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Provincial air pollution responsibility and environmental tax of China based on interregional linkage indicators

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ABSTRACT

Air pollution presents a serious public health risk globally, particularly in fast industrializing countries such as China. Effectiveness of local air pollution control measures is influenced by external forces such as atmospheric emission transport and interprovincial trade. However, there is lack of research on comparison of these two indicators and local indicators (e.g. per capita income and emissions) determines the responsibility allocation in pollution control. In this paper, cross-provincial air pollution is stimulated via atmospheric transport (atmospheric linkage indicator) based on Weather Research and Forecasting/Comprehensive Air Quality Model with Extensions (WRF/CAMx) model. The air pollutants embodied in interprovincial trade (trade linkage indicator) was studied by using the latest multi-regional input-output (MRIO) model. This study revealed the significant influence of atmospheric transport on neighboring provinces. However, transport of trade-induced embodied emissions affects both neighboring areas and larger areas. According to aggregation analysis of these two indicators, in most provinces of China, direction of atmospheric transport contradicts to that of the trade-induced transport. These findings are used to analyze the rationality of regional differences in environmental tax rate in the new environmental protection tax law of China. By comparing the local and interregional linkage indicators, we found the current environment tax for air pollutants was mainly affected by per capita income whereas other environment and linkage indicators show little correlation. Therefore, we integrated environment and linkage indicators to propose adjusted provincial environment tax rates plan for air pollutants as a cost sharing mechanism. The results of this paper provide novel perspective for central government to adjust fairness environmental responsibility between provinces of China by tax policy.

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1. Introduction

Air pollution has caused serious economic and health impacts in China and environmental protection is an expensive business in

nowadays. For example, in 2017, the Chinese Central Government allocated a special fund of RMB 16 billion (US\$ 2.55 billion) (Chinese Central Government, 2018a) to local governments for air pollution control, a 43% increase from the previous year. At the 2018 National Conference on environmental protection held in Beijing, a 3-year plan to improve air quality was proposed (Ministry of Ecology and Environment of the People's Republic of China, 2018).

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According to this plan, by 2020, the average PM_{2.5} concentration in the country's non-standard cities is scheduled to decline by 18% compared to 2015, and the proportion of 'good days' (i.e. PM_{2.5} concentration achieves Chinese ambient air quality grade II standards) will reach at least 80% (Ministry of Ecology and Environment of the People's Republic of China, 2018). This is the binding target of the 13th Five-Year plan (Chinese Central Government, 2018b). To achieve this plan, more funds need to be invested in air pollution control (Zhang et al., 2015). Therefore, it is not sensible or sustainable to rely on the Central Government budget for the long-term (Wang, 2018).

It is imperative to develop a cost sharing mechanism for local governments based on pollution responsibility. There has been an ongoing debate on who should be responsible for the pollution and consequently who should bear the cost: the producer or the consumer (Gallego and Lenzen, 2005; Lenzen et al., 2007). "Producer responsibility" is based on the "polluter pays principle" whereas the "consumer responsibility" allocates pollution to the final consumer (Huo et al., 2014). At present, the official statistics on pollutant emissions are based on producer responsibility. However, many scholars have proposed that the principle of consumer responsibility should be taken into account (Peters, 2008; Liang et al., 2017). For example, Peters et al. (2008) have made a comparative analysis of "producer responsibility" and "consumer responsibility" from the theoretical, empirical and policy perspectives. They pointed out that accounting for greenhouse gas emissions from countries based on producers will lead to "carbon leakage" from developed countries to developing countries. In the international negotiations in the post-Kyoto era, we should consider using "consumers" as the basis to calculate the emissions of countries in order to reduce carbon leakage. However, there are also some drawbacks of "consumer responsibility", which may reduce the enthusiasm of producer to apply cleaner production technology. From a consumer responsibility perspective, producers may not take the initiative to reduce emissions (Bastianoni et al., 2004).

Determining the responsibility is a complicated issue (Chen et al., 2005, 2017; Wei et al., 2014). It may be even impacted by some subjective understanding. The extent to who is responsible for a certain environmental pressure depends on the responsibility principle chosen (Marques et al., 2012). Although there is no perfect rule for environmental responsibility determination without any dispute, the environmental responsibility allocation is an important part of environmental management. One of the major applications of environmental responsibility is the formulation of regional environmental taxes. As an important economic tool, an environmental tax can serve as a cost sharing mechanism for local governments based on pollution responsibility. In China, the new Environmental Protection Tax Law has been effect since on January 1, 2018 (Ministry of Ecology and Environment of the People's Republic of China, 2017). It stipulates that the tax rates can be set at different levels by each province (Long et al., 2018). However, the current rates do not consider the distribution of pollution responsibility among regions. Each province is not only a producer but also a consumer. From a "producer responsibility" point of view, air pollution that originates from a province is the responsibility of that province. On the other hand, based on "consumer responsibility", emissions that are associated with the production of items consumed in a particular province (i.e. pollution embodied in trade) are the responsibility of the consuming province.

