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To cite this article: Jingxu Wang *et al* 2021 *Environ. Res. Lett.* **16** 124007

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ENVIRONMENTAL RESEARCH
LETTERS

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Towards reducing inter-city economic inequality embedded in China's environmental protection tax law

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Abstract

Cities are at the front line of combating environmental pollution and climate change, thus support from cities is crucial for successful enforcement of environmental policy. To mitigate environmental problems, China introduced at provincial level the Environmental Protection Tax Law in 2018. Yet the resulting economic burden on households in different cities with significantly different affluence levels remains unknown. The extent of the economic impacts is likely to affect cities' support and public acceptability. This study quantifies the economic burden of urban households from taxation of fine particle pollution ($PM_{2.5}$) for 200 cities nationwide from a 'consumer' perspective, accounting for $PM_{2.5}$ and precursor emissions along the national supply chain. Calculations are based on a multi-regional input–output analysis, the official tax calculation method and urban household consumption data from China's statistical yearbooks. We find that the current taxation method intensifies economic inequality between cities nationally and within each province, with some of the richest cities having lower tax intensities than some of the poorest. This is due to the fact that taxes are collected based on tax rates of producing regions rather than consuming regions, that cities with very different affluence levels within a province bear the same tax rate, and that emission intensities in several less affluent cities are relatively high. If the tax could be levied based on tax rates of each city where the consumer lives, with tax rates determined based on cities' affluence levels and with tax revenues used to support emission control, inter-city economic inequality could be reduced. Our work provides quantitative evidence to improve the environmental tax and can serve as the knowledge base for coordinated inter-city policy.

1. Introduction

Sustainable Cities and Communities is one of the United Nations Sustainable Development Goals (SDGs) [1]. With one fifth of the world's urban population [2], China plays a leading role in achieving such a goal [3–5]. At present, about two thirds of Chinese cities are struggling with air pollution [6–8] and resulting environmental [9, 10], health [11–14] and economic [15, 16] consequences. Chinese cities

have been struggling to balance environmental protection and socioeconomic equality. To combat air pollution, China's Air Pollution Prevention and Control Action Plan aimed at reducing the annual mean $PM_{2.5}$ concentration to 35 $\mu g\ m^{-3}$ for all cities by 2035 [17]. To achieve this ambitious goal, it is imperative to improve environmental protection policies, especially by better accounting for socioeconomic status and affordability of each city and enhancing inter-city collaboration [18]. Given that provinces are generally too large and counties tend to have little political power, cities may be better-suited units to implement effective environmental policies that account for local characteristics. However, despite a number of city-specific policies such as the 'gas for coal' and 'electricity for coal' projects enacted in 2017 for the '2 + 26' cities in north China [19], city-based policies are much fewer than national and provincial ones [20, 21].

In response to the severe environmental problems and growing public concerns, China put into practice its 1st Environmental Protection Tax Law (hereinafter referred to as 'the EPT Law') in 2018. Under the EPT Law, enterprises and public institutions that discharge regulated pollutants directly into the environment are subject to taxation for producing air pollution, water pollution, noise, and solid waste. The EPT Law stipulates that each provincial government sets its tax rate between 1.2 Yuan and 12 Yuan per air pollution equivalent (APE) based on its own socioeconomic context and needs. Nearly half of the provinces use the lowest tax rate (see supplementary table 1 (available online at stacks.iop.org/ERL/16/124007/mmedia) for an overview). Studies based on provincial production suggest that the current EPT Law is not stringent enough [22, 23]. More importantly, all cities within the same province use the same tax rate without considering inter-city variation in affluence, atmospheric chemical conditions (to convert emissions to ambient concentrations) and other factors.

How tax-induced economic burden affects consumers of cities with significantly different affluence levels is a major question, concerning public acceptability and cities' support of such taxation [24]. Of the 200 cities studied here, the highest per capita household expenditure in Shanghai is three times of the lowest per capita expenditure in Xinzhou (in Shanxi province) in 2015. Although the tax is paid by producers (e.g. factories), a portion of the tax will be transferred to consumers through increased prices of goods and services. From a 'consumer' point of view, the environmental taxation burden will finally fall on their shoulders. If the cities which are mostly responsible for the emissions and have the highest capacity to act carry the corresponding majority of the tax costs, the taxation would help reduce regional economic inequality and would be more acceptable to the wider public [25]. In contrast, economic inequality

would be intensified if households in richer cities bear a lower tax burden (defined here as tax intensity, see below) than in poorer cities.

Environmental taxes, as an often-cited example of Pigouvian taxes [26, 27] to reduce the negative externalities of environment pollution, can also introduce undesirable socioeconomic inequalities. Such socioeconomic inequalities are known results of carbon taxes [28, 29], but only a few take inter-regional trade into consideration [25, 30], even less studied are environmental taxes related to other air pollutants. To date, most studies on China's EPT Law focus on its impacts on emissions [23, 31], and a few look into the impacts on the provincial economic burden [32], particularly inter-regional economic inequality [33]. Almost all these studies are at provincial or national levels. However, the province-based tax rate neglects the large gaps in the average consumption affordability and affluence level of households across different cities within the same province. A city-level analysis of the EPT Law's impacts on consumers' economic burden and inter-city economic inequality is currently lacking.

Here, we evaluate the implications of the EPT Law on urban households' economic burden and regional economic inequality from a city-level consumption-based perspective, based on emissions and consumption data of 200 Chinese prefecture cities in 2015. Although the tax law was put into practice in 2018, our analysis is based on 2015, the most recent year for which all data are available. Our analysis is based on the official tax calculation method and a multi-regional input–output (MRIO) analysis (see section 2). Given the lack of city-level MRIO tables, we assume that all cities within a specific province share the same supply chain represented in the provincial MRIO table. Air pollutants subject to the tax here include the major primary pollutants related to ambient $PM_{2.5}$, i.e. sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), ammonia (NH_3), black carbon (BC) and primary organic carbon (POC). We use 'tax intensity' to quantify the tax induced economic burden of urban households in each city, which is calculated as the ratio of household environmental tax payment (associated with the production of goods and services they consumed) to their consumption expenditure (see section 2). We then investigate four alternative tax scenarios that could be used to improve the current levy scheme. To help discuss tax intensity and economic inequality between cities, we refer to the affluence level of a city as its per capita annual consumption expenditure (supplementary figure 1).

