the human body [49-53]. The harm to the human body depends on the particulate sizes; most particles larger than 10 μm stay in the nose and throat, while those smaller than 2 μm can reach the lungs, and finally deposit in the terminal bronchioles and alveoli. Small particles may also enter the blood circulation system through the alveoli. In addition, compared with PM10 (particles $\leq 10 \mu\text{m}$ in aerodynamic diameter) and TSP (total suspended particulate), PM2.5 particles have a larger specific surface area and stronger adsorption, which can enrich toxic substances on the surface. Therefore, small inhalable particles cause the greatest harm to the human body, not only to the respiratory system, but also contribute to cardiovascular and cerebrovascular diseases [54].

Table 2. E-R relationship between PM2.5 exposure and health endpoints

Health impact	Betas of the E-R relationship (β)		P_0
	Posterior mean	95% posterior intervals	

RM	0.0029	(0.0017, 0.0042)	0.07%
CM	0.0027	(0.0018, 0.0036)	0.27%
RHA	0.0109	(0, 0.0221)	1.33%
CHA	0.0068	(0.0043, 0.0093)	2.04%
AA	0.021	(0.0145, 0.0274)	5.61%

Note: β is the increase in mortality or hospitalization rate when PM2.5 concentration increases by 10 $\mu\text{g}/\text{m}^3$; P_0 is the baseline incidence of each health endpoint.

At a given PM2.5 exposure dose, the attributable cases of premature death or disease caused by air pollution were calculated, and then the changes in attributable cases due to this change in exposure dose is determined [24]. The changes in attributable cases were assumed to reflect health changes caused by inter-provincial migration.

$$p = p_0 * \exp [\beta * (C - C_0)] \quad (5)$$

Here, p and p_0 are the probabilities of each health endpoint for people exposed to the polluted and clean environments, respectively, where the latter is the baseline rate. In addition, β is the exposure-response coefficient; C is the actual concentration of PM2.5; and C_0 is the baseline concentration of PM2.5, taken as 15 $\mu\text{g}/\text{m}^3$ following China's National Primary Standard for Ambient Air Quality.

The number of attributable cases (AC), including deaths, hospital admissions, or asthma attacks caused by risk factors (PM2.5 exposure) were calculated using Eq. (6), where P is the size of the exposed population, i.e., inter-provincial migrants.

$$AC = (p - p_0) * P \quad (6)$$

The change in the number of attributable cases after migration ΔAC was calculated using Eq. (7), where AC_N and AC_B are the number of attributable cases after and before migration, respectively.

$$\Delta AC = AC_N - AC_B \quad (7)$$

2.2 Economic value evaluation

Here, the adjusted-human-capital method and cost-of-illness method were used to evaluate the economic value of health benefits. The adjusted-human-capital-method was used to analyze the contribution of human capital to economic growth from the perspective of the whole society. Since the adjusted-human-capital method uses the per capita GDP as the value of a single individual's statistical life year, there was no difference in individual value [55].

$$EL_{ij}^{mt} = \Delta AC \times HC_j^{pc} \quad (8)$$

EL_{ij}^{mt} is the economic loss caused by the premature death of the migrants from province i to province j ; and HC_j^{pc} is the human capital per capita in province j , as defined by Eq. (9).

$$HC_j^{pc} = GDP_j^{pc} \times \sum_{k=1}^t \left(\frac{1+\alpha}{1+\gamma} \right)^k \quad (9)$$

GDP_j^{pc} is the per capita GDP of province j ; α is the annual growth rate of per capita GDP; γ is the social discount rate; and t is the average remaining life expectancy of those who died prematurely due to exposure to high PM2.5 concentration. According to the report of the World Bank [56], we used $\gamma = 8\%$, and $t = 18$ y.

The health benefits calculated by the cost-of-illness method were quantified using the economic loss caused by diseases of the migrants from province i to province j , EL_{ij}^{mb} :

$$EL_{ij}^{mb} = \Delta AC \times Ex_j^{pc} \quad (10)$$

where Ex_j^{pc} is medical expenses of each health endpoint in the destination province j .

2.3 Data sources

This study used the national 1% population sample survey data from 2015 (Department of Population and Employment Statistics of China, National Bureau of Statistics), which had the largest sample size, widest coverage, and strongest representation in recent years. We assumed that the 1% sample survey fully reflected the characteristics of all inter-provincial migrants, and scaled the 1% results to 100% of the migrants. It should be noted that migration did not necessarily occur in 2015, but may occurred earlier.

The PM2.5 daily concentration data from 360 cities was obtained from the China Air Quality Online Monitoring and Analysis Platform. The per capita GDP and growth rate of each province were obtained from China Statistical Yearbook [57]. Expenses of medical service and hospital admissions were obtained from the China Health and Family Planning Statistical Yearbook [58].

3. Results

The number of total inter-provincial migrants was 150.7 million in 2015, three-fifths of which migrated from heavily polluted regions to areas with relatively mild pollution. Therefore, at the national level, the PWE of inter-provincial migrants was $49.36 \mu\text{g}/\text{m}^3$

after migration in the case of no personal protective measures, which decreased by 3.94 $\mu\text{g}/\text{m}^3$ compared to the counterfactual situation (no migration).

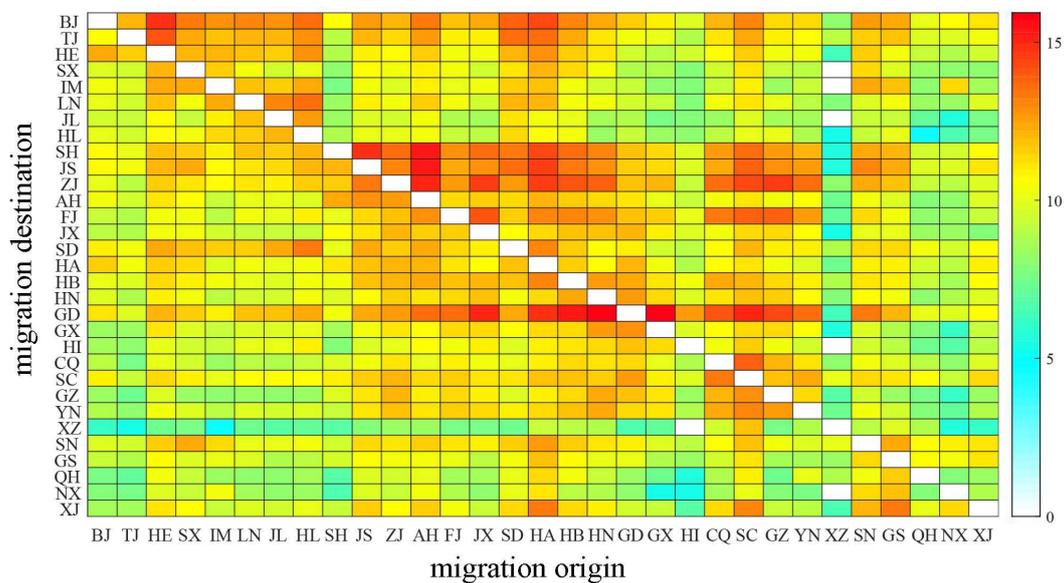


Fig. 1. Direction of inter-provincial migration in China in 2015, where the data show the logarithm of the number of migrants.

