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Original Research

Air pollutant emissions induced by rural-to-urban migration during China's urbanization (2005–2015)

Guang Shi [a], Xi Lu [a, b, c, d, *], Hongxia Zhang [e], Haotian Zheng [a, d], Zhonghua Zhang [a], Shi Chen [a], Jia Xing [a, d], Shuxiao Wang [a, d]

[a] *State Key Joint Laboratory of Environment Simulation and Pollution Control and School of Environment, Tsinghua University, Beijing, 100084, PR China*
[b] *Institute for Carbon Neutrality, Tsinghua University, Beijing, 100084, PR China*
[c] *Beijing Laboratory of Environmental Frontier Technologies, Tsinghua University, Beijing, 100084, PR China*
[d] *State Environmental Protection Key Laboratory of Sources and Control of Air Pollution Complex, Beijing, 100084, PR China*
[e] *School of Applied Economics, Renmin University of China, Beijing, 100872, PR China*

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ABSTRACT

As the world's most populous country, China has witnessed rapid urbanization in recent decades, with population migration from rural to urban (RU) regions as the major driving force. Due to the large gap between rural and urban consumption and investment level, large-scale RU migration impacts air pollutant emissions and creates extra uncertainties for air quality improvement. Here, we integrated population migration assessment, an environmentally extended input–output model and structural decomposition analysis to evaluate the NO_x, SO_2 and primary $PM_{2.5}$ emissions induced by RU migration during China's urbanization from 2005 to 2015. The results show that RU migration increased air pollutant emissions, while the increases in NO_x and SO_2 emissions peaked in approximately 2010 at 2.4 Mt and 2.2 Mt, accounting for 9.2% and 8.7% of the national emissions, respectively. The primary $PM_{2.5}$ emissions induced by RU migration also peaked in approximately 2012 at 0.3 Mt, accounting for 2.8% of the national emissions. The indirect emissions embodied in consumption and investment increased, while household direct emissions decreased. The widening gap between urban and rural investment and consumption exerted a major increasing effect on migration-induced emissions; in contrast, the falling emission intensity contributed the most to the decreasing effect benefitting from end-of-pipe control technology applications as well as improving energy efficiency. The peak of air pollutant emissions induced by RU migration indicates that although urbanization currently creates extra environmental pressure in China, it is possible to reconcile urbanization and air quality improvement in the future with updating urbanization and air pollution control policies.

1. Introduction

As the world's most populous country, China witnessed fast urbanization in past decades, with the urbanization rate increasing from 11.2% in 1950 to 59.6% in 2018, among which the population migration from rural to urban regions (RU migration) acted as the major driving force [1–4]. In addition, the scale of the floating population increased from 121 million in 2000 to 241 million in 2018 [2], among which more than 50% are migrants from rural to urban regions (RU migrants). Meanwhile, most Chinese cities still face the problem of air pollution, although the implementation of a series of control policies, such as the *Action Plan of Air Pollution Prevention and Control*, has significantly improved air quality [5]. In 2018, the annual ambient $PM_{2.5}$ concentration in 56.2% of 338 prefecture-level cities in China was higher than 35 μ g m^{-3}, the tier-2 limit of the *National Ambient Air Quality Standards*, and only 2.4% of the cities had concentrations lower than 15 μ g m^{-3} [6,7]. The concentration in some large-scale city agglomerations was even higher, such as the Beijing-Tianjin-Hebei region (60 μ g m^{-3}) and Yangtze River Delta (44 μ g m^{-3}) [6]. In 2018, 27.6% of the world premature deaths caused by $PM_{2.5}$ pollution (1.8 million out of 6.4 million) were in China [8]. Some studies found that RU migration

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[*] Corresponding author. School of Environment and Institute for Carbon Neutrality, Tsinghua University, Beijing, 100084, PR China.
E-mail address: xilu@tsinghua.edu.cn (X. Lu).

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during the urbanization process decreased indoor air pollution exposure since urban households consumed much fewer solid fuels than their rural counterparts [9], while premature deaths caused by ambient air pollution were exacerbated [10,11].

On the other hand, RU migration also increases air pollutant emissions in totality due to the significant differences in rural and urban lifestyles. Although rural income levels have continued to increase in recent decades, urban per capita income still trebles rural counterparts, leading to much higher urban consumption of goods and energy [1,12]. Increasing urban residents also requires supporting infrastructure and city expansion, which means extra investment and material inputs [13–15]. Such an increase in consumption and investment concomitant with RU migration drives extra air pollutant emissions, posing challenges to continuous air quality improvement. The Chinese government has implemented long-term air pollution control measures and proposed the 2035 ‘Beautiful China’ target, which requires the annual $PM_{2.5}$ concentration in all cities to be well below 35 $\mu g\ m^{-3}$ by 2035 [5]. To achieve this goal, it is important to understand the dynamic influence of RU migration on air pollution.

