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Article

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ABSTRACT

In order to combat environmental pollution, China enacted the Environmental Protection Tax Law in early 2018. Yet the impacts of the environmental tax on individual regions with different socioeconomic statuses, which are crucial for social justice and public acceptance, remain unclear. Based on a Multi-Regional Input-Output (MRIO) table and a nationally regulated tax payment calculation method, this study analyzes the distributional impacts of an environmental tax based upon province's consumption from both inter-provincial and rural-urban aspects. The national tax revenue based on the current levy mechanism is estimated to be only one seventh of the economic loss from premature mortality caused by ambient particulate matter ($PM_{2.5}$). The taxation may slightly alleviate urban-rural inequality but may not be helpful with reducing inter-provincial inequality. We further analyze two alternative levy mechanisms. If each province imposes taxes to products it consumes (rather than produces, as in the current mechanism), with the tax rate linearly dependent on its per capita consumption expenditure, this would moderately increase the national tax revenue and significantly reduce inter-provincial inequality. To better compensate for the economic costs of air pollution and reduce regional inequality, it would be beneficial to increase the tax rate nationwide and implement a levy mechanism based on provincially differentiated levels of consumption and economic status.

1. Introduction

China's fast economic growth over the past decades has been accompanied by serious air pollution [1–3], adverse health impacts [4,5], and economic loss [6]. In particular, exposure to particulate matter with aerodynamic diameter of less than 2.5 μm ($PM_{2.5}$) will result in higher risks for heart and lung diseases and strokes, because $PM_{2.5}$ can penetrate to and deposit within the lower respiratory region of the lung [7]. Although China's anthropogenic $PM_{2.5}$ related emissions have declined since 2012, especially in the power sector, its annual mean $PM_{2.5}$ concentration is still much higher than the recommended value of 10 μg/m^3 of the World Health Organization (WHO) [8,9]. According to a Global Burden Disease (GBD) study, in 2017, about 10% (0.94 million) of all deaths in China are attributable to ambient $PM_{2.5}$ pollution [10].

Meanwhile, China is facing serious problems of inter-provincial and urban-rural economic inequality. In 2017, the average per capita disposable income was 33,414 Yuan (or 4987 USD) per year in the eastern regions (i.e., provinces usually with higher affluence levels), which is about 1.7 times of the income in the west, and the east-west gap has increased over the previous five years [11]. In the 2010s, per capita disposable income of urban residents was about triple the income of rural residents. Therefore, actions to combat air pollution must take into account the potential impacts on regional economic inequality.

Taxation, among various means of solving environmental problems, has played an important role in improving the natural environment [12]. Environmental taxes will increase the prices of polluting products and discourage their consumption and production. According to the Organization for Economic Co-operation and

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Develop (OECD) public data (available at http://www.oecd.org/env/tools-evaluation/environmentaltaxation.htm), the ratio of environmental taxes to GDP was for example 4.5%, 3.5%, 0.88%, and 0.66% in Serbia, Italy, the United States and India in 2016. To mitigate pollution, China started to implement pollution discharge fees in 2003. Such a fee-based policy was later found to be compromised by local protectionism, low standards for the pollution discharge fee, and nonstandard collections. To more effectively reduce air pollution and other environmental problems (such as solid waste, water pollution, and noise), China enacted the "Environmental Protection Tax Law of the People's Republic of China" (the National People's Congress of the People's Republic of China (NPC); http://www.npc.gov.cn/npc/) in 2018. Under this law, all industrial enterprises that discharge pollutants into the environment must pay the environmental protection tax, and all major emitters (power plants and major industrial firms) are required to install online emissions monitoring systems. However, the impacts of the newly enacted environmental protection tax on individual regions with distinctive socioeconomic contexts, or the distributional effects of the taxation, are unclear. It has been suggested that those who are mostly responsible and have the largest capacity to act should carry the majority of the tax costs, which also helps with reducing regional economic inequality. To raise the acceptability of the taxation and reduce regional economic inequality, a levy mechanism whereby richer regions would pay for a higher ratio of tax to consumption expenditure would be more desirable [13].

The tax law allows each province to set their own tax rate between 1.2 and 12 Yuan per unit of "pollution equivalent", a measure aggregating different types of pollutants. In general, richer provinces tend to set higher tax rates (Table S1 online). The tax is charged based on the amount of emissions a factory produces. Thus, as (rich) provinces with higher tax rates purchase industrial products from those with lower rates, the high tax rate in rich regions potentially further promote emission leakage from consumers to producers [14] and, equally important, create tax savings for consumers in the rich regions. Yet the extent of such pollution tax saving is unknown.

