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Balance between poverty alleviation and air pollutant reduction in China

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Abstract

Key targets of the sustainable development goals might be in contradiction to each other. For example, poverty alleviation may exacerbate air pollution by increasing production and associated emissions. This paper investigates the potential impacts of achieving different poverty eradication goals on typical air pollutants in China by capturing household consumption patterns for different income groups and locations, and linking it to China's multi-regional input-output table and various scenarios. We find that ending extreme poverty, i.e. lifting people above the poverty line of USD 1.90 a day in 2011 purchasing power parity (PPP), increases China's household emissions by only less than 0.6%. The contribution increases to 2.4%–4.4% when adopting the USD 3.20 PPP poverty line for lower-middle-income countries. Technical improvements in economic sectors can easily offset poverty-alleviation-induced emissions in both scenarios. Nevertheless, when moving all impoverished residents below the USD 5.50 PPP poverty line for upper-middle-income countries, household emissions in China would increase significantly by 18.5%–22.3%. Counteracting these additional emissions would require national emission intensity in production to decrease by 23.7% for SO_2, 13.6% for NO_x, 82.1% for $PM_{2.5}$, and 58.0% for PM_{10}. Required synergies between poverty alleviation and emission reduction call for changes in household lifestyles and production.

1. Introduction

Ending poverty is one of the overriding goals on the global development agenda [1]. The first of the United Nation's sustainable development goals (SDG1) proposes to eradicate extreme poverty (living on an income below the World Bank's international poverty line of USD 1.90 a day) worldwide and to progressively reduce relative poverty (living in poverty according to the national situation) by 2030 [2]. However, the ensuing expansion in consumption is linked to increases in production, and associated resource consumption and air pollution endangering human health and welfare [3–5]. This in turn has impacts on SDG3 'Ensure healthy lives and promote well-being for all'. Coping with conflicts between efforts to address poverty and pollution issues, and potential trade-offs with other SDGs are critical challenges facing the world today [6, 7].

As the world's most populous country, China until quite recently had the largest poor population [8] and is still suffering from the world's largest air pollution-related health burden [3, 9, 10]. China's efforts are crucial in realizing the aforementioned SDGs. On the one hand, China has successfully implemented poverty alleviation initiatives such

as *the Rural Minimum Living Standard Guarantee Program* [11] and *the Development-oriented Poverty Reduction Program* [12]. Those initiatives have lifted 868 million people out of extreme poverty from 1981 to 2016 and contributed 72% of the world's total progress in eliminating poverty [8, 13]. On the other hand, after the promulgation of *the Action Plan of Air Pollution Prevention and Control* in 2013, measures such as strengthening emission standards, eliminating highly polluting and inefficient production sites, and promoting clean energies have been introduced in the power, industry, and transportation sectors [14–16]. These strategies have made remarkable progress in emission control and air quality improvements [17]. For example, national annual mean concentrations of $PM_{2.5}$, although still high, dropped significantly by about 30% from 2013 to 2017 [18, 19].

Recently, China has been exploring more ambitious post-2020 agendas for the two SDGs, which may lead to a more intense poverty-emission reduction conflict. First, after ending absolute poverty (defined by the Chinese government as living below China's current national poverty line, i.e. 2300 yuan per person per day at 2010 constant prices) in 2020, China is determined to continue eliminating relative poverty [20]. According to the World Bank's latest data, in 2016, about 75 million Chinese people were still living below the poverty line of USD 3.20 a day in 2011 purchasing power parity (PPP) (i.e. the poverty line for lower-middle-income countries). This number further rises to 330 million when adopting the poverty line consistent with China's current stage of development (i.e. the poverty line for upper-middle-income countries, USD 5.50 a day in 2011 PPP) [8, 13, 21]. Second, China still faces great challenges in air quality attainment. China committed to reduce its annual mean $PM_{2.5}$ concentrations to 35 μg m^{-3} in all cities by 2035 [22]. Taking the Beijing-Tianjin-Hebei region as an example, accomplishing this target requires reduction of emissions of major pollutants by 75%–85% compared to 2014 levels [23]. Prior to implementing China's new Five-year Plan, understanding the poverty-emission reduction conflict in China is crucial to the solution.

Quantifying the conflicts between poverty alleviation and pollution reduction is an emerging area of interest. Previous studies have investigated environmental impacts (e.g. CO_2 emissions [24–26], land use and deforestation [27]) of specific poverty-alleviation policies. For example, Chakravarty *et al* [26] and Rogelj *et al* [28] have measured additional CO_2 emissions caused by ensuring universal access to modern energy and basic energy services at a global scale, while some national-level studies have evaluated the environmental effects of targeted poverty alleviation via specific projects [25, 29]. Yet less is known about the impacts of poverty alleviation on other forms of pollution, and most research focused

on direct impacts, such as emission implications of switching the poor from traditional to modern means of energy [28]. Indirect impacts via reshaping consumption patterns and associated supply chain emissions are often overlooked [30–32]. Taking both direct and indirect impacts into consideration, Hubacek *et al* [33] projected the carbon consequences of poverty eradication by combining a consumption-based accounting framework with scenario analysis methods. However, as a global-level study, it ignored significant regional and urban-rural heterogeneities within countries.
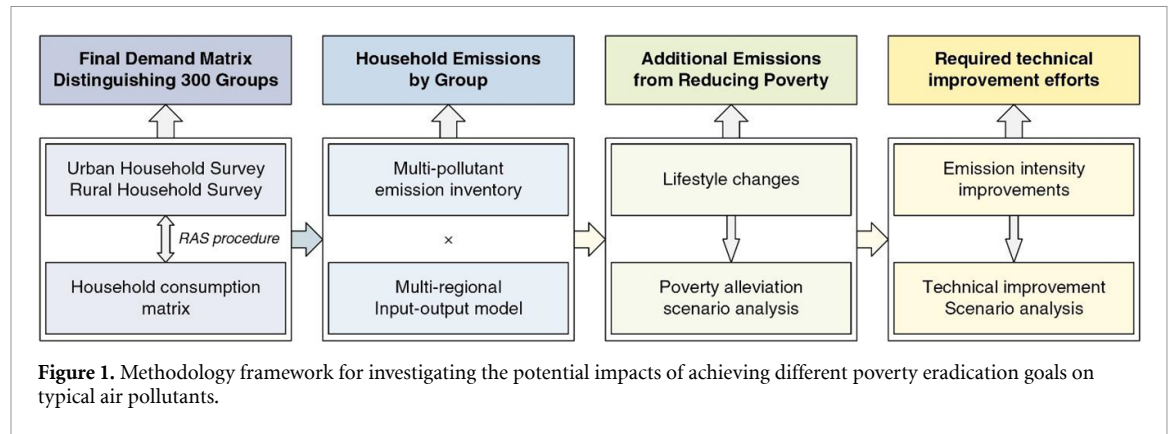
Here we investigate the potential conflict between China's poverty alleviation targets and emission reduction targets, by capturing household consumption patterns for different income groups and locations at a high level of detail, and linking it to China's multi-regional input-output (MRIO) table and various poverty scenarios. The implications of technical improvements on relieving the additional emission mitigation pressure from eliminating poverty are also discussed. To our knowledge, this is the first study investigating the overall impact of achieving different poverty alleviation goals on atmospheric emissions in China. Unlike previous studies that concentrate on carbon implications of poverty alleviation, this study sheds light on SO_2, NO_x, $PM_{2.5}$, and PM_{10} emissions, which are the most significant contributors to China's numerous health burdens [34, 35]. Our findings may provide valuable information for coordinating China's poverty alleviation, emission reduction, and health management targets, with potential relevance for other emerging economies to develop their pathway towards a sustainable future.

