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To cite this article: Xiurong Hu *et al* 2019 *Environ. Res. Lett.* **14** 054013

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Environmental Research Letters



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OPEN ACCESS

RECEIVED

29 November 2018

REVISED

3 April 2019

ACCEPTED FOR PUBLICATION

15 April 2019

PUBLISHED

13 May 2019

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Keywords: computable general equilibrium model, CGE, environmental protection tax, air pollution, climate mitigation, China

Supplementary material for this article is available [online](#)

Abstract

Environmental problems, associated with climate change and air pollution, have become increasingly serious for China in recent years, which have aroused great domestic and international concerns. To mitigate these problems with great efforts, the Chinese government has implemented the Environmental Protection Tax Law in the whole country since the beginning of 2018. Although the new tax law is perceived as an aggressive policy that tends to establish a taxation system for promoting air pollution control, evaluations of its effectiveness are insufficient and urgently needed for China. Using a multiregion multisector Computable General Equilibrium model, we, for the first time, quantify the impacts of this 'pollution tax' policy on modulating air pollutants emissions. Our analysis shows that current tax policy is generally able to reduce many short-lived air pollutants emissions (e.g. SO₂, NO_x, TSP, PM₁₀, PM_{2.5}, CO, VOCs, OC, NH₃ and BC), but the significant effects only happen in regions with large economic scale (i.e. Guangdong, Shandong and Zhejiang provinces) and in sectors with high emission intensity (i.e. the electric power and nonmetal manufacturing sectors). However, at the national level, the overall effect of the current policy on air pollution mitigation is relatively small, less than 2% compared to a business-as-usual scenario. Large emission reduction potentials exist if the tax increases. Therefore, a more ambitious tax policy is urgently needed in order to achieve China's air pollution mitigation target of 2020. We also find that in China for implementing any pollution tax policies, the rate of decline in CO₂ emissions is much larger than those of short-lived pollutants, which indicates a huge co-benefit on global climate change mitigation.

1. Introduction

The Environmental Protection Tax (EPT) Law which replaced the pollutant discharge fee has been implemented since the beginning of 2018 (Bo and Cong 2015). The EPT is China's first tax clearly targeting on environmental protection. Under the EPT Law, enterprises and public institutions that discharge relevant pollutants directly into the environment are subject to taxes for producing air pollution, water pollution, noise, and solid waste. Compared to

the pollution discharge fee, this law places more responsibility and accountability on local governments and law-enforcement agencies and sets higher standards for enterprises, and thus it is expected to effectively protect the environment, especially air quality. Some studies have analyzed the potential and limitations of the EPT Law. They pointed out that the transition from the pollution charge to the environmental tax could strengthen the legal support for China's environmental protection (Wu and Chen 2017), promote the industrial air pollution

control technology innovation and improvement (Xie and Liu 2019) and then reduce the air pollutants emissions. However, concerns exist that the EPT Law only partially innovates to institution by shifting the tax burden from fee to tax and the tax revenues might be too small to stimulate significant reductions of air pollutants emissions (Wu and Tal 2018). Presently very few studies have quantified the effectiveness of EPT on air pollution control. Liu and Hu (2017) simulated the EPT impacts on SO₂ and NO_x. The results showed that there would be approximately 294 Gg (1.13%) of reductions in SO₂ and 130 Gg (1%) of reductions in NO_x with the 1.2 RMB tax for SO₂ and NO_x. Since this analysis is carried out at the national level, it cannot differentiate the spatial variation in EPT taxes and their consequences in various provinces, which has been shown to be very important for policymaking (Li *et al* 2016). In addition, the EPT is collected by local governments. Different provinces have economic structures and emissions that vary greatly from each other. Thus, it is very important to evaluate the effects of EPT on energy use and pollution emissions at the province level.

Computable general equilibrium (CGE) modeling is a powerful and prevailing method for environmental policy analysis (He *et al* 2010). The CGE model integrates energy use and emissions release with economic activities to reflect the dynamic interactions between the economy and the environment. Thus, it is widely employed in analyzing environmental and energy policies (Liang *et al* 2014), such as the carbon tax (Lu *et al* 2010, Dai *et al* 2011, Liang and Wei 2012), energy tax (Sancho 2010, Rocchi *et al* 2014), energy subsidy (Lin and Jiang 2011), resource tax reform (Zhang *et al* 2013), changes in industrial technology (Schumacher and Sands 2007, Wang *et al* 2009), and co-benefits between climate policies and environmental policies (Thompson *et al* 2014, Garcia-Mendez *et al* 2015).

