Mismatched social welfare allocation and $PM_{2.5}$-related health damage along value chains within China

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Abstract

Value chains have played a critical part in growth. However, the fairness of the social welfare allocation along the value chain is largely under-investigated, especially when considering the harmful environmental and health effects associated with the production processes. We used fine-scale profiling to analyze the social welfare allocation along China's domestic value chain within the context of environmental and health effects and investigated the underlying mechanisms. Our results suggested that the top 10% regions in value chain obtained 2.9 times more social income and 2.1 times more job opportunities than the average with much lower health damage. Further inspection showed a significant contribution of the "siphon effect": major resource providers suffer the most in terms of localized health damage along with insufficient social welfare for compensation. We found that inter-region atmosphere transport results in redistribution for 53% health damages, which decreases the welfare-damage mismatch at "suffer" regions but also causes serious health damage to more than half regions and populations in total. Specifically, around 10% of regions have a lower social welfare and also experienced a significant increase in health damage caused by atmospheric transport. These results highlighted the necessity of a value chain-oriented, quantitative compensation-driven policy.

Synopsis

The different value chain roles led to significant mismatches between social welfare gains and health damage across regions. The mismatches were partially reduced with the effects of atmospheric transport at the expense of increase in health damage in densely populated and lower polluted regions.

Keywords: value chain, health damage, social welfare, equity, atmospheric transport.

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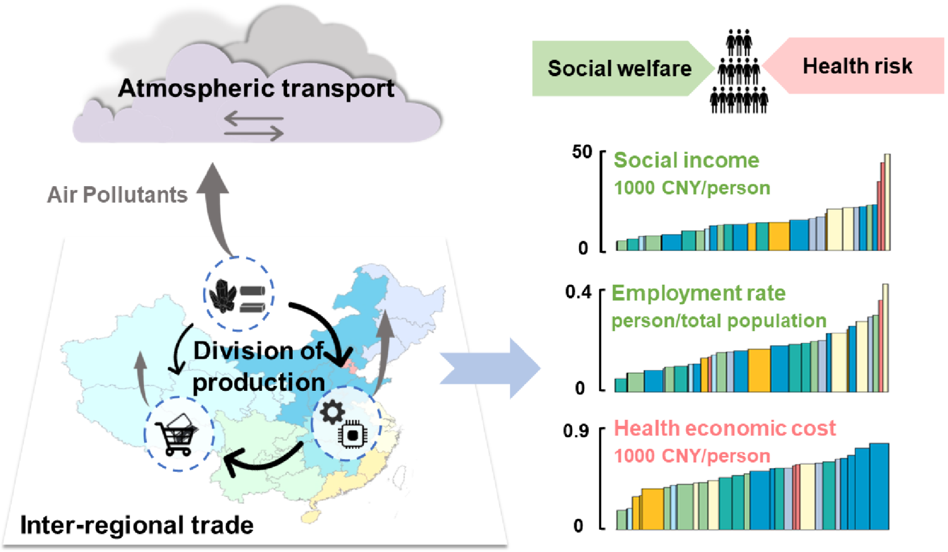
Atmospheric transport
Air Pollutants
Division of production
Inter-regional trade
Social welfare
Health risk
50
Social income
1000 CNY/person
0
0.4
Employment rate
person/total population
0
0.9
Health economic cost
1000 CNY/person
0

1. Introduction

During recent decades, emerging inter-regional trade with the expansion of global value chains led to an increasingly complex inter-regional production network [1,2]. Entities at different positions along the value chain provide diversified products and services (i.e., raw material and intermediate products for further production, manufacturing, and services for final products) [3]. It is suggested that participating in value chain promotes social welfare growth (such as higher salary, more job opportunities, and more public revenue) by improving the efficiency and quality of production and supply [4,5]; while the social welfare gains are not allocated evenly among different participants[6], and varying degree of external losses (e.g., environmental damage) also occur in various production stages[7], delivering the uneven gains and losses allocation along value chain.

Previous studies have revealed several common uneven environmental and health burdens associated with inter-regional trade [8,9], such as carbon [10,11] and pollutant flows [12,13] and health damage [14,15] transfer. However, they focused on the flowing between producer regions and final consumer regions, mostly falling short in modeling the uneven environmental and health impacts within inter-regional production processes. It leads to crucial knowledge gap how inequity is emerged in the division of production by distributing environmental and health burdens among producers for their different producing activities along the value chain. Meanwhile, previous studies have investigated the imbalanced environmental burdens and economic gains in the inter-regional trade[16], while few have considered the mismatch between welfare gains and health damage, leading to an incomplete understanding of the real allocations of people-oriented gains and losses given to the inconsistent spatial distribution of pollution emissions and health damage owing to atmospheric physicochemical transport process, uneven population density, and etc.

China is a vast country with 31 provincial regions on the mainland. As one of the countries with the most complete industrial chain, and competitive markets among provincial regions [17], China's domestic value chains now have remarkable inter-regional product and service flows as well as considerable social welfare, environmental pollutant [16,18], and health damage flows [19–21]. Under the significant transition towards "common prosperity", China has a strong motivation to realize the win-win target for the improvement of people's social welfare and environmental quality along with reduction of health burdens[22].

In this study, we aimed to quantify the accompanying features of social welfare gains and associated health damage for 31 provincial regions along the domestic value chain, and thus to decode how the inequity occur in division of production. To do so, we chose China's mainland in 2017 as a case, and established a comprehensive framework with a combination of the value chain method, a multi-regional input–output model, and an extended response surface model with polynomial functions and exposure–response functions. Compared to widely applied consumption-based accounting, the value chain approach with more complex mathematical formulas further decomposes the production network, allowing to trace how the environmental and health burdens, and social welfare gains allocate among producers who serving as different roles in the inter-regional industrial chain. The results empirically showed the contribution of the regions' "value chain role" and atmospheric transport to the mismatched social welfare gains allocation and health damage impact, which highlight the necessity of a value-chain-oriented, inter-regional compensation policy.