2. Materials and methods

The research framework consists of four major steps (see figure 1). First, we develop a household final demand matrix, which distinguishes expenditure patterns of 300 household groups reflecting differences in terms of income and urban/rural divide for different provinces. Second, taking provincial disparities in technologies into consideration, our study combines the MRIO table in China and the matrix above to account for household-related emissions per group. Third, through the poverty alleviation scenarios, we estimate the additional emissions from reducing poverty. Finally, considering that technological progress could reduce the pollution from production processes [14, 36], a series of technical improvement sub-scenarios are defined to estimate the required endeavors of economic sectors to offset the extra emissions.

2.1. Developing a household final demand matrix for different income groups

The household final demand matrix in the MRIO table serves as a critical input for emissions

Figure 1. Methodology framework for investigating the potential impacts of achieving different poverty eradication goals on typical air pollutants.

accounting. To identify the final consumption of different household groups, we decompose each province's final demand vector based on group-level consumer expenditure. Compared with previous attempts [31, 37, 38], the newly established household final demand matrix preserves the consumption pattern characteristics provided by statistical agencies to the maximum extent.

The original MRIO table is obtained from Zhang *et al* [39], which characterizes trade information between 30 provinces and 26 aggregated sectors (see table S1 in supplementary materials (available online at stacks.iop.org/ERL/16/094019/mmedia)). The expenditure data used in this study originates from the Urban Household Survey (UHS) and Rural Household Survey (RHS) organized by the National Bureau of Statistics (NBS) [40, 41]. Owing to difficulties in obtaining UHS and RHS micro-datasets [42] and the weights of each sampled household, the average data of different household groups reported in dozens of yearbooks is commonly regarded as the best available data for macro studies in China [40, 41, 43]. However, two major challenges hinder the application of household survey data in household emission research: (a) inconsistent aggregation of group-level expenditure patterns in different provinces; (b) mismatch between expenditure commodity categories in household surveys (e.g. grains, garments, housing) [40] and economic sectors in the MRIO table (e.g. coal mining, textiles, chemical industry) [44]. Further details are summarized in the supplementary materials.

To align group-level household expenditure categories across provinces, we assume that people with higher similarities in primary expenditure structure (PES) bear a stronger resemblance to each other in detailed expenditure patterns. Here the PES is determined by eight aggregated categories (including food, clothing, residence, household facilities, transport, education, health, and others), located on the top of expenditure trees obtained from China's statistics [40]. Referring to Cao *et al* [45], we measure the similarity of expenditure patterns between groups by Kullback-Leibler divergence as follows:

$$
\mathrm{KL}^{mn} = \left(\sum_{i=1}^{K} \left(E_i^m \times \log \frac{E_i^m}{E_i^n} \right) \right.
$$
$$
\left. + \sum_{i=1}^{K} \left(E_i^n \times \log \frac{E_i^n}{E_i^m} \right) \right) / 2 \qquad (1)
$$

where KL^{mn} is the Kullback-Leibler divergence of expenditure patterns between group m and n; E_i^m and E_i^n are group m's and n's expenditures on item i; K is the number of expenditure items considered.

Considering China's urban-rural duality [46, 47], this study deals with urban and rural data separately. First, we fill in the household expenditures available at all levels according to the expenditure tree. Applying the criteria that grouped data should be available in at least ten provinces, the multi-level expenditure categories used here are determined (see details in table S2 and table S3 in the supplementary materials). To deal with the missing data, three approaches are adopted:

- For the target group with missing expenditure items but complete PES, we find all groups with complete data on the target group's missing items, and select the most similar group (MSG) based on their PES. Using MSG's expenditures as proxies, the missing items are then supplemented according to the order of the expenditure tree (from top to bottom).
- For the target group with missing PES but available total expenditure, we list all provinces with complete grouping data for all items considered in this study, and identify the province whose expenditure pattern is most similar to where the target group comes from (i.e. the most similar province (MSP)). Taking expenditures of the corresponding group in MSP as proxies, the total expenditure of the target group can be split.
- For ungrouped provinces (UGP), we find its MSP using the same approach and scale up the group-level data of MSP based on UGP's and MSP's total expenditures.

To handle the mismatch problem, we introduce a matrix scaling procedure (RAS method) in building

the correspondence relationships between different expenditure items and economic sectors [48, 49]. As a method widely used for balancing IO tables, its application herein aims to simultaneously preserve household expenditure patterns derived from statistics and household consumption structures reflected in the MRIO. The initial correspondence matrix (see table S4 and table S5 in the supplementary materials) is developed based on NBS's definitions for expenditure items [40] and economic sectors [41]. Through iterations, the eventual correspondence matrix for province q and urban/rural divide u ($u = 1$: rural, $u = 2$: urban) $\boldsymbol{M^{qu}}$ can be obtained (see supplementary materials for details). The grouped expenditures are then allocated to the MRIO sectors as follows:

$$F_{l,ji}^{qu} = E_{l,i}^{qu} \times \frac{M_{ij}^{qu}}{\sum_{j=1}^{J} M_{ij}^{qu}} \tag{2}$$

where $E_{l,i}^{qu}$ and $F_{l,ji}^{qu}$ are province q urban/rural group l's expenditure on item i and that allocated to economic sector j, respectively.

Finally, we build a household final demand matrix $\boldsymbol{F}$ that distinguishes the final demand of 300 household groups from different provinces, differentiating between urban/rural divide, income, and multiple expenditure categories (52 for urban households, 8 for rural households):

$$\boldsymbol{F} = [\boldsymbol{F^1} \ \boldsymbol{F^2} \ \dots \ \boldsymbol{F^P}];$$
$$\boldsymbol{F^q} = [\boldsymbol{F_1^{q1}} \ \boldsymbol{F_2^{q1}} \ \dots \ \boldsymbol{F_L^{q1}} \ \boldsymbol{F_1^{q2}} \ \boldsymbol{F_2^{q2}} \ \dots \ \boldsymbol{F_L^{q2}}] \tag{3}$$

where P refers to the number of provinces; $\boldsymbol{F^q}$ is province q's household final demand matrix; $\boldsymbol{F_l^{qu}}$ is the sub-matrix for urban/rural province q's income group l; L is the number of income groups. Residents in each province are divided into ten income groups (five for rural and five for urban).

