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Measurement of air-pollution inequality through a three-perspective accounting model

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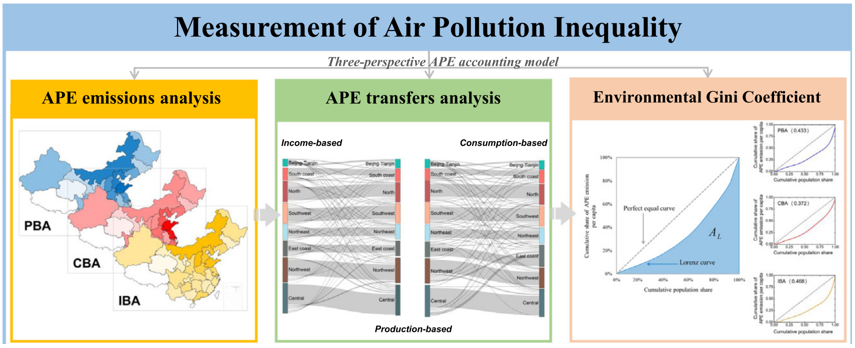
HIGHLIGHTS

- Developing a three-perspective atmospheric pollutant equivalents (APE) accounting model
- China's 30 provinces and 8 sectors in each province are studied.
- Three-perspective APE emissions and APE transfers analysis are introduced.
- Quantifying regional emission inequalities at both provincial and sectoral levels
- Proposing policy suggestions for future regional air pollution reduction

GRAPHICAL ABSTRACT



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ABSTRACT

China is suffering from serious air pollution. Regional air quality varies significantly due to intensive inter-provincial trades, diversified resource endowments and complicated economic structures. This study breaks the limitations of measuring environmental inequality only from a single perspective and establishes a three-perspective *atmospheric pollutant equivalents* accounting model (or APE accounting model) for air-pollution inequality assessment under environmentally-extend multi-regional input-output framework. From three perspectives of local production (i.e. production-based), final demand (i.e. consumption-based) and primary supply (i.e. income-based), APE emissions, APE transfers and environmental Gini coefficient are investigated to exam emission responsibilities of various impact factors, evaluate the impacts of inter-provincial trades on pollutants transfers, and characterize regional emission inequalities at both provincial and sectoral levels. The results indicate that local emitters are merely parts of contributors to air pollution. Direct emitters like Hebei Province, primary suppliers like Inner Mongolia and final consumers like Shandong Province induce large amounts of air pollutants as embedded within various economic activities. Because of unequal supply-demand levels and complex exchange mechanisms, three-perspective APE emissions are significantly heterogeneous, especially in mining, construction, energy and material-transformation sectors. Particularly, inequality of the mining sector in embodied emissions has the highest environmental Gini coefficient (0.881). This model provides a framework to assess regional environmental inequality and its findings provide scientific bases for the formulation of desired regional air pollution control policies.

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1. Introduction

Air pollution prevention and control is one of serious environmental issues faced by China's sustainable development. In 2017, only 29.3% of the 338 cities in China met the national air quality standard (i.e. the concentrations of the six pollutants, namely SO_2, NO_2, PM_{10}, $PM_{2.5}$, CO and O_3, all below the highest emission values) (Ministry of Environmental Protection, 2010). Scholars and policy-makers around the world are endeavoring to find solutions for air pollutants reduction (Song et al., 2018a; Wang et al., 2019; Yang et al., 2018).

For decades, Chinese government has already promulgated a series of laws and regulations to combat air pollution. Since 2003, the Ministry of Environmental Protection had directly imposed discharge fees on polluters according to *Regulation on the Administration of Collection and Use of Pollutant Discharge Fees* (Ministry of Environmental Protection of the People's Republic of China, 2003). Then, a new law issued in 2016 stipulated that pollutant dischargers should pay environmental protection taxes according to *the Schedule of Tax Items and Tax Amounts of Environmental Protection Tax* and *the Schedule of Taxable Pollutants and Equivalent Values*. (Standing Committee of the National People's Congress, 2016). However, these policies ignore the impacts of intensive inter-provincial trades on pollutants generation (Qu et al., 2018; Song et al., 2018b; Tan et al., 2018) and also underestimate the importance of source-side reduction for sustainable development (Chen et al., 2018c; Kong et al., 2018; Pan et al., 2018).

The United Nations Sustainable Development Goal 12 (SDG12) emphasizes that achieving sustainable development requires a reduction in ecological footprints through responsible consumption and production (United Nations, 2015). Previous studies demonstrated that socio-economic activities are one of the significant causes of air pollutant emissions, such as atmospheric mercury (L. Chen et al., 2018a, 2018b), carbon dioxide (CO_2) (Meng et al., 2018b; Wei et al., 2017; Xu and Lin, 2016), carbon (Shao et al., 2018, 2016), fine particulate matter ($PM_{2.5}$) (Tessum et al., 2019; Yang et al., 2018), black carbon (BC) (Meng et al., 2018a), ozone (O_3) (Lin et al., 2014) and greenhouse gas (GHG) (Liu et al., 2019; Xie et al., 2018; Zhou et al., 2018). For this reason, environmentally-extend multi-regional input-output (MRIO) model has been widely applied in order to investigate the complex material flows and exchange processes within a socio-economic system (Li et al., 2018a; Zhai et al., 2019; Zhang et al., 2014a), in which commodities are inputted for production and consumption activities, while air pollutants are emitted at various stages of the supply chain (Guan et al., 2019b; Ou et al., 2017). Such environmentally-extend MRIO model makes it possible to quantify direct and indirect material flows (i.e. trade-induced embodied and enabled flows) among provinces and among various economic sectors (Zhai et al., 2018b; Zheng et al., 2019).

Furthermore, developing three-perspective emission accounting (Liang et al., 2017; Liu and Fan, 2017; Zhang, 2015), namely production-based accounting, consumption-based accounting and income-based accounting, is useful to judge environmental responsibilities of various components (i.e. as a primary supplier, direct emitter or final consumer) (Guan et al., 2019b; Liang et al., 2016; Zhang et al., 2018a). Specifically, production-based emissions of a component refer to the direct emissions from its local production activities; consumption-based emissions of a component help to describe the embodied emissions that are triggered by its final demand (e.g. local consumption, investment and exports) but occur in all study areas; income-based emissions of a component mean the enabled emissions that are pulled by its primary inputs (e.g. supplies of capital and labor force) but occur in all study areas (Lv et al., 2010; Yu et al., 2019). All of the above prove the rationality of seeking emission mitigation strategies from a socio-economic perspective (An et al., 2016; Hao et al., 2016; Li et al., 2018b). Existing studies focus on the three-perspective emissions and suggested that regions should share production-based, consumption-based and income-based emission responsibilities (Liang et al., 2017, 2016; Shao et al., 2017).

China is a vast country with diversified resource endowments (e.g. natural resource, labor, capital and technology) (National Bureau of Statistics of China, 2016). The economic structures are complicated partly because of the government's early investment policies favoring coastal areas. Regional air quality varies significantly. In addition, according to the pollution haven hypothesis (PHH) (Zhang et al., 2014c), air pollutants may be transferred among regions due to intensive inter-provincial trades, resulting in more imbalanced regional emissions. At present, most studies have focused on embodied (i.e. consumption-based) emission transfers hidden in trades or the unequal relationships between environmental pollution and economic growth. However, the enabled (i.e. income-based) emission transfers hidden in China's inter-regional trades pulled by primary inputs has seldom been quantified. The quantification of enabled emission transfers may provide a new vision for describing the complex APE flows and uncovering the air-pollution inequality induced by regional trades from different perspectives.