2. Materials and Methods

2.1 Tracing social welfare and air pollutant emissions along the domestic value chain

We used the updated 2017 multi-regional input–output table for 31 provincial regions in China's mainland [23] to estimate the social welfare and air pollutants embodied in flows of products and services through the value chains. Thereinto, social welfare was quantified by social income and employment; and social income is the sum of compensation of employees, net taxes on production, and operation surplus, reflecting the income of residents, enterprises, and government. Air pollutants considered sulfur dioxide (SO_2), nitrogen oxides (NO_x), ammonia (NH_3), volatile organic compounds (VOC), and primary $PM_{2.5.}$

Multi-regional input–output analysis illustrates the linkages among provincial regions and sectors, and its row balance with G regions can be represented as follows [24]:

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

where $\boldsymbol{X}$ represents the total output vector; $\mathbf{I}$ represents the identity matrix; $\boldsymbol{A}$ represents the direct consumption coefficient matrix; $\boldsymbol{B}$ represents the Leontief inverse matrix; $\boldsymbol{Y}$ represents the vector of final demand.

To trace the flows of social welfare (social income and employment) and embodied pollutants along the value chain, we involved the pollutant emission vector and social welfare vector in equation (1):

$$\boldsymbol{f} = \boldsymbol{FBY} \tag{2}$$

where $\boldsymbol{F}$ is a vector that represents the pollutant emission intensity (i.e., the emission per unit of total output), social income per unit of total output, or the number of employed persons per unit of total output.

Based on equation (2), the pollution emissions, social income, and employment of region s can be decomposed into four parts that correspond to different production links and trading paths [25–27]:

$$\boldsymbol{f}_s = \boldsymbol{F}_s\boldsymbol{L}_{ss}\boldsymbol{y}_{ss} + \boldsymbol{F}_s\boldsymbol{L}_{ss}\sum_{r\neq s}^{G}\boldsymbol{A}_{sr}\sum_{t}^{G}\boldsymbol{B}_{rt}\boldsymbol{y}_{ts} + \boldsymbol{F}_s\sum_{r\neq s}^{G}\boldsymbol{B}_{ss}\boldsymbol{y}_{sr} + \boldsymbol{F}_s\sum_{t\neq s}^{G}\boldsymbol{B}_{st}\sum_{r\neq s}^{G}\boldsymbol{y}_{tr} \tag{3}$$

where $\boldsymbol{F}_s$ is a row vector of air pollutant emission intensity, social income per unit of total output, or the number of employed persons per unit of the total output of region s; $\boldsymbol{A}_{sr}$ is the sub-matrix of $\boldsymbol{A}$, representing the direct consumption coefficient matrix from region s to region r; $\boldsymbol{B}_{rt}$, $\boldsymbol{B}_{ss}$, $\boldsymbol{B}_{st}$ are sub-matrixes of $\boldsymbol{B}$; $\boldsymbol{L}_{ss} = (\boldsymbol{I}-\boldsymbol{A}_{ss})^{-1}$ is the local Leontief inverse matrix for region s, which reflects its internal production structure; $\boldsymbol{y}_{sr}$ represents the vector of final demand in region r produced by region s, and $\boldsymbol{y}_{ss}$, $\boldsymbol{y}_{ts}$, $\boldsymbol{y}_{tr}$ are similar. On the right side of the formula, the first term indicates the impact of intra-regional trade, the second term denotes the impact embodied in imported products, and the last two terms are the impact of region s exporting final and intermediate products, which are finally absorbed by other regions. Note that the latter three terms refer to the impact of inter-regional trade along the domestic value chain.

We further explored the local and upstream social welfare and air pollutant emissions impacts of bilateral trade between region *s* and *r* within inter-regional trade. Based on bilateral trade measures from the perspective of backward industrial linkage [26], the impact of product flows from region *s* to region *r* can be divided into local and upstream air pollution and social welfare impacts:

$$EX_{sr}=(\boldsymbol{F}_s\boldsymbol{B}_{ss})^{\mathrm{T}}\odot(\boldsymbol{Y}_{sr})+(\boldsymbol{F}_s\boldsymbol{L}_{ss})^{\mathrm{T}}\odot(\boldsymbol{A}_{sr}\sum_{t\neq s}^{\mathrm{G}}\sum_{u\neq s}^{\mathrm{G}}\boldsymbol{B}_{rt}\boldsymbol{Y}_{tu}) \tag{4}$$

$$FE_{sr}=\sum_{t\neq s}^{\mathrm{G}}(\boldsymbol{F}_t\boldsymbol{B}_{ts})^{\mathrm{T}}\odot(\boldsymbol{Y}_{sr})+\sum_{t\neq s}^{\mathrm{G}}(\boldsymbol{F}_t\boldsymbol{B}_{ts})^{\mathrm{T}}\odot(\boldsymbol{A}_{sr}\boldsymbol{L}_{rr}\boldsymbol{Y}_{rr}) \tag{5}$$

where EX_{sr} and FE_{sr} represent the local and upstream impacts respectively. "T" means the transpose matrix. The symbol "$\odot$" represents the Hadamard product.

The overall impact of product and service flows from region *s* to all other regions can be calculated based on equations (4) and (5):

$$EX_s=\sum_{r\neq s}^{\mathrm{G}}EX_{sr} \tag{6}$$

$$FE_s=\sum_{r\neq s}^{\mathrm{G}}FE_{sr} \tag{7}$$

where EX_s and FE_s represent the local and upstream impacts of the exporting activity of region *s*.

2.2 Estimates of PM$_{2.5}$-related mortality and morbidity

We used the extended response surface model with polynomial functions (pf-ERSM) [28,29] to estimate the PM$_{2.5}$ concentrations under different air pollutant emissions. The response surface modeling (RSM) technology provides an efficient way to quantify the response of air pollutant concentrations to emission changes. It does so by forming a "real-time" relationship between the concentrations and precursor emissions based on a large number of simulations of chemical transport models. The extended RSM (ERSM) renders the model applicable to a much larger number of regions [30,31]. In the pf-ERSM, the relationship between the concentrations and precursor emissions is developed by fitting a set of polynomial functions, which substantially reduces the computational burden of

ERSM [29,32]. A more detailed description of the pf-ERSM has been provided in Ding et al. [29].

To construct the pf-ERSM prediction system for China, we conducted chemical transport simulations using the Community Multi-scale Air Quality (CMAQ) model version 5.2 over a domain covering East Asia with a grid spacing of 27 km × 27 km. The simulation periods were January, April, July, and October in 2017, which represent winter, spring, summer, and fall. Detailed configurations of the CMAQ model, as well as evaluation of the simulation results against observational data, have been described in Ding et al. [33] We performed 755 CMAQ simulations with randomly determined emission rates for each air pollutant in each province to establish the pf-ERSM system. The response variables (dependent variables) were annual $PM_{2.5}$ concentrations in each province of China calculated from an average of the four months. The control factors (independent variables) were emission rates of SO_2, NOx, NH_3, VOC, and primary $PM_{2.5}$ in each province. In addition, we generated 50 independent scenarios for out-of-sample validation. We have proved in our previous study [28] that the pf-ERSM predicted $PM_{2.5}$ concentrations for the 50 scenarios agree well with the corresponding CMAQ simulated values.