2.2. Accounting household emissions by group

Household emissions comprise direct emissions during household direct energy use, as well as indirect emissions associated with the production of goods and services a household consumes. We include both and obtain production-based emissions from a multi-pollutant emission inventory developed by Zheng *et al* [50].

Direct emissions in this study include fossil fuel combustion, private car usage, and open biomass burning (only for rural households). Different proxies are applied to allocate emissions from the three sources. For fossil fuel combustion and private car usage, we assign provincial urban and rural emissions according to each group's expenditures on residence and transport, respectively [32]. For rural open burning, the proxy turns to biomass consumptions, estimated based on income. The correlation

between biomass consumption and per capita income is captured by Peng *et al* [51].

$$AED_l^{qu} = AED1^{qu} \times \frac{P1_l^{qu}}{\sum_{l=1}^{L} P1_l^{qu}} + AED2^{qu}$$
$$\times \frac{P2_l^{qu}}{\sum_{l=1}^{L} P2_l^{qu}} + AED3^{qu} \times \frac{P3_l^{qu}}{\sum_{l=1}^{L} P3_l^{qu}} \tag{4}$$

$$P3_l^{qu} = 0.7072 \times POP_l^{qu} \times INC_l^{qu-0.18} \tag{5}$$

where AED_l^{qu} is total direct atmospheric emissions caused by household activities in the urban/rural income group l of province q; $AED1^{qu}$, $AED2^{qu}$ and $AED3^{qu}$ are total emissions from fossil fuel combustion, private cars and open burning in urban/rural area of province q; $P1_l^{qu}$, $P2_l^{qu}$ and $P3_l^{qu}$ are corresponding proxies for the urban/rural income group l in province q; POP_l^{qu}, INC_l^{qu} are the population and per capita income of the urban/rural group l in province q, respectively.

Indirect emissions for different income groups are computed under the framework of China's MRIO table developed by Zhang *et al* [39], where provinces and sectors are linked through complex trade networks. The basic MRIO equation can be expressed as:

$$\boldsymbol{X} = (\boldsymbol{I} - \boldsymbol{A})^{-1} \boldsymbol{Y} \tag{6}$$

$$\boldsymbol{X} = \begin{bmatrix} \boldsymbol{X^1} & \boldsymbol{X^2} & \cdots & \boldsymbol{X^P} \end{bmatrix};$$
$$\boldsymbol{A} = \begin{bmatrix} \boldsymbol{A^{11}} & \boldsymbol{A^{12}} & \cdots & \boldsymbol{A^{1P}} \\ \boldsymbol{A^{21}} & \boldsymbol{A^{22}} & \cdots & \boldsymbol{A^{2P}} \\ \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{A^{P1}} & \boldsymbol{A^{P2}} & \cdots & \boldsymbol{A^{PP}} \end{bmatrix}; \tag{7}$$
$$\boldsymbol{Y} = \begin{bmatrix} \boldsymbol{Y^1} & \boldsymbol{Y^2} & \cdots & \boldsymbol{Y^P} \end{bmatrix}$$

where $\boldsymbol{I}$ is the identity matrix; $\boldsymbol{X^q} = \{x_k^q\}$ is the column vector of sectoral total output caused by final demand of province q; $\boldsymbol{A^{pq}} = \{a_{ij}^{pq}\}$ is the technical submatrix between province p's production and province q's consumption, given by $a_{ij}^{pq} = z_{ij}^{pq}/x_j^q$, in which z_{ij}^{pq} denotes the monetary flows from the sector i in province p to sector j in province q; $\boldsymbol{Y^q} = \{y_k^q\}$ is the column vector of sectoral total final demand of province q.

Then, we extend the MRIO model with an emission intensity vector $\boldsymbol{W}$ and introduce the household final demand matrix $\boldsymbol{F}$ we developed to calculate the indirect household emissions driven by various expenditures of different income groups. Notably, foreign emissions induced by China's household consumption are excluded, since our core concern lays in the impact of poverty alleviation on air pollutant in China.

$$\boldsymbol{AEI} = \widehat{\boldsymbol{W}}(\boldsymbol{I} - \boldsymbol{A})^{-1} \boldsymbol{F} \tag{8}$$

Table 1. China's urban and rural poverty prevalence in 2012.

Scenario	Urban	Rural	Total
$1.90/day	0.42%	13.02%	6.50%
$3.20/day	3.30%	38.35%	20.21%
$5.50/day	19.97%	70.53%	44.36%

$$AEI = \begin{bmatrix} AEI^1 & AEI^2 & \cdots & AEI^P \end{bmatrix} \qquad (9)$$

$$\begin{aligned} AEI^q = [&AEI_1^{q1} \quad AEI_2^{q1} \quad \ldots \quad AEI_L^{q1} \\ &AEI_1^{q2} \quad AEI_2^{q2} \quad \ldots \quad AEI_L^{q2}] \end{aligned} \qquad (10)$$

where AEI^q is the matrix of indirect atmospheric emissions driven by households in province q; $AEI_l^{qu} = \left\{ AEI_{l,ij}^{qu} \right\}$ is the matrix of indirect emissions driven by the urban/rural income group l in province q, and $AEI_{l,ij}^{qu}$ is sector i's emissions driven by item j's consumption from province q's urban/rural group l.

Consequently, the total emissions induced by the urban/rural income group l in province q can be written as:

$$AE_l^{qu} = AED_l^{qu} + \sum_i \sum_j AEI_{l,ij}^{qu}. \qquad (11)$$

2.3. Poverty alleviation scenario analysis

To reveal the impacts of combating poverty on air pollution, we define three poverty alleviation scenarios with reference to the widely accepted poverty lines proposed by the World Bank [13].

Scenario $1.90/day explores the environmental costs of eliminating extreme poverty in China using the global absolute poverty line of USD 1.90 a day in 2011 PPP. People living below the extreme poverty line cannot meet their basic needs for food, clothing, and shelter. Since this line has been adopted in the SDG target 1.1 (USD 1.25 in 2005 PPP) [2], scenario $1.90/day also implies the emission consequences of achieving target 1.1. Scenario $3.20/day and scenario $5.50/day further estimate the additional emissions caused by higher-level poverty eradication in China. The thresholds used for scenario $3.20/day and scenario $5.50/day are the two international poverty lines for lower-middle-income countries and upper-middle-income countries (USD 3.20 and USD 5.50 per day in 2011 PPP), respectively.

For each scenario, identifying the poor is the first step. We rank all 150 urban groups and 150 rural groups based on average income separately. By combining the population of each group with the poverty headcount ratio at different poverty lines (see table 1) [8], residents below the three poverty lines can be flagged, respectively.