To specifically characterize environmental inequality (Zhang et al., 2019; Zhang et al., 2014b), Wiedenhofer et al. used a carbon-footprint-Gini coefficient to quantify inequality of household's carbon footprints among people with different living standards in urban and rural areas (Wiedenhofer et al., 2017). Teng et al. used Gini index with adjustment to per capita historical cumulative emission to construct a carbon Gini index to measure inequality in climate change region from the perspective of local emissions (Teng et al., 2012). Wu et al. collected data on household energy consumption and assessed the inequality of energy consumption and expenditure in rural China (Wu et al., 2017). Zhang et al. combined several main air pollutants SO_2, NO_x, soot and dust uniformly according to the hazards to atmosphere and public health, and converted them into a new measure, called *atmospheric pollutant equivalents* (APE), and then employed the regional environmental inequality (REI) index to evaluate unequal transfers between air pollutant emissions and economic gain embodied in inter-provincial trades (Zhang et al., 2018c, 2018d). They found that most of the consumption-based emissions of richer regions were outsourced to other regions. In short, these studies have primarily focused on evaluating the inequalities triggered by consumption or final demand or only for the local emissions perspective (Carvalho et al., 2018; He, 2017).

However, in the past, policy-makers underestimated the impacts of socio-economic activities on air pollutant emissions, which are crucial for emission reduction from the source. In addition, some studies have mainly focus on simply evaluating direct emissions caused by local production or only calculating embodied emissions (i.e. consumption-based emissions) hidden in trades and often focused on APE transfers driven by final demand, which cannot cover all supply chains. Some studies have assessed regional environmental inequalities caused by consumption or final demand, while ignoring the importance of primary inputs to overall system (Zhai et al., 2018a; Zhang et al., 2018b). Furthermore, there are limited papers that pay attention to develop such a comprehensive three-perspective accounting model for environmental inequality assessment, which is significant for regional air pollutants reduction policies formulation (Liu et al., 2018a, 2018c).

To fill these gaps, this study establishes a comprehensive model to quantify the impacts of inter-provincial trades on APE emissions and transfers, and then measure the air-pollution inequality hidden in China's economic activities at both provincial and sectoral levels. It breaks the limitations of measuring environmental inequality only from a single perspective (production-based or consumption-based) in previous studies. The basic air pollutants emissions data of this study is based on the sectoral APE emission inventories of Chinese 30 provinces in 2012 published in Zhang's study (Zhang et al., 2018c, 2018d) (more details see Section 2.2). First, using the latest multi-regional input-output table and local APE emission inventories, we develop a three-perspective APE accounting model to calculate the production-based, consumption-based and income-based accounting of various components in the socio-economic system. Second, based on this model, APE emissions analysis, APE transfers analysis and environmental Gini coefficient are introduced for the measurement of air-pollution inequality. In detail, three-perspective APE emissions analysis is used to judge the environmental responsibility of each province, each sector and even each final demand and primary input pattern. Three-perspective APE transfers analysis provides a new vision for describing the APE flows throughout the supply chains (i.e. APE transfers not only form the final demand perspective, but also form the primary supply perspective) and uncovering the air-pollution inequality induced by regional trades. Moreover, three-perspective environmental Gini coefficient is introduced to more specifically characterize the regional air-pollution inequality at both aggregated and disaggregated sector level. It is expected that this model will help to establish a framework to assess regional environmental inequality in China, and the results will provide reasonable and scientific bases for the formulation of desired regional air pollution control policies.

2. Methodology

2.1. Three-perspective APE accounting model

In this study, a three-perspective atmospheric pollutant equivalents accounting model (or APE accounting model) is developed based on environmentally-extend multi-regional input-output framework (Liu et al., 2018b; Zhai et al., 2019). Then, APE emissions analysis, APE transfers analysis and environmental Gini coefficient are introduced to measure the air-pollution inequality hidden in China's economic activities. Fig. 1 illustrates the framework of the model.

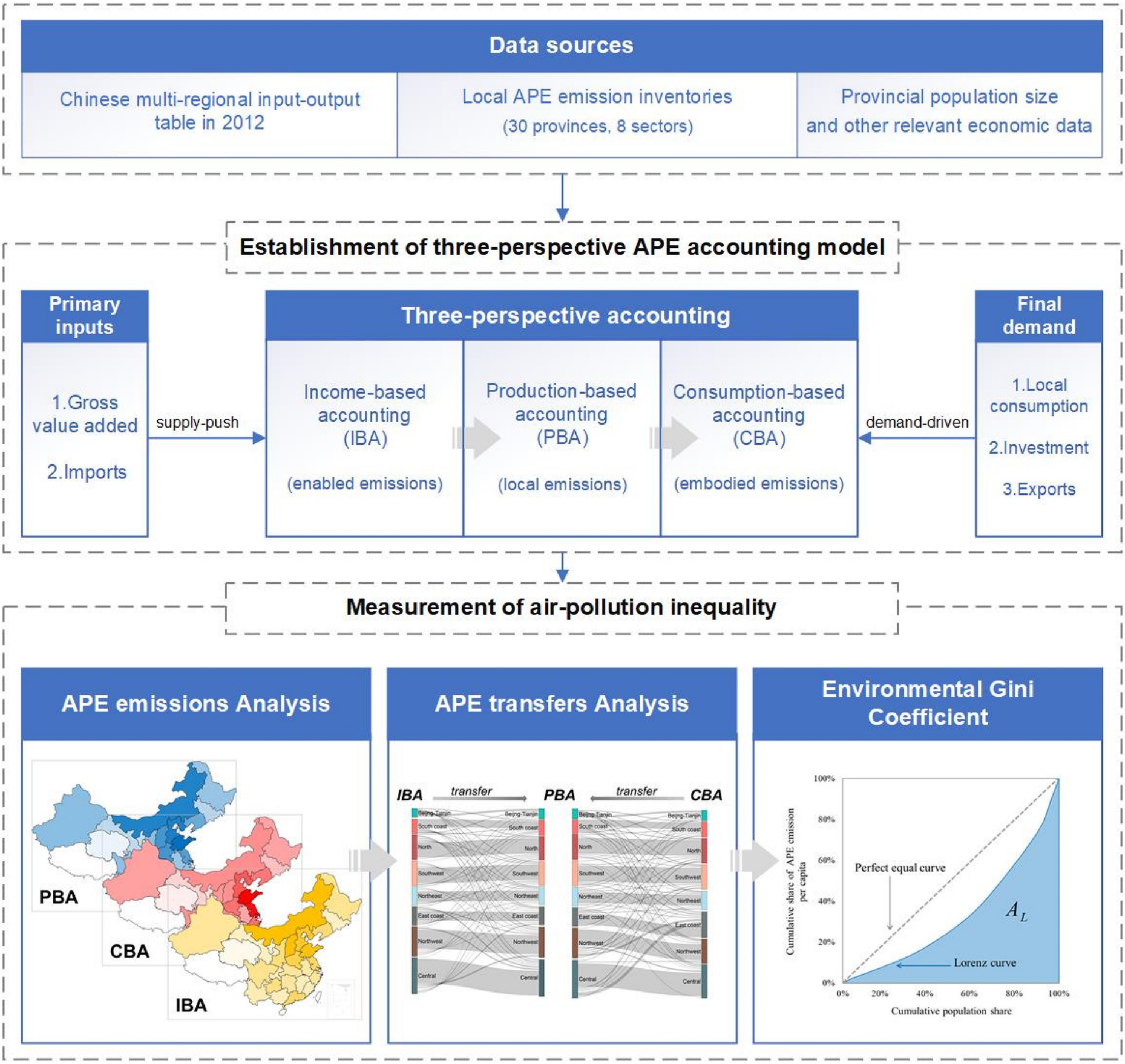


Fig. 1. The framework of this study.