Previous studies have mainly adopted econometric regression methods to explore the relationship between urbanization and air pollution. Research on countries worldwide shows that with the development of urbanization and the economy, the influence of urbanization changes from increasing to decreasing air pollution, implicating a relationship of inverted ‘U’ shape between urbanization and air pollution consistent with the environmental Kuznets theory [16–20]. Research on China shows discrepant results due to the selection of different indicators, and the conclusions are quite diverse and could be classified into three categories: 1) urbanization increased air pollution nationally [21,22]; 2) urbanization decreased air pollution and improved air quality [23,24]; and 3) nonlinear relationships, such as inverted ‘U’ shapes, existed between urbanization and air pollution [25,26]. These studies provide macroscopic insights on this topic, while the econometric analysis could hardly demonstrate the pathway along which urbanization exerts influences on emissions. In addition, the contradictory results indicate that the influence of urbanization on air pollution in China is complex and needs to be explored with detailed modeling with RU migration. Some scholars have adopted this framework and evaluated the influence of urbanization-induced population migration on emissions. Shen et al. [27] related rural and urban per capita emissions to RU migration and found that in 2010, RU migration decreased $PM_{2.5}$ emissions from residential and transportation energy consumption by 2.3 Tg. With a similar method, Qi and Li [28]found that interprovincial migration in 2010 increased residential carbon dioxide emissions by 24.1 million ton nationally. In our previous work, we integrated a population migration matrix, input–output analysis and emission inventory to evaluate the provincial pattern of NO_x, SO_2 and primary $PM_{2.5}$ emissions induced by RU migration in 2012 [29]. However, few studies have addressed the dynamic influence of urbanization on air pollution as well as the driving factors, which is critical for updating air pollution control and urbanization policies in China.

As a step forward, this study focuses on the time-series variation of NO_x, SO_2 and primary $PM_{2.5}$ emissions induced by RU migration in the urbanization process from 2005 to 2015, during the period in which various air pollution control policies were enforced and the urbanization rate grew rapidly. The emissions of air pollution induced by RU migration were quantified by multiplying the rural and urban emission gaps with the RU migration scale. RU migration was evaluated by the migration model developed in our previous work [29], tuned with data from the National Bureau of Statistics (NBS). The rural and urban per capita emissions from 2005 to 2015 were calculated using an input–output (IO) model and emission inventory. Here, we adopted the national IO tables compiled by the NBS for 2005, 2007, 2010, 2012 and 2015, which offer long-term production and consumption data under a consistent framework. In addition, the driving forces of the changes in migration-induced emissions were further explored through structural decomposition analysis (SDA). The results can not only estimate the dynamic contradiction between urbanization and air pollution control but can also provide policy implications from various aspects with an analysis of each driving factor.

2. Data and methods

2.1. Migration from rural to urban regions

The RU migrants in China could be classified into two categories: floating population and *hukou* migrants. *Hukou* location, also referred to as household registration location, is generally the permanent residence for an individual [30]. Since the mid-1980s, due to the economic reform in China, control over migration has been relaxed, and population mobility has increased, with the number of floating populations growing correspondingly [31]. According to the NBS, the floating population is defined as individuals living in a place other than the *Hukou* location for at least 6 months [32]. Since such a floating population lives in a new residence for a relatively long time, their lifestyle and consumption patterns will change, which consequently influences air pollutant emissions. In addition, some people directly change their *hukou* location when migrating to their new residence, which is defined as *hukou* migration in this research.

To evaluate the scale of the RU floating population from 2005 to 2015, we used the migration data from the sixth national population census of the People's Republic of China in 2010 [33] and the National Population Sample Survey of 2005 and 2015 [34,35]. These databases collected the migration matrix of the floating population among 31 provinces/municipalities (excluding Hong Kong, Macao and Taiwan). By summing the provincial RU migration, we obtained the national RU floating population of 2005, 2010 and 2015 and then adopted linear interpolation to evaluate the annual value of years in between. For *hukou* migration, we collected demographic data from the *China Population & Employment Statistical Yearbook* [36] and evaluated *hukou* migration into the urban region of each province with Eq. (1):

$$Imm_{i,t} = Uh_{i,t} - Uh_{i,t-1} \times (1 + R_{i,t}) \tag{Eq. 1}$$

In Eq. (1), i refers to each province/municipality; t refers to the year; Imm refers to *hukou* migration into urban regions; Uh refers to the population with urban *hukou* at the end of each year; and R refers to the annual natural growth rate of the population. We assumed that *hukou* migration into urban regions has the same source structure as the floating population and extract the RU *hukou* migration matrix from the total *hukou* immigration for each province. By aggregating the provincial data, we obtained annual national RU *hukou* migration.

2.2. Air pollutant emissions of rural and urban populations

The present analysis focused on three types of criteria air pollutants, namely, NO_x, SO_2 and primary $PM_{2.5}$. We classified the emissions related to rural and urban residents into three parts: household direct emissions and indirect emissions embodied in both consumption and investment (referred to as consumption emissions and investment emissions in the following sections). The household direct emissions are from household usage of fossil fuels and biomass for cooking, heating and private transportation activities. The consumption and investment emissions were calculated with the Environmentally Extended Input–Output model (EEIO), which is widely used to evaluate the supply chain environmental impacts of human activities [37–41]. Eq. (2) shows the details:

$$E_{j,a} = EF_a \times (I - A)^{-1} \times FD_j \tag{Eq. 2}$$

In Eq. (2), *j* refers to different categories of final demand, including rural and urban household consumption and investment; *a* refers to three types of criteria air pollutants; *E* refers to the indirect emissions embodied in the corresponding final demand category; *EF* is a row vector of emission intensity, elements of which show the direct emissions per unit output for each sector; *I* is an identity matrix; *A* is the direct requirement coefficient matrix derived from the IO table, with each column showing the direct input for the production of one-unit output of each sector; $(I - A)^{-1}$ is the Leontief inverse matrix, with each column showing the total requirement to satisfy per unit final demand for each sector; and *FD* is a column vector of final demand.

The single-region IO tables for China for 2005, 2007, 2010, 2012 and 2015 were obtained from the NBS [42]. The original IO tables differentiated between rural and urban household consumption, while the products and services required by rural and urban investment were combined. To disaggregate the rural and urban investment, we calculated the rural and urban ratio based on fixed asset data and an investment coefficient matrix. We first collected data on investment in fixed assets formed in rural and urban regions from the *Statistical Yearbook of the Chinese Investment in Fixed Assets* [43]. Then, we calculated the product and service input required for rural and urban investment, respectively, with the investment coefficient matrix[1] (see Fig. S1 for details) and obtained the rural–urban ratio. With this ratio, we split the ‘fixed capital formation’ column in the original IO tables into rural and urban types.