There are also some methods to allocate the responsibility based on "producer responsibility" such as based on cumulative emissions and per capita emissions. However, these allocation methods based on producer responsibility lack the consideration of inter-regional linkage, while interregional atmospheric transport just focuses on interregional linkage. The allocation of responsibility

becomes more complex when the atmospheric transport of pollution is also taken into consideration (Hu et al., 2015; Jiang et al., 2015; Zhang et al., 2017). A number of studies have been conducted to compare the patterns of atmospheric transport and interprovincial trade as well as their impacts on air quality, health, and climate (Lin et al., 2014, 2016; Zhang et al., 2017; Zhao et al., 2017). However, to our knowledge, studies of regional environmental responsibility based on interregional linkages i.e. atmospheric transport and trade transport to discuss regional environmental tax rates of China are absent to date.

The mechanism of sewage charge in China was formulated at the beginning of this century (Chinese Central Government, 2003). Initially, the standard for sewage discharge was low and it was 0.6 yuan per air pollution equivalent (APE). According to the new "Environmental Protection Tax Law of the People's Republic of China", the basic standard of environmental tax for air pollutants is 1.2 yuan per air pollution equivalent (APE) which had been increased compared with the original standard. According to the demand from central government, each provincial government can impose 1 to 10 times (1.2 yuan/APE to 12 yuan/APE) of this rate based on its own context and needs. Now every province has submitted their environmental tax rates to the central government and the official environmental tax rates of 31 provinces has been promulgated. However, nearly half provinces remain original 1.2yuan/APE (Long et al., 2018). From the perspective of each province itself, they don't like share environmental responsibility and worry the environmental tax will affect their economy.

Therefore, from the perspective of the whole country, this study aims to investigate the interprovincial air pollution flows in atmospheric transport and embodied in trade to suggest new indicators for allocation of responsibility and corresponding tax rates. The interprovincial cross-boundary air pollution via atmospheric transport ('atmospheric linkage indicator') is based on the WRF/CAMx (Weather Research and Forecasting/Comprehensive Air Quality Model with Extensions) model. Similarly, air pollutants embodied in trade are traced ('trade linkage indicator') using the latest MRIO (multi-regional input-output) model and emission inventory of China in 2012. Results provide useful inputs for introducing differential environmental tax rates in various provinces in China.

2. Materials and methods

2.1. Methodological framework

The overall framework of research is shown in the following diagram (see Fig. 1): (1) Transport of atmospheric air pollution (represented by PM_{2.5} concentration, for this is the main pollutant exceeding standard in China) is calculated based on an integrated air quality forecasting system WRF/CAMx. (2) The MRIO Model is applied to trace air pollution embodied in trade between provinces. (3) Based on the results of (1) and (2), the atmospheric and trade linkage indicators are calculated to reveal net contribution ratio induced by interprovincial atmospheric and trade transport, respectively. (4) Based on these two indicators, a rationale for environmental taxation is put forward.

2.2. Model description and configuration

2.2.1. Atmospheric transport model

The transport of atmospheric air pollution is calculated based on an integrated air quality forecasting system WRF/CAMx. The meteorological fields are provided by the non-hydrostatic meso-scale model WRF (Skamarock et al., 2008), while the air quality simulation is performed using the photochemical dispersion model

Fig. 1. Methodological framework

Note: The air pollutants related to trade in this paper include SO₂, NO_x, Soot and Dust, which are closely related to PM_{2.5} concentration (Yao et al., 2002; Wang et al., 2017b), and are provided by official statistics in China. In order to integrate these pollutants, we applied atmospheric pollutants equivalents (APE) to aggregate the four types of emissions (see equation (4)).

CAMx (ENVIRON International Corporation, 2010). WRF is a next-generation numerical weather prediction system designed to serve both operational forecasting and atmospheric research needs (Coelho et al., 2014). It is employed to generate the meteorological background for air quality simulation (Wang, 2018). The CAMx, a three-dimensional Eulerian air quality simulation model, is a state-of-the-science photochemical grid model that comprises a “1-atm” treatment of tropospheric air pollution over spatial scales ranging from neighbourhoods to continents. It includes gas and aerosol chemistry, wet and dry deposition processes, aqueous phase processes, thermodynamic partitioning of the inorganic aerosols and secondary organic aerosol formation/partitioning (Bove et al., 2014). WRF/CAMx modeling system is widely employed in pollutant concentration prediction and transport simulation to analyze atmospheric heavy pollution events (Wang et al., 2017a), to support state implementation plans (Nobel et al., 2015), and to assess air quality policies (Vijayaraghavan et al., 2012).