A single-regional input-output model is able to characterize the complex commodities exchange among different economic sectors (Liu et al., 2018b; Zhai et al., 2019), while a multi-regional input-output (MRIO) model is widely used to track economic flows among sectors and consumers of different regions (Chen et al., 2017a; Zhang et al., 2018a). In this study, there are $n = 30$ provinces and $k = 8$ economic sectors in each province, as shown in Fig. S1 and Table S1. The basic form of monetary MRIO table used in this research is presented in Table S2. Therefore, for each row of the MRIO table, the equilibrium equation is as follows:

$$x_i^r = \sum_{s=1}^{n}\sum_{j=1}^{k} Z_{ij}^{rs} + \sum_{s=1}^{n} y_i^{rs} + y_i^{re} \tag{1}$$

for each column,

$$x_j^s = \sum_{r=1}^{n}\sum_{i=1}^{k} Z_{ij}^{rs} + v_j^s + m_j^s \tag{2}$$

For Eq. (1)–(2), x_i^r is the total output of sector i in province r and x_j^s is the total output of sector j in province s. Z_{ij}^{rs} denotes the intermediate inputs from sector i in province r to sector j in province s. y_i^{rs} indicates the flow from sector i in province r for the final use (i.e. local consumption and investment) of sector i in province s. y_i^{re} refers to the international exports of sector i in province r. It is worth mentioning that final use and international exports are two different types of final demand. Meanwhile, v_j^s and m_j^s represent the different types of primary inputs: value-added and international imports of sector j in province s, respectively.

Based on the Leontief and Ghosh frameworks (Leontief, 1951), they can be expressed in matrix form as:

$$\mathbf{x} = (\mathbf{I}-\mathbf{A})^{-1} \times (\mathbf{y}+\mathbf{y}^e) = \mathbf{L} \times (\mathbf{y}+\mathbf{y}^e) \tag{3}$$

$$\mathbf{x}' = (\mathbf{v}+\mathbf{m}) \times (\mathbf{I}-\mathbf{B})^{-1} = (\mathbf{v}+\mathbf{m}) \times \mathbf{G} \tag{4}$$

where, $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$ is known as Leontief inverse matrix and $\mathbf{G} = (\mathbf{I} - \mathbf{B})^{-1}$ is called Ghosh inverse matrix (Augustinovics, 1970; Miller and Blair, 2009). $\mathbf{x} = [x_i^r]_{nk\times 1}$ and $\mathbf{x}' = [x_j^s]_{nk\times 1}$ are the total output vectors. $\mathbf{y}$, $\mathbf{y}^e$, $\mathbf{v}$ and $\mathbf{m}$ is used to represent vectors of y_i^{rs}, y_i^{re}, v_j^s and m_j^s.

If e_i^r is the local APE emissions of sector i in province r, and $\boldsymbol{\varepsilon} = [\varepsilon_i^r]_{kn\times 1} = [e_i^r/x_i^r]_{kn\times 1}$ refers to sectoral APE emission intensity vector, then Eq. (3)–(4) can be expressed as follows (Zhang et al., 2018c, 2018d):

$$\mathbf{C} = \hat{\boldsymbol{\varepsilon}} \times \mathbf{L} \times (\mathbf{y}+\mathbf{y}^e) \tag{5}$$

$$\mathbf{T} = (\mathbf{v}+\mathbf{m}) \times \mathbf{G} \times \hat{\boldsymbol{\varepsilon}} \tag{6}$$

Here, the notation $\hat{\boldsymbol{\varepsilon}}$ means the diagonalization of vector $\boldsymbol{\varepsilon}$. $\mathbf{C}$ represents the $nk \times 1$ vector of consumption-based accounting for each component, and $\mathbf{T}$ stands for the $1 \times nk$ vector of income-based accounting for each component.

After transformation, the $n \times n$ matrices of APE emission transfers among n regions under the Leontief and Ghosh frameworks can be calculated by the following equations:

$$\mathbf{C}^{rs} = \hat{\boldsymbol{\varepsilon}}^r \times \mathbf{L} \times \left(\hat{\mathbf{y}}^s + \hat{\mathbf{y}}^{se}\right) \tag{7}$$

$$\mathbf{T}^{rs} = \left(\hat{\mathbf{v}}^r + \hat{\mathbf{m}}^r\right) \times \mathbf{G} \times \hat{\boldsymbol{\varepsilon}}^s \tag{8}$$

$$\mathbf{nC} = \mathbf{C}^{rs} - \mathbf{C}^{sr} \tag{9}$$

$$\mathbf{nT} = \mathbf{T}^{rs} - \mathbf{T}^{sr} \tag{10}$$

where, the matrix $\mathbf{C}^{rs}$ indicates the embodied APE emissions occurred in region $r$driven by the final demand of region s (i.e. the embodied APE transfers from region s to r), while the matrix $\mathbf{T}^{rs}$ refers to the enabled APE emissions occurred in region s pulled by the primary input of region r through cross-regional trade supply chains (i.e. the enabled APE transfers from region r to s) (Guan et al., 2019b). $\mathbf{C}^{sr}$ and $\mathbf{T}^{sr}$ are the transposed matrices of $\mathbf{C}^{rs}$ and $\mathbf{T}^{rs}$, respectively. The matrices $\mathbf{nC}$ and $\mathbf{nT}$ represent the net flows from the perspective of primary supply and final demand, respectively (Chen et al., 2017b).

Therefore, production-based and consumption-based APE emissions of region r can be calculated through Leontief transfer matrix $\mathbf{C}^{rs}$ and $\mathbf{C}^{sr}$ (Guan et al., 2019a; Zheng et al., 2019):

$$PBA^r = \sum_{s=1}^{n} C^{rs} \tag{11}$$

$$CBA^r = \sum_{s=1}^{n} C^{sr} \tag{12}$$

At the same time, income-based and production-based APE emissions of region r can be calculated through Ghosh transfer matrix $\mathbf{T}^{rs}$ and $\mathbf{T}^{sr}$:

$$IBA^r = \sum_{s=1}^{n} T^{rs} \tag{13}$$

$$PBA^r = \sum_{s=1}^{n} T^{sr} \tag{14}$$

where, the element PBA^r of production-based APE emissions accounting refers to the local emissions that occur in region r and are attributed to its local production activities (Li et al., 2018a). The element CBA^r of consumption-based APE emissions accounting indicates the embodied emissions that are triggered by the final demand of province r but occur in all national regions, and the element IBA^r of income-based APE emissions accounting denotes the enabled emissions that are pulled by the primary inputs of province r but occur in all national regions (Liang et al., 2016).

Furthermore, three-perspective environmental Gini coefficient (e-Gini) is established (Damgaard and Weiner, 2000; Duro and Padilla, 2006). The essence of APE inequality assessment in this research is to more specifically characterize the allocation difference of APE emission regions based on three-perspective APE accounting (Guan, 2017; Teng et al., 2012). The index e-Gini selected in this study is derived from the Lorenz curve and Gini coefficient in economics (Scherer et al., 2018), which is widely used to investigate the allocation relationships between population shares and resident income shares (Wiedenhofer et al., 2017).