Referring to Hubacek *et al* [33], we assume that people lifted out of poverty adopt the lifestyles of the corresponding next higher income group within the same province and reflecting the urban/rural divide. However, changes in residential lifestyle (household spending, consumption patterns, and direct energy consumption) may have opposing effects on air pollution. Some of these lifestyle changes have more and some have less environmental impacts (e.g. lower emission intensity of service demand that tends to increase with higher income and lower direct consumption and open burning of biomass [51]). Both negative and positive emission effects of achieving poverty alleviation goals are taken into consideration. Then, the per capita household direct and indirect emissions of the impoverished group l under scenario b can be estimated as:

$$APAED_l^{qub} = PAED_{l+h}^{qu} \qquad (12)$$

$$APAEI_l^{qub} = \widehat{W}(I-A)^{-1} PF_{l+h}^{qu} \qquad (13)$$

where $APAED_l^{qub}$ is the adjusted per capita direct atmospheric emissions of province q's urban/rural group l below the poverty line in scenario b; $PAED_{l+h}^{qu}$ is the per capita direct atmospheric emissions of province q's urban/rural group $l+h$ right above the poverty line in scenario b; $APAEI_l^{qub} = \left\{ APAEI_{l,ij}^{qub} \right\}$ is the adjusted per capita indirect atmospheric emission matrix of province q's urban/rural group l below the poverty line in scenario b; PF_{l+h}^{qu} is the per capita final demand vector of province q's urban/rural group right above the poverty line in scenario b.

Therefore, in scenario b, the total household atmospheric emissions of a group below the poverty line can be written as:

$$AE_l^{qub} = \left(APAED_l^{qub} + \sum_i \sum_j APAEI_{l,ij}^{qub} \right) \times POP_l^{qu}. \qquad (14)$$

By replacing the AE_l^{qu} in 2012 with AE_l^{qub}, we can obtain the additional emissions under scenario b.

2.4. Technical improvement scenario analysis

As technology in production have been the main focus of emission abatement, we set up a series of technical improvement sub-scenarios in addition to the three basic anti-poverty scenarios.

Taking the basic scenario $1.90/day as an example, we further define 20 sub-scenarios, such as sub-scenario T95, sub-scenario T90, sub-scenario T85. In the sub-scenario T85, for instance, we identify the super-emitting provinces of each sector according to the provincial sectors' emission intensities (i.e. emissions per unit of economic output). The emission intensities of these super-emitters are greater than the 85th percentile of the corresponding sector. We assume a reduction of their emission intensities to the 85th percentile. Thus, sub-scenario T0 is the strongest

scenario where all provinces improve their technology to the most environmentally-friendly level, while sub-scenario T95 is the least effective.

Then, combined with adjusted household consumption, household emissions based on different levels of technology, accounting for the entire upstream supply chain, under the three poverty alleviation scenarios can be calculated similar to equations (12)–(14).

2.5. Uncertainty analysis

Analyzing uncertainty can help to partially alleviate concerns about limitations and provide the extent of potential deviation from the presented results. To calculate uncertainties brought by incomplete expenditure data, we first develop several sensitivity scenarios with reference to Zhao *et al* [31]. In each sensitivity scenario, we use the expenditures from one of the household groups with complete data as proxies to estimate the missing data for the target group. For instance, in the first sensitivity scenario, the grouped data is supplemented by the data of groups with the second most similar PES to the target groups. While in the last sensitivity scenario, we fill the missing data with the expenditures of their corresponding least similar groups in terms of PES. We have 69 sensitivity scenarios in total.

Additionally, uncertainties from the emission inventories [50] are also included in the uncertainty analysis of our research. Table S6 reports the uncertainty ranges of different sectors in the emission inventory (95% CI).

3. Results and discussion

3.1. Unequal household emissions

Our results show that households are significant contributors to China's atmospheric emissions, contributing 35.2% (9.5 million tons (mt)) of the country's SO_2 emissions, 30.5% (8.0 mt) of NO_x, 47.1% (5.3 mt) of $PM_{2.5}$, and 41.0% (6.5 mt) of PM_{10} in 2012.

Figure 2 presents the contribution of different types of household to consumption-based SO_2, NO_x, $PM_{2.5}$, and PM_{10} emissions. For convenience, we allocate the 300 household groups into 10 national groups (5 rural and 5 urban) based on their income. The five urban/rural groups are low-income, lower-middle-income, middle-income, upper-middle-income, and high-income quintiles.

Overall, the unequal distribution of the four atmospheric pollutants shows two completely different patterns. For SO_2 and NO_x, emissions generally increase with income levels in both urban and rural areas (see figures 2(a) and (b)). The urban high-income group comprises less than 10% of the population but is responsible for over 20% of household SO_2 and NO_x emissions. Whereas, the bottom half income earners only contribute about one-third of household

emissions of these two pollutants. The per capita SO_2 and NO_x emissions of the urban high-income group, which has the highest income, are 15.0 kg and 13.1 kg, respectively, approximately four times of those from the rural low-income group.

Unlike SO_2 and NO_x, the unequal distribution of $PM_{2.5}$ and PM_{10} emissions are mainly attributed to urban-rural disparities (see figures 2(c) and (d)). Rural residents dominate the country's household $PM_{2.5}$ and PM_{10} emissions, directly and indirectly contributing 77.6% and 72.3%, respectively. For individuals with similar income, rural residents produce much more primary PMs than urban residents. For instance, although the per capita income of the rural upper-middle-income group and the urban low-income group are roughly equal, the per capita $PM_{2.5}$ and PM_{10} emissions of the rural group are respectively 7.0 and 5.2 times those of the urban group. The patterns here can be explained by the distribution and contribution of direct and indirect emissions.

Direct emissions from direct energy consumption account for 16.7% of SO_2, 15.9% of NO_x, 75.2% of $PM_{2.5}$, and 68.0% of PM_{10} emissions of households. Despite a larger population concentrated in urban areas, the vast majority (70.3% for SO_2, 81.1% for NO_x, 96.0% for $PM_{2.5}$, and 95.5% for PM_{10}) of these direct emissions occur in rural areas, due to rural residents' insufficient access to modern energy services [52], high dependence on solid fuels [53–55], and insufficient emission control devices [17]. At the individual level, rural households' direct SO_2 and NO_x emissions are 2.7 and 4.9 times those in the urban groups. The numbers for $PM_{2.5}$ and PM_{10} rise to an astonishing 27.4 and 24.0 owing to the rural-specific dust-intensive activities (e.g. open burning).

Indirect emissions associated with household consumption of various goods and services contribute 83.3% of the household SO_2 emissions, 84.1% of NO_x, 24.8% of $PM_{2.5}$, and 31.6% of PM_{10}. Households with higher per capita incomes induce more indirect emissions. The top 9.4% of earners (the urban high-income group) trigger 22.5%–23.4% of the indirect emissions for the four pollutants, whereas the bottom 10.6% of earners induce only 3.1%–3.6%. This is mainly caused by larger household consumption in affluent families (see figure S1 in supplementary materials).