The emission data of households and economic sectors were from the Air Benefit and Cost and Attainment Assessment System (ABaCAS) emission inventory [44], which quantifies emissions of unit-based sources, including rural and urban residences, vehicles, industrial boilers, etc. To map it with the IO tables, we reorganized the sectors in the original IO tables into 28 ones (see Table S1; see also our previous work for details of mapping [29]). To facilitate analysis, we further classified these sectors into 8 categories based on their features and functions, namely, *agriculture, mining, raw material manufacturing*, *machine manufacturing*, *daily necessities and other manufacturing*, *power and heat supply*, *construction* and *service*. To eliminate the influence of price and facilitate the SDA (see Section 2.4), we conducted double deflation [38] and converted the IO tables into 2005 prices. We applied different price indices for each category to cover all sectors and fully considered the sectoral differences [45]: 1) producer price index (PPI) of farm products for *agriculture*; 2) PPI of industrial products for *mining*, *manufacturing* and *power and heat supply*; 3) price index of investment in fixed assets for *construction*; 4) retail price index for *wholesale and retail*; and 5) value-added index for *service* other than *wholesale and retail*. All these indices were from the *China Statistical Yearbook* [46]. Finally, combining the results from Eq. (2) and population data from the NBS [2], we obtained the per capita rural and urban emissions of NO_x, SO_2 and primary $PM_{2.5}$.

2.3. Air pollutant emissions induced by RU migration

The emissions induced by RU migration were evaluated with the migration scale and the gap in urban and rural emissions, as shown in Eq. (3).

$$E_{RU} = P_{RU} \times (GE_{Dir} + GE_{Con} + GE_{Inv}) \tag{Eq. 3}$$

In Eq. (3), E_{RU} refers to the emissions induced by RU migration; P_{RU} refers to the population of RU migration; *GE* refers to the gap in rural and urban per capita emissions; and the subscripts *Dir*, *Con* and *Inv* refer to household direct emissions, indirect consumption emissions and investment emissions. Here, we assumed that after migrating into urban regions, RU migrants will change their rural lifestyle to the urban type, and their emission levels will also change to the urban level. Relevant data were obtained with the methods in Sections 2.1 and 2.2.

2.4. SDA for change in emissions induced by RU migration

SDA was developed based on IO analysis and has been widely used to decompose major shifts within an economy over a period to the comparative static changes in underlying factors [47–51]. We adopted SDA to analyze the driving factors for the change in emissions induced by RU migration from 2005 to 2015 with a five-year interval, consistent with the time span of the development plan in China. Combining Eq. (2) and Eq. (3), the migration-induced emission can be classified into three parts, as shown in Eqs. (4–6):

$$E_{RU,\,Dir} = P_{RU} \times GE_{Dir} \tag{Eq. 4}$$

$$E_{RU,Con} = P_{RU} \times GE_{Con} = P_{RU} \times EF \times L \times G_{Con} \tag{Eq. 5}$$

$$E_{RU,Inv} = P_{RU} \times GE_{Inv} = P_{RU} \times EF \times L \times G_{Inv} \tag{Eq. 6}$$

In Eq. (5) and Eq. (6), *L* is the Leontief inverse matrix; *G* is a column vector, with elements showing the gap between rural and urban consumption or investment for each sector in monetary value (in 2005 prices); and the other abbreviations were defined in Eq. (2) and Eq. (3). Based on Eqs. (4–6), the emissions induced by RU migration are determined by six major factors: RU migration scale (P_{RU}), emission intensity (*EF*), production structure (*L*), the gap between urban and rural consumption (G_{Con}), the gap between urban and rural investment (G_{Inv}), and the gap between urban and rural direct emissions (GE_{Dir}). We conducted SDA for Eqs. (4–6) separately, with the decomposition form shown as Eqs. (7–9):

$$\Delta E_{RU,\,Dir} = \Delta P_{RU} \cdot GE_{Dir} + P_{RU} \cdot \Delta GE_{Dir} \tag{Eq. 7}$$

$$\begin{aligned}\Delta E_{RU,Con} = {} & \Delta P_{RU} \cdot EF \cdot L \cdot G_{Con} + P_{RU} \cdot \Delta EF \cdot L \cdot G_{Con} \\ & + P_{RU} \cdot EF \cdot \Delta L \cdot G_{Con} + P_{RU} \cdot EF \cdot L \cdot \Delta G_{Con}\end{aligned} \tag{Eq. 8}$$

$$\begin{aligned}\Delta E_{RU,Inv} = {} & \Delta P_{RU} \cdot EF \cdot L \cdot G_{Inv} + P_{RU} \cdot \Delta EF \cdot L \cdot G_{Inv} \\ & + P_{RU} \cdot EF \cdot \Delta L \cdot G_{Inv} + P_{RU} \cdot EF \cdot L \cdot \Delta G_{Inv}\end{aligned} \tag{Eq. 9}$$

In Eqs. (6–9), the denotation Δ represents the change in factors during the study period. Each additive term on the right side of Eqs. (6–9) represents the influence of one changing factor on emission, with other factors constant [52]. The influence of the gap between urban and rural household direct emissions, consumption and investment can be obtained directly from Eqs. (7–9), while the total influence of the RU migration scale should be obtained by summing the terms with ΔP_{RU} in Eqs. (7–9). Similarly, the total effect of emission intensity and production structure should be obtained by summing the terms with ΔEF and ΔL in Eqs. (8-9), respectively. The

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[1] Similar to the direct requirement coefficient matrix (*A* in Eq. (2)), each column of the investment coefficient matrix shows the product and service input required to complete one-unit investment in each sector.

decomposition form of Eqs. (6–9) is not unique, which incurs the nonuniqueness problem [47,53]. With *n* decomposed factors, the number of different decomposition forms is *n!* (i.e., 4! in Eq. (8)). Following the approach reported in the literature, we took the average of all first-order decomposition forms to address this problem [52,54,55].