We define the following variables for province r: e_i^r is the APE emissions of province r for product in sector i; pop^r is the population size of province r; $ep_i^r = (e_i^r/pop^r)$ is APE emission per capita of province r for product in sector i; $p^r = (pop^r/\sum pop^r)$ is the population share of province r; then $E_i^r = (ep_i^r/\sum ep_i^r)$ is the share of APE emission per capita of province r for product in sector i. As shown in Fig. S2, Lorenz curve in this paper plots population shares against shares of APE emission per capita, where cumulative population shares are on the horizontal axis, and cumulative shares of APE emission per capita are on the vertical axis (Duro and Padilla, 2006; He et al., 2009; Teng et al., 2012). If the distribution is perfectly equal, the Lorenz curve is a straight 45° line (i.e. the perfect equal curve in Fig. S2), otherwise inequality exists (i.e. the actual Lorenz curve in Fig. S1) (Wu et al., 2017). Define the area below the actual curve as A_L, then e-Gini can be built, shown as follows (Kong et al., 2019):

$$e\text{-}Gini = 1 - 2 \cdot A_L \tag{15}$$

where, $0 \leq e - Gini \leq 1$. The $e - Gini$ of 0 reflects absolute equality, while the $e - Gini$ of 1 reflects absolute inequality. A Gini coefficient of 0.4 is generally considered as a warning point to measure whether the inequality level is too high (Chen et al., 2017a; Kong et al., 2019; Zhang and Wang, 2017). This paper proposes three-perspective $e - Gini$ based on the aforementioned accounting model.

Considering the calculation of A_L, there are two highly recognized methods in previous studies (Teng et al., 2012). One way is to obtain a Lorenz curve equation by fitting scatter points with software, and then calculate the area through definite integral (Scherer et al., 2018). Another is to divide the blue area into several trapezoids, then A_L approximates the sum of the trapezoidal areas (Dai et al., 2018). This study selected the first method in order to obtain more accurate results.

2.2. Data sources

The basic data of this research comes from three parts: Chinese MRIO table in 2012, sectoral local APE emission inventories and population size in China's provinces. The original MRIO table used in this study is compiled by Mi's research (Mi et al., 2017), which includes 30 provinces (excluding Tibet, Hong Kong, Macau, and Taiwan provinces due to limited data, shown in Fig. S1) and 30 economic industries for each province. In view of the important significance of treating "imports" as a type of primary input in this study, the MRIO table is adjusted into the form shown in Table S2 according to previous studies (Ou et al., 2017; Zhang et al., 2018c). The basic sectoral air pollutants emission inventories of 30 provinces used in this study are derived from Zhang's published data (Zhang et al., 2018c, 2018d). Specifically, Zhang et al. obtained the emissions of several main air pollutants SO_2, NO_x, soot and dust emitted from economic and production activities of agriculture, industry, construction, transportation and service in detail, and then converted them into a new measure called *Atmospheric Pollutant Equivalents* (APE) (that is, 1 kg of APE is equal to 0.95 kg of SO_2, 0.95 kg of NO_x, 2.18 kg of soot and 4 kg of dust) according to the hazards to atmosphere and public health (Krewski et al., 2015; Yang et al., 2011). The population in China's provinces are obtained from China Statistical Yearbook (National Bureau of Statistics of China, 2016).

3. Results

3.1. Three-perspective APE emissions

Fig. 2 shows China's three-perspective APE emissions at provincial level in 2012. The total APE emissions in China reach 54,912 Gg. From a production-based perspective, Shandong, Hebei, Inner Mongolia, Henan and Shanxi provinces play the largest direct emitters. From a consumption-based perspective, the total APE emissions of the top 5 provinces, namely Shandong, Jiangsu, Hebei, Guangdong and Zhejiang, accounts for 33% of the national total. Moreover, from an income-based perspective, the total APE emissions in Inner Mongolia, Shanxi, Shandong, Hebei and Henan, the 5 major contributing provinces, amount to 19,058 Gg (accounting for 35% of the national).

In detail, Shandong province in the north, as one of the largest contributors to China's APE emissions, directly discharges 4309 Gg of production-based APE emissions during its local economic and production activities, accounting for 8% of the national total in 2012. However, its consumption-based APE emissions (5198 Gg) are much higher than the production-based and income-based (4046 Gg) APE emissions, indicating that Shandong Province is more important as a final consumer in the system. Due to the larger final demand in Shandong (e.g. the products demand form construction, general and specialist machinery and transport equipment industries), it purchases a great many of intermediate products from upstream suppliers, which causes these suppliers to emit large amounts of APE during the production of intermediate goods. The same situation exists in other areas, such as Jiangsu and Zhejiang in the east coast, Guangdong in the south coast, and Chongqing in the Southwest. Inner Mongolia in the Northwest and Shanxi in the central region have much higher income-based APE emissions than their related consumption-based and production-based emissions in 2012. For example, income-based APE emissions (i.e. 4269 Gg) of Inner Mongolia are 88% and 14% higher than its consumption-based (i.e. 2271 Gg) and production-based (i.e. 3747 Gg) APE emissions, respectively. Therefore, it is even more reasonable to treat these provinces as primary suppliers of the Chinese APE emissions system. These primary suppliers have better energy resource endowments, and provide a large number of energy-intensive and high-polluting commodities to other downstream provinces through intricate inter-provincial trade chains. Furthermore, provinces like Ningxia and Hebei that discharge more production-based APE than income-based and consumption-based APE are more significant as direct emitters in the system.

Fig. 3(a) disaggregates APE emissions of 30 provinces by 8 sectoral categories. Production-based APE emitted in the ET (energy and material-transformation) sector accounts for 39% of the total emissions, and the top 5 provinces (i.e. Shandong, Hebei, Inner Mongolia, Henan and Shanxi provinces) occupy the largest share (36%) in ET's emissions. The reason is that the intermediate products required for the production of ET sector are mainly high-polluting and energy-intensive. As the main contributor to consumption-based emissions, the C (construction) sector induces a total of 17,099 Gg embodied APE emissions nationwide, accounting for 29% of the total emissions. Especially in Shandong and Jiangsu, their C sector contributes 6% and 7% of total APE emissions, respectively. This result depends on the specific final demand structure of C sector — in the supply chains ending in C sector, the production of most intermediate products (such as nonmetal products in AM (advanced manufacturing) sector) requires C's upstream suppliers to discharge a large amount of APE. In addition, the M (mining) sector has much higher income-based APE emissions than production-based and consumption-based emissions, especially in Shanxi Province, indicating that the primary supply of M sector drives APE emissions from the downstream sectors.