We used the updated integrated exposure–response functions developed by Cohen et al. [34] to estimate premature deaths due to $PM_{2.5}$ emissions [35]. The model considers five health endpoints: ischemic heart disease, stroke, bronchial and lung cancer, chronic obstructive pulmonary disease in adults, and lower respiratory tract infections in children and adults. A log-linear exposure-response function [36,37] was applied to estimate four health endpoints of morbidity (chronic bronchitis, cardiovascular, asthma attack, and acute bronchitis). The health damage was estimated by contrasting a specific counterfactual scenario, where pollutant emissions resulting from trade activity were eliminated, with a baseline case representing the emission of all pollutants as per usual. In the counterfactual case, it was assumed that the sector's size contracted, resulting in the cessation of its supply of intermediate and final products to other regions within the domestic value chain, but the goods for local use or international export remained.

We conducted uncertainty analysis on the parameter estimations of $PM_{2.5}$ exposure-related health damage with the Monte Carlo method, and compared the results under varying baseline $PM_{2.5}$ concentration setting (5, 10, 15 μg m^{-3})[38–40] (see supporting information S1.1). For simplicity, the results analysis was shown as averages at 10 μg m^{-3} baseline $PM_{2.5}$ concentration level.

2.3 Measuring the level of regional mismatch in social welfare gains and health damage

To better understand the regional imbalances, two indexes, coefficient of variation (CV) and Gini coefficient, were applied to quantify regional inequity. CV is the standard deviation divided by the mean, representing the degree of data dispersion. It describes the gaps of social income, employment opportunities, and health risks. Gini coefficient has been applied for illustrating the inequality of income distribution [41]. Given that the Gini coefficient considers population distribution across regions unlike CV, we introduced it to measure the level of population-weighted regional disparity in social welfare gains and health damage. The Gini coefficient can be determined by:

$$\mathrm{Gini} = \sum_{i\neq 1}^{n} \boldsymbol{P}_i \boldsymbol{Y}_i + 2\sum_{i\neq 1}^{n} \boldsymbol{P}_i\,(1-\boldsymbol{T}_i) - 1 \tag{11}$$

where $\boldsymbol{P}_i$ represents population proportion of region i, and $\boldsymbol{Y}_i$ and $\boldsymbol{T}_i$ refers to proportion and cumulative proportion of social income, employment, health damage for each region. The Gini coefficient ranges from 0 to 1, meaning from complete equality to complete inequality. Note that the calculation here can only reflect the level of difference across a provincial unit, while the income groups, urban-rural disparity, employment of various ages, genders, and educated level groups are not accounted for, meaning this result may underestimate the genuine level of inequality in this study.

2.4 Data sources

The 2017 multi-regional input-output table of China is compiled by Carbon Emission Accounts and Datasets (CEADs). The social income, deriving from value added, can also be obtained from the input-output table [23]. We acquired the number of employees in each sector and provincial regions from the China Statistical Yearbook 2018 [42] and the China Population & Employment Statistics Yearbook 2018 [43]. The emissions of five air pollutants in 2017 were obtained from the ABaCAS-EI (Air Benefit and Cost and Attainment Assessment System Emission Inventory) developed by the School of Environment, Tsinghua University [35]. Multiple emission sectors are included in the inventory, allowing to map the emissions to sectors of input-output table, such as agriculture, chemical industry, metallurgy, nonmetal product, petroleum refining, coking, etc., electricity production and supply, construction, and, transport and storage, services. For the emissions from industrial boilers, we allocated it into industrial sectors according to sectoral energy consumption from CEADs. The detailed method to match the emission inventory with sectors of input-output table can be referred to previous study[44]. Data on population, aging structure, gender structure, and coefficients relevant to $PM_{2.5}$ exposure-related mortality estimation were consistent with previous work [35]. Data on the value of statistical life (VSL) of China varied. We collected and compared several VSL estimates of China from 14 studies on 23 cases (see Table S3 in supporting information), and the most updated results [45] were adopted. We also conducted a reliability analysis [46,47] on the time conversion of VSL; please find it in the Table S5-6 in supporting information.

3. Results

3.1 Significant but diverse impact of inter-regional trade on health damage associated with $PM_{2.5}$ exposure and social welfare gains

Inter-regional trade along the China domestic value chain contributed substantial impact on air pollutant emissions. In 2017, inter-regional trade triggered 4.1 Million tons (Mt for short), 7.3 Mt, 2.4 Mt, 7.3 Mt, and 3.2 Mt of SO_2, NOx, primary $PM_{2.5}$, NMVOCs, and NH_3 emissions respectively, contributing 34.3%~40.6% of total air pollutants emissions of the 31 provincial regions in China's mainland (Figure. 1a). The air quality level differed across regions, with a higher $PM_{2.5}$ concentration in middle and eastern areas of China (Figure. 1b). Among all the sources of emissions, inter-regional trade was one main contributor to the changes of $PM_{2.5}$ concentration in various provincial regions. For the 29 provincial regions (except Tibet and Qinghai), the range of maximum inter-regional trade impact is 2.8~26.8 μg m^{-3} of $PM_{2.5}$ concentration (Figure. S4).

The $PM_{2.5}$ concentration triggered pronounced pollution-related health damage. Inter-regional trade accounted for 35.2% (168.8 thousand people) of $PM_{2.5}$-related mortality and 36.6% (9.1 million people) of $PM_{2.5}$-related morbidity of China's mainland in 2017 (Figure. 1c), leading to a health economic loss of 760.6 billion CNY. The $PM_{2.5}$ exposure caused economic loss due to inter-regional trade was equivalent to 23.8% of the total medical expenditures in 2017. Meanwhile, inter-regional trade also contributed 35.2% of national employment, 34.8% of national household income, and 39.9% of total tax revenues (Figure. 1c).