3.2. Additional emissions from poverty alleviation

As shown in figure 3, overall, eradicating poverty imposes directly and indirectly adverse effects on air pollution by changing the total amounts and structure of consumption. Ending extreme poverty (i.e. scenario $1.90/day) has limited impacts on China's atmospheric emissions, increasing household emissions by 0.1%–0.5% from the 2012 levels. 96.9% of the extreme poor are rural residents with relatively low consumption increments after poverty alleviation
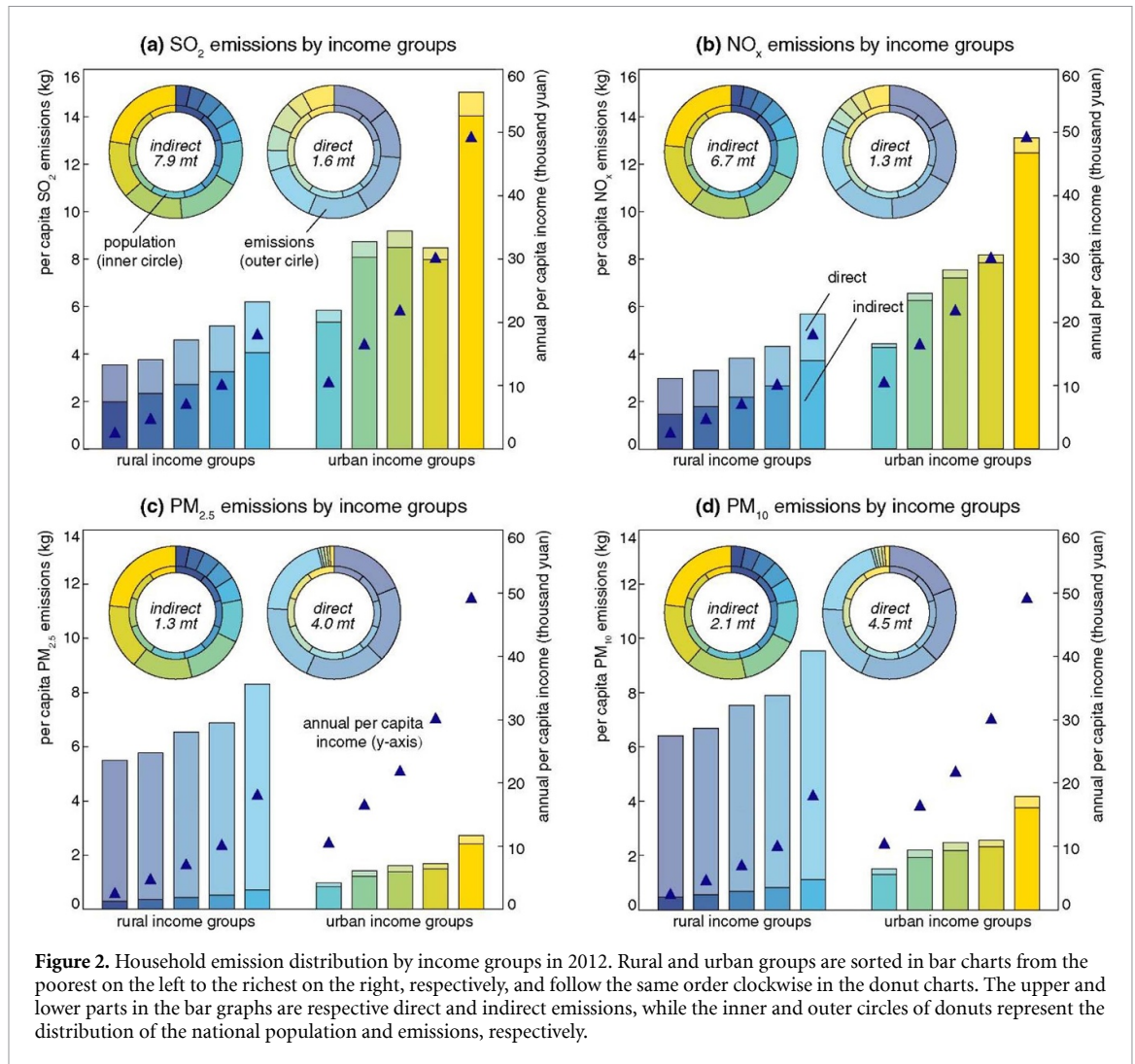
Figure 2. Household emission distribution by income groups in 2012. Rural and urban groups are sorted in bar charts from the poorest on the left to the richest on the right, respectively, and follow the same order clockwise in the donut charts. The upper and lower parts in the bar graphs are respective direct and indirect emissions, while the inner and outer circles of donuts represent the distribution of the national population and emissions, respectively.

[30]. When further liberating people from poverty (i.e. scenario $3.20/day), household emissions show a slight increase of 2.4%–4.4% compared to 2012 levels.

However, a more ambitious poverty alleviation target consistent with China's current stage of development (i.e. scenario $5.50/day) may lead to a significant increase in air pollutant emissions [13, 56]. When lifting people above the USD 5.50/day poverty line, household emissions of SO_2, NO_x, $PM_{2.5}$, and PM_{10} will be 18.5%, 13.0%, 22.3%, and 20.3% higher than those without poverty alleviation efforts. Notably, although the impacts of low-level poverty alleviation on PM emissions are relatively low compared with the other two pollutants, household emissions of $PM_{2.5}$ and PM_{10} emissions would significantly increase under the scenario $5.50/day. Taking $PM_{2.5}$ as an example, the scenario $5.50/day shows an increase of 1.2 mt, which exceeds the total emissions of the bottom nine provinces (including Qinghai, Hainan, Beijing, etc) in 2012. Surge in rural residents' fossil fuel consumption for heating and cooking is the major reason for the sharp increase. These additional emissions pose greater challenges to China's current emission reduction tasks. Previous studies

have demonstrated that meeting the 35 μg m^{-3} air quality commitment in all cities requires substantial reductions in emissions (85.2% of SO_2, 74.3% of NO_x, and 81.1% of $PM_{2.5}$ relative to 2012 levels) [16]. Poverty alleviation under the scenario $5.50/day would require an additional emission reduction of 6.5%, 4.0%, 10.5%, and 8.3% of SO_2, NO_x, $PM_{2.5}$, and PM_{10}, respectively.