In this study, the simulation time period is January, April, July and October in 2012, representing winter, spring, summer and autumn respectively in China. The simulation interval is 1 h. The space domain of CAMx simulation is 5380 km in the east-west direction and 4300 km in the north-south direction, with a 20-km nested grid structure over mainland China. There are fourteen vertical layers in the model. The projection is Lambert Conformal. The domain origin point is (103°E, 37°N), and the two parallel true latitudes are 25°N and 40°N, respectively. Other parameters are shown in Table S1 in the Supporting Information.

The meteorological field required by the CAMx model is

provided by the WRF model. Its spatial projection and grid resolution in horizontal direction is the same with CAMx. But the range is larger than the CAMx with 7200 km in the east-west direction and 5040 km in the north-south direction. There are thirty vertical layers in the WRF model, and the interlayer spacing increases gradually from bottom to top. Other WRF parameterization schemes are shown in the Supporting Information Table S2.

In this paper, WRF/CAMx model is applied to simulate the PM_{2.5} concentration values of the interaction by atmospheric movements between provinces. After doing this, the regional contribution ratio of PM_{2.5} concentration can be calculated by formula (1):

$$P_a^{rs} = C_a^{rs} / C_0^s \quad (1)$$

where P_a^{rs} is the contribution ratio of region s influenced by region r via atmospheric transport; C_a^{rs} is the PM_{2.5} concentration loss of region s without atmospheric transport effect from region r 's pollution according to simulation results by WRF/CAMx model; C_0^s is the actual monitoring data of PM_{2.5} concentration of region s .

In this paper, only the domestic impact is considered ignoring flows from abroad, for three reasons: 1) foreign emission inventories are difficult to obtain; 2) there are less air pollutant emissions in China's surrounding areas and countries, except from India whose pollutants are blocked by the Himalayas; 3) the focus of this paper on responsibilities among provinces in China.

2.2.2. Embodied emissions in trade

The Multi-Regional Input-Output Model (MRIO) is often applied to trace the pollutant emissions embodied in trade between regions (Davis and Caldeira, 2010; Liu and Wang, 2015; Zhang et al., 2018a; Zhao et al., 2015). Here, by applying the air pollution extended MRIO model, air pollutants are allocated to 31 provinces according to the final demand of consumers. The MRIO framework is shown in the Supporting Information.

The share of local emissions induced by production for exports to other regions can be calculated by equation (2).

$$P_t^{rs} = E^{rs} / E_0^s \quad (2)$$

where P_t^{rs} refers to the share of region s induced by production of exports to region r ; E^{rs} refers to the total amount of emissions in region s induced by consumption in region r ; E_0^s refers to the domestic or territorial emissions of region s .

The air pollutants related to trade in this paper include SO₂, NO_x, Soot and Dust, which are closely related to PM_{2.5} (Yao et al., 2002; Wang et al., 2017b), and are provided by official statistics in China. In order to integrate these pollutants, we applied atmospheric pollutants equivalents (APE) to aggregate the four types of emissions, as shown in equation (3). Based on China's pollution charge schedule in China Environmental Protection Tax Law (Ministry of Ecology and Environment of the People's Republic of China, 2017), the respective conversion coefficient to APE for SO₂, NO_x, Soot and Dust is 0.95, 0.95, 2.18 and 4, which means that 1 kg APE is equal to 0.95, 0.95, 2.18 and 4 kg of SO₂, NO_x, Soot and Dust, respectively. This integration method has shown to be reasonable and feasible for the research of air pollution embodied in trade (Zhang et al., 2018a, 2018b).

$$APE = E_{(so_2)} / 0.95 + E_{(no_x)} / 0.95 + E_{(soot)} / 2.18 + E_{(dust)} / 4 \quad (3)$$

2.2.3. Atmospheric linkage indicator and trade linkage indicator

The influence between two regions is reciprocal. In order to show the role for air pollution responsibility of every province

based on the effects of atmospheric transport and embodied trade transport, the atmospheric linkage indicator representing the net influence (in %) of atmospheric transport, and the trade linkage indicator representing the net influence of embodied trade transport (in %) were designed in this paper.

The atmospheric linkage indicator of region s is calculated as follows:

$$L_a^s = \sum_{r=1}^{31} netP_a^{sr} \quad (4)$$

$$netP_a^{sr} = P_a^{sr} - P_a^{rs} \quad (5)$$

where, L_a^s is the cumulative net contribution ratio of $PM_{2.5}$ concentration of region s induced by atmospheric transport from other regions, and $netP_a^{sr}$ equals P_a^{sr} minus P_a^{rs} as shown in equation (5). Here, 'a' indicates that it is an index related to atmospheric transport. The atmospheric linkage indicator L_a^s represents the net influence indicator of atmospheric transport. The greater the value of L_a^s , the more region s is affected by other regions. When L_a^s is greater than 0, indicating that the region s plays the role of receptor among 31 provinces in most cases; otherwise, region s influences air quality of other regions as a source by atmospheric transport.