Here, we use a multiregion and multisectoral CGE model to analyze how the EPT would impact the provincial air quality in China and the potential co-benefits for CO₂ mitigation. The objective of this study is to evaluate the short-term aggregated macroeconomic behavior in China's dynamic market system in response to with an environmental tax shock, the detailed long-term optimization behavior for individual industries under the EPT including the technology improvement and end-of-pipe emission control are not considered in this work and will be addressed in our follow-up studies. Air quality here focuses on conventional air pollutants, including sulfur dioxide (SO₂), nitrogen oxides (NO_x), total suspended particulates (TSP), particles with a diameter of 10 μm or smaller (PM₁₀), particles with a diameter of 2.5 μm or smaller (PM_{2.5}), carbon monoxide (CO), nonmethane volatile organic compounds (VOCs), primary organic carbon (OC), ammonia (NH₃) and black carbon (BC). We simulate three EPTs with different levels of

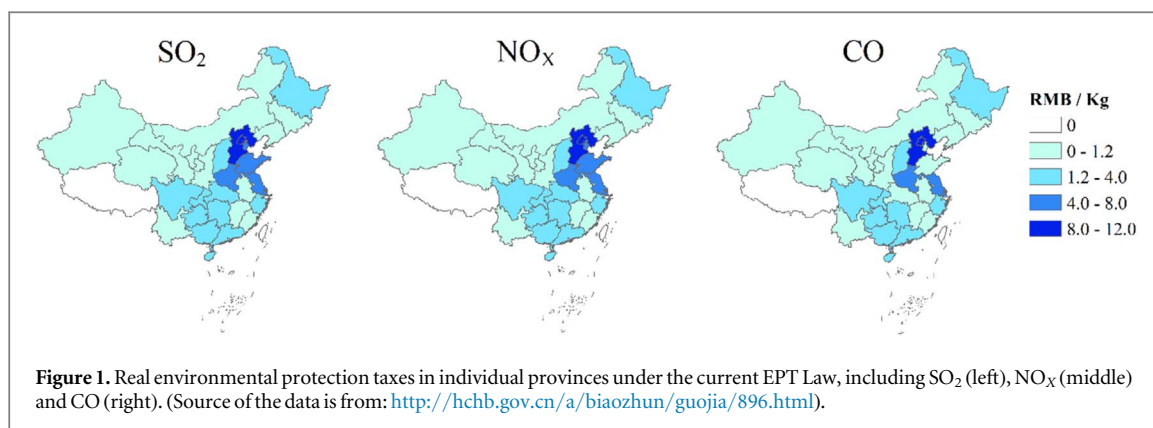
stringency relative to a business-as-usual (BAU) case in 2018. The resulting economic constraints lead to economic output changes and emissions changes that vary by policy, economic sector and region.

2. Methods

2.1. CGE model

We developed a multiregion and multisector CGE model to analyze the economic and environmental impacts of different sets of EPTs. The CGE model used in this study is based on a recursive dynamic CGE model developed by the Development Research Center of the State Council (DRC-CGE model). It was originally developed in 1997 (Zhai and Li 1997) and improved later, here, we expand it to 30 provinces and apply it to air pollution policy analysis. The model integrates rational economic agents' behavior with the equilibrium conditions assumption, describing the interactions of the price-dependent market, economic agents and income spending based on microeconomic theory (Thompson *et al* 2014). Firms minimize production costs with the inputs of intermediate goods from other sectors and the primary factors of production from households. Consumers maximize welfare under the reward from their supply to firms of factors of production (labor, capital and resources) and income from government transfers (Zhang *et al* 2015). Income thus earned is spent on goods, services and savings. The government collects tax revenues used for consumption, investment and household transfers. Energy resources are included in the CGE model as primary factors whose use is associated with the emissions of pollutants and carbon dioxide (CO₂). Nested constant-elasticity-of substitution cost functions are applied to characterize substitution possibilities between inputs in production, consumption and trade of goods (Lou 2015).

Our CGE model is calibrated to province-level economic data from a social accounting matrix (SAM) table, which covers all transactions among businesses, households, enterprise, government and foreign agents for the benchmark year of 2007. The SAM table is built on an input-output table (2007), the China Statistical Yearbook in 2008 (based on an investigation of 2007, the same as below), the China Finance Yearbook (2008) and the China Taxation Yearbook (2008). Energy data from the China Energy Statistical Yearbook (2008) and emissions data from PKU-Inventories (2007) are then merged with the economic data to provide physical flows of energy for air pollutants accounting. Both the economic and the air pollutant datasets are aggregated into 30 regions and 12 commodity groups (see tables S1 and S2 in the supplementary information for a description of regions and sectors used in this study). A detailed description of this model, including elasticities (tables S3 and S4 are available online: stacks.iop.org/ERL/14/054013/



mmedia) and validation results (figures S3–S5, and table S5), is also provided in the supplementary information.

2.2. EPT module

China's EPT is levied on the enterprises, public institutions and other producers and operators that directly discharge pollutants into the environment. The agricultural and mobile sources (including motors, vessels, aircrafts, etc) are exempt from the tax. Note that although no tax is levied on the agriculture and traffic sectors, those sectors indirectly contribute to the reductions through their interactions with other sectors in the CGE model.