There are large provincial discrepancies in the environmental impacts of poverty alleviation. Taking scenario $5.50/day as an example (see figure 4), we find that the bottom three provinces, with the lowest share of households moving to the higher income level, only account for about 10% (6.5% for SO_2, 12.1% for NO_x, 5.7% for $PM_{2.5}$, 5.8% for PM_{10}) of the national emission increase, while the top three provinces, with the largest share of poor households, generate more than 57% (73.4% for SO_2, 57.7% for NO_x, 66.1% for $PM_{2.5}$, 65.7% for PM_{10}) of the country's additional emissions from reducing poverty. In particular, Guizhou, Shanxi, Sichuan, Hunan, Henan, and Hebei are among the top-ranked for the poverty-alleviation-induced emissions of all four pollutants and need priority attention when

Figure 3. Changes in China's household emissions under different poverty alleviation scenarios.
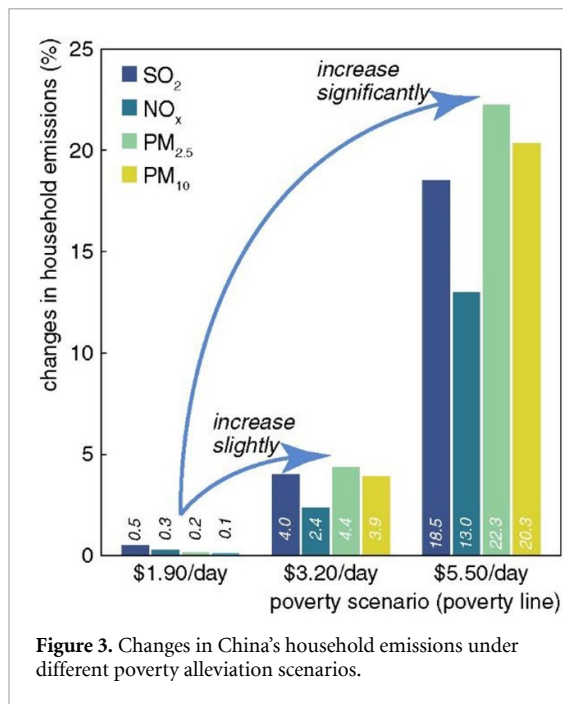
designing synergistic strategies against poverty and pollution. Although the absolute amount of increased emissions in some provinces are negligible, these may still pose considerable challenges, due to the relative added contribution (e.g. more than a 19% increase in PM emissions in Hainan and Qinghai).

The length of the bars indicates the additional emissions needed to move the poor household under USD 5.50/day to the next higher level within the same province and urban/rural divide. The bars are color-coded to reflect the contributions of other provinces to the changes in each province's emissions, from cyan (<30%) to green (30%–70%) to yellow (>70%).

Furthermore, increasingly complex and expansive supply chains make the environmental impacts of poverty alleviation more than just a local issue [57–59]. Through inter-provincial trade, increased household consumption in a province is likely satisfied by the production of upstream goods and services outside its boundary. As a result, additional emissions are likely to spill over to other areas [60]. The colors in figure 4 reflect the impacts caused by other provinces throughout the entire supply chain. For $PM_{2.5}$ and PM_{10}, local poverty eradication is the main contributor to emission increases in most provinces (24 out of 30 for $PM_{2.5}$ and 22 out of 30 for PM_{10}). This can be attributed to the dominance of local emissions from household direct energy consumption. As for SO_2 and NO_x emissions, consumption of goods and services is the primary source of household emissions, which is more likely to occur outside the provincial territory [61–63]. Some provinces may become the victims of anti-poverty campaigns elsewhere. For instance, Inner Mongolia has an increase of 62.9 kt NO_x under the scenario $5.50/day, 24.6% of which come from the province itself, while 27.6%
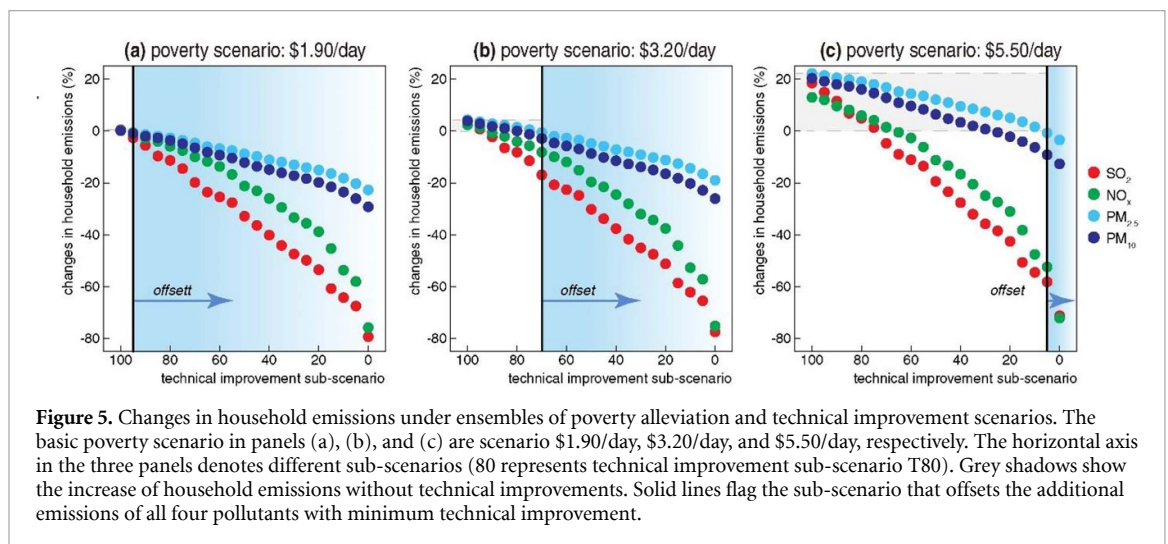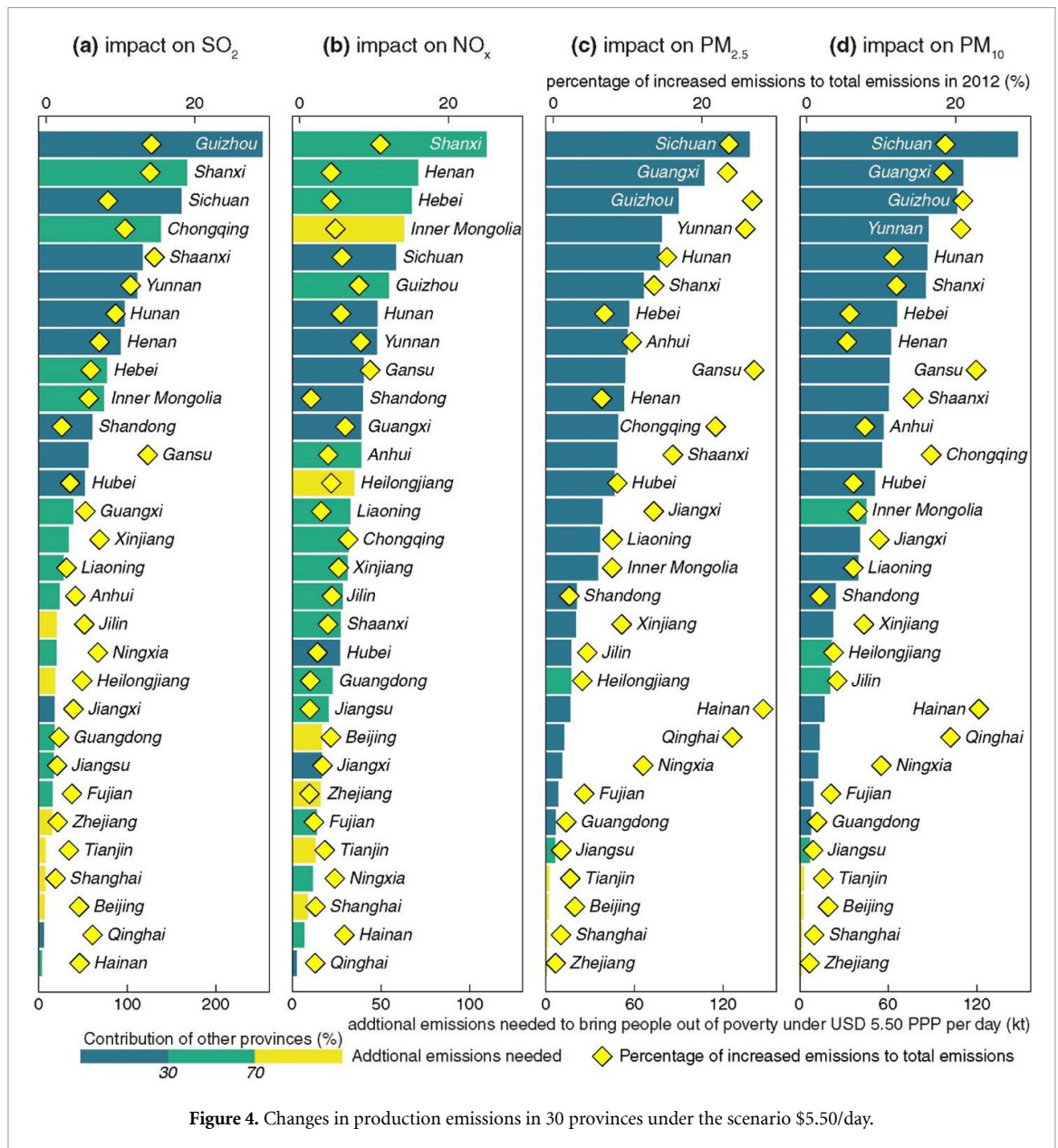
are induced by poverty alleviation in Shaanxi, Hubei, and Shanxi via interprovincial trade. In addition, anti-poverty efforts of other provinces at least quadruple the emission impacts of local poverty alleviation in prosperous regions [41] (e.g. Beijing, Shanghai, Tianjin, and Zhejiang). The results highlight the necessity of regional collaboration in the face of the 'poverty-emission reduction conflict'.