The contributions to health damages and social welfare might differ for regions to participate in inter-regional trade, that some regions suffer damages more from it. Only one-sixth of regions have a lower $PM_{2.5}$-related health damage by more than 30% (per unit social welfare gains, compared with intra-regional trade) from inter-regional trade. Meanwhile, interregional trade triggered more $PM_{2.5}$-related health damage for 42% of provincial regions, making up 40.2% of the total population (Figure. 1c). Geographically, ~70% of the northern provincial regions and ~15% southern provincial regions triggered higher $PM_{2.5}$-related health damage by participating in inter-regional trade (Figure. 1c).

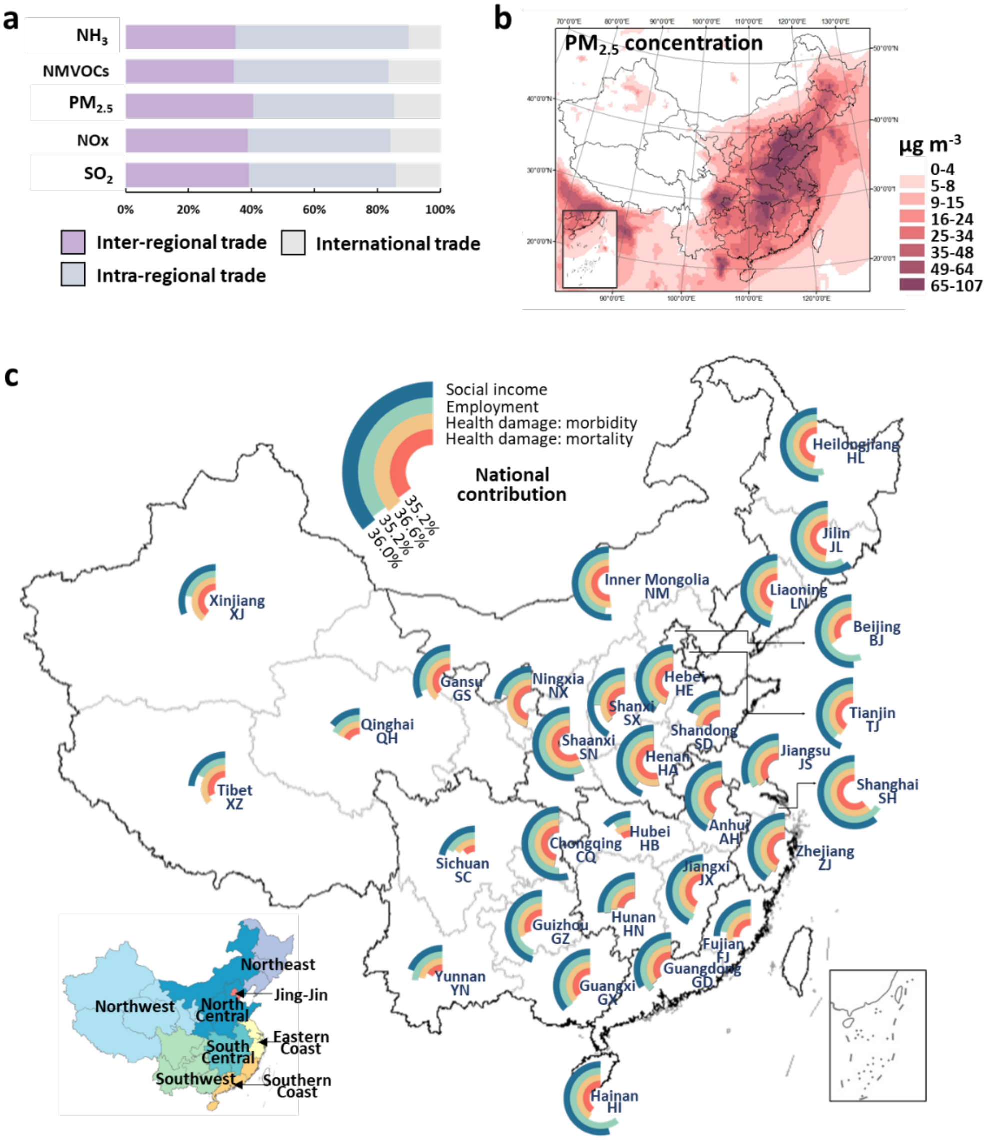

Figure 1. Air pollution, health damage and social welfare induced by participation in the inter-regional trade in 2017. a, Contributions of five air pollutant emissions by inter-regional trade at the national level. b, PM$_{2.5}$ concentration distribution in basic scenario in 2017. c, Contribution to social welfare and health damage by inter-regional trade at the national and provincial level. Provincial names and their abbreviations are labeled beside doughnut charts. Provincial regions are classified into eight zones as shown in the bottom left. Participation in inter-regional trade triggered more health damage to get to equal social

welfare in comparison to intra-regional trade when the contributions to health damage (yellow and red in doughnut chart) were higher than that to social welfare (blue and green).

3.2 Mismatch of social welfare gains and $PM_{2.5}$-related health damage along the inter-regional trade

The significant inter-regional gaps further intensified the mismatch of social welfare allocation and environmental-health burdens among regions (Figure. 2). The high Gini coefficient of provincial employment rate (0.32) and social income per capital (0.38) suggested that the top 10% provinces with the highest social welfare per capita and less than 6% of population gained 2.9 times higher social income (Figure. 2a) and 2.1 times higher job opportunities (Figure. 2b) than the average level. Several regions with higher employment rate and per capita social income benefits in Figure. 2a and 2b were found at the left side of Figure. 2c, indicating that they also have an equal or even lower (0.8~1.0) health economic loss. In contrast, the top 10% regions with the highest health damage per capita suffered 2.1 times more than the national average health damage and gained only an average level of social welfare.

Most of the regions from the three coastal areas (i.e., Jing-Jin, Eastern Coast, and Southern Coast) enjoyed much higher employment rate (~20%) and social income (23.1 thousand CNY/capita in average) from the inter-regional trade along the value chain, around 1.5~1.7 times the number for North Central and South Central. However, per capita health economic losses for the three Coastal areas (0.4 thousand CNY/capita in average) is only half of the number for North Central and South Central. Taking population effect into account, the three Coastal areas suffered 17.5% of health loss but obtained 34.4% and 38.3% of job opportunities and social income, respectively. In contrast, North Central created around 25% social welfare at the expense of significant higher health economic losses (44.4%).