Fig. 3(b) further disaggregates APE emissions of 30 provinces by final demand and primary input categories. On the primary supply side (i.e. income-based perspective), gross value-added creation is the main enabler, which leads to a total of 91% of national APE emissions

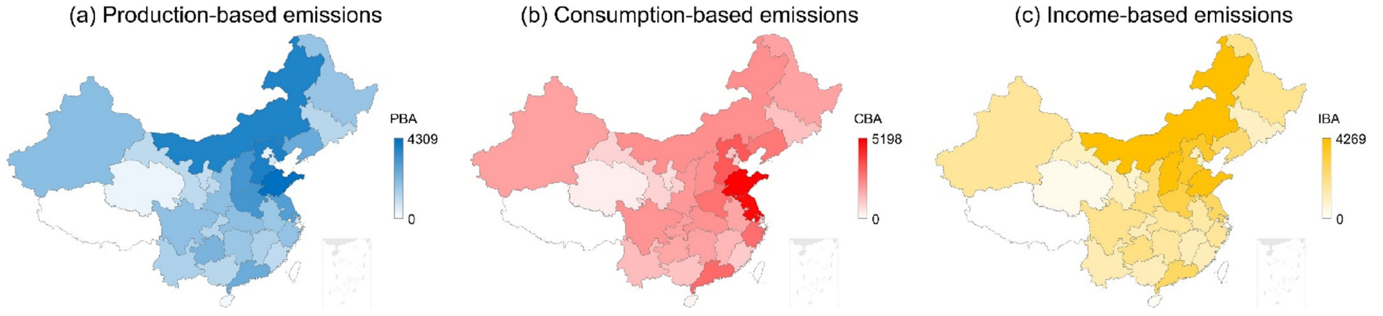
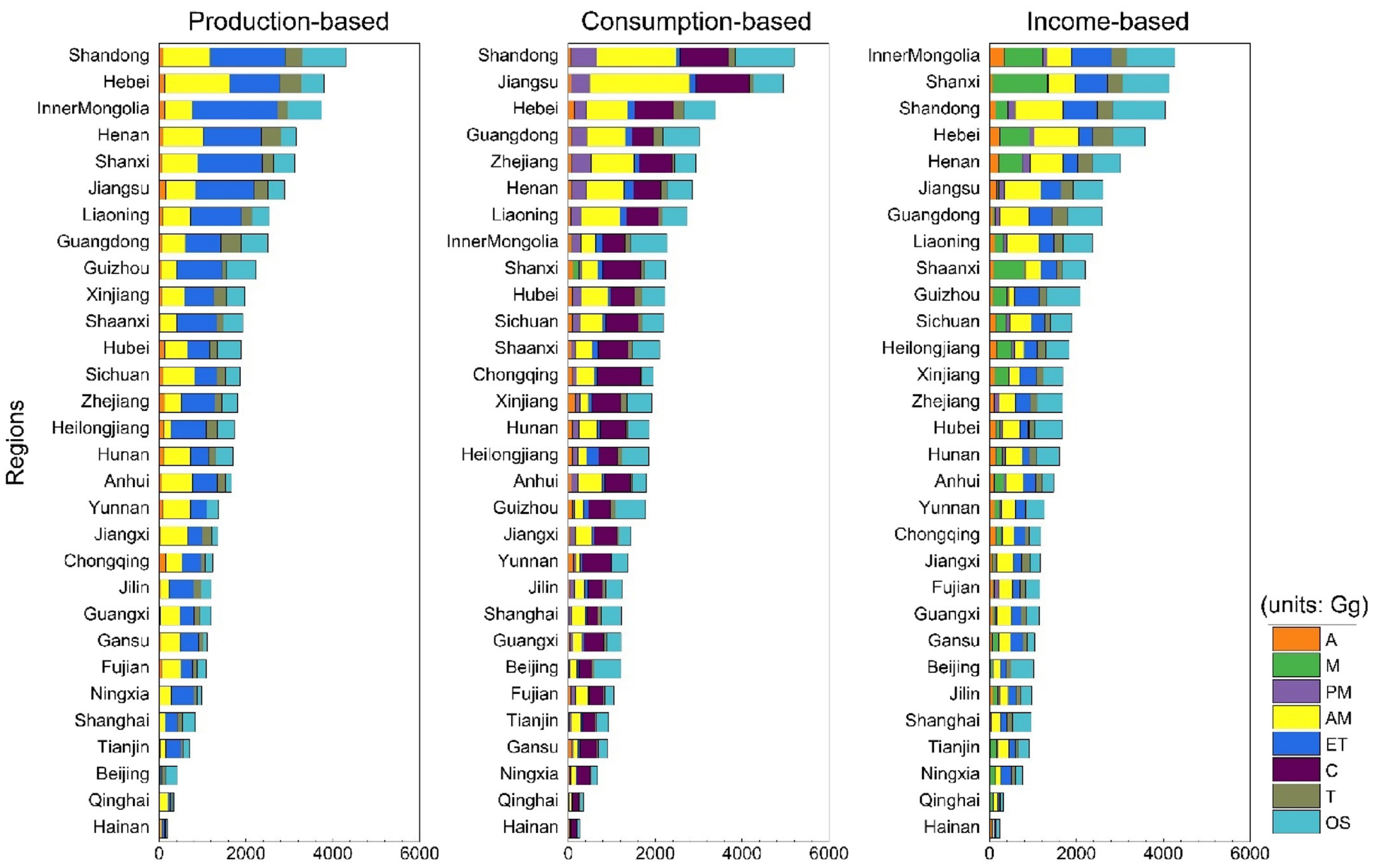


Fig. 2. Three-perspective APE emissions (Units: Gg) of Chinese provinces in 2012.

(a) Sectoral APE emissions



(b) APE emissions by final demand and primary input categories

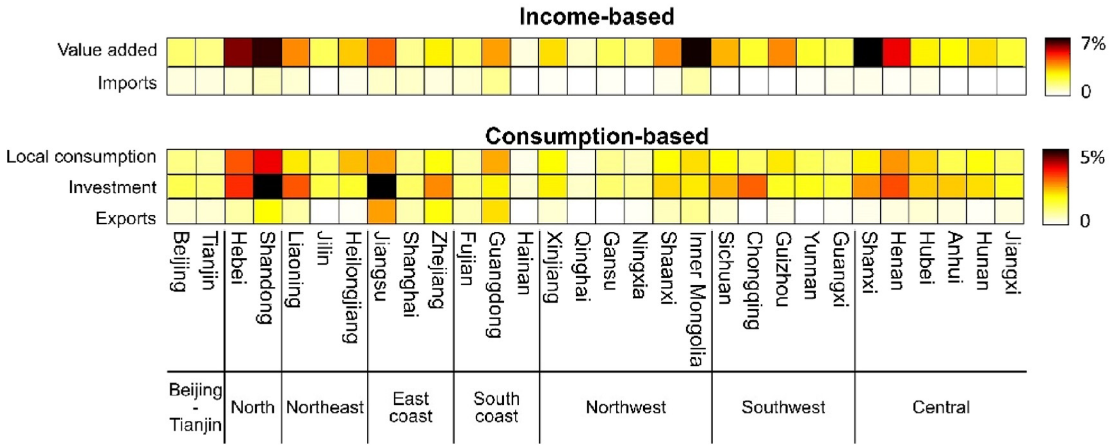


Fig. 3. Three-perspective APE emissions of provinces at sectoral level (a), and APE emissions of each province by final demand and primary input categories (b) in 2012. (The abbreviations of sectors in legend (a) are A (agriculture), M (mining), PM (primary manufacturing), AM (advanced manufacturing), ET (energy and material-transformation), C (construction), T (transport and storage) and OS (other services). The proportion in (b)'s legend refers to the ratio of the accounting of each item to the total accounting. More data is available in Supporting Information Table S3-S4 and Table S29-S30).

in 2012. Such part of APE emissions is mainly derived from gross value-added creation in Shanxi (8%), Inner Mongolia (8%), Shandong (7%) and Hebei (7%). In addition, 5041 Gg (9%) of the national enabled APE emissions are caused by imports, especially in Guangdong (641 Gg) and Inner Mongolia (526 Gg). On the final demand side (i.e. consumption-based perspective), investment is the major driver, contributing 49% of APE emissions in China in 2012. In particular, this part of APE emissions is mainly due to investment in Jiangsu (9%), Shandong (9%), Hebei (5%) and Liaoning (5%). Local consumption leads to 22,523 Gg (38%) of the national embodied APE emissions, especially in Shandong (1798 Gg) and Hebei (1468 Gg). Moreover, exports only lead to 13% of China's APE emissions, which are mainly concentrated on the east coast.