3.3. Offsetting effects of technical improvement

Despite the increase in air pollution caused by poverty alleviation, technological improvements (e.g. phasing out of highly polluting production processes, upgrading desulfurization and denitrification technologies, and installing dust collectors) could be a solution to offset additional emissions [14, 36]. For the scenario $1.90/day, emission reductions from technical change under the mildest sub-scenario (i.e. scenario $1.90/day T95) could more than offset additional emissions of all pollutants (see figure 5(a)). For the scenario $3.20/day, the additional emissions of SO_2, NO_x, $PM_{2.5}$, and PM_{10} from reducing poverty could be compensated under its sub-scenario T90, T90, T70, and T75 (see figure 5(b)), respectively. However, even for $PM_{2.5}$, the intensity improvements needed can be easily achieved, referring to historical data (see figure S2 in supplementary materials).

In principle, efforts in improving technology would be able to compensate for the extra emissions under the scenario $5.50/day (see figure 5(c)). Concerning SO_2 and NO_x, it is necessary to tap into the reduction potentials of large emitters with intensities higher than the 70th and 65th percentile (i.e. scenario $5.50/day T70 and T65). For $PM_{2.5}$ and PM_{10}, due to the dominance of direct emissions, additional emissions could not be offset until the sub-scenario T5 and T25, respectively. The needed improvements are equivalent to 82.1% and 58.0% decrease in emission intensity at the national level.

Yet only a handful of provinces have succeeded in such emission reductions during the 2007–2012 time period. Notably, for $PM_{2.5}$, even in the province with the steepest decline in emission intensity from 2007 to 2012, more aggressive measures would need to be implemented to achieve the median drop required to eliminate the emission impacts of poverty alleviation (see figure S2 in supplementary materials). Recently, China has made tremendous efforts to develop and promote clean technologies in the power and industrial sectors to tackle the severe air pollution issues. The strictest-ever clean air action plan proposed four measures for production process [64]: (a) large-scale application of high-efficient emission control devices (e.g. flue gas desulfurization, selective catalytic reduction, selective nonanalytic reduction systems); (b) phasing out small, inefficient and highly polluting companies; (c) upgrading industrial coal boilers; and (d) encouraging technical innovation and application by eliminating outdated capacities. Zhang

Figure 4. Changes in production emissions in 30 provinces under the scenario $5.50/day.

Figure 5. Changes in household emissions under ensembles of poverty alleviation and technical improvement scenarios. The basic poverty scenario in panels (a), (b), and (c) are scenario $1.90/day, $3.20/day, and $5.50/day, respectively. The horizontal axis in the three panels denotes different sub-scenarios (80 represents technical improvement sub-scenario T80). Grey shadows show the increase of household emissions without technical improvements. Solid lines flag the sub-scenario that offsets the additional emissions of all four pollutants with minimum technical improvement.

et al [14] estimated that these initiatives could reduce China's primary $PM_{2.5}$ by 2.96 mt. Their ensuing technical improvement is close to the sub-scenario T40, but still far from the level required to offset the additional emissions of the highest poverty scenario. Given the narrowing abatement potential from end-of-pipe controls and the pressing task of attaining certain levels of air quality [15, 16, 23], counteracting the extra emissions with technological progress alone is arguably unachievable under the scenario $5.50/day.

Since improvements in economic sectors are likely unable to keep up with additional emissions, reshaping lifestyles will be an inevitable choice for synergies between poverty alleviation and emission mitigation [33]. The focus of cutting PM in the residential sector is to reduce emissions from cooking, heating, and other direct combustion activities in rural areas, which calls for the wider dissemination of advanced stoves and clean fuels [65, 66]. The effectiveness of advanced devices (e.g. gas wall heater, air source heat pump [67, 68]) and initiatives to phase-out coal (e.g. China's Winter Clean Heating Pilot project [44, 69]) in $PM_{2.5}$ pollution control has been confirmed by numerous studies. For SO_2 and NO_x, encouraging sustainable ways of consuming should be equally important on the synergy task list [33]. As higher-income residents tend to consume more low-emission-intensive service products [70], the transition of consumption patterns across income ladders lowers the per capita emissions in most cases (see figure S1 in supplementary materials) but this is always overcompensated by the increase in consumption volume. Nevertheless, a careful analysis of and redirection toward low carbon consumption patterns is a necessary addtional measure to reduce emissions.