The first three items of pollutants ranked in descending order of pollution equivalents shall be subject to the EPT. The pollution equivalents value is the air pollution quantity that takes into account the harmfulness of the pollutants and the public cost of dealing with them. The listed air pollutants and their pollution equivalents are presented in table S6 in supplementary information. SO₂ and NO_x are the major pollutants subject to the EPT in almost all provinces (Liu and Hu 2017). Based on the values of pollution equivalents for individual air pollutants, in this study SO₂, NO_x and CO are the three pollutants subject to this tax across all regions. We also evaluate the effects if the EPT was placed on SO₂, NO_x and PM (the results are given in the supplementary figure S11).

According to the EPT Law in China, the taxes for air pollutants vary from 1.2 RMB to 12 RMB per pollution equivalent, depending on the region. Figure 1 shows the provincial taxes under current policy in which the Jing-Jin-Ji area has been set at (or close to) the maximum tax amount allowed under the law. Shanghai, Jiangsu, Shandong and Henan also have a relatively higher air pollution tax. In contrast, Liaoning, Jilin, Anhui, Jiangxi and Fujian, and Northwest China have employed the minimum tax level within that range.

The EPT is integrated into the CGE model as an *ad valorem* tax on energy input and output of production. Total air pollutants (SO₂, NO_x and CO) emissions are multiplied with the tax per pollution

equivalents quantity (t) to obtain the total emissions tax (TAX) (Arikan and Kumbaroglu 1999). The pollutants emissions are divided into fossil fuel combustion (E) and processing emissions (P) in each sector (C) and each region (R). Thus, the total tax includes TAXE on combustion and TAXP on processing emissions:

$$\text{TAXE}_{R,C} = E_{R,C,\text{SO}_2} \times t_{R,C,\text{SO}_2} + E_{R,C,\text{NO}_x} \times t_{R,C,\text{NO}_x} + E_{R,C,\text{CO}} \times t_{R,C,\text{CO}} \quad (1)$$

$$\text{TAXP}_{R,C} = P_{R,C,\text{SO}_2} \times t_{R,C,\text{SO}_2} + P_{R,C,\text{NO}_x} \times t_{R,C,\text{NO}_x} + P_{R,C,\text{CO}} \times t_{R,C,\text{CO}} \quad (2)$$

Then, we convert the specific duty rate into the *ad valorem* tax rate by dividing the duty by a unit value:

$$te_{R,C} = \text{TAXE}_{R,C} / \text{QEE}_{R,C} \quad (3)$$

$$tp_{R,C} = \text{TAXP}_{R,C} / \text{QQ}_{R,C} \quad (4)$$

where QEE is the domestic demand for energy, and QQ is the total production quantity. Therefore, the market price of fossil energy will be $(1 + te) * \text{PEE}$, and the production price will be $(1 + tp) * \text{PQ}$. PEE is the market price of fossil energy, and PQ is the production price.

In this model, the EPT directly affects the cost of fossil energies and the production prices, which in turn affect the supply and demand of products, government revenue, household consumption and the whole market (Guo *et al* 2014). Thus, energy consumption, products output and their related air pollutants emissions experience change.

2.3. Emissions inventory

Associated emissions (including SO₂, NO_x, TSP, PM₁₀, PM_{2.5}, CO, VOCs, OC, NH₃, BC and CO₂) from energy combustion, industrial processes, agricultural activities and transportation are used in the CGE model. As production-based emissions changes with the policy are the focus of this study, residential and biomass emissions are ignored (Li *et al* 2016). The provincial combustion emissions and production processing emissions are from PKU-Inventory (2007) for non-VOCs species and Wu *et al* (Wu *et al* 2016) for VOCs species. Then we project the sectoral emissions with different methods for combustion and

production processing emissions. Combustion emissions are divided into each sector based on the energy consumption data (Li *et al* 2016, Zhang *et al* 2017). These energy consumption data includes 30 provinces and 8 energy types (i.e. coal, coke, gasoline, kerosene, diesel, fuel oil, liquefied petroleum gas and natural gas (Li *et al* 2016). For production processing emissions, we follow the approaches used in previous studies, e.g. Liu and Hu (2017), to match the industrial processing emissions to the quantities of economic output to project sectoral production processing emissions. The construction of the baseline emissions starts from the 2007 benchmark. For the period up to 2018, the forward projection takes account of the most recent available data. In this CGE model, we capture the technology improvement with the parameters of energy efficiency and total productivity factor following Liu (2013) and Lou (2015). We compared the modeled emissions for other years and by sectors (see supplementary figures S6 and S7). Our modeled emissions in general agree well with the National Statistics and the Multi-resolution Emission Inventory for China (MEIC). And the sectoral emissions are consistent with previous studies (Zhang *et al* 2007, Wu *et al* 2016, Meng *et al* 2017, Saikawa *et al* 2017).

2.4. EPT scenarios

Four scenarios (BAU, EPT-1.2, EPT-current and EPT-12) are developed in the CGE model in accordance with the EPT law. Scenarios analyses are based on the 2018 model configuration with different tax levels.