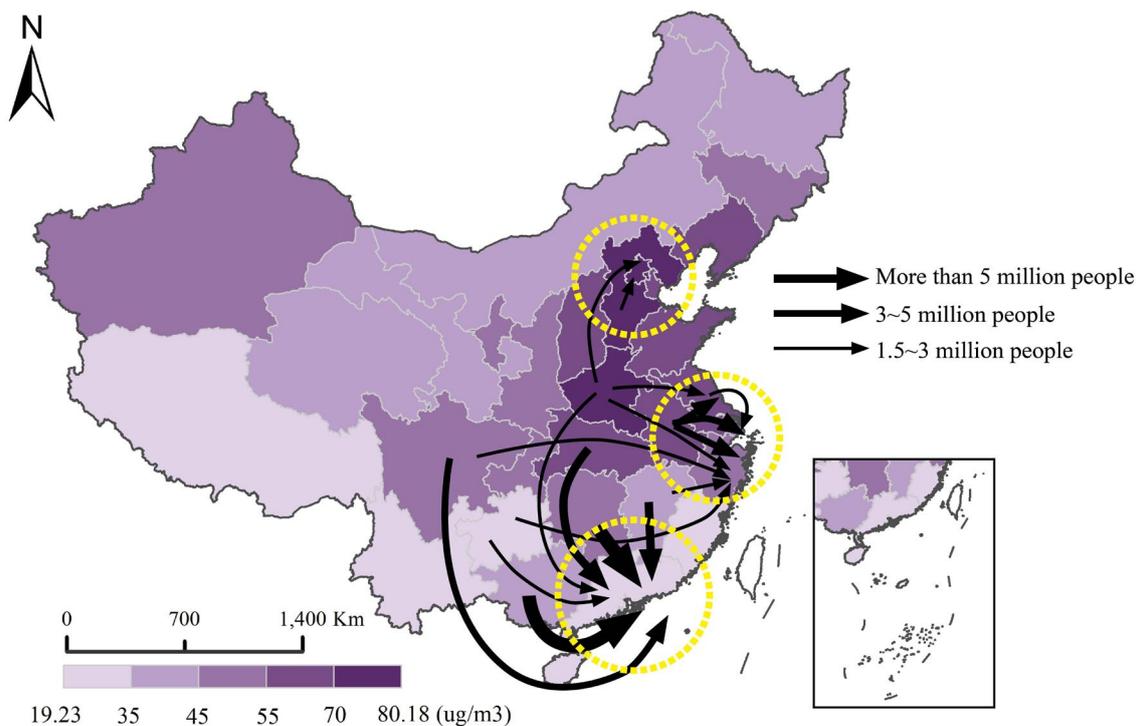


Fig. 2. PM2.5 daily average concentration of each province and main inter-provincial migration directions in China in 2015.

The PM2.5 concentration varies considerably across different regions of China. Due to the concentration of heavily polluting industries and the associated use of fossil fuels, the central east provinces of China are the most seriously affected by PM2.5 pollution, as shown in Fig. 2. The provinces of Henan, Beijing, Hebei, Tianjin, Shandong, Hubei, Jiangsu, and Anhui are heavily polluted, and 76.94% of the migrants from these provinces moved to regions with lower pollution and hence, reduced their health risks. Among the migrants who moved to more polluted regions, most migrated to Beijing. As the capital city, Beijing attracts numerous migrants, but suffers from severe air pollution, as shown in Fig. 3.

The main migration origins were concentrated in the central region of China, and the top provinces included Anhui, Henan, Sichuan, Hunan, and Jiangxi. The main migration destinations were concentrated in the southeast coastal provinces and three economic zones, where the top provinces included Guangdong, Zhejiang, Shanghai, Jiangsu, and Beijing. Guangdong attracted the most migrants, accounting for 25% of the total inter-provincial migrants. Although most of the motivation for migration from the heavily polluted central provinces to the lightly polluted southeast coastal provinces was economic, the migrants benefited from improved air quality.

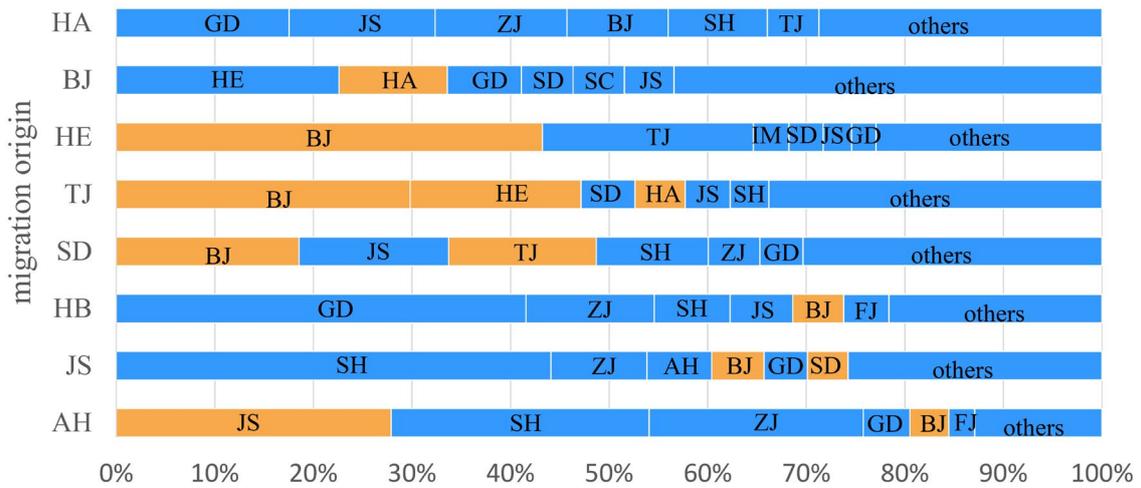


Fig. 3. The migration direction of migrants from the provinces with serious air pollution. The provinces with the highest PM_{2.5} concentration are shown on the y axis. Orange indicates migration to a more polluted province, while blue means less pollution.