Here we estimate the potential impact of environmental taxation levied on air pollutant emissions for each province of mainland China, except Xizang due to lack of data. We focus on how the taxation affects inter-provincial and urban-rural economic inequality. By combining production-based emission data [15,16], multi-regional input-output (MRIO) analysis [17] and the official tax calculation method, we quantify the pollutant emissions and tax revenue based on each province's consumption. The analysis is applied to 2012, the most recent year for which all necessary data are available, although the tax law was enacted in 2018. To investigate the impacts on regional economic inequality, we use the "pollution tax intensity" which is defined as the ratio of all households' pollution tax payments to their consumption expenditure. We further discuss two alternative levy mechanisms that may help reduce regional economic inequality.

2. Materials and methods

This study is conducted with the following steps. First, a consumption-based emission inventory is derived by integrating production-based emission data and a provincial multi-regional input-output table. Then, the consumption-based pollution tax revenue is calculated based on consumption-based emissions and each province's environmental tax rates. Finally, two hypothetical levy mechanisms are designed and detailed analysis of their impacts on regional economic inequality is provided.

2.1. MRIO analysis

MRIO tables are widely used to trace monetary flows and economic interconnections among multiple sectors and regions, and thus the environmental footprints of trade and consumption [18–20]. In this study, we use China's MRIO table [17] that comprises 30 economic sectors in China's 30 provinces (excluding Xizang) for 2012. We also use data in the MRIO table for all consumption types (urban and rural households, government, and fixed capital formation). Below is a brief introduction of how to use the MRIO table and a production-based emission inventory to calculate consumption-based emissions on a provincial and sectoral basis. A detailed introduction of MRIO can be found in previous studies [18,21,22].

The MRIO table is extended from the standard IO table whose basic principle can be described with

$$x = Ax + y. \tag{1}$$

Thus,

$$x = (\mathrm{I} - A)^{-1} \cdot y. \tag{2}$$

Here, x denotes the total output vector whose element x_i^r is the output of sector i in region r. A denotes the direct requirement coefficient matrix representing the technical structure of the whole economic system; an element of the matrix a_{ij}^{rs} denotes the volume of sector i in region r directly required to produce per unit output of sector j in region s. Ax denotes the intermediate output vector, which can also be expressed as Z whose element z_{ij}^{rs} records production of sector i in region r to supply sector j in region s. y denotes the final demand vector whose element y_j^s is the final demand of sector j in region s. I denotes the unity matrix. $(I - A)^{-1}$ denotes the Leontief inverse matrix, which can also be expressed as L whose element l_{ij}^{rs} represents the total direct and indirect requirements of sector i in region r to satisfy per unit of final demand of sector j in region s.

Eq. (3) calculates the consumption-based emissions:

$$E_c = f \cdot (\mathrm{I} - A)^{-1} \cdot y^*. \tag{3}$$

Here, f denotes a diagonal matrix whose diagonal element f_i^r denotes the production-based emission intensity in sector i and region r. f is derived by dividing production-based emissions (taken from the inventory) by monetary output x. E_c denotes the consumption-based emissions for each sector and region associated with final consumption y^*. Eq. (3) is applied to calculate emissions for each pollutant.

2.2. Production-based emissions data

Air pollutants considered in this study include SO_2, NO_X, CO, BC, OC and NH_3, which are major primary pollutants related to $PM_{2.5}$. Volatile organic compounds and anthropogenic dust are not included due to lack of data in the production-based emissions dataset used. Production-based emissions data of SO_2, NO_X, CO, BC and OC for 2012 are taken from Zhao et al. [16]. The emissions dataset contains provincial emissions for 8 aggregated sectors, which are further interpolated to 51 sectors based on the sectoral structure in the Community Emissions Database System (CEDS) inventory [23]; detailed sectoral mapping is shown in Table S2 (online). Emissions data for NH_3 in 5 aggregated sectors are taken from Huang et al. [24] and further mapped to CEDS sectors (Table S2 online). All emissions in 51 CEDS sectors are then mapped to the 30 MRIO sectors (Table S3 online).

2.3. Calculation and scenario design of environmental tax levy mechanism

In accordance with the law, we apply the taxation only to production in the power and industrial sectors, since production in transportation, residential and agricultural sectors are exempt from taxation. The collected tax revenue along the supply chain is then assigned to consumption of each province based on the MRIO approach. Although taxes are collected from producers under the current levy mechanism, they are assumed to be eventually paid by consumers, because any tax revenue would be transferred from producers to consumers through increased product prices [25]. Under this assumption, all taxes charged along the supply chain, which may involve multiple provinces, of a product consumed by a particular province are allocated to that province. In reality, the producers may share some portion of the tax charge, depending on the price elasticities of the products; however, the share is assumed to be zero here due to lack of accurate elasticity data. Here, we focus mainly on consumption by urban and rural households, although the other types of consumption (fixed capital formation and government consumption, such as construction of public facilities, purchase of public machinery equipment, land reclamation, etc.) are also included in the discussion of national total tax revenues. We also use official population and GDP statistics [26] to facilitate the analysis.