2. Methods and data

2.1. Socioeconomic data
In this study, we collect data for population and per capita consumption expenditure of 200 cities

(supplementary table 6) in 30 provinces (except Tibet due to lack of data) (supplementary table 2) in 2015 from national, provincial and city-level statistical yearbooks [34]. Household consumption expenditure is defined as all expenditures of households to satisfy consumption in daily life, including cash payments and in-kind exchanges (which are less relevant in urban households), and is divided into eight categories: food, residence, clothing, household facilities, transport and communications, education and recreation, health care and medical services, and other goods and services (supplementary table 3). The affluence level of a province or a city is defined based on its per capita consumption expenditure. Due to data availability, only the consumption of urban households is analyzed in this study and consumption of rural households is excluded. Here, the 200 cities are all prefecture-level cities, spread over 30 provinces of China (supplementary figure 1), and are representative for cities of different affluence levels in China. Together, these cities contribute 74% of China's urban population and 76% of its household consumption expenditure in 2015. For 16 cities lacking socioeconomic data for 2015, we use the data for 2014 or 2016 instead (supplementary table 6). The substantial difference in affluence (i.e. per capita consumption expenditure) across the 200 cities also reflects their different ability to afford a consumption related environmental tax.

2.2. Emission inventory

The emission inventory of 2015 used in this study is merged with the multi-resolution emission inventory for China (MEIC: www.meicmodel.org) [35, 36] and greenhouse gas and air pollution interactions and synergies (GAINS: www.iiasa.acat/webhome/research/researchPrograms/air/Asia.html) [37–39]. Air pollutants considered in this study include SO_2, NO_x, CO, NH_3, BC and POC, the major primary pollutants related to $PM_{2.5}$. MEIC provides the amounts of emissions for five aggregated sectors in each province. The GAINS inventory provides provincial-level emission data for 56 detailed sectors. For each province, we apply sectoral proportions in GAINS data to the total emissions in MEIC and obtain a merged emission inventory. The merged, provincial-level emission inventory is then re-mapped from 56 to 30 sectors to match the MRIO table; the mapping is shown in supplementary table 7.

In the 'consumer city affluence-based levy mechanism + emission control' scenario, we consider revenue recycling to subsidize emission control with 'ultralow emissions' (ULE) technology, which has been commonly applied to Chinese coal fire power plants but not in other sectors. Therefore, our work further estimates the emissions after the ULE technology is applied to coal-fired power and industrial sectors in Shanxi province and nationwide. Given

the limited data availability for ULE emission factors, we only consider SO_2 and NO_x emissions for ULE technology deployment. The ULE related emissions are calculated based on the ULE emission factors of standard coal updated by Liu *et al* [40]. The coal consumption in power and industrial sectors are collected from regional energy balance table in China Energy Statistics Yearbook 2016 [41]. Since raw coal consumption is recorded in the Yearbook, we convert it to standard coal consumption according to their lower heating values:

$$W_S = W_R \times Q_R/Q_S \qquad (1)$$

where Q_S denotes lower heating value for standard coal, Q_R denotes lower heating value for raw consumed coal, and W_R denotes the raw coal consumption by mass collected from the Yearbook. The factor Q_R/Q_S is applied as 0.7143 in this study following the common usage in coal consumption calculations of China.

Then, the emissions of each species (SO_2 and NO_x) from coal combustion in power and industry after applying the ULE technology can be calculated as:

$$E_{ULE} = \sum_j (W_{S,j} \times EF_{ULE}) \qquad (2)$$

where EF_{ULE} denotes the emission factors [40] after applying ULE technology ($EF_{ULE,SO_2} = 0.17\,\mathrm{g\,kg^{-1}}$, $EF_{ULE,NO_x} = 0.41\,\mathrm{g\,kg^{-1}}$). $W_{S,j}$ denotes the standard coal consumption in sector *j* (detailed coal-fired sectors are listed in supplementary table 4). Although the emission factors are collected for power plants, we assume that industrial coal combustion processes reach the same emission level as in power plants.

The combustion in China's power plants and industries can be fueled by coal, gas and oil. The GAINS inventory used here separates emissions from individual fuel types for power plants, industrial combustion processes and industrial non-combustion processes. We calculate the fraction of coal combustion related emissions in the total emissions in GAINS, as well as the fraction for non-coal combustion emissions. Applying the non-coal combustion fraction to the total emissions in the merged inventory and then adding the ULE related coal-fired emissions leads to a new emission inventory for SO_2 and NO_x. Here we assume that the ULE technology is applied nationwide. The difference between the two emission inventories (merged versus new) unveils the emission reduction of SO_2 and NO_x after applying ULE technology.

2.3. Cities' consumption-based emissions

Before estimating emissions related to urban household consumption in each city, we first calculate consumption-based emissions for urban households

of each province based on the provincial-level MRIO analysis. MRIO is widely used in tracing emissions embodied in trade between regions [42–46]. In this study, input–output analysis was selected due to its simplicity and transparency, compared with other economic system accounting methods such as computational general equilibrium models (CGE). Here, air pollutants are allocated to 30 provinces according

to final consumption of urban households. We use the latest provincial MRIO table for the year of 2015 [47, 48]. The basic MRIO framework is described as follows.

The MRIO framework begins with an accounting balance of monetary flows between industrial sectors and regions

$$
\begin{bmatrix} x^1 \\ x^2 \\ x^3 \\ \vdots \\ x^m \end{bmatrix} = \begin{bmatrix} A^{1,1} & A^{1,2} & A^{1,3} & \dots & A^{1,m} \\ A^{2,1} & A^{2,2} & A^{2,3} & \dots & A^{2,m} \\ A^{3,1} & A^{3,2} & A^{3,3} & \dots & A^{3,m} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A^{m,1} & A^{m,2} & A^{m,3} & \dots & A^{m,m} \end{bmatrix} \begin{bmatrix} x^1 \\ x^2 \\ x^3 \\ \vdots \\ x^m \end{bmatrix} + \begin{bmatrix} \sum_s y^{1,s} \\ \sum_s y^{2,s} \\ \sum_s y^{3,s} \\ \vdots \\ \sum_s y^{m,s} \end{bmatrix}. \tag{3}
$$

where m indicates the number of regions, which is 30 provinces in this study; x^r is a vector of total economic output of each sector in region r ($r = 1, 2, \dots, m$); $y^{r,s}$ is a vector of each sector's output produced in region r and finally consumed in region s ($s = 1, 2, \dots, m$); $A^{r,s}$ is the direct requirement coefficient matrix whose columns reflect the input from sectors in region r required to produce one unit of output from each sector in region s.