3. Results

3.1. Per capita emissions of rural and urban populations

As illustrated in Fig. 1, the urban and rural NO_x and SO_2 emissions have similar structures, with indirect emissions embodied in investment and consumption (referred to as investment emissions and consumption emissions in the following sections) accounting for the majority, while the total urban value is much higher than the rural counterpart. In 2015, the urban per capita emission levels were 16.7 kg NO_x and 14.1 kg SO_2, while the rural per capita emissions were 4.6 kg NO_x and 4.8 kg SO_2, respectively. Although the rural population had more household direct emissions resulting from a less clean energy structure than its urban counterpart [56], the total urban emissions were still higher due to the larger scale of consumption and investment. For example, in 2015, the rural household direct emissions of SO_2 were 1.7 kg per capita, higher than the urban value of 0.4 kg per capita. On the other hand, the urban indirect SO_2 emissions were 13.7 kg per capita, among which 69.2% was embodied in investment and 30.8% was embodied in consumption. In contrast, rural indirect emissions were much lower, with a value of 3.1 kg per capita, 48.9% embodied in investment and the other 51.1% embodied in consumption. Such a discrepancy could be explained by the gap between urban and rural economic levels. In 2015, the average urban investment and consumption levels were 26.7 thousand and 17.7 thousand CNY per capita (in 2005 prices, the same below), respectively, while those for the rural population were 4.3 thousand and 6.3 thousand CNY per capita, respectively (see Table S2).

On the other hand, the total primary $PM_{2.5}$ emissions of urban and rural populations were comparable, with an urban value of 5.2 kg per capita and a rural value of 4.1 kg per capita in 2015. Due to the unfavorable energy structure (i.e., coal, biomass) and lack of emission control in rural households [56,57], the household direct primary $PM_{2.5}$ emissions of rural residents were especially high and accounted for 68.5% (2.8 kg per capita) of the total per capita emissions in 2015. The urban household direct emissions were merely 0.1 kg per capita, which allowed the rural per capita total emissions to almost 'catch up' with the urban level. Rural household emissions are one of the main sources of primary $PM_{2.5}$ in China [58].

Urban air pollutant emissions have shown a decreasing trend in recent years, especially for SO_2 and primary $PM_{2.5}$. The urban SO_2 emissions decreased from 26.7 kg per capita in 2005 to 14.1 kg per capita in 2015, representing a decrease of 47.3%. This was because continuously upgraded air pollution control policies promoted a decline in emission intensity [5], which offset the effects of increasing investment and consumption. Since the national NO_x control policy started in 2011, later than that for SO_2 and industrial dust [5], urban NO_x emissions peaked in approximately 2010 at 23.3 kg per capita and then decreased to 16.7 kg per capita in 2015. In comparison, rural NO_x and SO_2 emissions show no obvious decreasing trend. The rural per capita investment and consumption increased by 303.6% and 260.8%, respectively, in the study period, higher than the urban counterpart (251.6% and 204.2%, respectively); thus, the decrease in emission intensity could not offset this increase, resulting in a fluctuation in rural per capita emissions. However, rural per capita primary $PM_{2.5}$ emissions decreased considerably, which was attributed to the rapid decline of household direct emissions from 4.9 kg per capita in 2005 to 2.8 kg per capita in 2015. Due to income growth and infrastructure construction, the demand-side energy structure of rural populations improved with an increasing proportion of clean energy such as electricity [59], leading to declining primary $PM_{2.5}$ emissions. Based on these changes, the urban-rural gap in SO_2 emissions decreased continuously after 2005, and the rural and urban NO_x emissions started to converge in approximately 2010, while the gap in primary $PM_{2.5}$ fluctuated and decreased obviously between 2012 and 2015.

3.2. Peak of emissions induced by RU migration

Fig. 2 shows the air pollutant emissions induced by RU migration from 2005 to 2015. Because the urban per capita emissions were higher than the rural level, RU migration increased the emissions of NO_x, SO_2 and primary $PM_{2.5}$. The increases in NO_x and SO_2 emissions both peaked in approximately 2010, at 2.4 million tons (Mt, 9.2% of national NO_x emissions) and 2.2 Mt (8.7% of national SO_2 emissions), respectively. Due to the decrease in the urban–rural gap in per capita NO_x and SO_2 emissions as well as the slowing RU migration (see Fig. S2) after 2010, the emissions induced by RU migration declined. The peak year of emissions induced by RU migration is consistent with that of national total emissions to some extent. For example, national NO_x emissions entered a plateau in 2010 and decreased after 2013, and the peak year of migration-induced emissions was approximately 2010, which is consistent with the plateau time (see Fig. S3). Since cities are the major energy consumer and air pollutant emitter [60], the