3.4. Uncertainties and limitations

Our study is subject to some limitations and uncertainties. First, the incomplete expenditure data may introduce uncertainties when building the household final demand matrix. As noted earlier, the aggregated household survey data from statistical yearbooks is the best accessible data for the purposes of this study, and we preserve the characteristics of consumption patterns provided by the aggregated yearbook data to the maximum extent. Improvements in the reporting resolution and standardization of household surveys or other type of data such as credit card spending will eliminate these uncertainties in the future but are not currently available to the required extent and quality. Second, the emission inventories have uncertainties due to errors in activity data and lack of localized emission factors [50]. The multi-pollutant emission inventory used in this study has been broadly applied in multiple chemical transport models and proved to be in line with the air quality obtained from observational sites [16, 23]. We analyze the uncertainties from the above two factors. The results show that the overall uncertainties are acceptable to support our conclusions. Taking the poverty scenario $5.50/day as an example, the uncertainty ranges of changes in household SO_2, NO_x, $PM_{2.5}$, PM_{10} emissions are 18.5% (15.5%–21.8%), 13.0% (11.0%–14.6%), 22.3% (16.3%–26.8%) and 20.3% (14.0%–30.3%), respectively. Detailed results of the uncertainty analysis are shown in table S7 and table S8 in the supplementary materials.

In recent years, China has implemented targeted poverty alleviation initiatives with emission reduction benefits such as photovoltaic poverty alleviation (PV-PA) [71]. However, the carbon emissions reduced by PV-PA are ignorable compared with the national total (less than 0.1%) [25]. And to the best of our knowledge, their specific contribution to lifting the poor segment out of poverty, and their emission reduction potentials for typical air pollutants have not yet been assessed due to current data restrictions. The intention of this paper is not to evaluate the performance of any specific anti-poverty policy, but to measure the overall additional emissions associated with different poverty eradication goals. As any anti-poverty policy will have to deal with the fact that household income will increase and thus trigger related lifestyle changes, we capture the emission reduction gains of these initiatives only when reflected in the poor's lifestyles (household spending, consumption patterns, and direct energy consumption).

We make the assumption that people lifted above the poverty line match the lifestyles of the corresponding higher income group within the same province and the same urban/rural characteristics. As more complicated assumptions about the poor's lifestyles may aid in even more uncertainties, we prefer to adopt the most parsimonious assumptions in our poverty alleviation scenarios given the lack of sufficient supporting data. Similar assumptions have been accepted in previous research [33].

We highlight the impacts of poverty alleviation-related behavioral changes on emissions by assuming changes in the poor's lifestyles. However, those changes caused by factors other than poverty alleviation (such as demographic transitions to smaller family sizes and the aging society, and future migration across provinces) are not considered in the poverty scenarios. We do acknowledge that projecting future changes in behavior of different households, inter-provincial migration, and associated emissions are important components [72–74]. But it is complex, lacks reliable supporting information (e.g. predicted future time-use data of different provinces and population migration matrix between provinces), and thus has a high degree of uncertainty to date [72, 75, 76]. We believe this limitation is acceptable as our purpose is not to predict China's future emissions taking into account the large range of socio-economic trends but we instead point out what the implications of moving

people to higher levels of income, which is the prime intend of any poverty alleviation policy.

This study does not model introduction and impacts of specific clean technologies and how these affect emissions, because our research focuses on the impacts of poverty alleviation, rather than technological progress. The technical improvement subscenarios answers how much effort is needed to compensate for additional emissions from eliminating different levels of poverty. Furthermore, we examine whether such compensation is feasible with reference to historical data and estimated performance of current technical improvement policies [14, 16].

Last but not least, the coronavirus disease 2019 (COVID-19) pandemic is likely to affect our results [77]. On the one hand, the national lockdown in response to the epidemic seems to curb production and employment in the short term [78, 79]. As a result, people may fall back into poverty [13]. On the other hand, COVID-19 has inadvertently altered our ways of life with possible ramifications on consumption and household emissions [80, 81]. However, we believe that these effects are limited. Compared with high-income groups, poorer segments of society have a stronger need to maintain their household expenses, and are also able to apply for different targeted subsidies (e.g. unemployment benefits and transportation subsidies for migrant workers) [82]. At the same time, the poor's income is mainly spent on life's necessities. Thus, their consumption tends to be relatively stable.

4. Conclusions

This study examines the impacts of achieving different poverty alleviation goals on air pollution in China. Emissions are estimated by developing and introducing a newly established household final demand matrix into China's latest MRIO framework. The improved final demand matrix distinguishes the expenditures of 300 household groups while keeping the details of their consumption patterns to the greatest extent. The emission impacts here include both changes in direct emissions as well as indirect or emissions along the entire supply chain.

Our results reveal a significantly unequal distribution of atmospheric emissions among various household groups in China. Dominated by indirect emissions, household SO_2 and NO_x emissions increase with income and consumption levels. The top 10% earners are responsible for more than 20% of the household SO_2 and NO_x emissions, whereas the bottom half of income earners contribute only about 1/3. Led by direct emissions, the inequalities of household $PM_{2.5}$ and PM_{10} emissions are mainly driven by differences in urban-rural consumption. Rural households comprise more than 70% of the country's household $PM_{2.5}$ and PM_{10} emissions due to a lack of modern energy services.

Poverty alleviation in China would bring additional challenges for emission abatement. Fortunately, ending extreme poverty would only lead to an increase in household emissions by less than 0.6%. When bringing everybody above the poverty line for lower-middle-income countries, household emissions are estimated to increase by 2.4%–4.4% from 2012 levels. In both scenarios, the required endeavors of economic sectors to compensate for the extra emissions are highly attainable. Nevertheless, when lifting people above the poverty line for upper-middle-income countries, household SO_2, NO_x, $PM_{2.5}$, and PM_{10} emissions would increase significantly by 18.5%, 13.0%, 22.3%, and 20.3%, respectively. Vulnerable provinces include Guizhou, Shanxi, Sichuan, Hunan, Henan, Hebei, Hainan, and Qinghai. To neutralize extra abatement pressures in this case, for SO_2, NO_x, PM_{10}, and $PM_{2.5}$, sectors with emission intensities above the respective 70th, 65th, 25th, and 5th percentile should be identified as superemitters.

In past decades, China has made historic achievements in eradicating poverty. Almost all Chinese have achieved an income above the current national poverty line by the end of 2020 [20]. However, ending extreme poverty is only the start of China's combat against poverty. Ranking as an upper-middle-income country, China requires the participation of more sectors to achieve more ambitious anti-poverty and anti-pollution goals in a compatible manner. In addition to the continuous efforts of the economy, emission reduction in the residential sector needs to be accelerated. The popularization of advanced stoves and clean fuels can be effective options for reducing direct emissions in rural regions. Given the possible emission-intensive transition of consumption patterns across income ladders, encouraging less polluting consumption patterns has now become a top priority of indirect emission control. Economic measures such as environmental taxes are considered effective to provide consumption incentives, yet their impacts are often regressive [83, 84]. Policies promoting sustainable lifestyles should be designed with the poor's sensitivities and vulnerabilities in mind.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Acknowledgments

Conflict of interest

The authors have no conflict of interest to declare.

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