Equation (3) can be simplified as:

$$
X = AX + Y. \tag{4}
$$

Thus,

$$
X = (I - A)^{-1} \cdot Y. \tag{5}
$$

Here, I represents the identity matrix, and $(I - A)^{-1}$ is the Leontief inverse matrix.

Urban household consumption-based emission for a pollutant k can be calculated as follows:

$$
E_{c,k} = f_k \cdot (I - A)^{-1} \cdot Y_d. \tag{6}
$$

Here, f_k is a diagonal matrix, and its diagonal element $f_{k,i}^r$ represents the emission intensity of a pollutant k (i.e. SO_2, NO_x, CO, NH_3, BC, or POC) calculated by sector i's total production-based emission of pollutant k (taken from the merged inventory) divided by its total output in a given region r. Y_d is the domestic final demand of urban households without import. $E_{c,k}$ denotes the consumption-based emission for a pollutant k associated with final consumption Y_d.

Then, urban household consumption-based emission intensity for a pollutant k ($f_{c,k}$) is calculated as urban household consumption-based emissions ($E_{c,k}$) divided by its respective total consumption (**CON**):

$$
f_{c,k} = \frac{E_{c,k}}{\mathbf{CON}}. \tag{7}
$$

Here, the element $f_{c,k,i}^r$ denotes emissions of pollutant k induced by per unit consumption of sector i in province r. The 30 sectors in $E_{c,k}$ are mapped to the eight consumption sectors in **CON** (see supplementary table 8).

In this study, we assume that cities within a specific province share the same supply chain. Such an assumption is valid for urban households, because their consumption is usually supplied through trade. Thus, emissions of a pollutant k related to urban household consumption of a city $E'_{c,k}$ is calculated by multiplying its urban household sectoral consumption (**CON'$_c$**) by the consumption-based emission intensity ($f_{c,k}$) of the province it belongs to:

$$
E'_{c,k} = f_{c,k} \times \mathbf{CON}'_c. \tag{8}
$$

2.4. Tax and tax intensity calculation

According to the EPT Law, the tax is levied on enterprises, public institutions and other producers and operators who directly discharge pollutants into the environment [49]. Emissions from agriculture, mobile pollution sources and residential are exempted according to the EPT Law. The Law regulates that tax rates for air pollutants set by each province and vary from 1.2 Yuan/APE to 12 Yuan/APE (see supplementary table 1). From a consumption-based perspective, we assume that all taxes are eventually paid by consumers through increased product prices [25, 33]. In reality, part of the tax charge will be shared by the producers, depending on the price elasticities of the products; however, the share is assumed to be zero here due to lack of accurate elasticity data.

It should be noted that a few other specific tax regulations in the EPT Law are not considered in this study due to a lack of data. For instance, the EPT policy considers only the top three pollutants (in terms of the amount of emissions) from each discharge outlet, but the emission data of individual

discharge outlet is not available at present. Thus, we include emissions of six pollutants here (SO_2, NO_x, CO, NH_3, BC and POC). This simplification does not affect our general conclusion, because SO_2, NO_x and CO contribute more than 80% of the total emissions in each province [23, 50]. In addition, the EPT regulates that companies could have different levels of tax exemption based on how much their emission intensity is less than the governmental standard. This exemption is also not considered due to lack of data, which leads to an overestimation of the tax payment.

The basic formula to calculate environmental tax for a particular air pollutant is as follows:

$$\text{TAX}_k = N_k \cdot R = \frac{E_k}{C_k} \cdot R. \quad (9)$$

Here, N_k represents the quantity of APEs for a pollutant k, which is calculated as its emission (E_k) divided by the respective pollutant equivalent coefficient (C_k) (supplementary table 5). R denotes the tax rate ranging from 1.2 to 12 Yuan/APE (supplementary table 1).

According to the EPT Law, the tax is collected from producers based on tax rates determined by each province. This mechanism is referred to in this study as a 'producer province-based levy mechanism'. Under this mechanism, the environmental tax due to urban household consumption in city s is calculated as follows:

$$\text{TAX}^s = \sum_r \sum_{k,i,j} (N_{k,i,j}^{r,s} \cdot R_{\text{province}}^r) \quad (10)$$

where $N_{k,i,j}^{r,s}$ denotes the quantity of APEs for pollutant k due to production in sector i of province r to supply consumption in sector j of city s; R_{province}^r denotes the official tax rate in province r.

We further design four alternative levy mechanisms. The 'consumer province-based levy mechanism' differs from the current 'producer province-based levy mechanism', such that each province applies its current tax rate to all emissions along the supply chain induced by the products it consumes (equation (11)). The 'consumer province affluence-based levy mechanism' is similar to the 1st alternative scenario, except that the provincial level tax rates (1.2–12 Yuan/APE) are set to be linearly dependent on their per capita consumption expenditure (supplementary table 1) (equation (12)). The 'consumer city affluence-based levy mechanism' is similar to the 2nd alternative scenario, except that the tax rate is determined by each city and set according to its per capita consumption expenditure (equation (13)). In the 'consumer city affluence-based levy mechanism + emission control', on top of the 3rd alternative scenario, the ULE emission control technology is applied to NO_x and SO_2 in the coal-fired power and industrial sectors (equation (14)) (see section 2.2)

$$\text{TAX}^s = \sum_r \sum_{k,i,j} \left(N_{k,i,j}^{r,s} \cdot R_{\text{province}}^s \right). \quad (11)$$

$$\text{TAX}^s = \sum_r \sum_{k,i,j} (N_{k,i,j}^{r,s} \cdot R_{\text{province}}'^s) \quad (12)$$