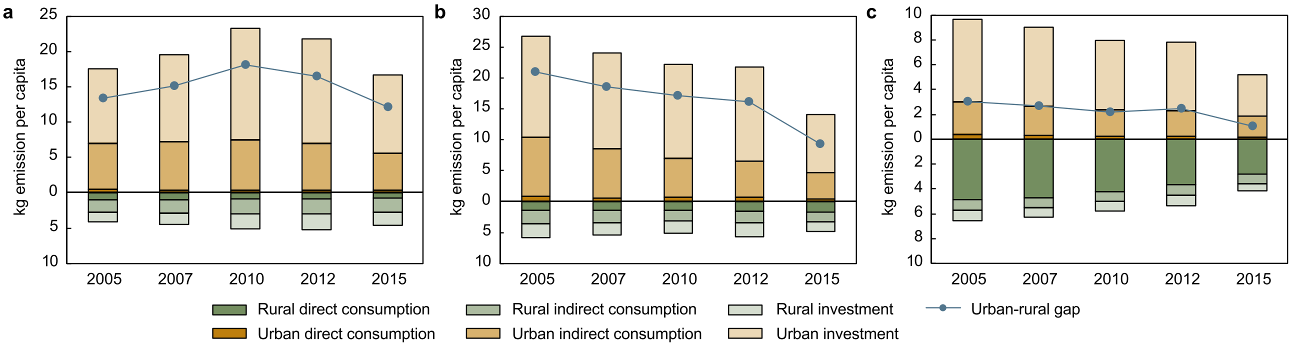

Fig. 1. Per capita NOx (**a**), SO_2 (**b**) and primary $PM_{2.5}$ (**c**) emissions of urban and rural populations and the gap between urban and rural levels. 'Direct consumption emission' refers to the emissions caused by household direct energy use, including cooking, indoor heating and private transport. 'Indirect consumption emission' refers to the indirect emissions embodied in household consumption. 'Investment emission' refers to the indirect emissions embodied in the products and services required by investment activity.

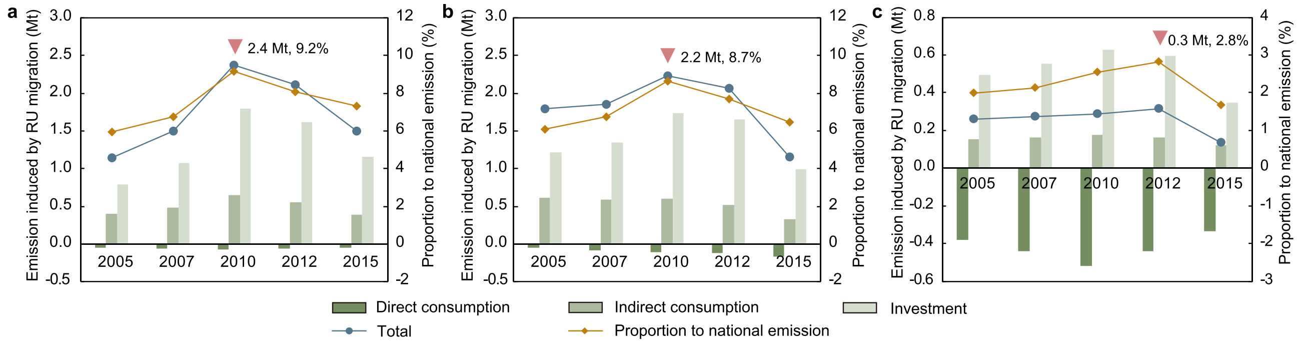

Fig. 2. The change in NOx (**a**), SO_2 (**b**) and primary $PM_{2.5}$ (**c**) emissions induced by RU migration. 'Total' refers to the total emission change, which is the sum of changes in household direct emissions and indirect emissions driven by consumption and investment (direct and indirect consumption and investment emissions). The proportion of total migration-induced emissions to national emissions reflects the extent of influence from RU migration. The triangle indicates the peak year of emission increase for each air pollutant, with the peak amount and proportion beside it.

national total emissions have decreased when urban emissions have been well controlled in recent years [5]. With these measures, urban per capita emissions also decreased, leading to declining emissions induced by RU migration. The primary $PM_{2.5}$ induced by RU migration showed a peak in approximately 2012 with a smaller scale than the other two air pollutants (0.3 Mt, 2.8% of the national emissions) because the urban-rural gap in primary $PM_{2.5}$ was smaller and obviously narrowed only after 2012. In recent years, the Chinese government has implemented coal-to-gas and coal-to-electricity programs to phase out the use of solid fuels for heating in rural regions [59]; thus, the rural per capita emissions of primary $PM_{2.5}$ could decline further in the future. In this case, the gap between urban and rural emissions might increase, and migration-induced emissions might fluctuate.

The total RU migration-induced emissions are classified into household direct emissions, consumption emissions and investment emissions. The investment emissions contributed the most to the emission increase, since the urban-rural gap in investment was larger than that in consumption. In 2015, the gap between urban and rural investment was 22.4 thousand CNY per capita, while that in consumption was 11.3 thousand CNY per capita, 49.4% lower (see Table S2). The emission increase was mainly driven by the soaring demand for products and services in the construction sector, followed by the machine manufacturing and service sectors, which could directly satisfy investment and consumption activities. However, the power and heat supply and raw material manufacturing sectors acted as the actual emitters, which assumed most of the emission pressure induced by RU migration (see Table S1 for details of sector classification). For example, in 2015, 0.7 Mt SO_2 emissions were caused by increasing construction demand, which accounted for 56.1% of the indirect emissions induced by RU migration, followed by machine manufacturing (17.7%) and the service sector (14.7%). On the other hand, 51.0% of the increasing SO_2 emissions (0.7 Mt) was actually emitted by the raw material manufacturing sector, followed by the power and heat supply sector (32.1%) (see Fig. S4). This was because sectors such as construction required large amounts of raw material with high emission intensity (i.e., cement, metal) and electricity as input; thus, their embodied emission intensity was high despite low sectoral direct emissions [57]. For NO_x, another major actual emitter was the service sector, since urbanization augmented the demand for transportation both as an intermediate input and final product and increased NO_x emissions from vehicles [61]. RU migration decreased household direct emissions, especially for primary $PM_{2.5}$, due to cleaner demand-side energy use of urban households [62]. In this case, RU migration could contribute to the reduction of indoor air pollution exposure [9]. Because of the higher demand for private transportation by vehicles of urban households, the gap between rural and urban direct NO_x emissions was smaller than that of the other two air pollutants; thus, the decrease in NO_x household direct emissions was the smallest.