Considering the origin provinces, the PWE of the migrants from Henan, Hubei, Beijing, Hunan, Chongqing, and Hebei changed the most after migration, where their average PM_{2.5} exposure decreased by 17.00 $\mu\text{g}/\text{m}^3$ (9.00–27.25 $\mu\text{g}/\text{m}^3$). In terms of destination provinces, the PWE of the migrants migrating to Hainan, Yunnan, Fujian, Guizhou, Tibet, and Guangdong changed the most, where the average PM_{2.5} exposure decreased by 19.90 $\mu\text{g}/\text{m}^3$ (16.33–29.59 $\mu\text{g}/\text{m}^3$).

We further calculated the impact of PM_{2.5} exposure changes on health and the corresponding economic value. Due to inter-provincial migration, the number of premature deaths related to air pollution decreased by 6114, hospitalizations decreased by 233.4 thousand, and asthma attacks decreased by 1.5 million. The economic value of these health benefits was about 10.44 billion yuan, accounting for 0.02% of the national GDP in 2015.

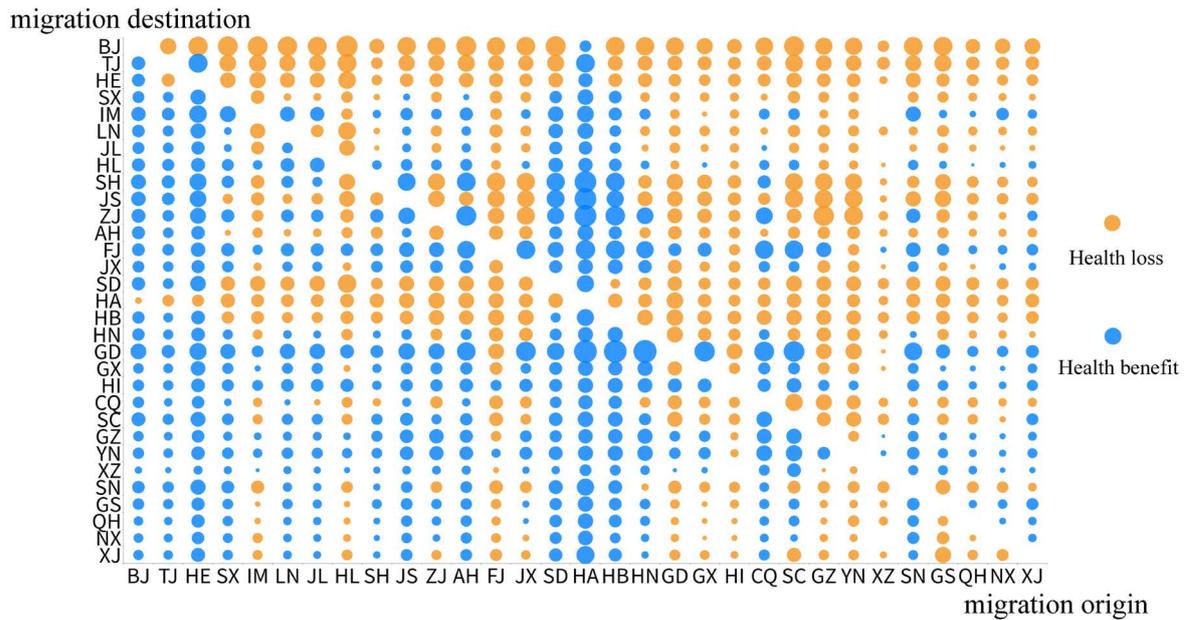


Fig. 4. Changes in health effects related to air pollution caused by inter-provincial migration in 2015.

Orange indicates an increase in pollution after migration (i.e., health loss), while blue means a decrease in pollution (health benefit). The bubble size indicates the relative amount of change. The data show the logarithm of the amount of health effects.

As shown in Fig. 4, among the origin provinces, the largest positive effect on health occurred in migrants from Henan, Hubei, Hunan, Hebei, Chongqing, and Anhui; among the destination provinces, the largest positive effect on health occurred in migrants migrating to Guangdong, Fujian, Zhejiang, Shanghai, Inner Mongolia, and Jiangsu. The severity of harm caused by air pollution to these inter-provincial migrants was greatly reduced after migration, resulting in health benefits. Among the origin provinces, the largest negative effect on health occurred in migrants from Heilongjiang, Guizhou, Fujian, Yunnan, Inner Mongolia, and Gansu; among the destination provinces, the largest negative effect on health occurred in migrants migrating to Beijing, Tianjin, Hebei, Henan,

Shandong, and Hubei. Although these migrants may have obtained economic benefits after migration, they were exposed to increased risk of disease due to the poorer air quality.

Due to the severe haze in China, many people take personal protective measures, and even some schools, hospitals, shopping malls, and other public areas have protective systems in place. For individuals and families, masks are often used for outdoor activities. According to Ali Health Research Center, during red alerts for haze in Beijing, the sales of masks on their retail platform increased significantly (9.3 times the usual quantity). Many families also install air purifiers and ventilation systems. According to the Wind Database, cumulative sales of air purifiers reached 64.57 million from 2013 to 2018. Therefore, we also considered the effect of such personal protective measures.

In this scenario, PM_{2.5} exposure of these migrants decreased by 3.60 $\mu\text{g}/\text{m}^3$ after inter-provincial migration, resulting in a decrease of 5519 premature deaths, 204.5 thousand hospitalizations, and 1.24 million asthma attacks, corresponding to health benefits worth about 9.10 billion yuan. These effects were slightly lower than the results for the full-exposure scenario, as shown in Fig. 5. Therefore, even if migrants adopt air pollution protection measures, it is difficult to significantly reduce the health risks of air pollution. According to Chinese Air Purifier Industry Alliance and Chinese Mechanical Ventilation Industry Alliance, the average selling price of an air purifier is 2319 yuan, and the average selling price of a ventilation system is 10750 yuan in 2015. When ongoing expenses, such as the costs of electricity, maintenance, and repair are taken into account, the cost of using protective measures is large, but the resulting health benefits are not

significant.