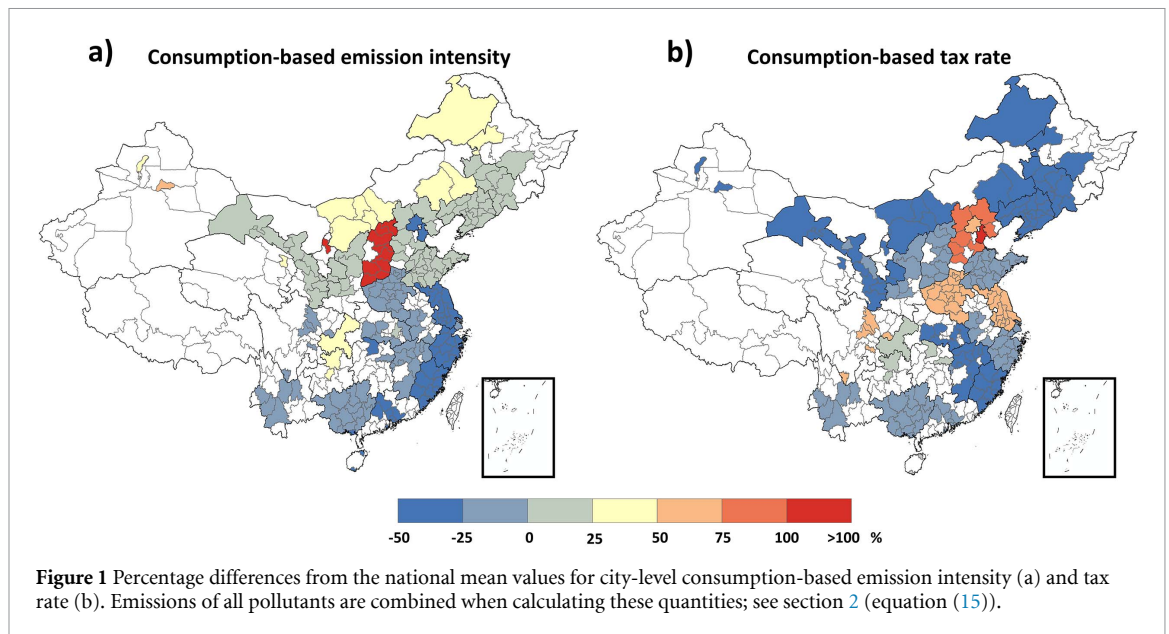$$\text{TAX}^s = \sum_r \sum_{k,i,j} \left(N_{k,i,j}^{r,s} \cdot R_{\text{city}}'^s \right) \quad (13)$$

$$\text{TAX}^s = \sum_r \sum_{k,i,j} \left(N_{k,i,j}'^{r,s} \cdot R_{\text{city}}'^s \right). \quad (14)$$

Here, R_{province}^s denotes the official tax rate of the province that city s belongs to. $R_{\text{province}}'^s$ denotes the new provincial tax rate (supplementary table 1) of the province that city s belongs to, for the scenario in which the provincial-level tax rates are set linearly dependent on their per capita consumption expenditure. We assume that Shanghai (most affluent) and Guizhou (least affluent) are levied based on 12 Yuan/equivalent (the maximum level under the EPT Law) and 2.4 Yuan/equivalent (Guizhou's current tax rate) respectively. Thus, we obtain a linear equation to assign tax rates to other provinces as $R_{\text{province}}'^s = 0.0005\text{CON} - 6.7$ (where CON is urban household total consumption expenditure of each province in 2015). The new provincial tax rate in Beijing is fixed at 12 Yuan/equivalent, its current tax rate. $R_{\text{city}}'^s$ denotes the city-determined tax rate (supplementary table 6) of city s in the alternative scenario 'consumer city affluence-based levy mechanism'. Similar to the calculation method of $R_{\text{province}}'^s$, the equation of linear regression is calculated as $R_{\text{city}}'^s = 0.0004\text{CON}^s - 3.5$ (where CON^s is urban household total consumption expenditure of city s in 2015). $N_{k,i,j}'^{r,s}$ denotes the quantity of APEs for pollutant k after applying ULE technologies, due to production in sector i of province r to supply consumption in sector j of city s.

Then, tax intensity of urban households in city s can be calculated as the environmental tax due to urban household consumption divided by their total consumption expenditure:

$$\text{TI}^s = \frac{\text{TAX}^s}{\text{CON}^s} = \frac{\sum_k N_k^s}{\text{CON}^s} \cdot \frac{\text{TAX}^s}{\sum_k N_k^s} = f_c^s \cdot R_c^s \quad (15)$$

where f_c denotes the consumption-based emission intensity encompassing all pollutants, i.e. the quantity of APEs for every unit of monetary consumption. R_c denotes the respective consumption-based tax rate, i.e. the tax for every unit of consumption-based APE. The results for f_c and R_c are shown in supplementary figure 3, and their differences from the respective national mean values are shown in figure 1.

Figure 1 Percentage differences from the national mean values for city-level consumption-based emission intensity (a) and tax rate (b). Emissions of all pollutants are combined when calculating these quantities; see section 2 (equation (15)).

2.5. Uncertainty analysis

The emission inventories [51–53] and MRIO table [54–56] used here contain uncertainties. Limited by data availability, we include six air pollutants for tax calculations instead of choosing the top three pollutants from each discharge outletas in the Law, which leads to a slight overestimate of tax payment. The MRIO analysis captures short-run effects before structural changes in the economy take effect. Thus, using the MRIO table instead of a dynamic economic model means that the market response to taxation and the respective changes in economic structure is not accounted for here. Nonetheless, recent work by Hu *et al* [23] shows that for small environmental tax rates as in our study, the market response to increasing tax rates is generally linear, which means that our economic inequality results calculated based on the MRIO table hold. A report of the International Monetary Fund states that the short-term estimate provided by a simple input–output analysis may be closer to the perceived impact by the public than the CGE estimation [57].