According to the environmental tax law of China, the general formula converting emissions of each pollutant (SO_2, NO_X, CO, BC, OC, or NH_3) for each province to the respective tax revenue is as follows:

$$TAX = N_{\mathrm{APE}} \cdot R = \frac{E}{C} \cdot R. \tag{4}$$

To aggregate different types of pollutants, we use a measure named "atmospheric pollutant equivalent" (APE), and N_{APE} represents the number of APE. E denotes emissions of a pollutant. C denotes the pollutant equivalent value that is used to convert one unit of pollutant emissions to the number of APE (Table S4 online). The pollutant equivalent value is designed to account for the pollutant's eco-environmental impacts, toxicity on organisms, and the technical feasibility for removal. The detailed data of the pollutant equivalent value are given in Table S4 (online), and the value for BC and OC are according to the value of smoke. R denotes the tax rates ranging from 1.2 to 12 Yuan per unit of "pollutant equivalent", for individual levy mechanisms discussed in this study. TAX denotes the pollution tax revenue for the pollutant.

We discuss current and two alternative levy mechanisms in this study. The current levy mechanism is producer province-based – as per the Environmental Protection Tax Law, the tax is collected from producers (i.e., a factory) based on their emissions. Thus, under this producer province-based (current) levy mechanism, the tax revenue for a pollutant due to consumption in province s is

$$TAX^s = \sum_r \sum_{i,j} \frac{E_{i,j}^{r,s}}{C} \cdot R^r. \tag{5}$$

Here, $E_{i,j}^{r,s}$ denotes the emissions in province r and sector i due to production to supply consumption in province s and sector j. R^r denotes the official tax rate in province r (Table S1 online).

Under the first alternative mechanism, namely the consumer province-based levy mechanism, each province applies its current tax rate to all products it consumes, regardless of where the products are produced. Thus,

$$TAX^s = \sum_r \sum_{i,j} \frac{E_{i,j}^{r,s}}{C} \cdot R^s, \tag{6}$$

where R^s is the official tax rate in province s (Table S1 online).

Under the second alternative mechanism, namely the consumer affluence-based levy mechanism, on top of the consumer province-based levy mechanism, the provincial tax rates are set to be linearly dependent on their per capita consumption expenditure. Thus,

$$TAX^s = \sum_r \sum_{i,j} \frac{E_{i,j}^{r,s}}{C} \cdot R'^s, \tag{7}$$

where R'^s is the new provincial tax rate (Table S5 online). According to the range of tax rates allowed by the tax law (1.2–12 Yuan/equivalent), the tax rates for each pollutant in Shanghai and Beijing are set at 12 Yuan/equivalent. These are two most affluent provinces in terms of per capita consumption expenditure. In addition, the tax rate of Guizhou, the province with the lowest per capita consumption expenditure, is set at the current value of 2.4 Yuan/equivalent. For other provinces, the tax rates are set by linear interpolation based on their per capita consumption expenditures.

2.4. Uncertainty analysis

The uncertainties and limitations in this work arise from three aspects: emissions data, MRIO analysis, and tax allocation. Calculations of air pollutant emissions are subject to large uncertainties. Uncertainties of the emissions data used here are estimated to be from −40% to 136% [16,27,28]. This emissions dataset, similar to other datasets, may miss or misrepresent emissions from some small enterprises. Uncertainties in the MRIO analysis are related to sectoral aggregation and data accuracy. This work assumes that all tax revenue is paid in full by consumers (through increased product prices), although in reality some portion of the tax revenue may be paid by producers. The taxation in this work is assumed to be static, in which the socioeconomic and emission changes brought by the taxation are not considered. In addition, based on the environmental tax, only the top three air pollutants in terms of amounts of emissions will be charged in one vent (an opening for the emissions to pass out into the environment), but the emissions data of each vent are not available at present. So all the six main air pollutants are subject to tax in this study.

3. Results

3.1. Environmental tax revenue with producer province-based (current) levy mechanism

Fig. 1 shows the estimated tax revenue based on 2012 emissions attributed to each province's urban and rural household consumption under the current levy mechanism (Eq. (5)). Consumption in the eastern, more developed provinces leads to a larger total and per capita tax revenue than that in other provinces. Consumption in Shandong leads to the greatest tax revenue (5 billion Yuan/a or 0.7 billion USD/a, equivalent to 0.1% of its GDP) due to its large consumption volume (Tables S6 and S7 online), high local emission intensity (Fig. S1 online), and high tax rates for SO_2 and NO_X (Table S1 online). The total tax revenue from consumption of the 10 least taxed provinces combined is even smaller than that of Shandong. Tianjin has the highest per capita tax revenue (78 Yuan/(pop a)) mainly due to its fourth highest per capita consumption expenditures (Table S6 online) and second highest tax rate for all pollutants (Table S1 online). Consumption of urban households leads to a higher tax revenue than consumption of rural households due to a higher consumption volume, especially