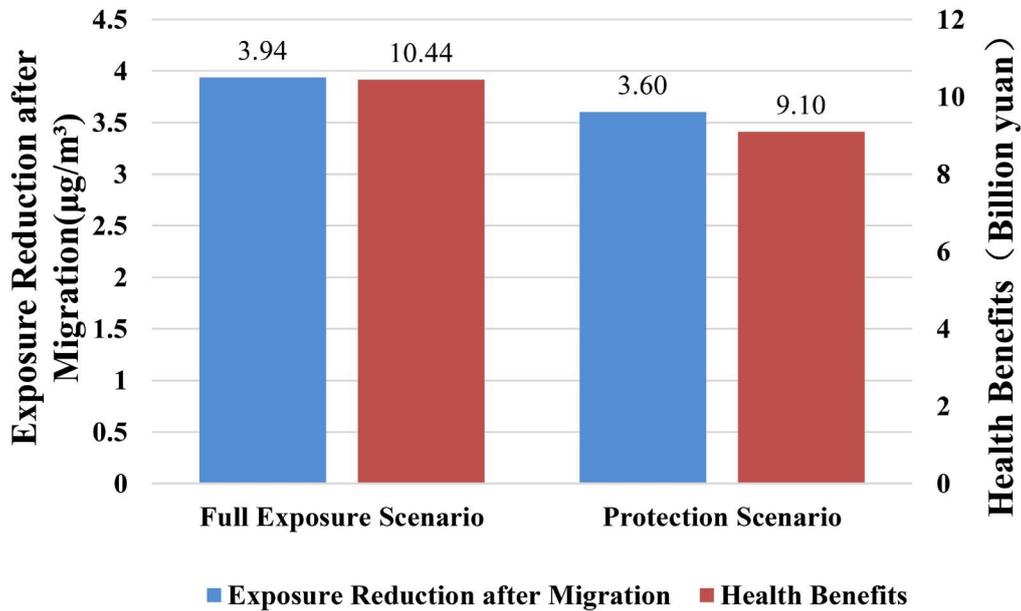


Fig. 5. Comparison of full exposure scenario and protection scenario.

4. Discussion

According to the latest ambient air quality standard of China, the first annual average concentration limit is $15 \mu\text{g}/\text{m}^3$, and the second limit is $35 \mu\text{g}/\text{m}^3$. Most urban observation points still fail to meet these standards [21]. Among the total inter-provincial migrants, the labor force aged 15–59 accounts for more than 90%, where the main purpose of migration is to seek jobs and do business [59]. In general, these migrants obtained both economic and health benefits after migration. However, air pollution is expected to lead to a further decline in the attractiveness of the central provinces to the labor force, which aggravates the “brain drain” and population loss in these areas. Most of the inter-provincial migrants are young adults, while those who stay in their hometown are often

young children and the elderly. Hence, these regions lose a lot of human capital and are facing the pressures of an aging population, which poses huge challenges to their economic development, and is not conducive to China's regional balance.

The proportion of the aged and children in the total inter-provincial migrants is less than 10%, but in recent years, this fraction has been increasing [59]. The aged and children have lower tolerance to heavy pollution and are more likely to generate motivation for environmental migration. The wealthier level of society has higher expectations for health standards and living environments, and serious air pollution will reduce their willingness to reside in highly polluted regions. To sum up, environmental pollution may become another important motivation for inter-provincial migration. As the number of migrants motivated by air pollution increases, the demographics of both the origin and destination provinces changes, which is expected to affect economic development of the entire country [60].

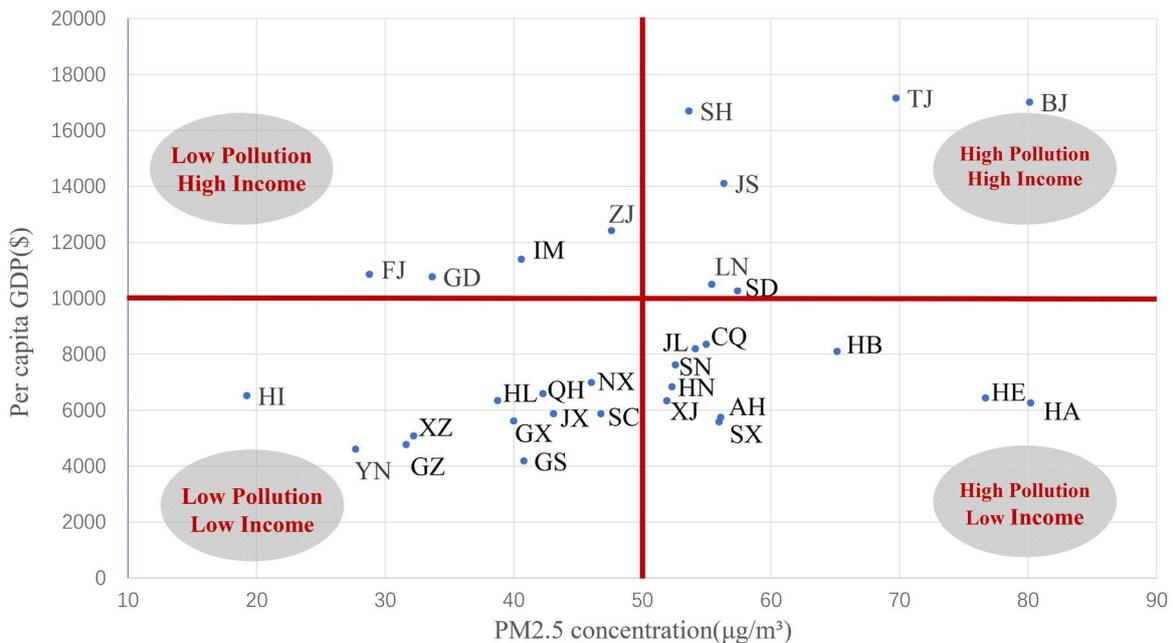


Fig. 6. PM2.5 concentration and per capita GDP of 31 provinces in China in 2015 divided into four categories: high pollution and high income; low pollution and high income; low pollution and low income; and high pollution and low income.

Considering the main economic motivation for inter-provincial migration, the population flows from low-income to high-income provinces. High-income provinces can be divided into high-pollution group and low-pollution group. The low-pollution group includes Fujian, Guangdong, Zhejiang, and Inner Mongolia. The migrants flowing into these provinces obtain the dual benefits of increased income and improved health. Shanghai, Jiangsu, Beijing, Tianjin, and Shandong with high levels of pollution are among the top ten provinces with the largest inflow of migrants, which may receive higher income and better employment prospects, but are subjected to increased risk of disease caused by air pollution. Therefore, air pollution control should be a focus in these provinces. For low-income provinces, such as Hebei, Henan, and Shaanxi, the brain drain problem is already very serious, and migration motivated by air pollution will aggravate this issue. These provinces will be in a very unfavorable position to attract talented workers.

Air pollution not only affects domestic population migration, but also leads to foreign emigration. However, such migrants are mainly the wealthy with abundant financial resources. Sixty percent of China's high net worth individuals (with a net worth of more than \$1 million) are considering or have completed emigration [61]. Emigrants usually choose the Euro-American countries with developed economies and excellent air

quality. Hence, in addition to the motivation of affluent living conditions and abundant educational resources, environmental quality has become an important factor of concern for emigrants.