In addition, we assume all tax burdens are transferred from producers to consumers through price increase, although producers also bear a portion of the tax burden in reality. Such an assumption results from the fact that the nature of input–output analysis does not allow allocation of tax burdens between producers and consumers. Allocating tax to factories and consumers would require a dynamic economic model, which however may be limited by lack of and/or inaccuracies in model parameters and data (e.g. elasticity for each sector and province). Such an assumption is in line with other studies on taxes and their distributional effects [25, 58]. Moreover, we assume that cities belonging to the same province share the same supply chain and consumption-based emission intensities due to lack of city-level data.
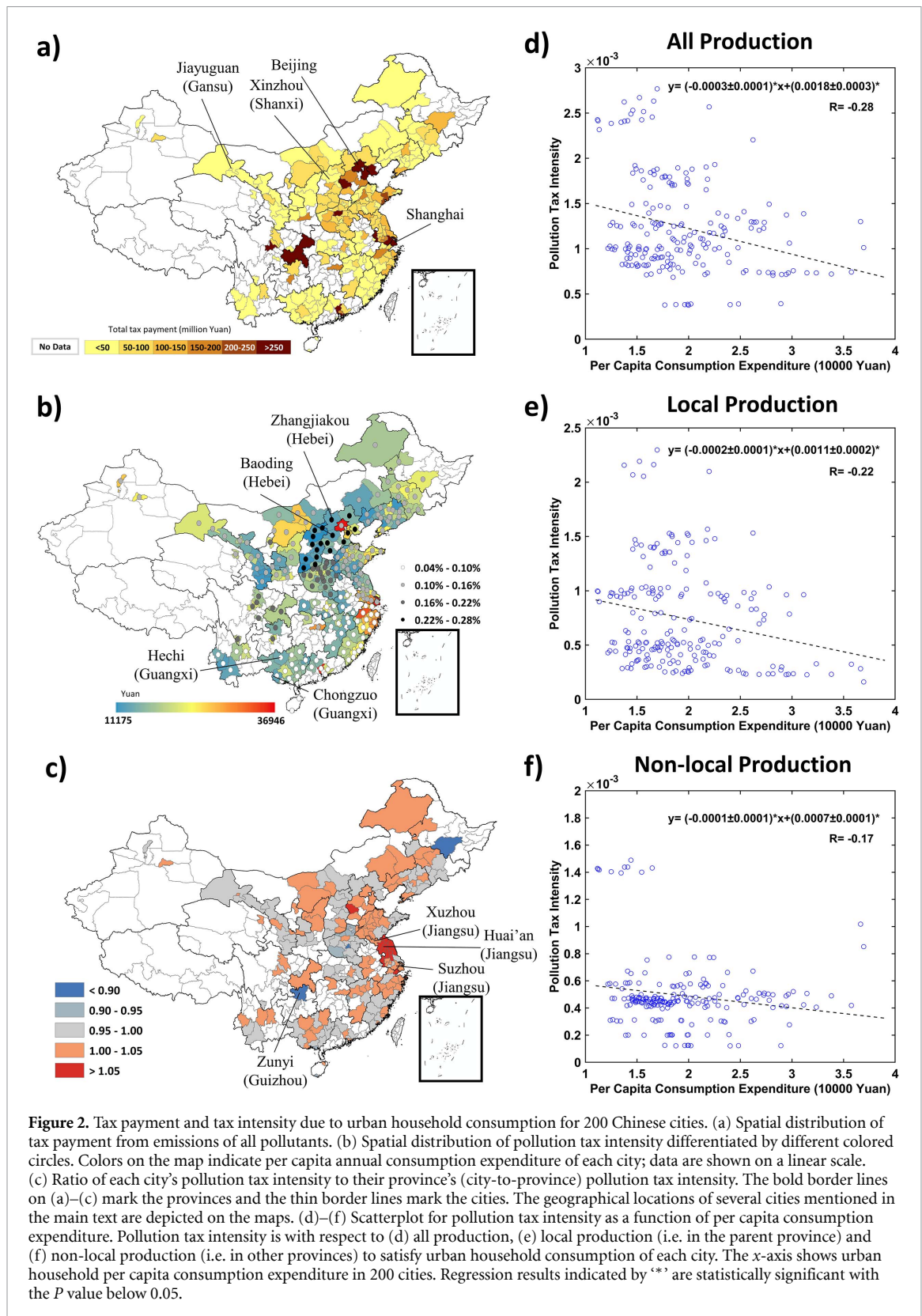
Finally, levy mechanisms considered here do not control for the demographic compositions of different cities, although recycling the tax to support less affluent individuals would further reduce their economic burden and improve equality.

3. Results

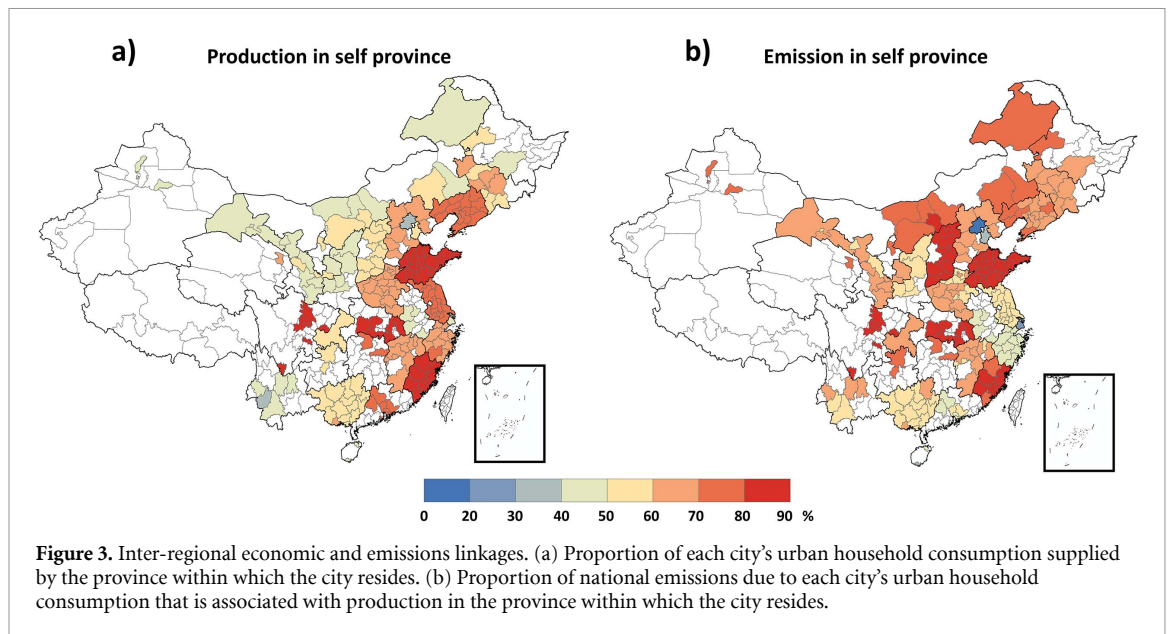### 3.1. Pollution tax intensity of 200 cities under current EPT law

Figure 2(a) shows the tax payment due to urban household consumption in 200 cities in 2015 estimated based on the EPT Law. The total tax payment is about 15.6 billion Yuan (or 2.5 billion USD), about 0.12% of total consumption expenditures of urban households of these cities. The tax payments range by a factor of 172 from 5.2 million Yuan in Jiayuguan (Gansu province) to 895 million Yuan in Beijing. Urban households' per capita tax payment (supplementary figure 4) varies by a factor of 9 ranging from 6.7 Yuan in Nanping (Fujian province) to 57.8 Yuan in Tianjin, with a national average of 27 Yuan. Expenditure for food and residence contributes 7.8 billion Yuan, or half of the tax payment, whereas payments for transport and communications and education and recreation together contribute 25%, and the other four sectors make up the remaining 25% (supplementary figure 5).