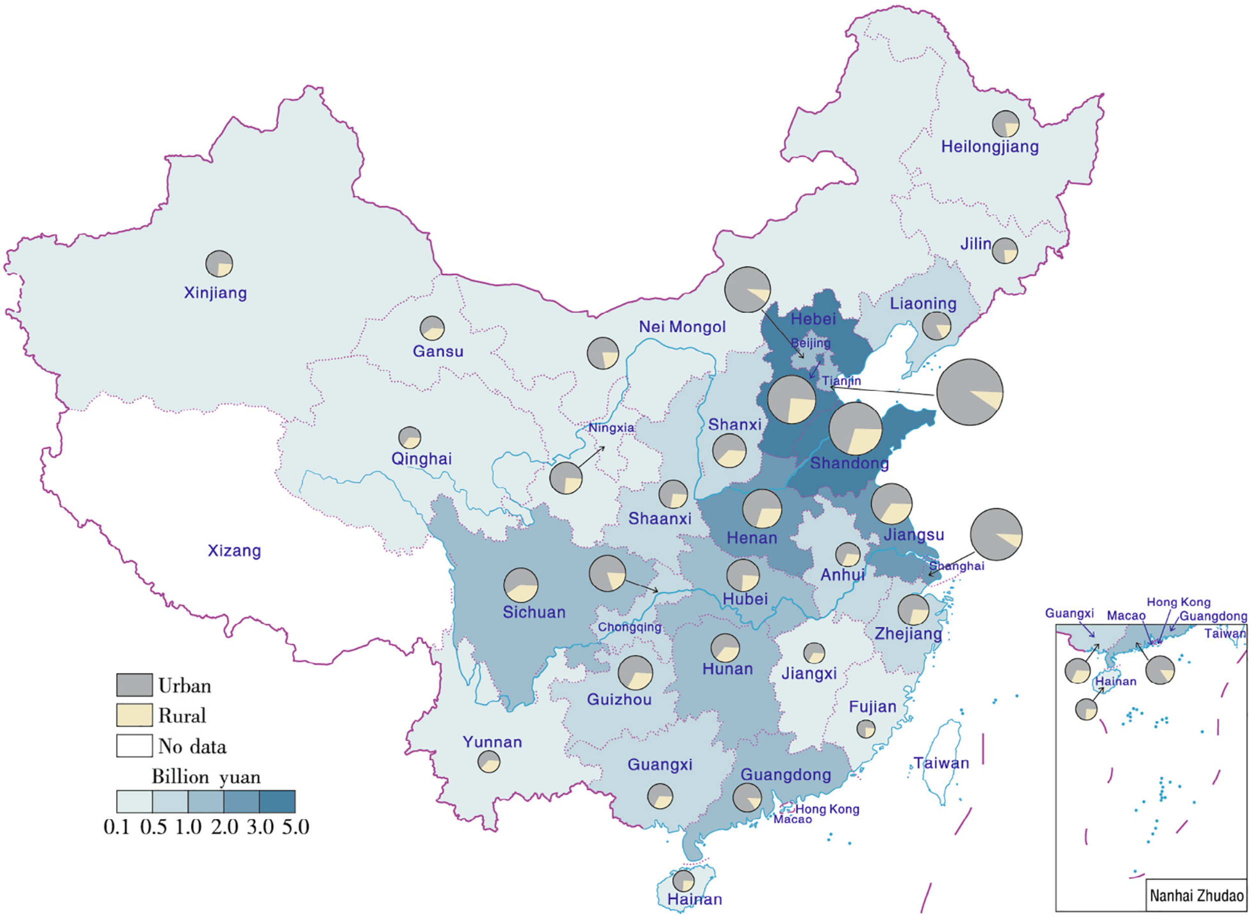

Fig. 1. Provincial total pollution tax revenue due to urban and rural household consumption in 2012 under producer province-based (current) levy mechanism. The map shows the provincial distribution of tax revenues. The pie plots differentiate the contributions of urban and rural household consumption to the tax revenue in each province. The size of the pie chart reflects the magnitude of per capita tax revenues. The value of Xizang is blank due to lack of data.

in the more developed provinces such as Beijing, Tianjin and Shanghai.

The national total tax revenue in 2012 due to consumption of urban and rural households would have been about 32 billion Yuan (or 4.8 billion USD), or 0.06% of GDP. Including government consumption and fixed capital formation would have increased the tax revenue to 130 billion Yuan (or 19.4 billion USD), or 0.24% of GDP. This is because in each province, the total final demand of government consumption and fixed capital formation is about 2–4 times of total urban and rural household consumption, and they are mainly supplied by power and industrial sectors. If the tax revenue of anthropogenic dust is also considered, the total tax revenue would have risen to about 136 billion Yuan (or 20.3 billion USD). Fig. S2 (online) further shows the tax revenue of the two cases (without and with government consumption and fixed capital formation) from 2010 to 2017, calculated based on the current levy mechanism and the national emissions totals in the Multi-scale Emissions Inventory for China (MEIC) [29]. For both cases, the estimated national pollution tax revenue would have decreased by 50% from 2012 to 2017 due to declining emissions. The national tax revenue for the two cases would have been about 0.07% and 0.30% of GDP in 2010, declining to 0.02% and 0.08% by 2017, respectively. Data are inadequate to attribute the national tax revenue to provincial consumption.