The BAU scenario sets a framework for China's socioeconomic development from 2007 to 2018 without considering the EPT law. To assess the effectiveness of the current EPT and evaluate the potential reduction of the tax, we compare current policy with the lowest (1.2 RMB) and the highest (12 RMB) bounds of the EPT range. In EPT-1.2, the lowest bound of EPT law (that is, the 1.2 RMB per pollution equivalent tax) is imposed in all regions. EPT-current is based on the actual EPT levels employed in individual provinces (figure 1). EPT-12 assumes that the most aggressive tax (that is, the 12 RMB per pollution equivalent tax) is imposed in all provinces. We then compare each policy to the BAU case to identify the impact of each EPT policy.

3. Results

3.1. National level emission changes

National level air pollution emissions and GDP changes for all scenarios are listed in table 1, and the percentage changes are presented in figure 2. The results show that the EPT leads to the largest declines in SO₂ and NO_x emissions under all scenarios because the emissions impacts of EPT are dominated by the SO₂ and NO_x related sectors which suffer the largest tax burden.

Table 1. The reductions of national level air pollutants emissions (Gg) and GDP (RMB, 100 million) under different EPT scenarios in 2018.

	EPT-1.2	EPT-current	EPT-12
SO ₂	-153	-325	-1272
NO _x	-188	-386	-1561
TSP	-156	-331	-1316
PM ₁₀	-57.9	-122	-490
PM _{2.5}	-32.4	-68.4	-277
CO	-543	-1120	-4980
VOCs	-0.10	-0.23	-0.87
OC	-0.78	-1.76	-7.02
NH ₃	-0.54	-1.17	-4.82
BC	-1.17	-2.63	-10.7
GDP	-344	-920	-3419

Under the EPT-current scenario, we find a 339 Gg (1.9%) decline in SO₂ and a 402 Gg (1.9%) decline in NO_x relative to the BAU scenario, mainly due to the emissions reduction from the power electricity and nonmetal manufacturing sectors. PM also experiences substantial reductions (approximately 343 Gg, 127 Gg and 71 Gg for TSP, PM₁₀ and PM_{2.5}, respectively), mainly from the power electricity sector. However, the EPT-current has a limited effect on CO, VOCs, OC, NH₃ and BC emissions, and the reduction rates are all less than 1%, as their emissions sources are only slightly or indirectly impacted by this tax.

Comparing the EPT-current scenario with the EPT-1.2 and EPT-12 scenarios, emissions reduction under the current tax is approximately two times larger than the lowest bound of tax and approximately three to four times smaller than the highest bound of the tax (figure 2). The reduction potential mostly stems from the power electricity sector, nonmetal manufacturing sector and metal manufacturing sector, as they are levied a higher tax rate on SO₂, NO_x and CO emissions than the rest sectors.

Although a substantial reduction in pollution emissions was found in the EPT-12 scenario, it has a relative minor effect on national GDP (figure 2). The introduction of EPT increases domestic prices, which reduces household consumption, export and import demand. However, government consumption increases, largely through the income from the environmental tax. Thus, the tax ultimately has a slightly negative effect on GDP. Detailed changes are shown in table 2.

3.2. Sectoral emissions changes

The impacts of the EPT on air pollution emissions are different among sectors. These differences are due to the BAU pattern of sectoral emissions and the various tax rates levied on each sector.

The pattern of BAU sectoral emissions in 2018 is shown in figure 3(a). The electric power sector and nonmetal manufacturing sector (including iron and steel and nonmetallic materials) are two major source