Figure 2(b) shows the spatial distribution of the pollution tax intensity of urban household consumption across the 200 cities. Overall, the tax intensity of a city does not match its affluence level—richer cities tend to bear lower tax burdens ($R = -0.28$, figure 2(d)). Thus, the EPT Law aggravates economic inequality between cities. Beijing, the 2nd richest city and with the highest tax rate, only has a tax intensity of 0.13%, which is only at the 30th percentile of the 200 cities. Over 60% of products consumed in Beijing

Figure 2. Tax payment and tax intensity due to urban household consumption for 200 Chinese cities. (a) Spatial distribution of tax payment from emissions of all pollutants. (b) Spatial distribution of pollution tax intensity differentiated by different colored circles. Colors on the map indicate per capita annual consumption expenditure of each city; data are shown on a linear scale. (c) Ratio of each city's pollution tax intensity to their province's (city-to-province) pollution tax intensity. The bold border lines on (a)–(c) mark the provinces and the thin border lines mark the cities. The geographical locations of several cities mentioned in the main text are depicted on the maps. (d)–(f) Scatterplot for pollution tax intensity as a function of per capita consumption expenditure. Pollution tax intensity is with respect to (d) all production, (e) local production (i.e. in the parent province) and (f) non-local production (i.e. in other provinces) to satisfy urban household consumption of each city. The *x*-axis shows urban household per capita consumption expenditure in 200 cities. Regression results indicated by '*' are statistically significant with the *P* value below 0.05.

are supplied by imports from other regions, and 94% of its consumption-based emissions are created outside the city. These emissions are levied with lower tax rates compared with those directly emitted in Beijing, contributing to its relatively low consumption-based tax rate (figure 1(b)). Some affluent cities whose consumption is mainly supplied by local products and services, such as southeast coastal cities, bear the lowest tax intensity (figure 2(b)) partly because their local tax rates are low (figure 1 and supplementary table 1). In comparison, tax intensities of some less affluent central and western cities, such as those in Henan and Hebei province (see supplementary figure 6 for province location), are the highest (figure 2(b)) due to high local tax rates and high fractions of consumption supplied by local production (figure 3).

Figure 3. Inter-regional economic and emissions linkages. (a) Proportion of each city's urban household consumption supplied by the province within which the city resides. (b) Proportion of national emissions due to each city's urban household consumption that is associated with production in the province within which the city resides.

Less affluent cities in Shanxi province also have high tax intensities (figure 2(b)) because of their high local emission intensities (figure 1(a) and supplementary figure 7).

To further analyze the effect of trade on inter-city inequality, we separate the tax intensity associated with each city's urban household consumption under current EPT Law (figure 2(d)) into the portion associated with local production (figure 2(e)) and the other portion associated with production in other regions (figure 2(f)). Here local production refers to production of the province within the city resides, and non-local production refers to production in other provinces, since our calculation is based on provincial-level MRIO. On average, the tax intensities associated with local and non-local production are similar (0.07% vs 0.05%) across the 200 cities. However, the cross-city distribution of tax intensity associated with local production (figure 2(e)) is very different from the distribution associated with non-local production (figure 2(f)): the tax intensity for non-local production is fairly constant across the cities, albeit with some outliers (i.e. cities in Shanxi Province in the upper left corner of the panel). The relatively constant tax intensity for non-local production reflects a net result of (a) each city's consumption volume supplied by non-local production normalized with respect to that city's total consumption expenditure, (b) the emission intensities of non-local producers, and (c) the tax rates set by the non-local producers.

The province-based tax rate formulated in the EPT Law has an important implication for inter-city economic inequality even within the same province. Figure 2(c) unveils that for most provinces, tax intensities of individual cities within a specific province are close to the provincial level, even if cities' per capita consumption expenditure varies by a factor of more than two within some provinces. Within Jiangsu

province, Suzhou and Xuzhou have the same tax intensity even though Suzhou's urban household per capita expenditure is twice that of Xuzhou. Similarly, although cities' per capita consumption expenditure varies from 12 405 to 26 319 Yuan in Shandong province, their tax intensities are all between 0.12% and 0.13%. The lowest city-to-province tax intensity ratio is 0.84 in Zunyi (Guizhou province) and the highest ratio is 1.08 in Huai'an (Jiangsu province).

The province-based tax rate also contributes to economic inequality between cities with the same affluence level but situated in different provinces. To avoid intensifying economic inequality, households with comparable affluence levels and affordabilities should bear similar tax burdens regardless of where they live [25, 59]. However, under current EPT Law, tax intensities of cities in different provinces with the same affluence level can vary greatly. For instance, some cities in Hebei province (e.g. Zhangjiakou and Baoding) and Guangxi province (e.g. Hechi and Chongzuo) share a similar affluence level, but their tax intensities differ by a factor of three.

The above results suggest that under current EPT Law, inter-city economic inequality both within the same province and across the provinces would increase by collecting taxes based on tax rates of producing regions rather than consuming regions, province- rather than city-based tax rates, inter-city trade, and spatial diversities in tax rate and emission intensity. The following sections discuss four alternative levy mechanisms that can be considered by policymakers to tackle these issues.

3.2. Paying tax based on consumption

Collecting environmental tax based on production, under the EPT Law, contributes to the aggravated inter-city economic inequality across provinces. Alternatively, the tax could be collected based on consumption, that is, each city applies its local province's

tax rates to all emissions along the supply chain induced by the products it consumes. Such a mechanism is referred to as the 'consumer province-based levy mechanism', which mainly affects the tax intensities of cities as large net importers. For example, the tax intensity of Beijing increases from 0.13% to 0.46% due to its local tax rates being the highest among all cities. By comparison, although Shanghai is also a major net importer, its tax intensity remains low because its local tax rates are relatively low. Across the 200 cities, the correlation between per capita consumption expenditure and tax intensity is about −0.12. This means a slight reduction in inter-city economic inequality compared to that under current EPT Law, although there is still a lot of room for further improvement.