Similarly, the trade linkage indicator of region s is calculated as follows:

$$L_t^s = \sum_{r=1}^{31} netP_t^{sr} \quad (6)$$

$$netP_t^{sr} = P_t^{sr} - P_t^{rs} \quad (7)$$

where, L_t^s is the sum of the shares of net emissions of region s associated with the production of exports to the other 30 provinces; $netP_t^{sr}$ equals P_t^{sr} minus P_t^{rs} as shown in Formula. (7). Here, t indicates that it is an index related to trade transport. The trade linkage indicator L_t^s represents the net influence of trade transport. The greater the value of L_t^s is, the more region s is affected by other regions' consumption through trade. When L_t^s is greater than 0, this means that the region s emits air pollutants for other regions as a net importer of embodied emissions; otherwise, it means that region s is a net exporter of embodied emissions. As mentioned above (methodological framework), air pollutants include SO_2 , NO_x , Soot and Dust which are aggregated into a new indicator APE.

2.3. Data sources and processing

As shown in Table S3 in the Supporting Information, the initial and boundary field data of WRF simulation was from the Final Operational Global Analyses data with 1° resolution produced by the National Center for Environmental Prediction's (NCEP) Global Forecast System (Wang, 2018; National Center for Atmospheric Research, 2016). The original data were observed every 6 h and were used for objective analysis and four-dimensional assimilation using NCEP ADP data (NCEP, 2016).

The emission inventory data was derived from the China Environmental Statistics (CES) database (MEP, 2013), which contains 147,996 industrial sources and different types of vehicles in all 31 provinces (No data in Taiwan, Hong Kong and Macao) in 2012. It contains three main types of air pollutants (i.e. SO_2 , NO_x and PM) from industry and transportation (agriculture and service emissions were estimated based on energy consumption). The CES database is regarded as the most authoritative survey data source for pollution in China and has been used and published in a number

of recent articles (e.g. Wang et al., 2017c; Zhang et al., 2018a). Based on this, we established 20 km-resolution grid emission inventories. Because of the lack of VOCs and ammonia statistics of the database, the emission data of human sources such as NH_3 , VOCs (including the main components) were from the Multi-resolution emission inventory for China (MEIC) of Tsinghua University (<http://www.meicmodel.org/>, accessed 20 June 2018). The VOCs emission data of biological source was calculated online based on the Model of Emissions of Gases and Aerosols from Nature (MEGAN) (Emissions of atmospheric compounds and compilation of ancillary data, 2013).

We employed Chinese MRIO table and sectoral air pollutant emission inventories to quantify air pollution emissions embodied in traded products. This MRIO table was compiled based on China's original provincial monetary input-output tables for 2012, which were released in 2016 by the National Bureau of Statistics (NBS, 2016; Zhang et al., 2018a). Based on the inflow and outflow data provided by each province's input-output table, a hybrid technique based on maximum entropy and dual-constrained gravity models (Oguledo and Macphee, 1994; Robinson and Cattaneo, 2001) was employed to track inter-sectoral trade flows in the MRIO compilation processing. This MRIO table includes 30 sectors of 31 provinces (excluding Taiwan, Hong Kong, and Macau for lack of data). The income and average $PM_{2.5}$ concentration data are derived from the national statistical yearbook of China (NBS, 2013–2017).

3. Results

3.1. Interprovincial atmospheric pollution transport and pollution embodied in trade

3.1.1. Cross-provincial atmospheric transport

As local air quality can also be affected by atmospheric transport of pollution from distant sources, the interprovincial cross-boundary air pollution influence via atmospheric transport was calculated based on WRF/CAMx modeling. Fig. 2(a) shows atmospheric transport-induced contribution ratios matrix based on equation (1). Each cell in the grid shows the atmospheric contribution through transport of emissions from the emitting region (in the rows) to the receiving region (in the columns). The diagonal reflects contribution to air quality in a region due to a region's local emissions. The interprovincial cross-boundary influence of atmospheric transport is closely correlated to distance. The own-contribution ratio resulting from local emission range from 29% in Hainan and 48% in Shanghai (SH) to nearly 100% in Xinjiang (XJ). In these provinces, the contribution of the local region to the total emissions is the largest, followed by the neighboring provinces, and then those provinces in far distance.

3.1.2. Interprovincial trade transport

Local emissions can also be induced by consumption of other regions through trade. Fig. 2(b) illustrates trade-induced contribution ratios matrix between provinces based on equation (2). Each cell in the grid shows the contribution of export production for provinces listed in columns to emissions of provinces listed on the abscissa axis. For example, the first column indicates the ratios of emissions in Heilongjiang province that are induced by production for domestic consumption as well as exports to the other 30 provinces. The matrix also exhibits a darker diagonal similar to Fig. 2(a), which reflects the fact that most emissions are related to production for local consumption and that export related emissions represent a relatively small part of emissions. Especially, in western China (e.g. Tibet and Qinghai), emissions associated with production for local consumption accounts for more than 90%. According to our calculated results, the transfer of air pollution induced by