Among the total inter-provincial migrants, over 60% had rural Hukou registration, where the main motivation for migration was to find industrial or engineering work [59]. When rural migrants move to cities, they can access cleaner energy, such as electricity and natural gas, which reduces the harm of indoor air pollution. However, we lack the accurate number of rural migrants in each province, this study did not consider indoor pollution.

Our evaluation of the health benefits of inter-provincial migration in China from the perspective of air pollution had the following limitations:

a) The exposure-response model used to evaluate the risk of premature death and diseases caused by PM_{2.5} exposure does not clearly define the exposure duration and inhalation pathway of pollutants.

b) Only premature death and hospitalization caused by respiratory and cardiovascular diseases and asthma attacks were included in the health endpoints, which are the main health effects selected according to the existing epidemiological research. Hence, the health impacts may have been underestimated. The actual health impacts are also affected by the lifestyle and physical condition of the individual. The health risks of vulnerable groups, such as the elderly and children, are more significant.

c) Due to the diverse demographic and environmental characteristics, the

coefficient of the exposure-response model may vary between regions, but this study assumed that this coefficient was equal for all regions.

d) In risk and health benefit assessments, selecting different values of factors such as the disease mortality, hospitalization rate, and value of a statistical life can cause deviations in the results.

e) The adjusted-human-capital and cost-of-illness methods used here to evaluate the economic value of health benefits only considered the direct loss of premature death and disease caused by air pollution. The psychological loss borne by the inter-provincial migrants and the burden on the social medical security system were not considered, resulting in the underestimation of the results.

5. Conclusions

This study is the first attempt to provide information for improving the environmental health benefits of inter-provincial migrants by evaluating the impact of air pollution on the health of migrants in 31 provinces of China. At the national level, the overall reduced exposure to PM_{2.5} pollution of inter-provincial migrants greatly reduced the number of premature deaths and hospitalizations, which was worth millions of yuan to the economy. At the regional level, most of these benefits were a result of the migrant flow from the central region to the southeast coastal region of the country, which is expected to further reduce the attractiveness of the central provinces to the labor force. However, migrants flowing into large cities only obtained economic benefits, while exposing themselves to greater health risks. Personal protective measures did not

significantly increase the health benefits of the migrants. Hence, national pollution control measures are required to curb air pollution. According to the results of this study, the following suggestions are given:

a) We recommend strengthening air pollution control in the central provinces to alleviate the brain drain. The central provinces should take measures to improve air quality and promote livability to attract the labor force. Such measures could include: optimizing the industrial and energy structures; rationalizing industrial distribution; popularizing air pollution prevention technology and equipment; and promoting the concept of low-carbon consumption to residents.

b) High-income provinces focus on improving air quality and reducing the health risk of air pollution. Such provinces have a large population inflow, and the benefits of pollution control measures in the high-income provinces with high population density will be more significant. In particular, for provinces with high pollution concentration, pollution control can effectively reduce the health costs caused by migration.

c) Household protective equipment, such as air purifiers and ventilation systems, does not significantly reduce health risks, so improving the air quality should be a priority.

The results of this study did not consider involve intra-provincial migration, or rural-urban migration. In future research, these topics will be considered to extract further knowledge from the available data.

Abbreviations

AH:Anhui;BJ:Beijing;FJ:Fujian;GS:Gansu;GD:Guangdong;GX:Guangxi;GZ:Guizhou;
HI:Hainan;HE:Hebei;HA:Henan;HL:Heilongjiang;HB:Hubei;HN:Hunan;JL:Jilin;JS:Jia
ngsu;JX:Jiangxi;LN:Liaoning;IM:InnerMongolia;NX:Ningxia;QH:Qinghai;SD:Shando
ng;SX:Shanxi;SN:Shaanxi;SH:Shanghai;SC:Sichuan;TJ:Tianjin;XZ:Tibet;XJ:Xinjiang;
YN:Yunnan;ZJ:Zhejiang;CQ:Chongqing.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

All of the authors have reviewed and approved the manuscript for publication.

Availability of data and materials

Please contact the author for data requests.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

Yu-Ou Yang: Conceptualization; Formal analysis; Methodology; Writing - original draft; Writing - review & editing. Juan-Juan Hou: Visualization; Resources. Xin-Yu Chen: Writing - review & editing. Shi-Wei Yu: Formal analysis; Writing - original draft. Jiu-Tian Zhang: Formal analysis; Methodology. Lan-Cui Liu: Conceptualization; Formal analysis; Methodology; Resources; Software; Validation; Writing - original draft; Writing - review & editing.