3.3. Tax rates set based on provinces' affluence levels

Tax rates disconnected from each province's affluence level is another driver of inter-city economic inequality across different provinces. Therefore, inequality can be alleviated in a 'consumer province affluence-based levy mechanism', in which the tax rate (1.2–12 Yuan/APE) of each province is set to be linearly dependent on per capita consumption expenditure of its urban households, with the most affluent province having the highest rate (12 Yuan/APE) and the least affluent province having the lowest rate (1.2 Yuan/APE) (see section 2). In this case, the correlation between per capita consumption expenditure and tax intensity is 0.47 across the 200 cities (figure 4(b)). Tax intensities of affluent eastern coastal cities (e.g. Shanghai, and cities in Jiangsu and Zhejiang province) would be much higher than those under current EPT Law because of the significant increases in their tax rates. This alternative levy mechanism would reduce the tax intensities of less affluent cities of Hebei province from 0.3% to 0.1% through reductions in their tax rates. It would greatly reduce inter-city economic inequality across different provinces. However, inequality within each province would not be reduced because cities with different affluent levels still share the same province-based tax rate.

3.4. Tax rates set based on cities' affluence levels

Another alternative 'consumer city affluence-based levy mechanism' could be based on cities' consumption with tax rates (1.2–12 Yuan/APE) being linearly dependent on each city's affluence level, with the most (least) affluent city having the highest (lowest) rate (see section 2, supplementary table 6). Under this mechanism, tax rates would increase in most cities. Thus, the average tax intensity of the 200 cities would rise to 0.30%, which would be about 2.5 times of the average intensity under the current levy mechanism. Such a more stringent levy mechanism would stimulate a greater emission reduction [23]. Furthermore, this mechanism would reduce
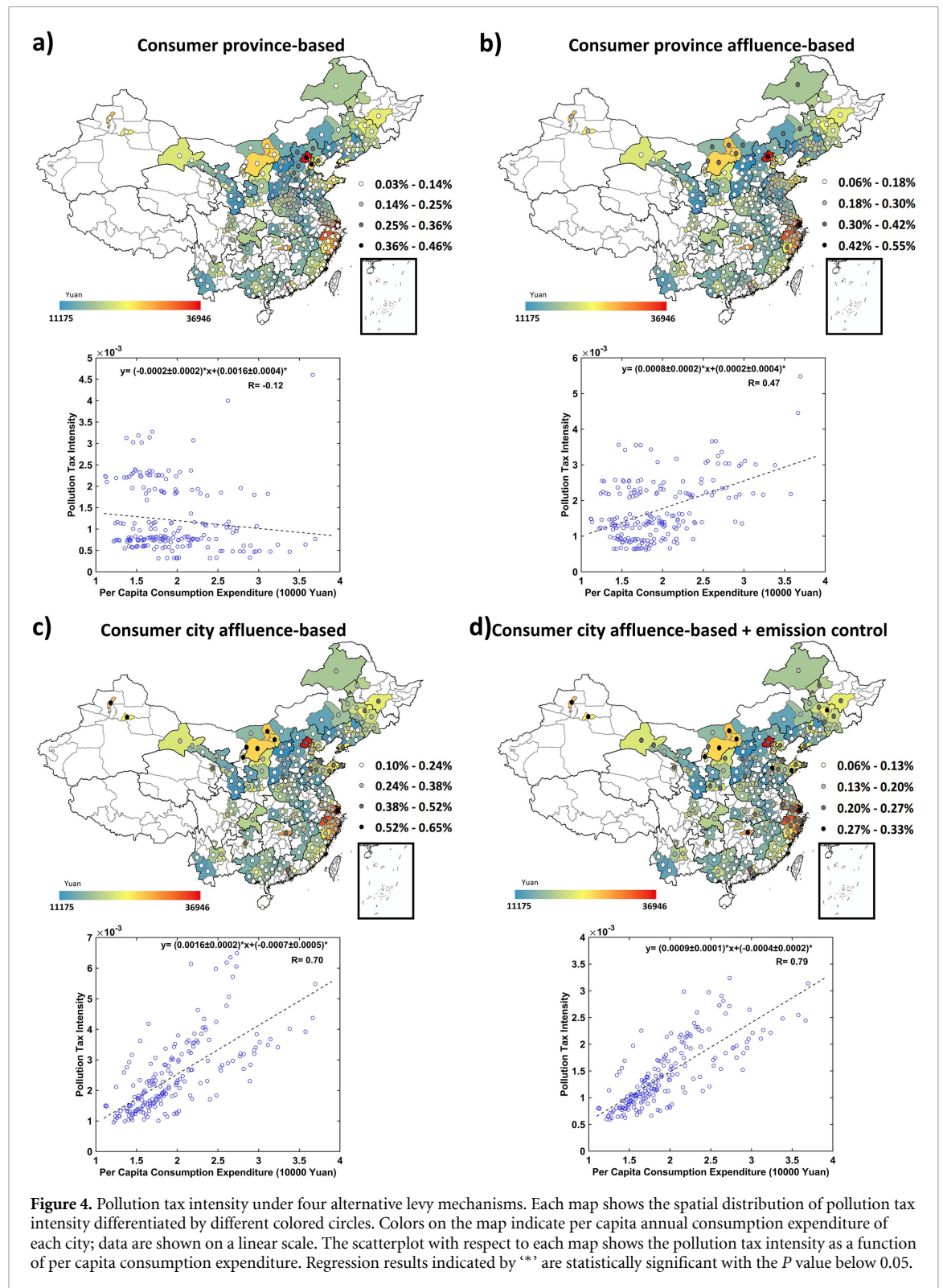
inter-city economic inequality within and between provinces (figure 4(c)), which leads to a high correlation between per capita consumption expenditure and tax intensity (0.70). In particular, cities' tax intensities within each province would begin to follow their affluence levels instead of being relatively constant as in the current levy mechanism. In Shandong province, the range of cities' tax intensities would expand from 0.12% to 0.13% and 0.10% to 0.50%. Additionally, tax intensities of cities with similar affluence levels in different provinces would be close to each other under this alternative levy mechanism.