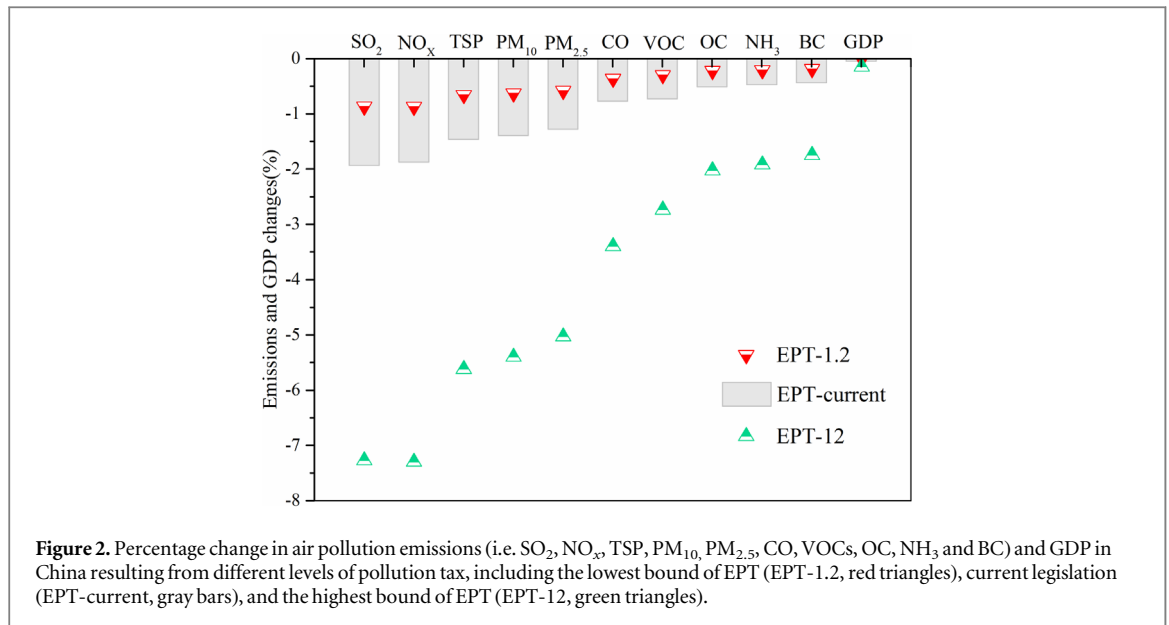
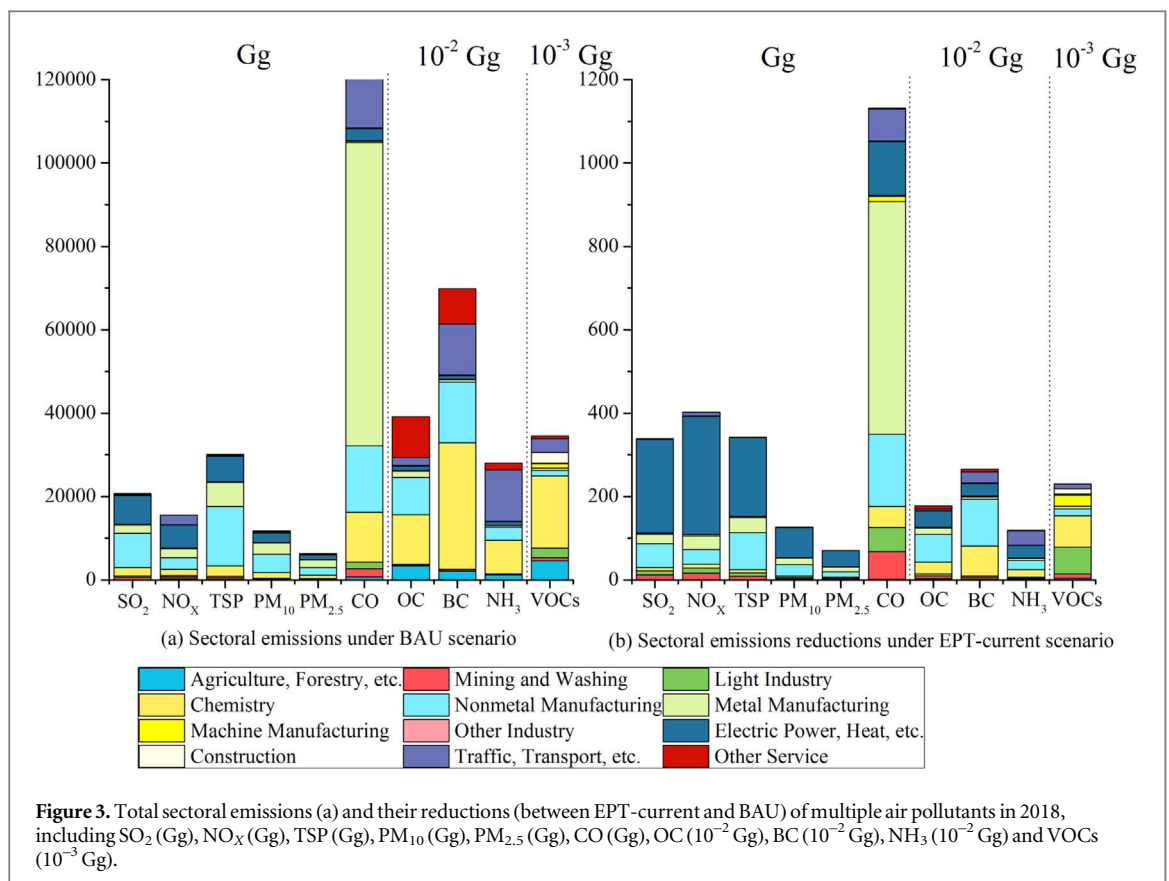
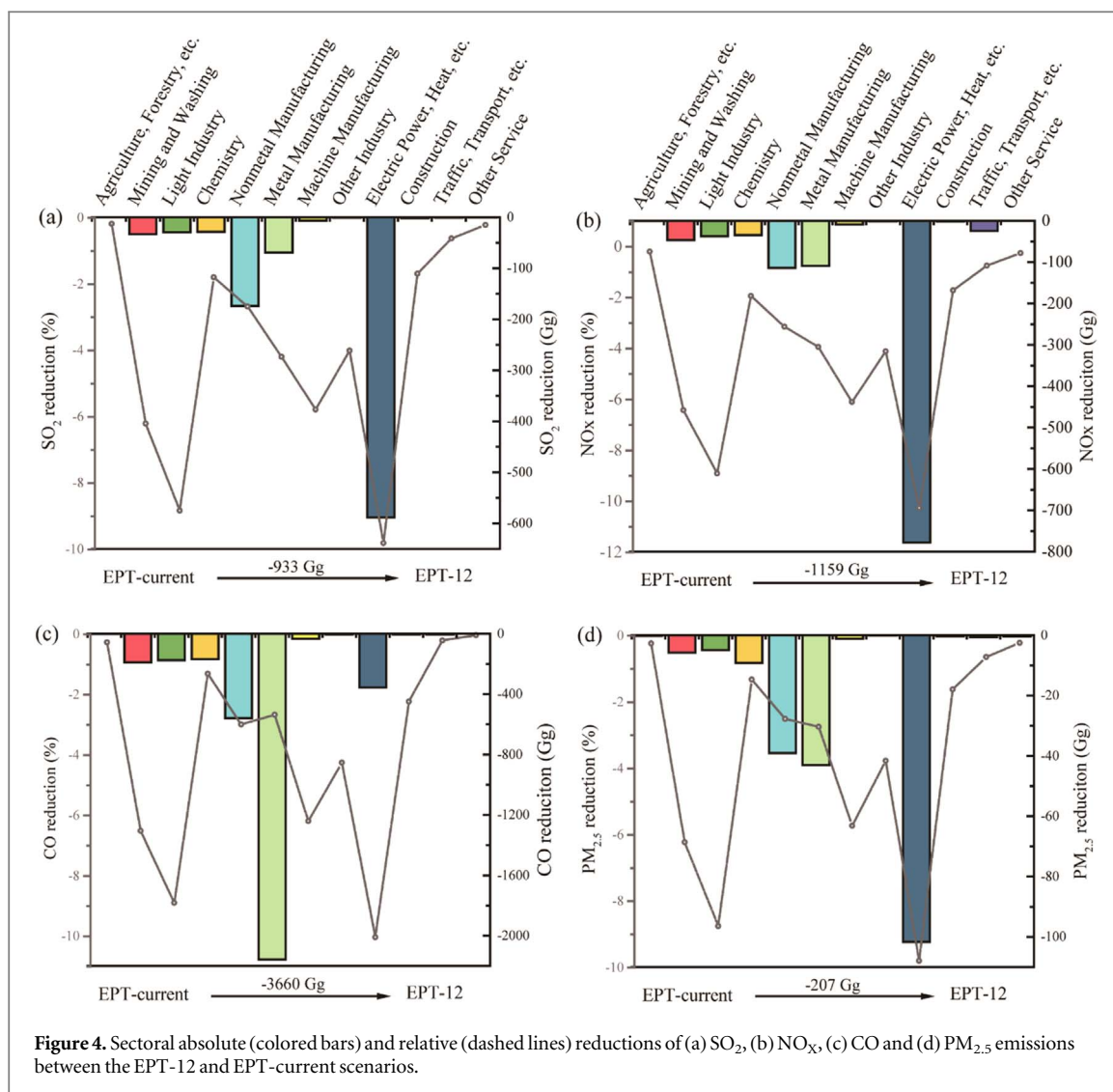