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Figures

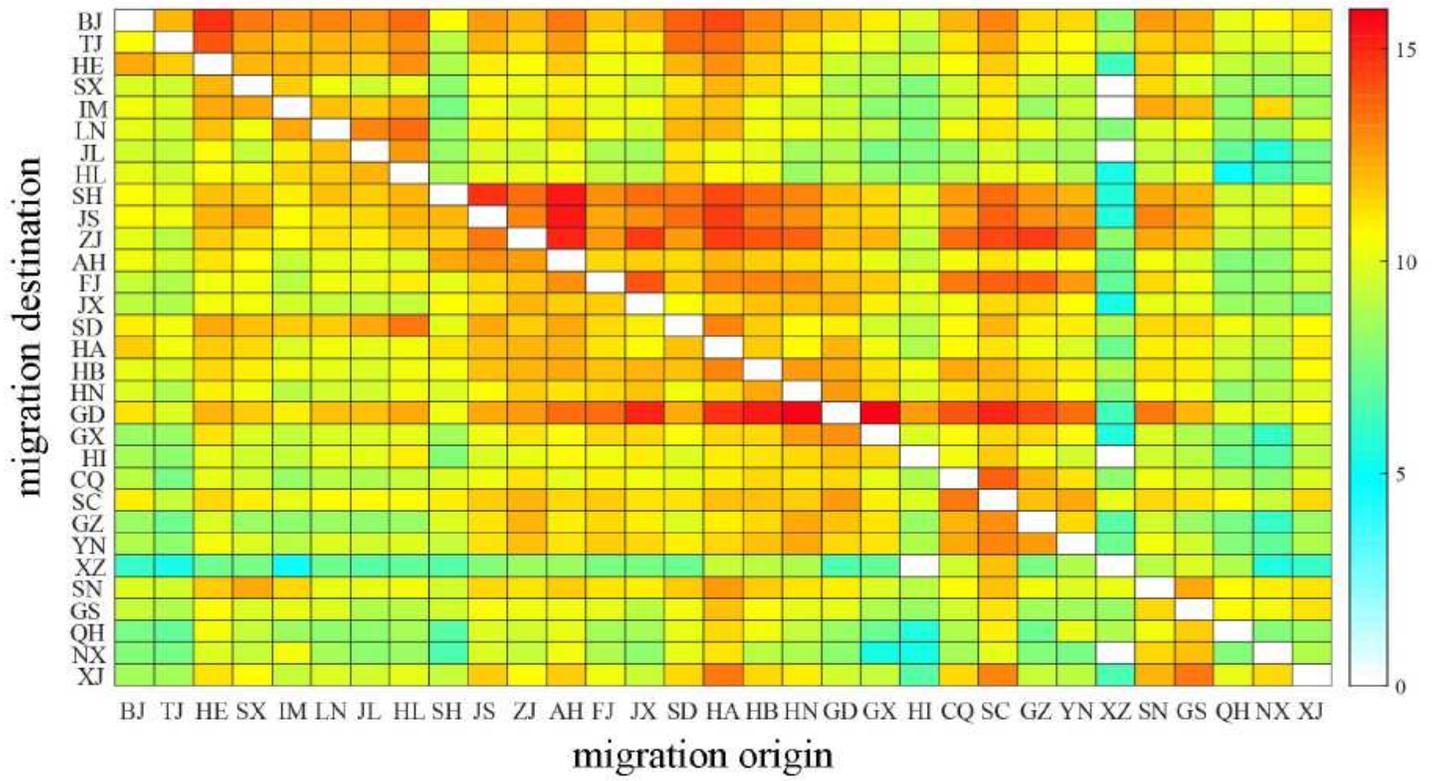


Figure 1

Direction of inter-provincial migration in China in 2015, where the data show the logarithm of the number of migrants.

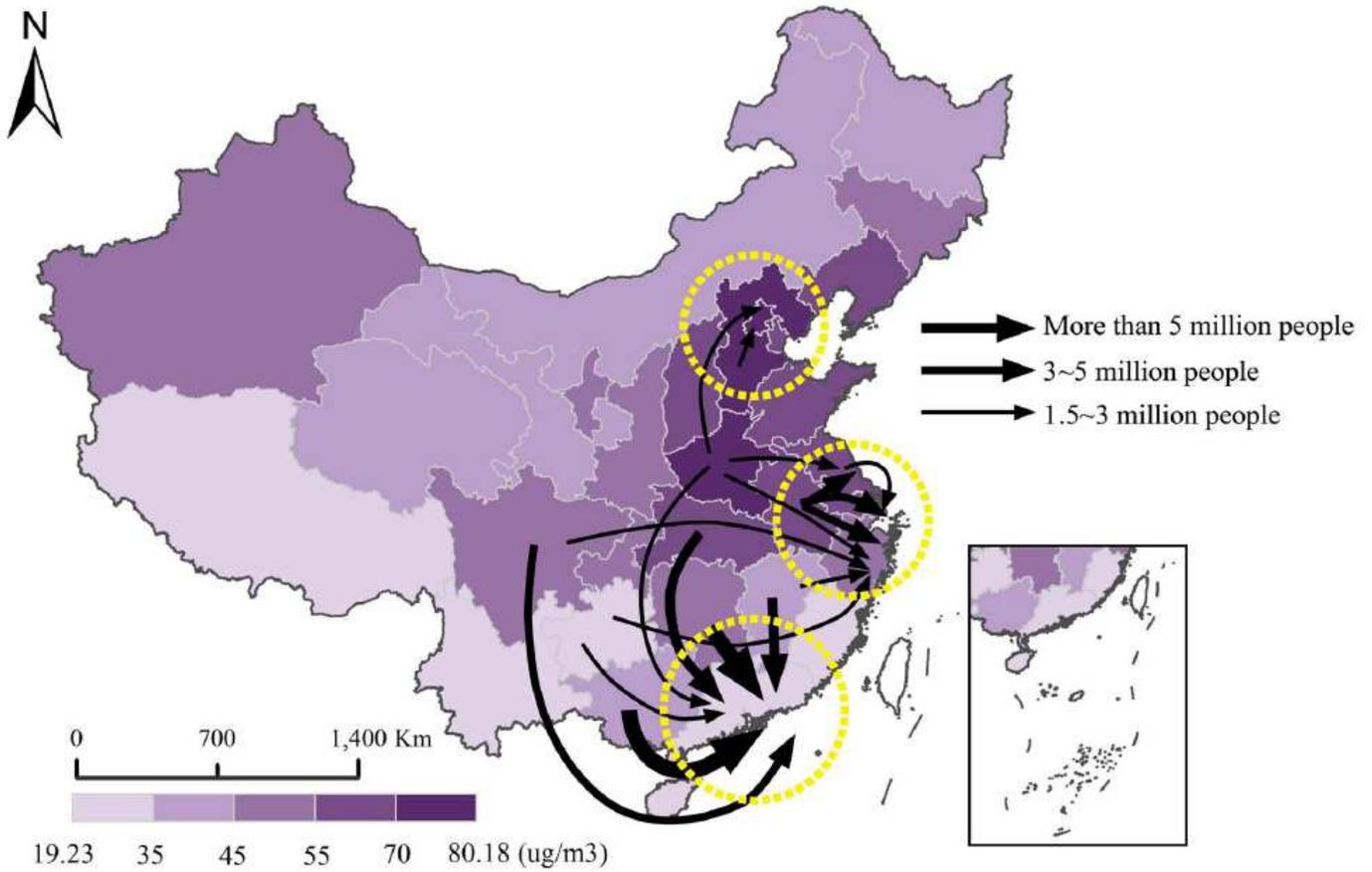


Figure 2

PM2.5 daily average concentration of each province and main inter-provincial migration directions in China in 2015. The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