3.3. Impacting factors for emissions induced by RU migration

In this research, we consider the influence of six major factors, including RU migration scale, emission intensity, production structure, the gap between urban and rural consumption, the gap between urban and rural investment, and the gap between urban and rural household direct emissions. Fig. 3 shows the contribution of each factor to the change in emissions induced by RU migration from 2005 to 2015 with a five-year interval. The factors with increasing effects are mainly the urban-rural gap in investment and consumption. The gap between urban and rural investment increased from 9.2 thousand CNY per capita in 2005 to 17.4 thousand CNY per capita in 2010 and further increased to 22.4 thousand CNY per capita in 2015 (see Table S2). This widened investment gap increased the NO_x, SO_2 and primary $PM_{2.5}$ emissions induced by RU migration by 65.1%, 56.1% and 145.4%, respectively, from 2005 to 2010. However, the increasing effect weakened, which increased the emissions of the three air pollutants by 20.5%, 18.4% and 56.2%, respectively, from 2010 to 2015. This was because the growth of urban per capita investment slowed down, decreasing from 9.4 thousand CNY between 2005 and 2010 to 6.7 thousand CNY between 2010 and 2015. At the same time, the growth of rural per capita investment accelerated, increasing from 1.2 thousand CNY between 2005 and 2010 to 1.7 thousand CNY between 2010 and 2015. As a result, the widening of the urban-rural investment gap slowed. The gap between urban and rural consumption and its effect on emissions had a trend similar to those of investment, while the increasing effect of consumption was lower due to the smaller urban-rural gap in consumption compared with investment (see Table S2).

The major factor with a decreasing effect was emission intensity. For example, the declining emission intensity decreased SO_2 emissions induced by RU migration by 109.5% from 2005 to 2010 and further decreased emissions by 67.3% from 2010 to 2015. An SDA analysis for emission intensity showed that improvement of end-of-pipe removal efficiency contributed the most to the emission intensity decrease (see Section S1 in supplementary information). The increasing end-of-pipe removal efficiency decreased the SO_2 emission intensity by 37.0% from 2005 to 2010 and further decreased the emission intensity by 36.4% from 2010 to 2015. Since the 11th Five-Year Plan (2006–2010), the Chinese government has set a restrictive target