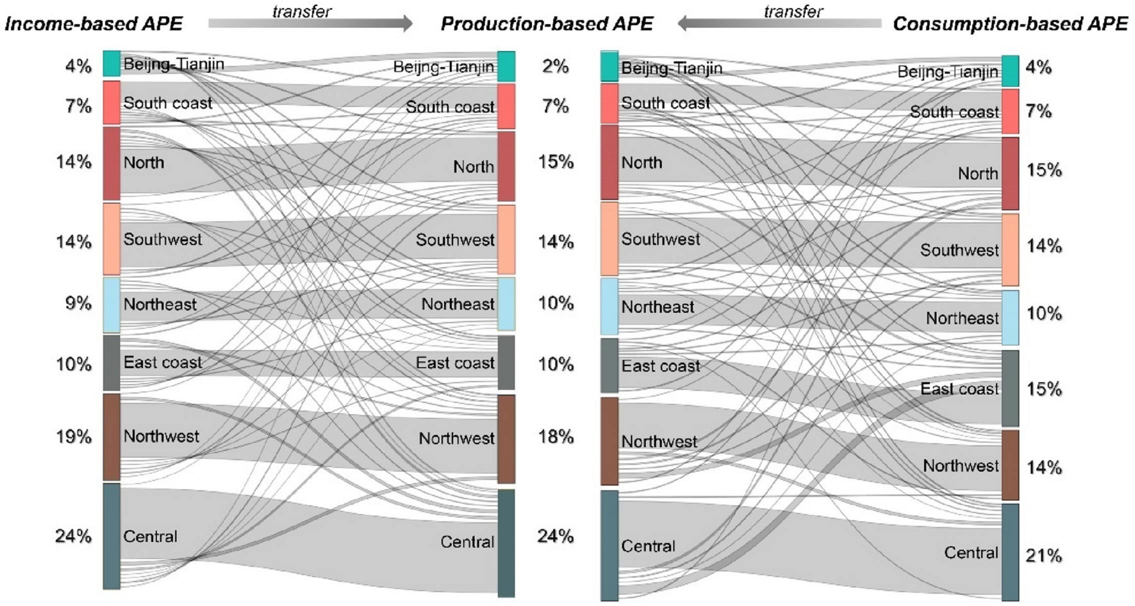
In general, the three-perspective emissions analysis reveals the characteristics of China's APE emissions more comprehensively from all stages of the supply chain, indicating that air-pollution inequality among regions is significant.

3.2. Three-perspective APE transfers

Fig. 4(a) shows the regional APE transfers among China's regions. A region's income-based APE is transferred due to its supply of products to the downstream, and emitted as production-based APE in the downstream regions. At the same time, a region's consumption-based APE is transferred, due to its demand for products from the upstream regions, and emitted as production-based APE in in the upstream regions. For example, Beijing-Tianjin region triggered 4% income-based APE emissions (i.e. enabled emissions), 47% of which occurs locally and 53% of which actually occurs in other downstream regions. Primary supply from all regions results in 2% of total national production-based APE emissions (i.e. local emissions) in Beijing-Tianjin, 79% of which is to meet its local final demand, and 21% of which is to meet the final demand of other downstream regions. Meanwhile, 4% of the total national consumption-based APE (i.e. embodied emissions) discharge in all regions, in order to meet Beijing-Tianjin's total final demand.

It is worth noting that in addition to Beijing-Tianjin region, almost 74% of enabled emissions in each region occur locally. Except for the east coast, nearly 80% of local emissions in each region are caused by their own primary inputs. At the same time, for the three poorer areas (i.e. northwestern, southwestern and central regions), approximately 85% of embodied emissions are driven by their own final demand, but for the two richer areas (i.e. Beijing-Tianjin and the east coast), embodied emissions are driven by their own final demand only accounting for 41% and 55%, respectively. In particular, for northwestern region, its total local emissions are as high as 10,836 Gg (accounting for 18% of

(a) APE transfers



(b) Net transfers from the perspective of final demand **(c) Net transfers from the perspective of primary supply**

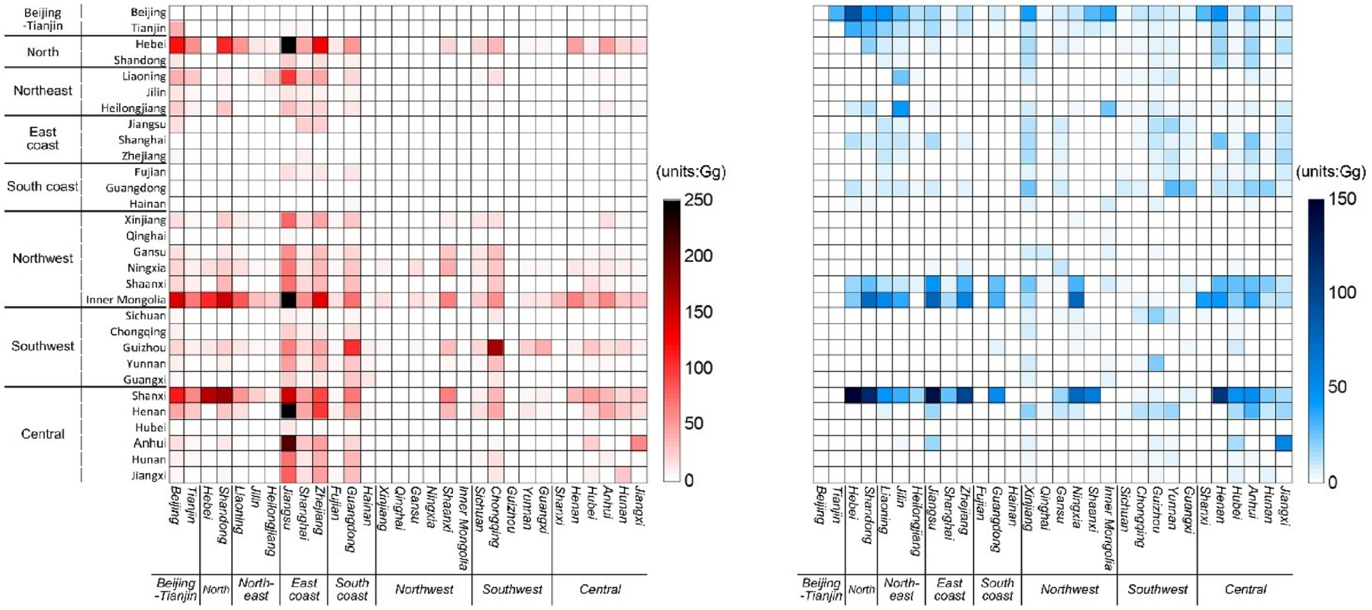


Fig. 4. APE transfers among 8 regions (a), net transfers from the perspective of final demand (b) and net transfers from the perspective of primary supply (c) among 30 provinces.

the total national production-based emissions), while only 7178 Gg is to meet its own final demand.