According to previous studies, the monetary value of a statistical life (derived from individuals' valuation of their willingness to pay for a small reduction in the risk of dying [30]) in China is about 1 million Yuan (or 0.15 million USD) [31]; and China's national premature mortality related to ambient $PM_{2.5}$ pollution in 2012 is about 0.92 million deaths [32]. Based on these values, the economic loss from ambient $PM_{2.5}$ related mortality is estimated to be around 920 billion Yuan (or 137 billion USD) in 2012, or 7 times the current pollution tax revenue due to all four consumer groups (130 billion Yuan or 19 billion USD). Similarly, based on the death data from the GBD study [33], $PM_{2.5}$ related economic loss in 2015 (965 billion Yuan or 144 billion USD) is about 11 times the national pollution tax revenue (84 billion Yuan or 12.5 billion USD). The difference between the tax revenue and pollution related economic loss would be larger if the loss due to other air pollutants (e.g., ozone) was included. From this aspect, the current environmental tax rate has not reached the level to sufficiently compensate for pollution related economic loss.

3.2. Pollution tax intensity with producer province-based (current) levy mechanism

The grey bars in Fig. 2 show the provincial pollution tax intensity (i.e., tax revenue associated with the production of consumption items of households and accrued over the entire supply chain divided by their consumption expenditures) based on urban and rural households' consumption under the current levy mechanism. The provincial tax intensity varies from 0.05% to 0.41%, with a national average of about 0.17%. This shows that the pollution tax

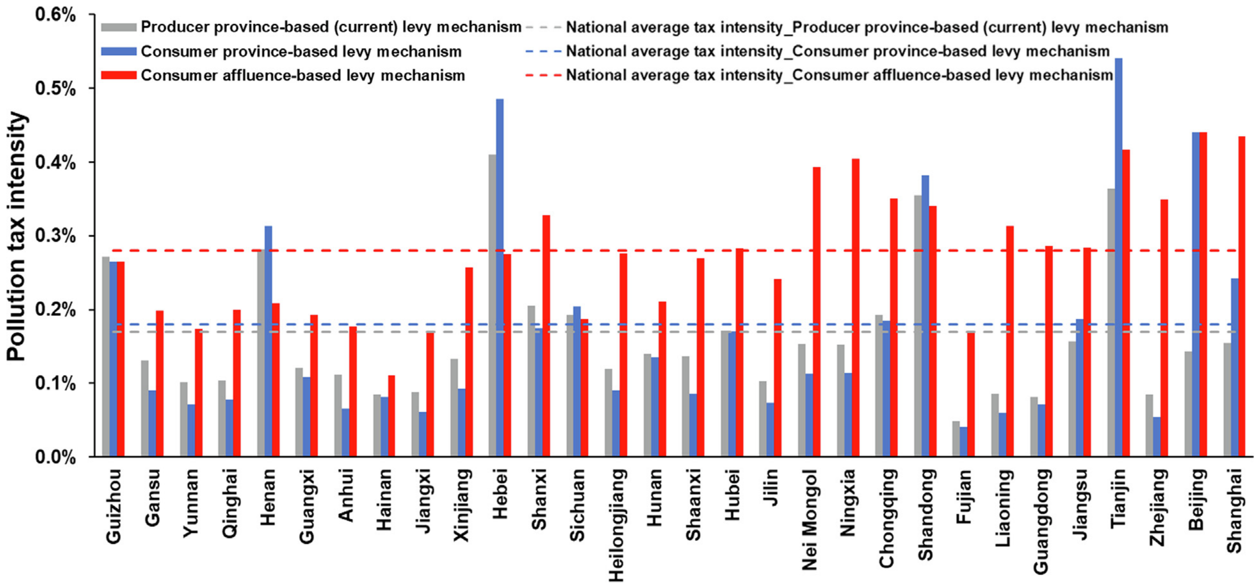

Fig. 2. Provincial pollution tax intensity due to urban and rural household consumption in 2012 under three levy mechanisms. The provinces are ranked by per capita consumption expenditure in increasing order.

revenue is only a very small share of household consumption expenditure.

There exists a great mismatch between the provincial distribution of per capita consumption (Fig. 3a) and the distribution of pollutant tax intensity (Fig. 3c). Many developed provinces (i.e., those with high per capita consumption expenditure), especially some eastern coastal provinces, tend to have relatively low tax intensities, such as Shanghai, Beijing, Zhejiang, Jiangsu, Guangdong, Liaoning and Fujian. The tax intensity in the provinces with moderate per capita consumption expenditure (Chongqing, Hubei, Sichuan and Shanxi) is close to the national average. The tax intensity is relatively high in some less developed provinces such as Hebei, Henan and Guizhou. Fig. 3f further shows that across the provinces, the pollution tax intensity has no obvious positive correlation with per capita consumption. Therefore, the current levy scheme does not alleviate inter-provincial economic inequality.