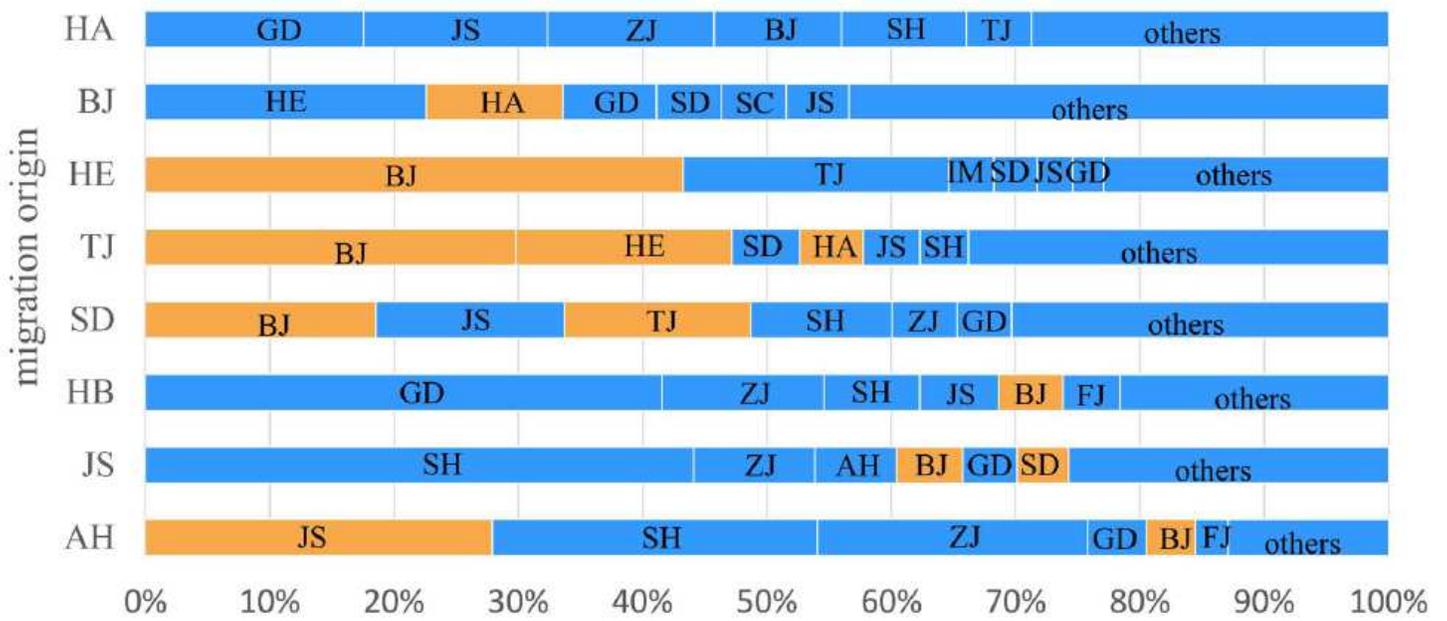


Figure 3

The migration direction of migrants from the provinces with serious air pollution. The provinces with the highest PM2.5 concentration are shown on the y axis. Orange indicates migration to a more polluted province, while blue means less pollution.

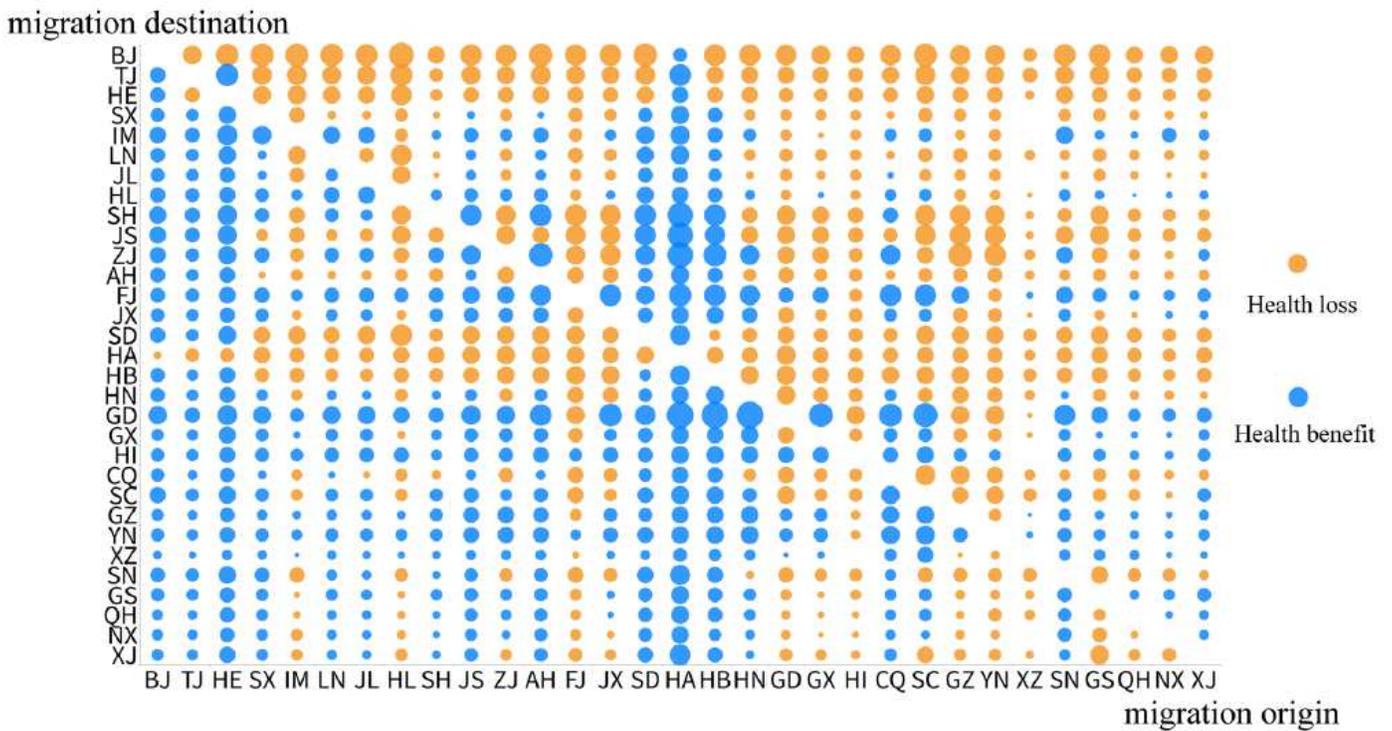


Figure 4

Changes in health effects related to air pollution caused by inter-provincial migration in 2015. Orange indicates an increase in pollution after migration (i.e., health loss), while blue means a decrease in pollution (health benefit). The bubble size indicates the relative amount of change. The data show the logarithm of the amount of health effects.