In addition to the "virtual" transfer embodied in products and services along the value chain, the inter-region atmospheric transport (i.e., the "physical" transfer) could cause the health damage suffering regions different from the ailment-triggering one (i.e. regions which produce pollution). The atmospheric transport process redistributed 53.0% of health damage triggered by the inter-regional trade. While the atmospheric transport process reduced the health damage of North Central and Northwest, which both triggered the highest health damage, by 21.6% (73.1 billion CNY) and by 25.5% (7.0 billion CNY), all the other regions experienced a significant increase in health damage by 20.3% on average. Especially, it aggravated the damage at Jing-Jin, Southern Coast, and Southwest by 33.3%~77.3% (Figure. 2e); in addition, 58.1% of provincial regions with 65.0% of the population suffered more serious health damage even with the seemingly decreased Gini coefficient in the “suffer” regions (Figure. 2d). In particular, around 10% regions with a lower social welfare (31.3%~66.8% of the national average level) experienced a 12%~116% increase in health damage after atmospheric transport.

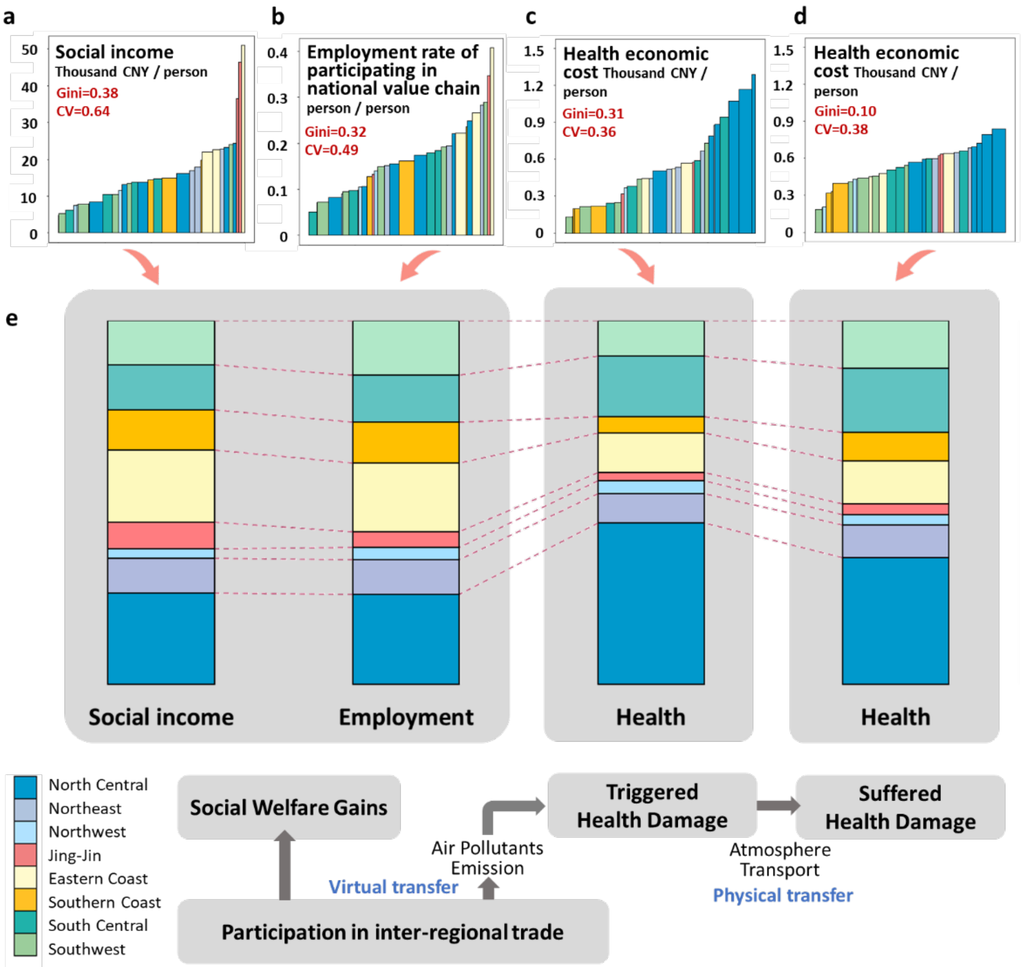

Figure 2. Social welfare allocation and health damage. a, Allocation of social income shared by the individual. b, Allocation of employment triggered by participation in the inter-regional trade to the total population in each province. c, Allocation of triggered health damage shared by the individual. d, Allocation of suffered health damage shared by the individual. Width of bars are consistent with population scales of provinces or municipalities. The color of bars reflects regional classification. e, Regional contribution to social welfare gains and health damage. The allocation of social welfare and health damage in the inter-regional trade is virtual transfer, and the redistribution of health damage by atmosphere transport is the result of physical transfer of pollutants. The detailed data for 2a-d can be seen in Table S7 in Supporting Information.

3.3 Flows of embodied social welfare and $PM_{2.5}$-related health damage along the inter-regional value chain

We further investigated the underlying mechanisms accounting for the inter-regional trade–driven inequity by inspecting the inter-regional flow of social income, employment, and $PM_{2.5}$-related health damage.

The model revealed significant driving flows among the eight economic zones within China's mainland. In particular, the three Coastal areas, which were beneficiaries of inter-regional trade, drive 38.3% of the health damage of China's mainland. For instance, Guangdong, Zhejiang, and Jiangsu, three typical regions from the Coastal areas, were the main drivers for health damage by the inter-regional trade along the value chain (24.4%). Also, these three regions propelled considerable damage to inland areas, such as accounting for 22.8%~33.5% of South Central, Southwest, and North Central's losses (Figure. 3a). Meanwhile, we also noticed significant flows between adjacent regions at different developmental stages. Relatively developed provincial regions (e.g. Beijing and Jiangsu) drove the pollutant emissions of their neighbors (e.g. Anhui and Hebei), while they suffered increasing health damage from their neighbors through atmospheric transport. For instance, the outflow paths from Anhui, Hebei, and Heilongjiang to their neighbors (Jiangsu, Beijing, and Jilin, respectively) were among the top "virtual" flow paths with the highest damages of $PM_{2.5}$ exposure (6.7 ~ 14.0 billion CNY). Of note, such driving direction is opposite to the impact of “physical” atmospheric transport.

The joint effects of “coastal pulls” and “neighboring exchanges” described above may further aggravate health risks of northern areas. The northern areas, centered on Henan and Hebei, suffered exaggerated health risks: Shaanxi, Shandong, and Hebei triggered 9.2, 4.7, and 4.6 billion CNY of health damage by outsourcing to their common neighbor Henan (Figure. 3a).