To further demonstrate the APE transfers among provinces, Fig. 4 (b) and (c) depict the color block diagrams of net transfers not only from the perspective of final demand but also from the perspective of primary supply, each of which reveals a total of 435 pairs of net APE flows relationships. Fig. 4(b) clearly shows that, driven by final demand, the net APE flows are mainly transferred from relatively developed areas, especially the east coast, to the less-developed regions (such as the northwestern, southwestern and central regions). At provincial level, Hebei (the largest steel manufacturing province in China), Inner Mongolia and Shanxi (the two major coal producing areas in China) discharge a vast amount of APE locally because of the intensive transfers driven by the final demand of other provinces. Jiangsu, Zhejiang, Shanghai and Guangdong, China's consumer giants, caused a large amount of embodied APE, leading to intensive transfers from them to other provinces. From the perspective of primary supply, the net APE transfers among various provinces can be revealed by Fig. 4(c). Through the complex supply of pollution-intensive products (such as coal, mineral products, etc.) from Shanxi, Shaanxi and Inner Mongolia to other provinces, large amounts of enabled APE are induced and emitted in the latter provinces. It is worth mentioning that the APE transfers from Beijing and Tianjin to other provinces cannot be ignored, which are caused by primary inputs of the booming OS (other services) sector of the former (according to the results in Fig. 3(a)). It is difficult to identify such a result only through the final demand analysis in Fig. 4(b). Overall, three-perspective APE transfers analysis in this section provides a new vision for describing the complex APE flows and uncovering the air-pollution inequality induced by regional trades.

3.3. Three-perspective environmental Gini coefficient

In this section, Lorenz curves and environmental Gini coefficient (e-Gini) are applied to further quantify the inequality in APE emissions of Chinese provinces. APE emissions per capita is used to describe the hazard levels of air pollution to human health. The e-Gini can investigate environmental inequality from the distribution of environmental risks. Chinese 30 provinces are sorted in ascending order by their APE emission per capita in Fig. 5. The results reveal great differences among various accounting and among various sectors.

The e-Gini value for production-based accounting (i.e. PBA) at aggregated sector level reaches 0.433, which is higher than the warning point of 0.4, indicating that the regional allocation of air pollutants emitted in local activities is unreasonable. At disaggregated sectoral level, in terms of local emissions (i.e. PBA), ET (energy and material-transformation) sector yields the highest e-Gini of 0.527, because more than 80% of the total APE is emitted by provinces with higher per capita PBA emissions, and the total population of these provinces is less than 50% of the country (Table S8). It is followed by OS (other services) sector (0.468), half of which is discharged by about 15% of the population. The e-Gini values of A (agriculture) and AM (advanced manufacturing) sectors also reach relatively high levels of 0.417 and 0.447, respectively. Moreover, the e-Gini value for consumption-based accounting (i.e. CBA) at aggregated sector level is 0.372, which is less than 0.4. However, after decomposition to sectoral level, the results are quite different. In terms of embodied emissions (i.e. CBA), almost every sector has an e-Gini value above 0.4, except for the PM (primary manufacturing) and AM sectors. It is worth noting that the inequality measure of M (mining) sector has the highest e-Gini of 0.881, as more than 90% of its APE emissions are driven by only 23% of the population. It is found that e-Gini for A, ET, C (construction), T and OS sectors are similarly unequally distributed among Chinese provinces in 2012 (around 0.5). The e-Gini value for income-based accounting (i.e. IBA) at aggregated sector level (i.e. 0.468) also reaches a level higher than the warning point. As for enabled emissions (i.e. IBA), higher air-pollution inequality can be found in M (0.701), and ET (0.544) and C (0.528) sectors, and the e-Gini values of other three sectors (i.e. A, T and OS; around 0.45) are also slightly higher than the warning level.

In addition, it is easy to find higher inequalities for M, ET and C sectors, while those for PM and AM are more equally distributed among Chinese provinces under all scenarios. For example, the distribution of M's emissions is far from the perfect equality line, showing the greatest inequality, partly because of the great disparity in demand degrees and supply capacities of mineral products in various provinces. The areas with poor mineral resources (such as Beijing) bear most of the consumption responsibilities, and the areas with abundant mineral resources (such as Shanxi) shoulder most of the supply responsibilities. For ET sector, its economic activities require a large variety of energy and pollution-intensive products. During its production process, efficient desulfurization, denitrification and dust elimination technologies have a significant impact on local air pollutants emissions. And ET also needs to play as a primary supplier to provide intermediate commodities to its downstream. Hence, three-perspective regional air-pollution in ET sector is quite unequal. In comparison, the inequality of APE emissions in PM sector is relatively low, mainly thanks to the wide coverage of light industry plants and intricate inter-provincial products supply and demand networks.

4. Discussion and conclusion

The air quality varies widely across China, mainly due to diversified resource endowments and complicated economic structures. The government has enacted all sorts of laws and regulations to mitigate the impacts of such inequality on the economic prosperity and sustainable development of various regions, from “Western development” to “West—east power transmission project”. Meanwhile, the intricate inter-regional trades caused by economic activities makes such inequality more notable. The unequal regional distribution of air pollutants emission is an issue of great importance, but previous studies on the measurement of air pollution inequality are limited.

The current research highlights the importance of quantifying inequality from three perspectives of local production (i.e. production-based), final demand (i.e. consumption-based) and primary inputs (i.e. income-based), identifies the emission responsibilities of primary suppliers, direct emitters and final consumers along the products supply chains in three-perspective APE emissions analysis, investigates the complex APE flows induced by regional trades in three-perspective APE transfers analysis, and proposes three-perspective environmental Gini coefficient (e-Gini) to characterize the regional air-pollution inequality. It breaks the limitations of measuring environmental inequality only from a single perspective and establishes an innovative framework for environmental inequality assessment through comprehensive analysis. The results indicate that local emitters are merely parts of contributors to air pollution, hence it is not justified to formulate regional air pollution reduction policies only from a perspective of local emissions.

In detail, direct emitters, such as Hebei in the north and Ningxia in the northwest, have relatively developed high-polluting and energy-intensive plants like steel plants and thermal power plants. These direct emitters discharge vast amounts of APE directly during local production activities, especially in ET (energy and material-transformation) sector. Primary suppliers, such as Inner Mongolia in the northwest and Shanxi in central region, have richer natural resource endowments like mineral products. They input large numbers of polluting-intensive products which enable high downstream emissions, especially in M (mining) sector. Final consumers, such as Shandong in the north, and Zhejiang and Jiangsu in the east coast, have richer capital, labor and technology resource endowments and their final demand drives high upstream emissions, especially in C (construction) sector. It is because of such unequal supply capacities and demand degrees among provinces that regional income-based and consumption-based APE emissions are significantly heterogeneous, especially in the M, C and ET sector.