Table 2. Final consumption from household, government, investment, export, and import (values in the parentheses represent the percentage changes from BAU) under different EPT scenarios (RMB, billion).

	BAU	EPT-1.2	EPT-current	EPT-12
Household consumption	455	454 (-0.09%)	454 (-0.26%)	451 (-0.92%)
Government consumption	72	72 (0.19%)	72 (0.52%)	73 (1.79%)
Investment	269	269 (-0.05%)	268 (-0.15%)	267 (-0.52%)
Export	202	202 (-0.04%)	201 (-0.13%)	201 (-0.40%)
Import	185	185 (-0.05%)	185 (-0.16%)	184 (-0.52%)





sectors for SO_2 , NO_x and PM (TSP, PM_{10} and $\text{PM}_{2.5}$) (Zhang *et al* 2007, Saikawa *et al* 2017). For CO emissions, metal manufacturing is the largest emitter, accounting for 55% of total emissions (not including residential and biomass emissions). BC and OC are largely generated from the nonmetal manufacturing sector and metal manufacturing sector. Except for the residential and biomass burning sectors, a tremendous amount of NH_3 is released from the chemistry and transportation sectors (Meng *et al* 2017). The chemicals manufacturing sector largely contributes to VOCs emissions within industrial processes (Wu *et al* 2016).

Figure 3(b) shows the sectoral emission reductions in the EPT-current scenario as compared to BAU, and the relative contribution by sectors is shown in supplementary figure S7(b). Primary PM and its precursors SO_2 and NO_x have the largest reduction in electric power and nonmetal manufacturing (including iron and steel and nonmetallic materials) sectors. These two sectors are the main emitters of SO_2 and NO_x and bear more of the tax burden. Thus, they could reduce production output and energy consumption to lower the burden from the EPT. Other pollutants (e.g. TSP,

PM_{10} and $\text{PM}_{2.5}$) that share the same sources will experience similar significant reductions. CO is the only pollutant that has the most emissions reduction in the metal manufacturing sector. VOCs emissions fall mostly due to the processing reduction in the chemical sector and light industry. BC and OC reduction are mainly due to the nonmetal manufacturing sector and the chemical sector. In contrast, EPT has a relatively minor effect on NH_3 emissions because most of which estimated in this study are emitted from the chemical and transportation sectors. However, there is no tax levied on transportation, and the reduction rate from the chemical sector is relatively low (see the relative sectoral changes in supplementary table S7).