The conflicts between coastal areas and inland areas were further highlighted when taking the social welfare flows into account (Figure. 3b-c). While coastal regions drove less than a quarter of social welfare for inland regions along the value chain (23.3% of social income, 24.3% of employment), they “trigger” much higher health damage (31.4%) for Inland regions. In particular, three coastal regions drove 16.4% of health damage to North Central, nearly 2 times higher than its contribution to social welfare gains. Meanwhile, inland regions not only undertook polluted activity and high health loss, but also drove a lot of social welfare for the Coastal areas. For instance, Henan from North Central contributed 8.5% of social income and 8.8% of employment nationwide in the inter-regional trade along the value chain; particularly, it drove 12.4%~26.9% for Tianjin and Zhejiang, both coastal.

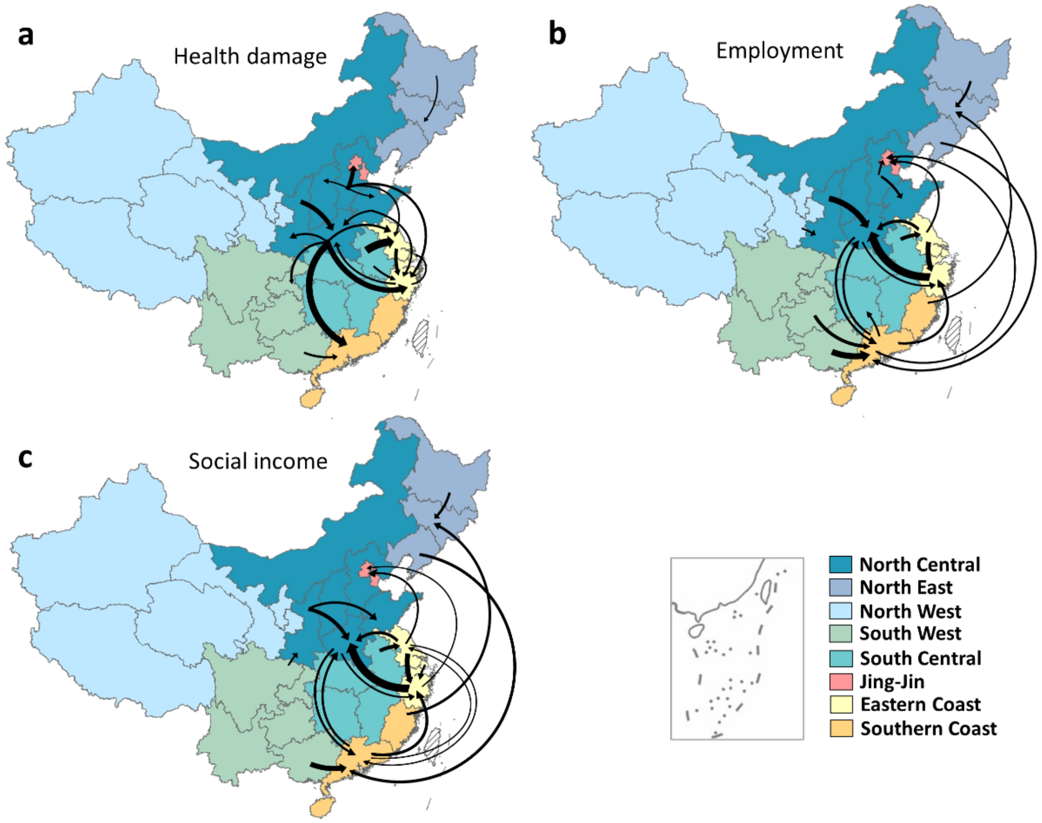

Figure 3. Top 20 flows of embodied social welfare gains and health loss among provincial regions driven by the inter-regional trade in 2017. a, Health damage flows. b, Employment flows. c, Social income flows. The arrow direction represents the flowing direction of intermediate and final goods; and wider arrow means higher impacts triggered by the flows. The widest arrows with highest flows are from Anhui to Jiangsu (14.0 billion CNY), from Zhejiang to Henan (4.0 million person), and from Zhejiang to Henan (307.7 billion CNY) in terms of health damage, employment, and social income.

3.4 The value chain role in the inter-regional trade determines the uneven degree in social welfare gains and health damage

The flow of intermediate products (which are unfinished goods or services being re-input into the production system to be further processed rather than be finally consumed) across regions plays an important role in the domestic value chain [48,49], with significant contributions to social income (59.5%), employment (59.1%), and health loss (71.1%). While flows of resource and energy intermediate products created around a quarter of social welfare (25.2% of social income and 23.7% of employment), it triggered half of the health damage (49.2%) through the inter-regional trade. In contrast, flows of final goods contributed only 28.9% of health damage with around 40% of social welfare along the value chain. This highlights the significant contribution of a particular region's "value chain role" to its social welfare gains and health damage impact via the inter-regional trade. Consistently with earlier analysis, in the inter-regional trade, most of the final goods were provided by coastal areas, while Northwest and North Central participated in supplying more resource and energy intermediate products, which are of high health damage due to intensive pollution and relatively lower social welfare gain (Figure. 4).