Fig. 3b shows that under the current levy mechanism, the tax intensity for urban household consumption is higher than that for rural consumption in most provinces, although the urban-rural difference is negligible for Shandong and a few other provinces. The higher urban than rural tax intensity is most evident in Tianjin, Hebei, Guizhou and Henan. This implies that the current levy mechanism helps reduce urban-rural economic inequality.

The following analysis focuses on how to improve the levy mechanism to reduce inter-provincial economic inequality. Urban-rural economic inequality is not explicitly discussed.

3.3. Pollution tax intensity with consumer province-based levy mechanism

In China's economy, the developed provinces tend to be net importers of industrial products from less developed provinces, and tend to outsource pollution intensive production to less developed provinces [34,35]. For example, Beijing has moved a large number of factories to Hebei and other neighboring provinces [36,37]. Such a strategy can not only reduce air pollutant emissions (physically released) in richer provinces but also help these provinces reduce pollution tax payments, because the tax rates in less developed provinces are usually lower (Table S1 online). This phenomenon is in line with the Pollution Haven Hypothesis (PHH) [38–40]. Thus, an interesting question is raised here: if each province applies the consumer province-based tax rate, what will be the resulting impacts on the provincial pollution tax intensity and regional economic inequality? For example, a product made in Hebei for final consumption in Beijing is levied with Beijing's environmental tax rates, and the taxes are collected from Beijing consumers according to the total embedded emissions in the products consumed by Beijing households and the tax rate in Beijing. We ignore here differences in transaction costs and administration of having the consumer versus the producer as a tax subject. Such a provincial consumer province-based tax scenario (Eq. (6)) is examined in this section.

The blue bars in Fig. 2 show the provincial pollution tax intensity based on the consumer province-based levy mechanism. The provincial tax intensity varies from 0.04% to 0.54%. The national average tax intensity is about 0.18%, close to that with current producer province-based mechanism (0.17%). Compared to the producer province-based levy mechanism, the consumer province-based mechanism reduces the pollution tax intensity in most of the less developed provinces due to reduced tax payments for products imported from richer provinces, because less developed provinces tend to have lower tax rates (Table S1 online). In contrast, the consumer province-based mechanism increases the pollution tax intensity in developed regions such as Shanghai, Beijing, Tianjin, Jiangsu and Shandong. Fig. 3g further shows that the pollution tax intensity has a weak positive correlation with per capita consumption expenditure, indicating that the consumer province-based levy mechanism slightly alleviates regional economic inequality.

A few undesirable effects arise from the consumer province-based levy mechanism. Compared with the producer province-based mechanism, the consumer province-based mechanism increases the pollution tax intensity for Hebei and Henan, two less developed provinces. This is because the two provinces set high tax rates (Table S1 online), such that applying their tax rates to imported products enhances their overall tax payments. In some developed provinces such as Zhejiang, Guangdong, Liaoning and Fujian, the consumer province-based mechanism reduces their tax intensities due to their low tax rates (Table S1 online). Overall, the provincial distribution of tax intensity under the consumer