3.5. Revenue recycling for emission control

That some less affluent cities bear heavy tax burdens is in part due to their high local emission intensities, such as those in Shanxi province. A further step to lower tax intensities in these cities and to reduce inter-city economic inequality is feasible by reducing emission intensities in these cities on top of the 'consumer city affluence-based levy mechanism'. One particular possibility is to deploy ULE technologies effectively and efficiently. The ULE involves advanced end-of-pipe emission control technologies. Its implementation began in 2014 and is expected to cover about 90% of coal-fired power plants by 2020 [60, 61] and 80% of the iron and steel industry by 2025 [62] in China. In a 'consumer city affluence-based levy mechanism + emission control' scenario, we assume that suites of ULE technologies are applied to the coal-fired power and industrial sectors nationally to cut NO_x and SO_2 emissions [40]. Calculation of ULE associated emissions is detailed in section 2.

Such a levy mechanism would eliminate most inter-city economic inequality across the 200 cities, with the correlation between per capita consumption expenditure and tax intensity reaching as high as 0.79 (figure 4(d)). Meanwhile, the average tax intensity of the 200 cities is about 0.18%. Even if the ULE technology is only applied in Shanxi province, tax intensities of its (usually less affluent) cities will decrease greatly compared to other alternative levy mechanisms (supplementary figure 8). Applying the ULE technology to Shanxi would also reduce tax intensities in other provinces, because Shanxi provides much of the consumption in these provinces. If importers of Shanxi products help the province to reduce its emissions, this would also reduce these importers' own tax intensities, i.e. a win–win situation. Thus, inter-regional coordinated strategies for emission reduction should become a key part of local environmental governance.

Environmental tax revenue is an appropriate and desirable income source for installing suites of ULE technology. Installing ULE technologies in the power and industrial sectors nationally reduces the total emissions of SO_2 and NO_x by 51% and 34% respectively (see section 2). Our previous study has estimated that about half the total annual operating cost

Figure 4. Pollution tax intensity under four alternative levy mechanisms. Each map shows the spatial distribution of pollution tax intensity differentiated by different colored circles. Colors on the map indicate per capita annual consumption expenditure of each city; data are shown on a linear scale. The scatterplot with respect to each map shows the pollution tax intensity as a function of per capita consumption expenditure. Regression results indicated by '*' are statistically significant with the *P* value below 0.05.

of ULE technologies applied in China's coal-fired power plants can be financed by environmental tax revenues [33]. The rest of ULE costs could be financed by other sources or by further enhancing tax rates. Further enhancing tax rates to better cover the ULE costs might also be appropriate, given that the current national tax revenue is very low compared with economic losses from $PM_{2.5}$ related premature mortality [33] and that strengthening the environmental tax policy will promote emission reductions

in China [23]. In any case, recycling tax revenues will greatly reduce tax payers' economic burden by cutting emissions, and will alleviate regional economic inequality while improving the environment.

4. Conclusion and policy implications

Our results show that implementing China's current EPT Law would increase inter-city economic inequality both within each province and across

provinces. This is due to the fact that taxes are collected based on levels of production with tax rates set by each province, in addition to regional disparities in emission intensities and tax rates. Alternatively, collecting taxes based on consumption of each city and setting tax rates according to each city's affluence level would considerable remove such inequality. Using the tax revenue to reduce emission intensities in major emitting and usually less affluent cities would further lower the national average tax intensity and inter-city inequality.

Emissions embedded in products consumed can be calculated based on life-cycle assessment, footprint analysis or other approaches [63, 64]. For example, producers of raw, intermediate and final goods could provide information on the amount of emissions induced in the process of producing the goods, and the buyer cities of final products can levy its consumers with local tax rates based upon the total emissions of each product (or at least product category). The government could work with independent researchers to monitor and assess the emissions to ensure data accuracy. In fact, many leading companies such as Apple have made their own efforts to track emissions along their supply chains and moved towards greener supply chains [65]. The government could work with independent researchers, companies and non-governmental organizations to monitor and assess emissions to ensure data accuracy.

China's EPT law has lots of room for improvement, in addition to the issue of inter-city inequality studied here. For example, the tax rates of different pollutants could be set based on how much the pollutants can affect public health both within and outside the emission source area through atmospheric chemical processes and transboundary transport [14, 66, 67]. In addition to subsidizing emission reduction (e.g. installing ULE technologies) in emission-intensive regions, tax revenues can be further recycled to subsidize low-income groups consuming clean products.

Improvement of the EPT Law could be an important step towards achieving the 10th (reduced inequalities) and 11th (sustainable cities and communities) SDGs for China [1]. Over the past few years, many easier and less costly measures have been taken to reduce air pollution in China [68]. Further reducing air pollution would require more difficult and expensive actions, including raising the tax rates. This could aggravate the inter-city inequality under current province-based EPT Law, affecting public acceptance of this policy. Thus, improving the EPT Law will become more important in coming years. Our study provides quantitative evidence to improve the EPT Law from an equality perspective that also addresses the issue of sustainable cities.

As part of efforts to mitigate climate change under the Paris Agreement, many countries including China have pledged to be carbon neutral by 2050 or 2060. On the way to China's carbon neutrality, a suite of environmental policies are expected to be implemented in the next decades [69, 70]. Our study serves as an example to address potential limitations, in terms of resulting cross-city economic inequality, in China's current province-based environmental policy design framework. Based on our findings, in addition to national and provincial strategies to achieve carbon neutrality, specific policies should be designed and implemented based on thorough consideration of local characteristics of individual cities, including but not limited to affluence levels, natural resource availability, and pollution levels. To this end, our study contributes to formulation of more effective and fairer environmental policies to fulfill China's ambitious national emission commitment. It also serves as a basis for coordinated environmental policies in other countries, especially for developing countries whose environmental policies are at a very early stage.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://zenodo.org/record/4724231#.YIjQVrUzYuU.

Author contributions

J L, J W and K F conceived the research. J W, J L and K F designed the research and led the analysis. J W and J L led the writing. J W performed the research. J W and J L designed the scenarios. J W collected the socioeconomic and tax data. Y L provided the MRIO table. X J helped with ULE emission calculation. R N helped with emission data collection. J W, J L, K F, M D and K H analyzed the results with comments from all authors. All authors contribute to the writing.

Conflict of interests

The authors declare no competing interests.

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