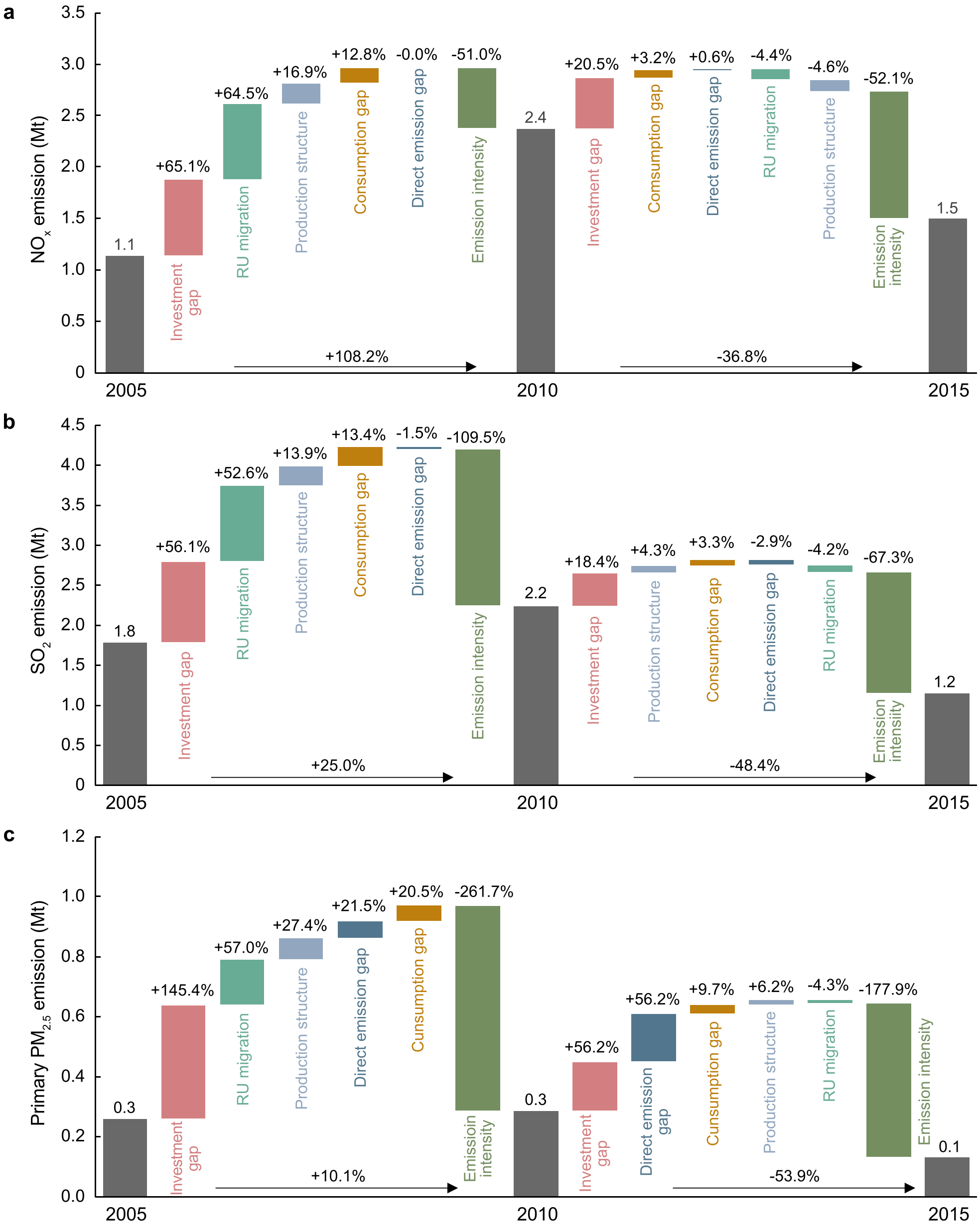

Fig. 3. The contributions to the change in NOx (**a**), SO_2 (**b**) and primary $PM_{2.5}$ (**c**) emissions from six factors induced by RU migration, including RU migration scale, emission intensity, production structure, the gap between urban and rural investment, the gap between urban and rural consumption, and the gap between urban and rural household direct emissions. The gray bar shows the emissions induced by RU migration in 2005, 2010 and 2015. The percentage shows the influence of each factor compared with the emissions induced by RU migration in 2005 and 2010.

on SO_2 reduction, and the penetration rate of flue gas desulfurization in thermal power plants increased from 14% in 2005 to 86% in 2010 [5]. By 2015, 99% of the coal power capacity had deployed desulfurization equipment [63]. The restrictive control on NO_x started later in the 12th Five-Year Plan (2011–2015) but has developed quickly, with the penetration rate of selective catalytic reduction in thermal power plants increasing from 12% in 2010 to more than 80% in 2015 [5]. With the implementation of the *Action Plan of Air Pollution Prevention and Control* in 2013, the emission standards of industrial kilns (i.e., cement, metallurgy) were also tightened, which further reduced industrial primary $PM_{2.5}$ emissions [64]. Another major factor contributing to emission intensity reduction was the improvement of energy efficiency. The growing energy efficiency decreased the SO_2 emission intensity by 16.9% from 2005 to 2010 and further reduced the emission intensity by 14.1% during 2010 and 2015. In the study period, the energy consumption per unit output declined by 43.9%, which helped reduce air pollutant emissions from the source. On the other hand, the adjustment of the energy structure contributed slightly to the decrease in emission intensity from 2005 to 2015 (less than 2%, see Fig. S6), indicating that there is still potential for energy structure improvement. In recent years, the Chinese government has accelerated the development of renewable energy. In 2019, the proportion of nonfossil fuel energy in primary energy consumption increased to 15.3%, and the proportion of renewable electricity to total electricity production reached 32.7% [65].

The effect of the RU migration scale changed from increasing to decreasing migration-induced emissions because after 2010, the scale of RU migration slightly decreased (see Fig. S2). One possible reason for this is that the Chinese government has conducted rural revitalization and poverty eradication strategies in recent years, with the development of both the rural economy and environmental quality [1,66]; thus, more rural populations choose to stay. However, *hukou* migration has shown an increasing trend in recent years (see Fig. S1) due to the reforms of the *hukou* and residential permit system, which make it easier to change the *hukou* registered place [1]. Another factor with a changing effect was the production structure, which increased migration-induced NO_x emissions by 16.9% between 2005 and 2010 but decreased it by 4.6% between 2010 and 2015. For SO_2 and primary $PM_{2.5}$, the increasing effect of the production structure also weakened obviously. From 2010 to 2015, the forward linkage[2] [38] of some sectors decreased, especially sectors with high emission intensity, such as power and heat supply, nonmetal mineral products and transportation and postal service (see Fig. S5), indicating improved efficiency of material and energy usage during production. In recent decades, the Chinese government has carried out energy-saving measures continuously, developed rail transportation, especially high-speed rail, and eliminated overcapacity after entering the new normal stage [67–70]. These policies have increased production and transportation efficiency, thus contributing to air pollutant control.

For primary $PM_{2.5}$, the change in the gap in household direct emissions also contributed significantly to the increase in RU migration-induced emissions. As shown in Fig. 2, RU migration decreased the household direct emissions of primary $PM_{2.5}$. However, due to the decrease in rural household direct emissions (see Fig. 1), the emission reduction induced by RU migration shrank; thus, the change in the household direct emission gap exerted an increasing effect on migration-induced emissions.

4. Discussion

The results of the present analysis indicate that in China, urbanization causes extra environmental pressure and contradicts air quality improvement to some extent. However, the peak of emissions induced by RU migration and its decline in recent years shows that with updating urbanization and air pollution control policies, it is possible to minimize or even eliminate the contradiction between urbanization and air quality improvement in the future. For example, in developed countries whose urbanization has already entered the mature stage, such as Austria, the urban per capita carbon footprint is lower than the rural counterpart due to the agglomeration effect of cities [71]. In this case, RU migration and an increasing proportion of the urban population will decrease emissions and create environmental cobenefits. Currently, in China, both urban air pollutant emissions and the carbon footprint are higher than their rural counterparts [72]. Such a phenomenon does not mean we should constrain the development of urbanization, and it indeed emphasizes the importance of controlling urban per capita emissions by making full use of the agglomeration benefits and guiding the scientific development of cities [60,71].