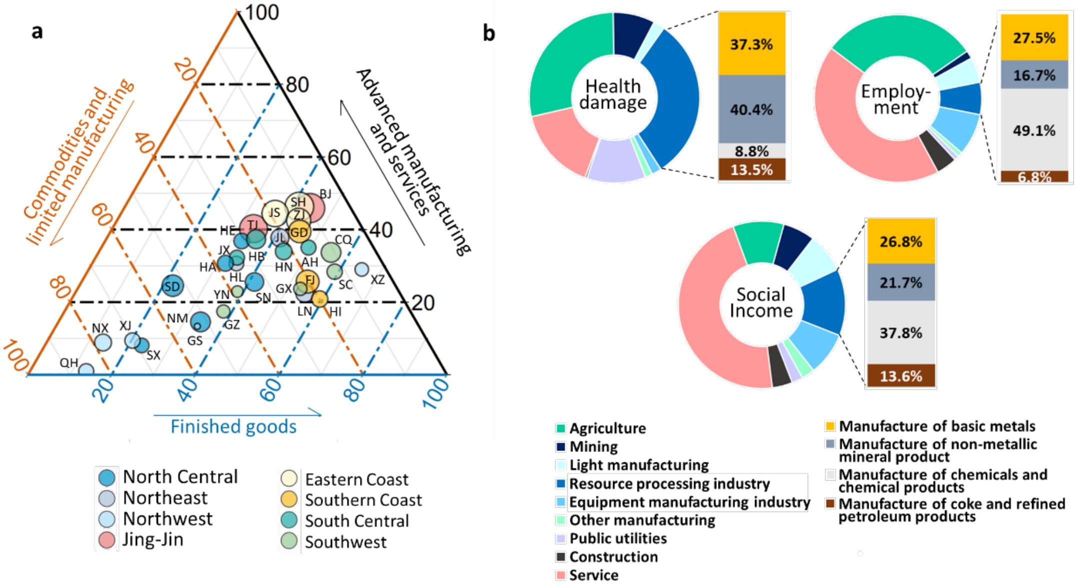

Figure 4. Roles in participating in the inter-regional trade. a, Proportions of three ways participating in inter-regional trade. The size of the bubble is related to the gross domestic product per capita, and a larger size means greater gross domestic product per capita. Intermediate products are classified as two types, in which resource and energy intermediate products include the intermediate products of agriculture, mining, resource processing industry, and electricity, heat, gas, and water production and supply industry;

the remainder of the intermediate products refer to equipment and other manufacturing, construction, and service. b, Sectoral contributions to the social income, employment, and health economic loss. Provincial names and their abbreviations have been labeled in Figure 1.

Regional differences in value chain roles were largely a result of diverse labor divisions of production in the inter-regional trade. The Central areas, especially North Central, are both primary suppliers and important drivers of resource and energy intermediate products in the inter-regional trade (Figure. 5a-d). In the flows of resource and energy intermediate products within China, 62.0% of raw mining and 40.4% of processing resource production activities occurred in North Central (as shown in Figure. S5). Meanwhile, 30.0% of the health economic loss, 30.9% of the social income, and 33.2% of the employment during raw minerals outsourcing were associated with Hebei, Henan, and Jiangxi.

Mutual but diverse drives happened between the Coastal and Inland regions. The Coastal regions occupied downstream of value chains, which absorbs resource products of Inland areas; the Inland regions drove manufacturing and services of the Coastal regions (Figure. 5e-h). For example, Eastern Coast drove over 20% of resource and energy intermediate products of North Central with not only raw minerals (e.g., 31.4% of Shanxi’s coal intermediate outflows) but also resource processing products (e.g., 24.6% of Hebei’s metal smelting and processing intermediate outflows, 26.5% of Shandong’s petroleum, coking, and nuclear fuel processing intermediate outflows). In addition, to support their production and processing activities, Eastern Coast and North Central were also the important drivers of services from coastal regions (e.g., 74.0% of Guangdong’s real estate and 65.8% of Beijing’s finance).

Considerable imbalances between social welfare allocation and health loss transfers were also found between the upstream and downstream components of the value chain. In particular, compared to intermediate manufacturing products and services and final goods, resource and energy intermediate product outflows led to a higher proportion of health damage borne locally with a lower level of social welfare gains (Figure. 5). For example, the former four provincial regions in North Central bore 88.7%~98.9% of the health loss when exporting raw minerals and resource processing products (Figure. 5a-d) in comparison to 29.9%~70.1% for the latter four to exporting manufacturing and services (Figure. 5e-h). In addition, there existed disparities in social welfare gains among different types of resource intermediate products. Different from metal and non-metallic processing products, raw mining and petroleum processing were heavily polluted but also highly profitable. Shanxi and Shandong captured around 90.3~97.6% of social welfare when exporting coal and exporting petroleum, coking, and nuclear fuel processing intermediate products (Figure. 5a-b), whilst Hebei and Henan captured 66.9%~81.0% of social welfare when supplying smelting and processing metal products and non-metallic mineral products to other regions (Figure. 5c-d).

It should be noted that the “virtual” transfer of $PM_{2.5}$ exposure-related health damage occurred in parallel to the “physical” one. For instance, Hebei, as a producer and supplier of smelting and processing metal products for Beijing and Tianjin, generated tons of air pollution and triggered 631.6 million CNY of health economic loss, in which 41.8% of health damage occurred in Hebei. On the other hand, as the close neighbors of Hebei, Beijing and Tianjin also suffered from this self-inflicted dirty air, with 71.7 million CNY health economic loss (about 11.3% of the total).

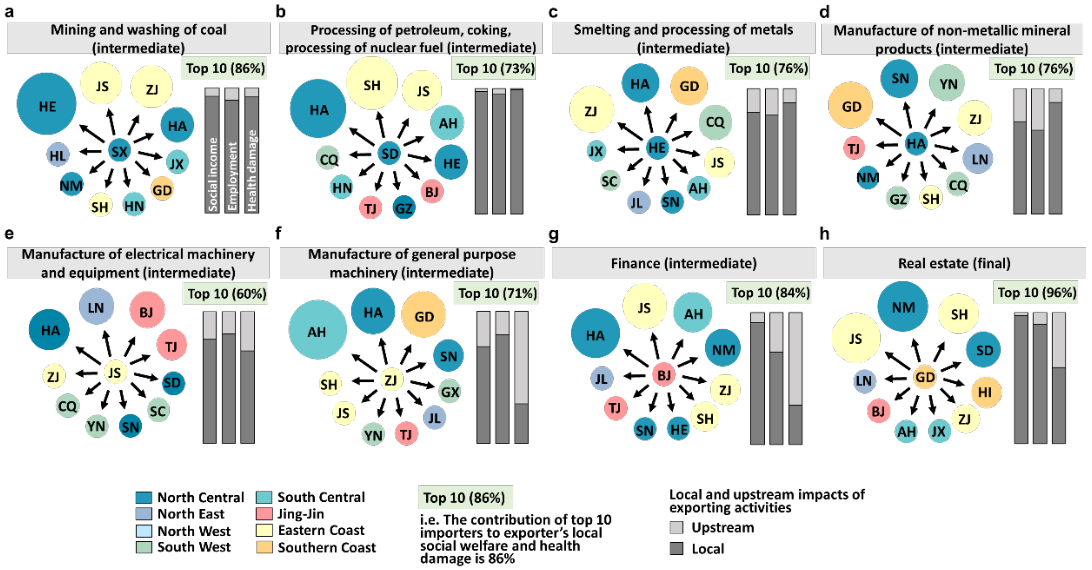

Figure 5. Local and upstream social welfare and health damage. Top 10 direct importers are presented on the left, and the impacts are on the right of exporting intermediate or final products or services on their local and upstream social income, employment, and health damage. Provincial names and their abbreviations have been labeled in Figure 1.