Fig. 2. Interprovincial atmospheric pollution transport and pollution embodied in trade. (a) Atmospheric transport-induced contribution ratios matrix for $PM_{2.5}$ concentration of 31 provinces in 2012 (in %). (b) trade-induced contribution ratios matrix for emissions of 31 provinces in 2012 (in %). In the boxes, the regions in the columns are receivers of air pollutants, and the ones in the rows are emitters. In the legend, darker shading represents higher contribution of $PM_{2.5}$ concentration (a) and air pollution emissions (b). Province abbreviations are HL, Heilongjiang; JL, Jilin; LN, Liaoning; BJ, Beijing; TJ, Tianjin; HB, Hebei; SD, Shandong; SX, Shanxi; HE, Henan; UB, Hubei; HU, Hunan; AH, Anhui; JX, Jiangxi; JS, Jiangsu; SH, Shanghai; ZJ, Zhejiang; FJ, Fujian; GD, Guangdong; HA, Hainan; GX, Guangxi; CQ, Chongqing; SC, Sichuan; GZ, Guizhou; YN, Yunnan; TB, Tibet; QH, Qinghai; NM, Inner Mongolia; SA, Shaanxi; NX, Ningxia; GS, Gansu; SJ, Xinjiang. The provinces are organized by distance.

export of China in international trades accounts for 17.8% of air pollution emission in China. And in more than half of the provinces, this proportion is between 10% and 20% (see Fig. S1 in Support Information). As mentioned above, the international trade is not the main impacts on China's domestic pollution. The results of this study are similar to those of other studies. For example, Zhao et al. (2015) estimated that primary $PM_{2.5}$, SO_2 , NO_x and NMVOC accounts 15%, 21%, 23% and 21% of total Chinese production-based emission were embodied in goods or services exported internationally. Therefore, this paper focuses on air pollution transfer and responsibility between provinces in China.

Unlike Fig. 2(a), the trade-induced contribution ratios matrix shows a more dispersed distribution, which indicates that trade-induced emissions transport affects not only neighboring area but also more distance area. The trade physically separates production activities further away from consumption activities, with pollution occurring within the producing region and nearby downwind regions. Fig. 2(b) shows that the producing region is often far from the regions where those goods are ultimately consumed.

3.2. Atmospheric and trade linkage indicators

Fig. 3 (a) shows atmospheric transport-induced atmospheric linkages among 31 provinces. It shows there is not only significant atmospheric transport between contiguous provinces, but also a core area with serious pollution to affect other regions, including Inner Mongolia, Hebei, Shanxi, Shandong, Jiangsu and Anhui (see green series color areas). Red series color areas are affected by other regions. According to the direction of the net atmospheric linkage indicator (see those arrows in the map, the beginning of which is the emitter of air pollution via atmospheric transport, and the end point of which is the receiver). The thickness of the arrows indicates the relative magnitude of the absolute cross-provincial contribution of $PM_{2.5}$ concentration). It seems these provinces are separated by the so-called "Qinling Mountains and Huaihe dividing line"

which is considered the geographical demarcation line between the south and the north of China (see the red line in Fig. 3(a)). In the north, almost all arrows point to north, for example, 22.3% of $PM_{2.5}$ concentrations in Beijing and 24.3% of Tianjin are contributed by Hebei. However, in the south, most arrows point to south. Remarkably, Jiangsu is responsible for 24.2% of $PM_{2.5}$ concentration of Shanghai while Guangzhou contributes to 22.9% $PM_{2.5}$ concentration in Hainan.

Fig. 3(b) shows emissions transport embodied in trade of 31 provinces in China. Most arrows originated from the highly developed eastern, coastal provinces to less developed western and northern inland areas. Those eastern coastal provinces, such as Guangdong, Shandong, Zhejiang, Fujian, Hubei, Hunan and Sichuan (green areas) cause air pollution through outsourcing the production of their consumption items. Those inland provinces, such as Inner Mongolia, Heilongjiang, Hebei, Shanxi, Shaanxi, Xinjiang, Anhui and Guizhou (see the red areas) suffer from air pollution derived from the production for other provinces.

Atmospheric transport exerts most influence on neighboring provinces. By contrast, trade can export pollutants to remote provinces as indicated by the length of the arrow in Fig. 3(b). In Beijing-Tianjin-Hebei region and its surrounding areas (a region heavily affected by serious air pollution and a key area for air pollution control measures), the distance of emissions transport embodied in trade is relatively small and mainly focuses on local Beijing-Tianjin-Hebei region (see the arrows within the smallest blue circle). The geographical distance of emissions transport embodied in trade in the Yangtze River Delta region is larger than that of Beijing-Tianjin-Hebei region (see the arrows within the purple circle), and the transport path is beyond the boundary of the Yangtze River Delta region. The Pearl River Delta region has the longest distance of emissions transport embodied in trade (see the arrows within the black circle). In this region, emissions embodied in trade are transferred to those provinces in far distance, e.g. Inner Mongolia, Henan, Xinjiang and Shaanxi.