To evaluate the emissions reduction potential of China's EPT system, we compared the EPT-current scenario to the EPT-12 scenario on SO_2 , NO_x , CO and $\text{PM}_{2.5}$ (figure 4). Large potential emissions reductions can occur in the electric power, nonmetal manufacturing and metal manufacturing sectors. These sectors are the main emissions sources of SO_2 , NO_x and CO, so they have a close association with this tax. Both the largest absolute and the largest relative changes in

SO₂, NO_x, and PM_{2.5} occur in the electric power sector, which emits a large amount of air pollutants and has a high tax rate. Although the relative changes are low in the nonmetal manufacturing sector and the metal manufacturing sector, they make a substantial contribution to the mitigation of all air pollutants due to a large amount of base emissions in the BAU scenario. In addition, the light industry sector and the mining and washing sector have high reduction rates, as they suffer from relatively high tax rates (shown in figure S87 in the supplementary information). The traffic sector also has a large reduction potential for CO, as it is one of the key sources of CO emissions.

3.3. Spatial changes in air pollution emissions

At the provincial level, the spatial distributions of SO₂, NO_x, CO and PM_{2.5} emission reductions have similar patterns under all scenarios (figure 5). An increase in the flat tax across all provinces does enhance emissions mitigation but has little effect on their spatial pattern, e.g. EPT-1.2 and EPT-12. The results indicate that the provinces with larger economic scales, such as Guangdong, Shandong, Zhejiang and Hebei, have higher emissions reductions, as they have high levels of emissions (as shown in figure S9 in the supplementary information). Beijing and Shanghai have relatively lower emissions and reductions than expected based on their economic level due to their higher fraction of service activities in the economic structure. However, Guangxi, Jiangxi, Yunnan, and Xinjiang also experienced substantial reductions even though their BAU emissions are not very high. These provinces have a relatively high tax rate (see figure S87 in the supplementary information). The tax rate is calculated based on pollutant emissions per economic output, which is called the emissions coefficient. Thus, a high tax rate resulting from a high emissions coefficient causes large relative emissions reductions (listed in table S7). Hainan Province has a high emissions coefficient, but its BAU emissions are low, such that the reduction is less than those in other provinces.

Emissions reductions under the current policy (EPT-current) have a similar spatial distribution to the lowest bound of the EPT range (EPT-1.2), except that Hebei, Shandong, Henan, Sichuan, Hunan and Hebei have greater reductions with higher taxes. Among them, Hebei has the highest reduction as much as 67.4 Gg (4.4%) for SO₂, 68.6 Gg (4.7%) for NO_x, and 211 Gg (2.0%) for CO under EPT-current. The absolute and relative changes are listed in tables S8 and S9 in the supplementary information.

Comparing EPT-current to EPT-12 (the maximum tax level scenario), there will be substantial reduction potentials in provinces with large economic scales, such as Guangdong, Shandong and Zhejiang, and those provinces with high-emissions-intensity industries, such as Xinjiang, Guangxi, Jiangxi and Yunnan (Li 2010, Wang and Yang 2014). There will be

limited reduction potential in Beijing and Tianjin since they already levied the highest tax rate. Air pollution emissions in Beijing could even increase when all provinces levy the highest 12 RMB tax. This indicates a 'pollution leakage' phenomenon similar to 'carbon leakage'.

Apart from the regional reduction, figure 6 shows the provincial SO₂, NO_x, CO and PM_{2.5} reduction potential as a flat tax increased from 2 RMB to 12 RMB. The response of reduction potential for all pollutants is generally linearly related to tax increase. Similarly, provinces with larger economic scales such as Guangdong, Zhejiang, Shandong and Hebei, along with provinces with a higher emissions intensity such as Guangxi, Jiangxi and Xinjiang, have a higher reduction potential. CO is slightly different in that the reduction in Xinjiang Province is significantly higher than that in other provinces, while the reduction in Yunnan Province is relatively low compared to that of other types of pollutants.

3.4. Co-benefits of CO₂ mitigation

Actions to mitigate short-lived air pollutants simultaneously reduce co-emitted CO₂, bringing co-benefits for climate change mitigation. This can partially offset the costs of implementing the EPT policy when a climate mitigation target is implemented. The national level co-benefit of CO₂ reduction is estimated to be 212 Tg (2.1%) under the EPT-current policy, and about 97 Tg (1.0%) and 805 Tg (8%) reductions, respectively, under the EPT-1.2 and EPT-12 policies (figure 7). Both the absolute and relative reductions in CO₂ emissions at the national level are much larger than the reductions in any short-lived air pollutants. This is because the sectors which are largely influenced by the EPT have a larger contribution to CO₂ than other emissions. For instance, the EPT has the largest impact on the electric power sector which contributes 41% of total CO₂ emissions but only 35% (37%) of total SO₂ (NO_x) emissions (figure S10). In contrast, the relative changes in CO₂ differ greatly from those in BC and NH₃ because they are emitted from different sources.