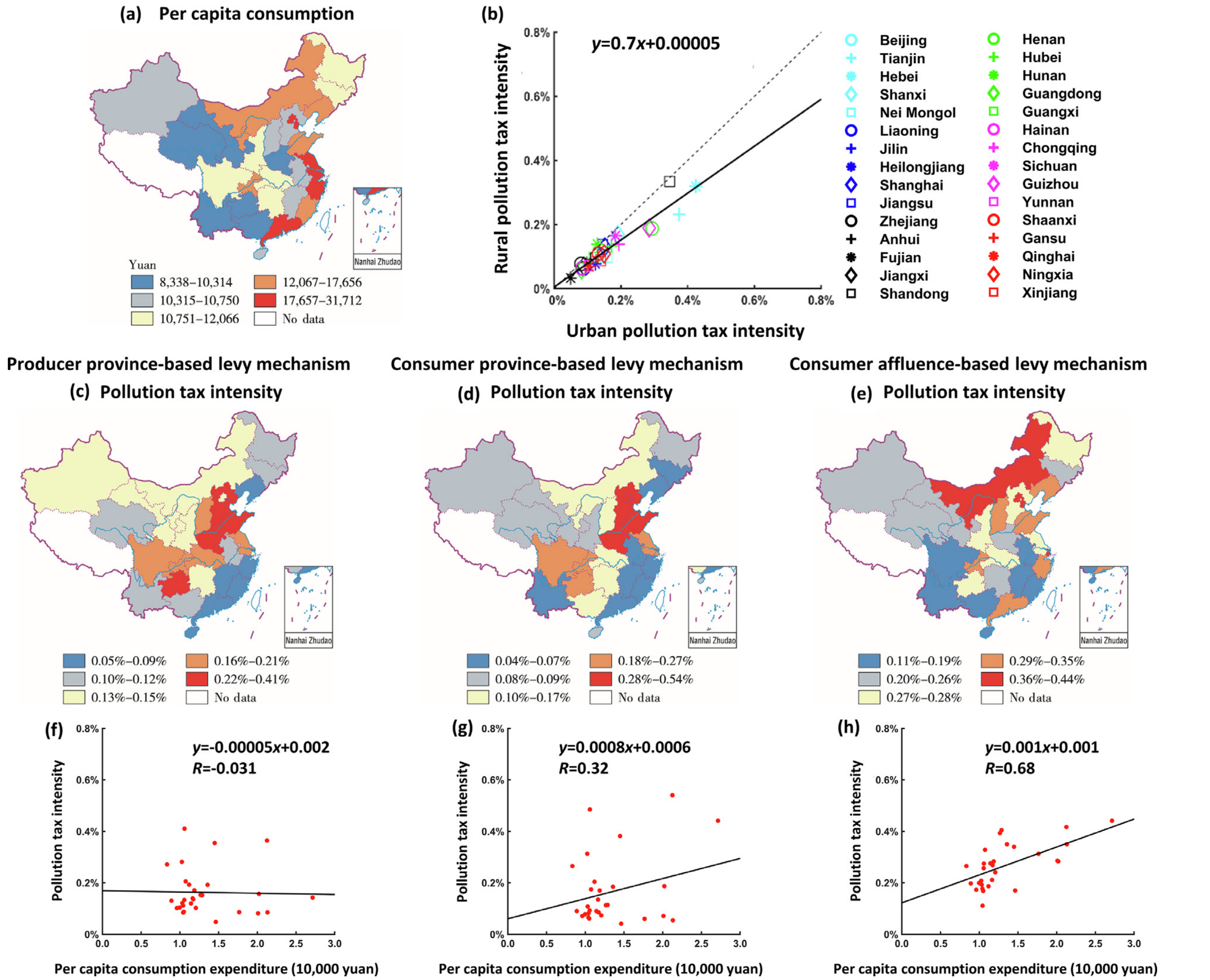

Fig. 3. Provincial pollution tax intensity in comparison with per capita consumption expenditure of urban and rural households in 2012 under three levy mechanisms. (a) Per capita consumption by urban and rural households. (b) Scatterplot for urban versus rural household tax intensity under the producer province-based (current) levy mechanism. (c)–(e) Provincial distributions of pollution tax intensity due to urban and rural households' consumption under three levy mechanisms. In (a), (c)–(e), legend ranges are partitioned based on their quantiles such that each color covers the same number of provinces. (f)–(h) Scatterplots for provincial tax intensity and per capita consumption expenditure under three levy mechanisms.

province-based levy mechanism (Fig. 3d) is still not closely linked to per capita consumption (Fig. 3a).

Contrasting consumer and producer province-based levy mechanisms also provides quantitative information on how the current producer province-based mechanism may lead to "environmental tax saving" for provinces outsourcing to others with lower tax rates. Here, a province's tax saving is defined as the tax payment (related with urban and rural households' consumption) based on consumer province-based levy mechanism minus the tax payment based on the producer province-based levy mechanism. A positive value for tax saving means that the province saves pollution tax payment under current producer province-based levy mechanism, and a negative value represents a "tax loss". Fig. 4 shows that over two thirds of all provinces experience tax loss whereas other, usually richer provinces experience a tax saving. Beijing gains the largest tax saving (1.7 billion Yuan or 0.25 billion USD), which is about twice its tax payment (0.8 billion Yuan or 0.12 billion USD). For Shanghai, Hebei, Tianjin and Jiangsu, the respective tax saving exceeds 10% of their estimated tax payment. Most of the less developed provinces experience tax loss due to higher tax rates of their exporters (Table S1 online). The tax loss is less than 50% of the tax payment for each province. Tax savings and losses contribute to regional economic inequality under the current levy mechanism.

3.4. Pollution tax intensity with a consumer affluence-based levy mechanism

To effectively reduce inter-provincial economic inequality, each province's environmental tax rate could be set in terms of the province's affluence level, which leads to a consumer affluence-based levy mechanism (Eq. (7)). The red bars in Fig. 2 depict the provincial pollution tax intensity under the consumer affluence-based levy mechanism. The provincial environmental tax intensity varies from 0.11% to 0.44%, with a national average tax intensity of 0.28%. The tax intensity in most of the less developed western provinces is below the national average value. The provincial distribution of tax intensity (Fig. 3e) is in line with the distribution of per capita consumption expenditure (Fig. 3a). Fig. 3h further shows that this mechanism results in a strong positive correlation (0.68) between