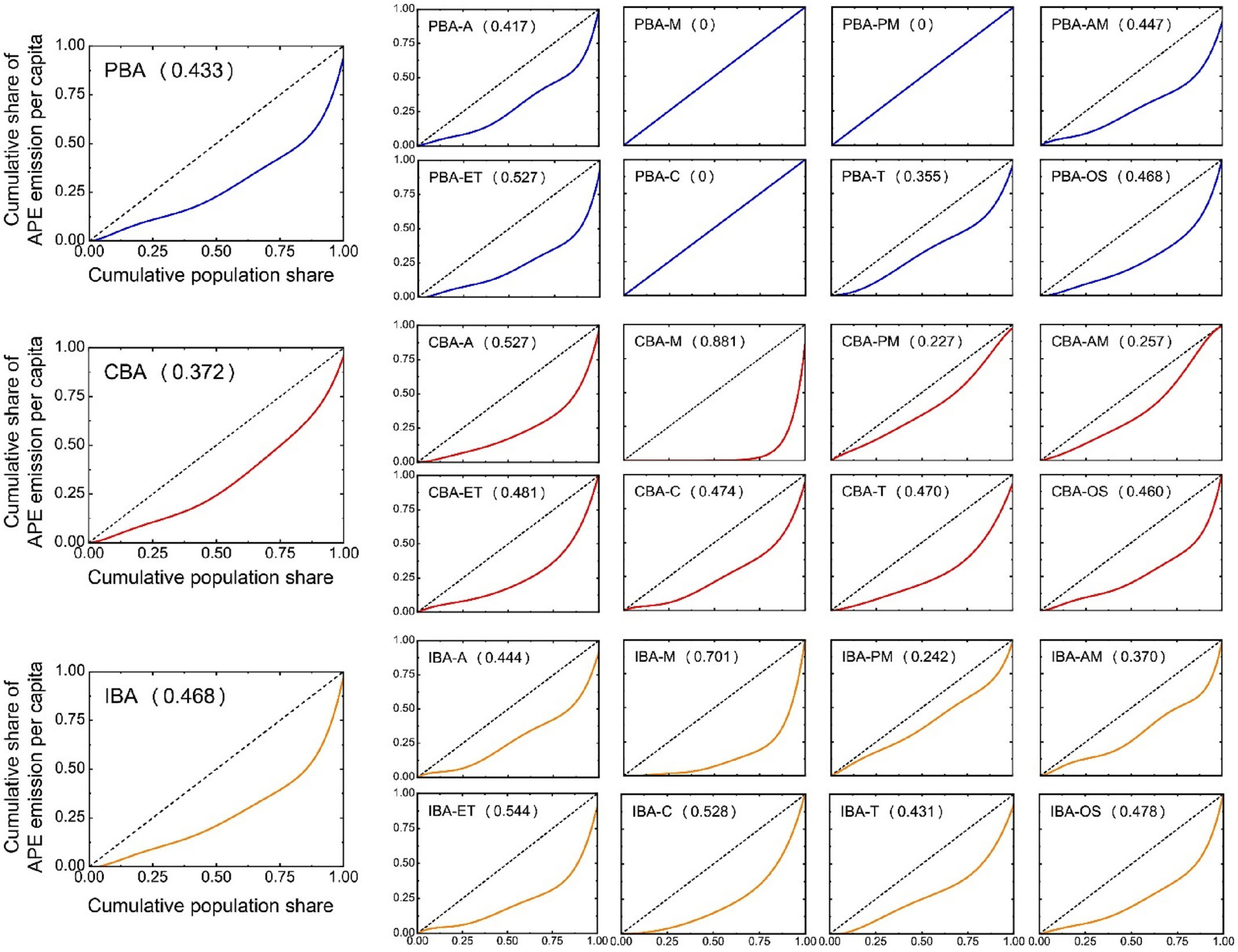


Fig. 5. Lorenz curves and environmental Gini coefficient of APE emissions for Chinese 30 provinces in 2012. (The diagonal is the perfect equality curve. The numbers presented in parentheses are the environmental Gini coefficient. PBA is production-based accounting, CBA represents consumption-based accounting and IBA refers to income-based accounting. The abbreviations of sectors are A (agriculture), M (mining), PM (primary manufacturing), AM (advanced manufacturing), ET (energy and material-transformation), C (construction), T (transport and storage) and OS (other services). Because the values of provincial production-based APE emissions in M, PM and C sectors equal to zero, we define them to be absolutely equal for 30 provinces, and the e-Gini values for PBA-M, PBA-AM and PBA-C are all zero. Full data supporting this graph are listed in Table S5-S28.)

In addition, APE transfers analysis results indicate that APE emissions are transferred from the primary suppliers located in relatively less-developed areas to others in the view of primary supply, and from the final consumers in relatively developed areas to others in the view of final demand. Over time, the products requirement is increasing from the pollution-intensive industries of primary suppliers in less-developed regions, leading to greater enabled emission intensities and national air pollution. At the same time, final consumers in relatively developed regions are increasingly dependent on the system, resulting in greater embodied emission intensities and nationwide air pollution. It is because of such transfers that the inequalities in regional APE emissions are ever more serious. Furthermore, the primary input pattern and final demand pattern also play important roles in the APE accounting system. For example, in terms of primary suppliers such as Inner Mongolia, primary inputs mainly consist of large value-added inputs and product imports in resource-based industries. As for final consumers like Jiangsu, final demand is mainly dominated by investment and exports in high-tech and high-hierarchy industries.

We also observe a great regional disparity in air-pollution by three-perspective e-Gini. At aggregated sectoral level, the e-Gini from the production-based and income-based perspectives all exceed the warning value of 0.4, indicating higher unreasonable distribution in regional APE. At the disaggregated sectoral level, the e-Gini values of various sectors from three perspectives vary significantly. Consistent with previous results, M, ET and C sectors have higher air-pollution inequality among Chinese provinces. Particularly, inequality of the M sector in embodied emissions has the highest e-Gini value, at 0.881.

There is much to be done to reduce APE emissions at all stages of the supply chains, thereby mitigating regional emissions inequality. First of all, large emission enterprises in each province (e.g. large power plants in Hebei, large mining companies in Inner Mongolia and Shanxi, construction companies in Zhejiang and Jiangsu, etc.) should be encouraged to compile the accounting lists of air pollutants emissions according to the pollution intensity of various products, including production-based emissions occurred in local province, consumption-based emissions embodied in inter-provincial trades driven by their final demand, and income-based emissions enabled in inter-provincial trades pulled by their primary inputs. Then judge their emission responsibilities and take targeted reduction measures. Specifically, production-side reduction measures (i.e. production-based perspective), such as improving energy usage efficiency, optimizing energy mix and applying efficient and synergistic pollutant removal technologies to achieve ultra-low emissions, are effective for direct emitters like Hebei and Ningxia provinces. Under the background of the “One belt and one way”, international trades are bound to be strengthened. Therefore, supply-side emission reduction measures (i.e. income-based perspective) can be implemented by selecting imported products with less polluting intensity, influencing product allocation behaviors (e.g. cutting production taxes, increasing government subsidies, and supporting employment for those enterprises willing to sell resources with less enabled intensity to downstream users), and shifting product supply pattern (e.g. properly limiting government subsidies and loan for those enterprises that have high income-based APE emissions),etc. In addition, considering the relatively advanced production technologies and abundant labor forces in the richer coastal areas, demand-side emission reduction measures (i.e. consumption-based perspective) should be taken for these final consumers, such as changing consumption structure by adding consumption taxes on high embodied intensity products, influencing consumption behaviors by encouraging to choose commodities with low consumption-based APE emissions, and transferring advanced production technologies from the final consumers to direct emitters.

In this paper, there are some limitations that should be addressed in future studies. Studies on how to uniformly measure air-pollution inequality from the three perspectives accounting methods will be conducted.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.133937.

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