Policies should be taken to maintain the decreasing trend of migration-induced emissions. The SDA shows that the reduction in air pollutant emission intensity is the largest decreasing factor; thus, whether it continues to decrease in the future will determine the trend of migration-induced emissions. To further reduce the air pollutant emissions from industrial sectors, the Chinese government has promoted ultralow emission retrofitting in emission-intensive sectors, such as electricity generation and steel and building material production [73]. However, some studies have found that reliance merely on end-of-pipe control technologies is not enough, and decarbonization of the energy supply, such as promoting renewable energy, plays a key role in future air quality improvement and could also decrease CO_2 emissions [74,75]. According to our results, the adjustment of the energy structure exerted a limited decreasing effect on emission intensity from 2005 to 2015 (see Fig. S6). Hence, future reductions in air pollutant emission intensity and the emissions induced by RU migration will largely depend on the decarbonization of the energy system. Another factor that might contribute to the decrease in migration-induced emissions is the production structure. As our results show, the production structure has improved to some extent in recent years, with decreasing reliance on some raw material sectors, such as electricity, nonmetal mineral products and transportation. However, the reliance on the highly emitting chemical industry and metallurgy increased from 2005 to 2015 (see Fig. S5), indicating that the production structure still requires further transformation. Production in China generally relies more on material input, while producer services, the service sector providing intermediate input for production, have not been fully developed [76]. Economic structural transformation should be further promoted to increase the proportion of producer services, and material efficiency should be improved through technology updating and recycling.

We adopted the Monte Carlo method to measure the uncertainty of the results (see Section S2 in the supplementary information for details). Taking 2015 as an example, the 95% confidence intervals of migration-induced emissions are [1.2 Mt, 2.1 Mt] (or [−18.9%, 40.2%] around the central value) for NO_x, [0.9 Mt, 1.6 Mt] (or [−20.3%, 39.7%]) for SO_2, and [0.0 Mt, 0.4 Mt] (or [−74.7%, 225.7%]) for primary $PM_{2.5}$. The uncertainty for primary $PM_{2.5}$ is much higher because of the high uncertainty of the primary $PM_{2.5}$ emission inventory (see Table S6). The uncertainty mainly comes from the emission inventory and the proportion of rural and urban investment, indicating the importance of improving emission inventory compilation and distinguishing rural and urban investment in the original IO tables. Since the influence of urbanization on air pollution is complex, there are some limitations in this study that need to be addressed in future research. First, since this study focuses on the time dynamics of RU migration-induced emissions, we adopted national input–output tables, which were compiled with higher frequencies and covered longer time spans; however, they could not implicate regionally differentiated policies. For future research, it is critical to adopt multiregional input–output tables after they are compiled for more years to conduct time-dynamic and multiregional research. In addition, in this research, we do not consider the demographic characteristics of migrants, such as age and household size, due to data limitations. These demographic characteristics could influence the emission level and thus cause changes to our results. For example, a shift to aging and small households will lead to more energy use and carbon emissions [77]. We suggest that future research take such demographic transformation into consideration and investigate more detailed influences of migration.

5. Conclusions

The urban per capita emissions of NO_x and SO_2 are much higher

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[2] Forward linkage refers to the change of one sector's output when the final demand for all sectors increases by one unit. It shows how one sector supports the production of other sectors by providing intermediate input. Higher value means the sector provides more raw material or basic services. In this research, we calculated this index for each sector by summing up the elements of each row in the Leontief matrix (L).

than the rural levels due to higher urban consumption and investment. In 2015, the urban NO_x and SO_2 emissions were 16.7 and 14.1 kg per capita, respectively, while the rural values were 4.6 and 4.8 kg per capita, respectively. The urban and rural emissions of primary $PM_{2.5}$ were comparable, which were 5.2 and 4.1 kg per capita, respectively, in 2015 due to the high rural household direct emissions. With increasingly stringent air pollution control policies, urban per capita emissions have been decreasing in recent years. The gap between urban and rural per capita NO_x and SO_2 emissions witnessed an evident decrease.

RU migration increased air pollutant emissions, but the emission increase peaked. The NO_x and SO_2 emissions induced by RU migration peaked in approximately 2010, at 2.4 Mt (9.2% of national NO_x emissions) and 2.2 Mt (8.7% of national SO_2 emissions), respectively, and migration-induced primary $PM_{2.5}$ emissions peaked in approximately 2012 at 0.3 Mt (2.8% of the national emissions). The indirect consumption and investment emissions increased, with the latter contributing the most to the emission increase, while household direct emissions decreased, especially for primary $PM_{2.5}$.

The major factors with increasing effects on emissions induced by RU migration are the widening urban-rural gap in investment and consumption, while the effect has weakened due to the slowing growth of urban investment and consumption. Falling emission intensity contributed the greatest decreasing effect, benefitting from the improvement of end-of-pipe removal and energy efficiency. The effect of the RU migration scale changed from increasing to decreasing emissions because after 2010, RU migration slightly decreased. Similarly, the production structure increased migration-induced NO_x emissions by 16.9% between 2005 and 2010 but decreased it by 4.6% between 2010 and 2015, indicating an improvement in production efficiency.

The peak of air pollutant emissions induced by RU migration indicates that although urbanization contradicts air quality improvement currently in China, it is possible to make urbanization and air quality targets consistent in the future with updated policies. Actions should be taken to control urban per capita emissions by making full use of the agglomeration benefits. Both updating end-of-pipe control technologies and decarbonization of the energy system should be emphasized for a further decline in emission intensity. In addition, the production structure should be transformed by increasing the proportion of producer services and decreasing the reliance on material input.

CRediT authorship contribution statement

Guang Shi: Methodology, writing-original draft. Xi Lu: Methodology, writing-review and editing. Hongxia Zhang: Providing data. Haotian Zheng: Providing data. Zhonghua Zhang: Methodology. Shi Chen: Writing-review and editing. Jia Xing: Writing-review and editing. Shuxiao Wang: Writing-review and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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