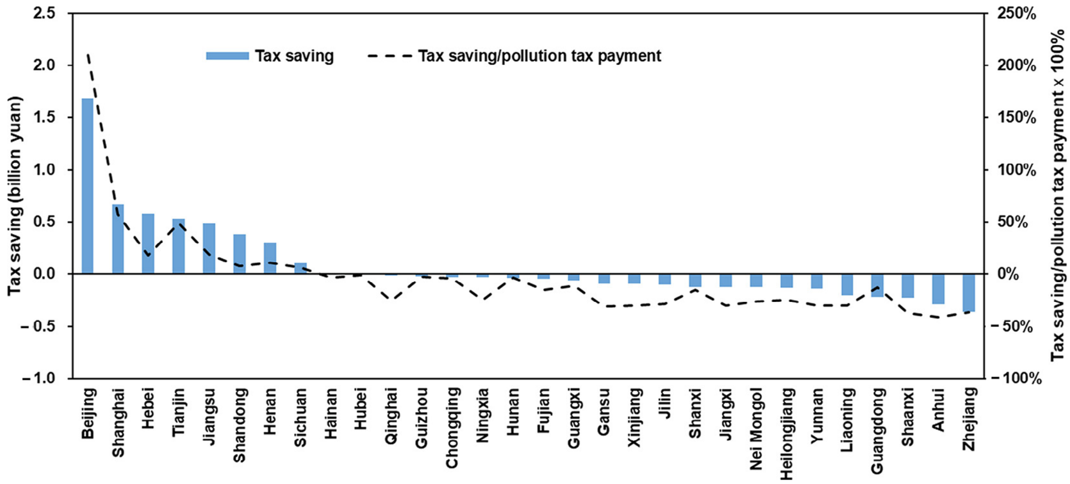

Fig. 4. Provincial pollution tax saving with respect to urban and rural households' consumption. The provinces are ranked by the magnitude of tax saving in decreasing order.

provincial pollution tax intensity and its per capita consumption expenditure. In other words, the consumer affluence-based levy mechanism significantly reduces the inter-provincial economic inequality.

Under the affluence-based levy mechanism, the national pollution tax revenue is about 53 billion Yuan (or 8 billion USD) for urban and rural household consumption. Including government consumption and fixed capital formation would increase the tax revenue to 200 billion Yuan (or 30 billion USD), which is less than one fourth of the economic loss caused by ambient $PM_{2.5}$ pollutions (920 billion Yuan or 137 billion USD).

4. Discussion and conclusions

China's recently enacted producer province-based pollution levy mechanism for air pollutant emissions is a major step forward to combat air pollution. This is a significant improvement beyond the previous pollutant discharge fee. However, our study indicates that the existing levy mechanism does not help alleviate inter-provincial economic inequality. Changing from a producer province-based to a consumer province-based levy mechanism may only slightly alleviate inter-provincial economic inequality, but further adjusting the tax rates according to provincial income levels would significantly reduce economic inequality.

Our results show that without drastically increasing the tax rate at the national level, none of the three levy mechanisms fully compensates for economic loss caused by ambient air pollution. In addition, the estimated national tax revenues due to consumption of all four groups (urban, rural, government and fixed capital formation) is only about half of the total annual operating cost of "ultra low emissions" [41] instruments deployed in China's coal-fired power plants (224.1–244.3 billion Yuan) [42]. To make the tax more effective at reducing emissions and fully compensate for such economic loss, it would be necessary to increase the tax rates by about an order of magnitude, i.e., to enhance the tax revenue to a few percent of household consumption expenditure. The resulting economic burden for households may be reduced by cycling the tax revenue back to taxpayers through increasing social benefits of low income groups [43–46], which may further reduce economic inequality between rich and poor households. Such tax recycling would minimize adverse socioeconomic impacts of environmental taxation (especially at the early stage of tax implementation) while helping to sustain a healthy environment and reduce economic inequality, which are critical for China's sustainable development. Our study provides quantitative evidence to help improve the environmental levy mechanism in terms both of the magnitude of tax rates and of how the tax rates may be differentiated between provinces with distinctive economic statues.

Conflict of interest

The authors declare that they have no conflict of interest.

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Author contributions

Jintai Lin and Jingxu Wang conceived the research. Jingxu Wang, Jintai Lin, Kuishuang Feng and Klaus Hubacek designed the research and led the analysis and writing. Jingxu Wang performed the research. Jingxu Wang, Jintai Lin, Kuishuang Feng, Peng Liu and Jing Cao collected the socioeconomic and tax data. Yu Zhao provided the emission data. Zhifu Mi provided MRIO table. Jingxu Wang, Jintai Lin, Kuishuang Feng and Klaus Hubacek analyzed the results with comments from all authors. All authors contribute to the writing.

Appendix A. Supplementary materials

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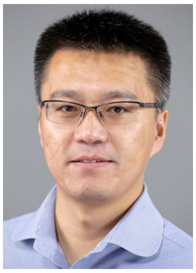

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