4. Discussion

Social welfare (SDG1, 8), environmental quality, and human health (SDG3) are three main themes in sustainable developmental transition[50]. In this study, we quantitively delineated social income, employment, and the health damage along the China domestic value chain. We identified regional imbalances in social welfare gains and $PM_{2.5}$ exposure-related health damage and its association with their distinct roles in the inter-regional trade:

- Regions that are major producers and exporters of resource and energy products provide intermediate products to support downstream manufacturing and services in other regions end up suffering most of the health damage locally and fail to obtain commensurate social welfare in compensation.
- Regions which focus on equipment and final-product manufacturing, construction, and services have more beneficial positions, as they obtain more social welfare by utilizing the intermediate materials which they import from the resource and energy producing provinces.
- Atmospheric transport process makes health damage more even in overall, but it leads to secondary damage, particularly to several provincial regions mainly in South Central.

Equitable development across regions is critical for the "common prosperity" goal, which is proposed as a more rational and fair welfare distribution pattern and important development target for China[22]. We found a siphon effect in which resources were transferred between the coastal regions and the northern inland regions, as well as between neighboring provinces with different value chain roles, especially under different development stages. Thus, at a national scope, it is necessary to take advantage of the positive role of the domestic value chain in driving social welfare improvements in China's Central and Western inland areas and to diminish the transfer of negative impacts such as pollution and health damage during inter-regional trade. It is becoming imperative to formulate stringent industrial standards to propel technical innovation. Since 2014, China has implemented ultra-low emission standards and introduced ultra-low emission technology retrofits for coal-fired power plants, resulting in effective control of SO_2, NOx, and particulate matter emissions[51]; Ultra-low emission retrofits are also currently being promoted for non-electric industries (e.g., steel, cement, coking, etc.) in key regions (e.g., Shandong, Shanxi, Hebei of North Central, etc.)[22]. In addition, downstream enterprises' requirements of suppliers for higher standards (e.g., lower carbon footprint, higher energy efficiency, better safety) of materials and products will be conducive for greening transition of the whole supply chain. On a global view, there have been arising several regulations on the imported products in terms of environmental or ecological impacts in the past few years. For instance, the European Union commission proposed the Carbon Border Adjustment Mechanism in 2020 on certain products (i.e. iron and steel, electricity, cement, and etc.) with high carbon intensity and several precursors and downstream goods. The new battery regulation of the European Union proposed in 2022 also attempts to ensure the sustainability of battery production along the whole supply chain by raising standards on the carbon footprint and material recycling. Such initiatives on imported products put great pressure on the industries in the upstream, stimulating the exporters to cut emissions. China is the vital manufacturer and exporter (e.g. steel and battery) in the world, with many enterprises playing important roles in supplying intermediate and final products to other countries; thus, certain emitters would be bound by the higher standards as mentioned above. The international pressure may trigger ripple effects on China's domestic value chain and help with the transition of certain industries and its upstream to be cleaner and greener.

Meanwhile, a better cross-regional coordination mechanism that supports regional compensation needs built to ensure the costs and benefits of socioeconomic development are shared equitably. Pollution-intensive industries, represented in this study by resource processing industries, were responsible for heavy air pollution and high $PM_{2.5}$-related health damage but had limited capacity to create social welfare, yet their products were also required by downstream industries such as manufacturing. Some regions will inevitably have to perform resource-related production activities. Notably, existing major resource and energy provinces have played these roles for a long time because of their unique and irreplaceable natural endowments, historical socioeconomic development, etc. It is also a common phenomenon for some countries in the globe. How to compensate them for the damage the resource-related processes cause and how to find an effective path for making industrial areas more socially and environmentally sustainable will require additional research.

This study suggests that economic compensation and sharing among regions will be important, both in domestic and international trading systems. On the one hand, through capital and technology transfers, developed regions and emerging high-tech enterprises are encouraged to provide assistance for developing regions, thereby increasing the potential for sustainable development of less-developed economies and greening of global industrial chains. Focusing on resource-rich areas, China's central government has been aware of the importance to actively promote energy-saving, efficient and green resource extraction, and to support the development of clean energy and resource refining industries; and counterpart support and collaboration is encouraged, such as intellectual support in key fields across regions, east-west cooperation in education, and east-west labor collaboration[52]. On the other hand, in addition to coordination of the economy and employment, the health damage caused by embodied pollutant emission transfers deserves more attention; compensation mechanisms must be developed to mitigate the health impacts of product flows between regions. However, the existing environmental pollution related health damage compensation is identified and defined through a rigorous legal argumentation process, and not applicable for inter-regional compensation at a national level. In addition, given that air pollutants easily cross boundaries between regions, the health damage caused by $PM_{2.5}$ exposure must be shared by the whole region, even if social welfare (such as income) is concentrated in a few areas or controlled by a few people. Low-income regions in heavily polluted areas are particularly vulnerable and require more attention. In short, there exists great difficulty to construct compensation mechanism to relieve the inequality of mismatched allocation of health damage and social welfare.

Imbalances in social welfare allocation and the associated pollution transfers are a global problem [53]. Compared with the whole planet, the imbalances within a given country are more practical to manage, making it easier to coordinate compensation among regions to maximize the interests of residents of these regions. Taking China as an example, we provided insights that can guide the coordination and common development among regions. How to achieve common prosperity and reduce inequity of environment and health is not only a development topic for China but also of great significance to global sustainable development. The same approach could be extended in future research to promote cooperation among countries based on the perspective of a Community with a Shared Future for Mankind.

Data availability

Multi-regional input–output table of China in 2017 used in this study is from CEADs https://www.ceads.net/. The MRIO table, satellite data including social income, pollutants emissions, and number of employments, and codes for value chain estimation are provided in supporting information. An online version of the pf-ERSM prediction system for China can be assessed by http://abacas.see.scut.edu.cn/RSM_API/Help.

Supporting Information

The Supporting Information is available free of charge to readers, including uncertainty analysis on the estimation of health damage and health economic loss, original source and data of VSL, the impacts of inter-regional trade on $PM_{2.5}$ concentration variation, provincial regions' resource product exports in the national value chain, relevant references, and code (Figures S1-S5 and Tables S1-S8).

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