Fig. 3. Atmospheric and trade linkage indicators. (a) Atmospheric linkage indicator. (b) Trade linkage indicator. The colors in these maps indicate that degree and direction of linkage indicators (L_a or L_t based on equations (4) and (6)). If one province's linkage indicator is negative (the green series color), this means this province is a source affecting air quality of other provinces by atmospheric transport or trade; if one province's linkage indicator is positive (the red series color), this indicates this province is like a receptor to be influenced by emissions from other provinces. The arrow in the maps shows the direction and the relative magnitude of the top 5% net linkage indicator between two provinces ($netP_a^{pr}$ or $netP_t^{pr}$ in equations (5) and (7)). The end point of the arrow is where the emissions are emitted and the beginning is where it is caused by consumption. The red line in (a) is the "Qinling Mountains and Huaihe dividing line" which is considered the geographical demarcation line between the south and the north of China. The circles in (b) represent the distance of pollution transfer of the three economically developed regions of China. For instance, i.e. Beijing is the core of the Beijing-Tianjin-Hebei region and its surrounding areas; Shanghai is the core of the Yangtze River Delta region; and Guangzhou is the core of the Pearl River Delta region. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

3.3. Pollution responsibility based on atmospheric linkage and trade linkage

Comparing the atmospheric linkage indicator L_a and the trade linkage indicator L_t , the results show that the interprovincial atmospheric linkage indicator ranges from -71% to 75% , while the interprovincial trade linkage indicator ranges from -163% to 136% . In other words, the impacts of trade on local $PM_{2.5}$ pollution is larger than that of atmospheric transport. The purpose of the introduction of these two indicators is to reveal the potential linkages of air pollution among different regions, and assist the government to allocate environmental responsibility and formulate effective and fair pollution tax policies. According to the transport direction of atmospheric linkage indicator L_a and the trade linkage indicator L_t , we separated the 31 provinces into four zones.

When the value of one province's atmospheric linkage indicators are negative, this province is the pollution sources to emit pollutants to affect other provinces through the atmospheric transfer. We refer this case as "interregional producer responsibility". At the same time, we need to consider "interregional consumer responsibility" based on interprovincial trade linkage indicator. It is worth noting that not all consumption-based emissions are seen as the responsibility of the consumer in existing studies. Indeed, different shares of responsibility have been advocated between consumer and producers of trade related emissions (see e.g. Gallego and Lenzen, 2005; Lenzen et al., 2007). In this paper, we found the 1/3 of provinces the direction of "interregional producer responsibility" is in agreement with the "interregional consumer responsibility" (The A-I and B-I zone in Fig. 4). However, the 2/3 of provinces the direction of trade linkage indicator is not in concordance with the atmospheric linkage indicators (The A-II and B-II zone in Fig. 4). This indicates that there is a contradiction between "interregional producer responsibility" and "interregional consumer responsibility". For example, the Hebei province causes

the atmospheric pollution of surrounding areas, however these emissions are to some extent a result of producing goods for other provinces. In sum, there has been an ongoing debate on "interregional producer responsibility" and "interregional consumer responsibility". Given that there are two independent mechanisms that might lead to contradicting outcomes, it seems reasonable to combine them and associated responsibilities.

4. Policy implications of responsibilities in analysis of environmental tax zones in China

A number of studies have discussed policy implications of interregional atmospheric transport and trade and their impact on local air quality (Li et al., 2016; Zhao et al., 2017). These studies recommended transboundary policies such as interregional eco-compensation and cooperation for air pollution control (Zhang et al., 2018a). However, very few studies have discussed the combination of transboundary atmospheric flows and embodied pollution in trade for the purpose of determining an environmental tax. In addition, pollution cost should be internalized in commodity prices, and the overall costs of such policies might be shared amongst types of polluters according to the relative contributions or similar mechanism (Zhang et al., 2017; Wang et al., 2017d). An environmental tax internalizes pollution costs through adding a price tag on the pollution and consequently affects producer and consumers' actions. In addition, regional differences in environmental taxes are seen as an important practical way of interregional eco-compensation by the central government. The tax revenue can be allocated for specific purposes by setting up funds or mechanisms for reallocating the revenue to environmental protection projects, incentivizing cleaner technologies, and to compensate lower income groups for welfare losses that they might incur from an eco-tax (Wang et al., 2016).

In order to compare the impact of the different indicators on

Fig. 4. Zoning of pollution responsibility

Note: L_a refers to the atmospheric linkage indicator; L_t refers to the trade linkage indicator.

responsibility assignment and tax formulation, we choose popular local indicators based on other studies and interregional linkage indicators proposed in this paper to carry on scenario analysis.