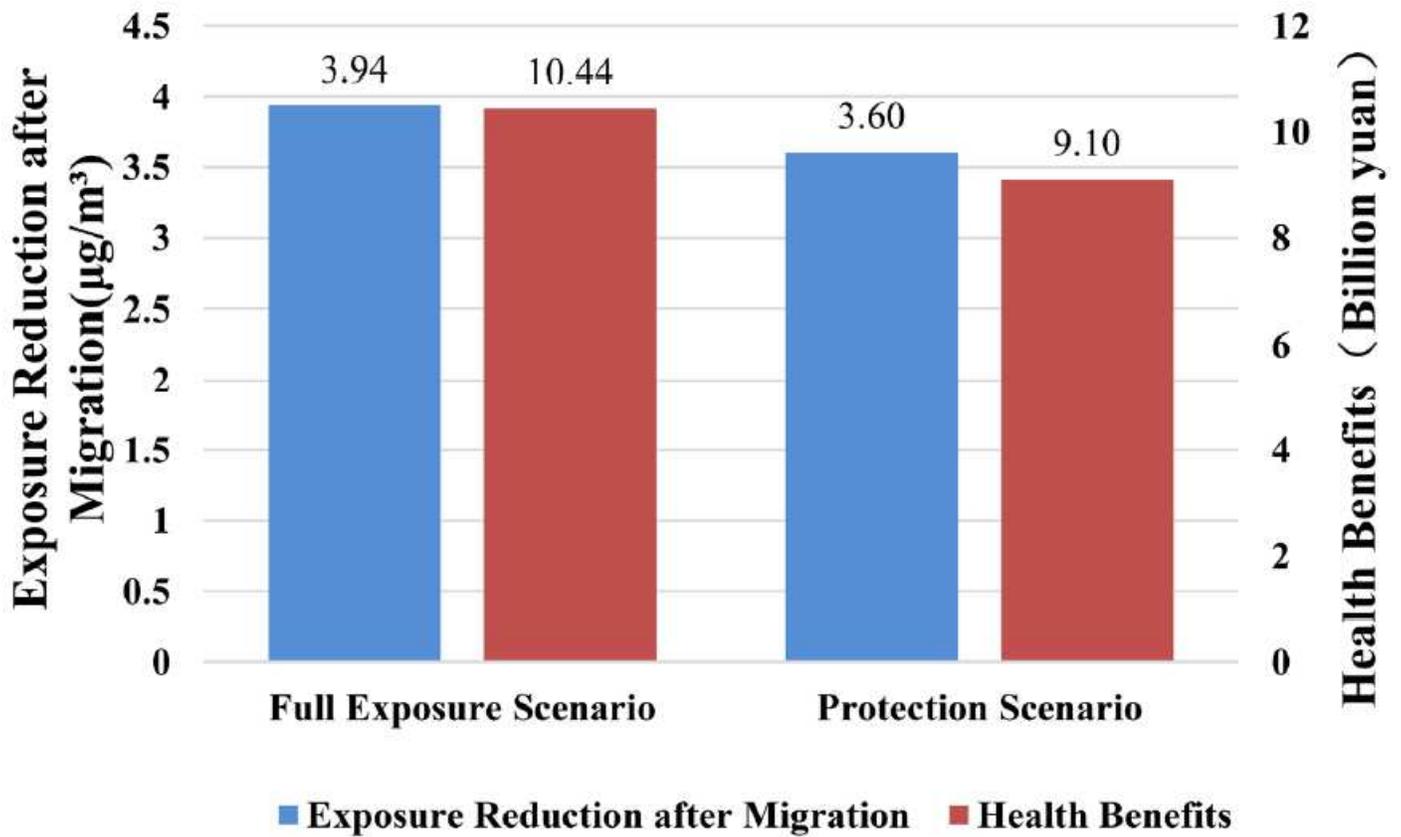


Figure 5

Comparison of full exposure scenario and protection scenario.

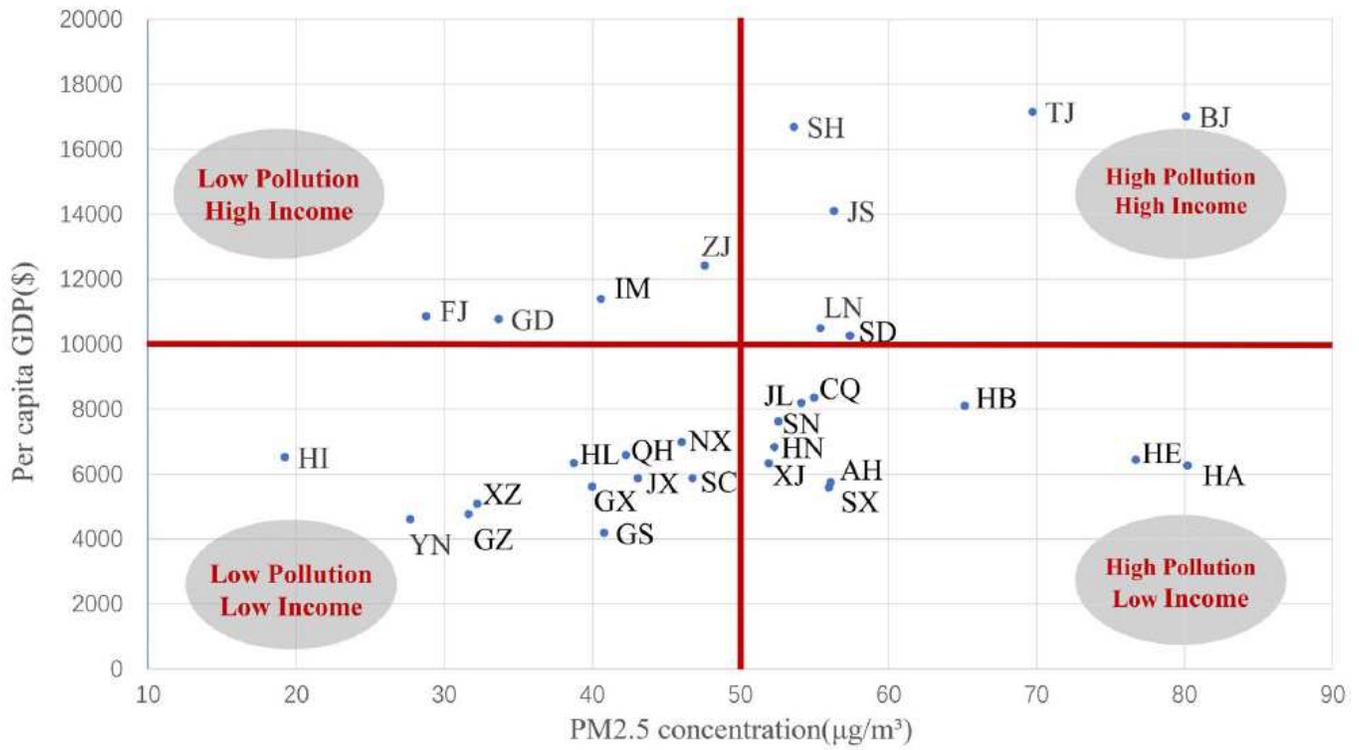


Figure 6

PM2.5 concentration and per capita GDP of 31 provinces in China in 2015 divided into four categories: high pollution and high income; low pollution and high income; low pollution and low income; and high pollution and low income.