In this paper, the current regional tax rates reported by provincial government are as the base scenario(S0). We set two scenarios to compare with the base scenario (see Table 1). The first scenario(S1) is only considering simple local indicators to allocate responsibility; the second scenario(S2) is only considering interregional linkage indicators. Under local indicators perspective, we refer to previous studies to select the representative economic indicators and environmental indicators, such as per capita income, annual mean concentration of $PM_{2.5}$ and per capita emissions. For these local indicators, the greater the value, the greater the responsibility for distribution. From the interregional linkage perspective, the atmospheric and trade linkage indicator previously studied in this paper are the linkage indicators of each province related to other provinces. For these linkage indicators, the greater the value, the lower the responsibility for distribution.

Then we apply hierarchical cluster model in SPSS software to divide the data of every indicator into 10 grades as responsible

distribution index. The 1–10 grades are for correspondence of 1–10 times of basic standard of environmental tax (1.2 yuan/APE).

At last, we calculate provincial tax rates under different scenario as the equation below.

$$T^s = 1.2 \times R^s \quad (8)$$

where, T^s is the environmental tax rate of region s for air pollution; R^s is the environmental responsible distribution index of region s for air pollution, $R = 1, 2 \dots 10$.

Firstly, according to local indicators and the interregional linkage indicators in the Table 1, we apply the correlation analysis to explore the relationship between current provincial environmental tax rates and all indicators from different province. However, the correlation analysis is used to understand the nature of relationships between only every two individual variables. Then we applied the standardized coefficients of multiple regression by SPSS software for further confirmation. Because the multiple regression is applied to model the relationship between two or more explanatory variables at the same time.

Table 1
Scenario and indicator for responsible distribution.

Scenario	Indicator	value	responsible distribution
Scenario 1 (S1, local indicators)	Per capita income	↑	↑
	Mean concentration of $PM_{2.5}$		
	Per capita APE emissions		
Scenario 2 (S2, interregional linkage indicators)	Atmospheric linkage indicator	↓	↑
	Trade linkage indicator		

No matter the results from the correlation analysis or the multiple regression shows that the correlation of the per capita income with the current tax rates is the most strongly positive with significance 99%, i.e. the correlation coefficient is 0.63 and the standardized coefficients of multiple regression is 0.64 (see Table 2). This indicates the provincial difference in current environmental tax rates is mainly affected by per capita income. By contrast, the correlation coefficients and standardized coefficients of other indicators did not pass the saliency test with significance 99%. Especially the interregional indicators, their correlation coefficients with current tax rates only is about 0.1. These results show that most of the current environment tax rates for different provinces are mainly based on the income level of the local people. This seems reasonable because the provincial governments would like to give priority to local economic level and rarely consider linkage factors. Therefore, it is imperative that the central government should revise the tax rate proposed by local government from a national perspective. The air pollution responsibility based on interregional linkage and environmental indicator should be considered.

According to hierarchical cluster model and equation (8), the responsibility distribution index and related tax rates of different indicators are shown in Table S4 in the Supporting Information. A comparison of Scenario 0 and 1 shows that even only based on income indicator 1/3 of provinces should improve tax rates. Because nearly half provinces remain original 1.2 yuan/APE (the value in 2003) whereas some of them had relatively high per capita income, such as Zhejiang and Guangdong province. Considering the emission and concentration indicators the tax still needs increase greater than that of current level.

Comparing average tax rates of Scenario 1 and 2 for each province (see Fig. 5), we found under interregional linkage perspective (S2) the tax should decrease in most north provinces and province-level municipality. For example, although Inner Mongolia province has relatively high local indicators such as per capita emissions and PM_{2.5} concentration, its emissions are to some extent a result of producing electricity and heavy industrial goods for other provinces. The “interregional consumer responsibility” offsets some of the “interregional producer responsibility”. However, the current tax rate of 1.2 yuan/APE are still too low for Inner Mongolia province. For those province-level municipality, such as Beijing, Tianjin and Shanghai. They are metropolises. The main reason for their high tax rates is their high per capita income and PM_{2.5} concentration. However, from atmosphere transport perspective, these urban areas suffer from neighboring province air pollution.

On contrast, comparing with Scenario 1, most south provinces should increase tax rates based on interregional linkage indicators (S2). For example, although Guangzhou province has good air quality and low per capita emissions, it induces embodied numerous emissions from long distance and large area. According to air pollution responsibility based on interregional linkage, Guangzhou province should increase their tax rates and share the

cost of air pollution. Although the environmental tax in the current stage is only levied on the producers, it may lead to the higher price of final consumer goods. However, during the short period, the cost of reduction pollution or the tax is mainly undertaken by the producer region because of market competition pressure. In order to be more equitable, this study proposes to reduce differences of environmental taxes between production-oriented areas and consumption-oriented areas according to “interregional consumer responsibility”. Although the tax is levied on the producers even in the consumption-oriented provinces, it at least reflects a fairer policy that both producer and consumer regions are responsible for the pollution.

In the future, we can consider to determine different objects of environmental tax collection in production-oriented areas and consumption-oriented areas. For example, in the production-oriented area, the environmental tax is still levied on the producers to motivate factories to reduce pollution. In the consumption-oriented areas, the intermediate goods (the input with the great pollution emission intensity) and final consumer goods are the main levied object of environmental tax to achieve the financial effect of environmental tax. This kind of tax is for the purpose of raising funds to achieve the regional compensation mechanism.

According to the results of this research, it is equitable to consider both atmospheric and trade interregional linkage in determining each province's environment tax rates from the whole country perspective. However, the local indicators should not be ignored. It is difficult to determine which indicators is more important. In this paper, all indicators are given the same weight. We calculated the average of S2 and S1 as the adjusted tax rates. For comparison, we divided the current tax rate and the adjusted tax rate into five categories (see Fig. 6). Although current tax rates of all provinces should be raised, there are regional difference. By strengthening both local environmental indicators and interregional linkage indicators, the high tax region (the III-V zone in Fig. 6 (a) and the IV-V zone in Fig. 6 (b)) should be extended. For example, Inner Mongolia, Shanxi, Zhejiang and Guangdong province should increase their tax rates from 1.2 yuan/APE to about 6–7 Yuan/APE (IV zone in Fig. 6 (b)), which close to the tax rate of Hebei province. The moderate tax region (the II zone in Fig. 6 (a) and III zone in Fig. 6 (b)) needs spatial adjustment. The southwest area belongs to moderate tax region. However, considering interregional linkage indicators, the southwest area belongs to low tax region. By contrast, the Liaoning province, Xinjiang province and provinces in Central China should belong to the main moderate tax region with tax rate about 4–6 Yuan/APE (III zone in Fig. 6 (b)). The other provinces belong to low tax region with tax rate 2–4 Yuan/APE (II zone in Fig. 6 (b)), which is still higher than low tax region of the current tax rate.

5. Conclusion

By calculating the atmospheric linkage indicator and trade linkage indicator, we found the 2/3 of provinces have a

Table 2

The correlation analysis and standardized coefficients of multiple regression between indicators and current environment tax rates.

Indicators or independent variable		Correlation coefficient with current tax rates	Standardized coefficients of multiple regression with current tax rates as dependent variable
S1 (Local indicators)	Per capita income	0.63**	0.64**
	Mean concentration of PM _{2.5}	0.38	0.44
	Per capita APE emissions	−0.29	−0.1
	Atmospheric linkage indicator	−0.1	0.06
S2 (interregional linkage indicators)	Trade linkage indicator	−0.12	0.11

Note: Sig. P<0.01

Fig. 5. The difference between the tax rates based on linkage indicators (S2) and local indicators (S1).

Fig. 6. Comparison of current and adjusted provincial environment tax rates for air pollutants.

contradiction between “interregional producer responsibility” and “interregional consumer responsibility”. Many studies recommended develop a cost interregional sharing mechanism and cooperation to avoid Interregional inequity. At present, the differentiated environmental tax system may be a practical method to adjust fairness between provinces. According to the results of this paper, the current provincial environmental tax rates were mainly impacted by per capita income. Obviously, this kind of tax system lacks consideration of environmental indicators and interregional relationship indicators. The provincial environmental tax system

should take equitable allocation of the environmental responsibility into account. However, the allocation environmental responsibility is a complicated issue with some subjective disputes.

In this paper, we tried to compare different results of allocation responsibility and related tax rates based on different indicators. The results show that the tax rates of most northern provinces of China based on the interregional linkage indicators lower than that based on local indicators. As producer, most northern provinces emit air pollutants to affect air quality of other provinces by atmospheric transport. However, these emissions and pollution are to

some extent the result of producing goods for consumption in other provinces. The “interregional consumer responsibility” offsets some of the “interregional producer responsibility”. In the some developed southern provinces of China, the situation is just on the contrary. These developed southern provinces cause emissions in other provinces through trade transfer. At same time, these provinces suffer from other provinces’ pollution through atmospheric movement. Although these provinces as receivers should be compensated with low tax rates, their consumption-responsibility would increase tax rates for compensation. Considering the tax is also affected by local economic and environmental factors, we calculated the average tax rates based on local indicators and interregional linkage indicators as the adjusted tax rates. The determinants of tax rate and their mechanism are complicated, not only limited to the “producer responsibility” and “consumer responsibility”. Therefore, the findings of this paper can provide implications for improving the tax rate design for a certain perspective but not all. This revised provincial environment tax plan for air pollutants provide novel perspective for central government to improve current environment tax systems.

Future research could be undertaken to study impacts of tax changes in each region on PM_{2.5} concentration in China. One possibility is enterprises may move to a different province to avoid higher tax according “Pollution heaven hypothesis”. The other possibility is enterprises don't move because the benefit of location factors and technological innovation will offset environment tax costs based on “Porter hypothesis”. This is more challenging research.

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Appendix A. Supplementary data

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