At the sectoral level, the co-benefits of CO₂ mitigation are largely due to the reduction in the electric power sector. The transformation of nonmetal manufacturing and metal manufacturing also contributes to CO₂ reductions, with a 17 Tg and 16 Tg reduction under EPT-current, respectively. There is great potential for reductions in the power electricity sector, non-metal manufacturing sector and metal manufacturing sector when the tax is increased in all regions.

The spatial distribution of CO₂ reduction, shown in figure 8(a), is similar to that of air pollutants. Provinces with large emissions, such as Hebei, Shandong, Henan and Jiangsu, and regions with a high tax rate, such as Guangxi, Sichuan, Hunan and Hubei, show larger CO₂ reductions. The spatial distribution of CO₂

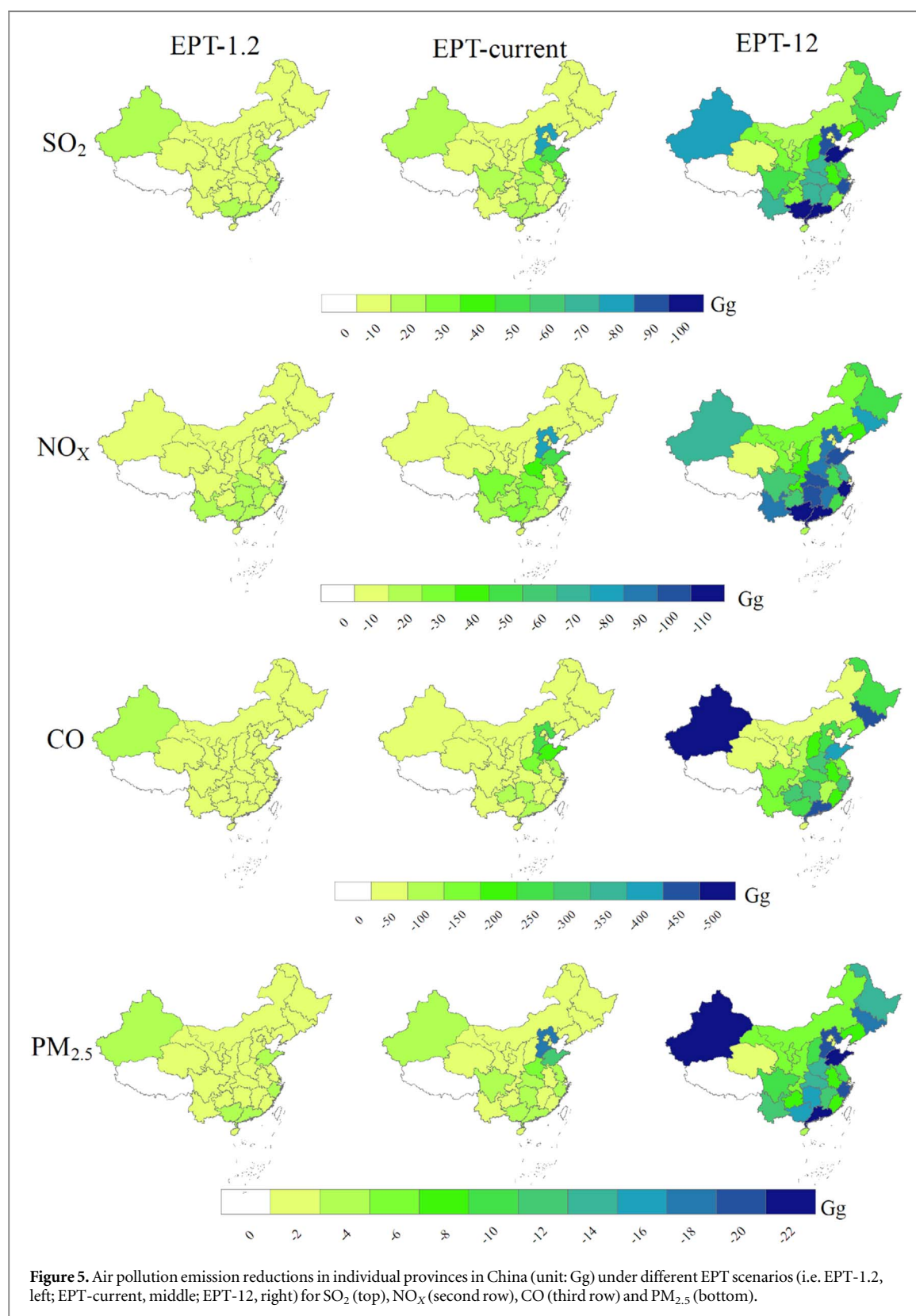
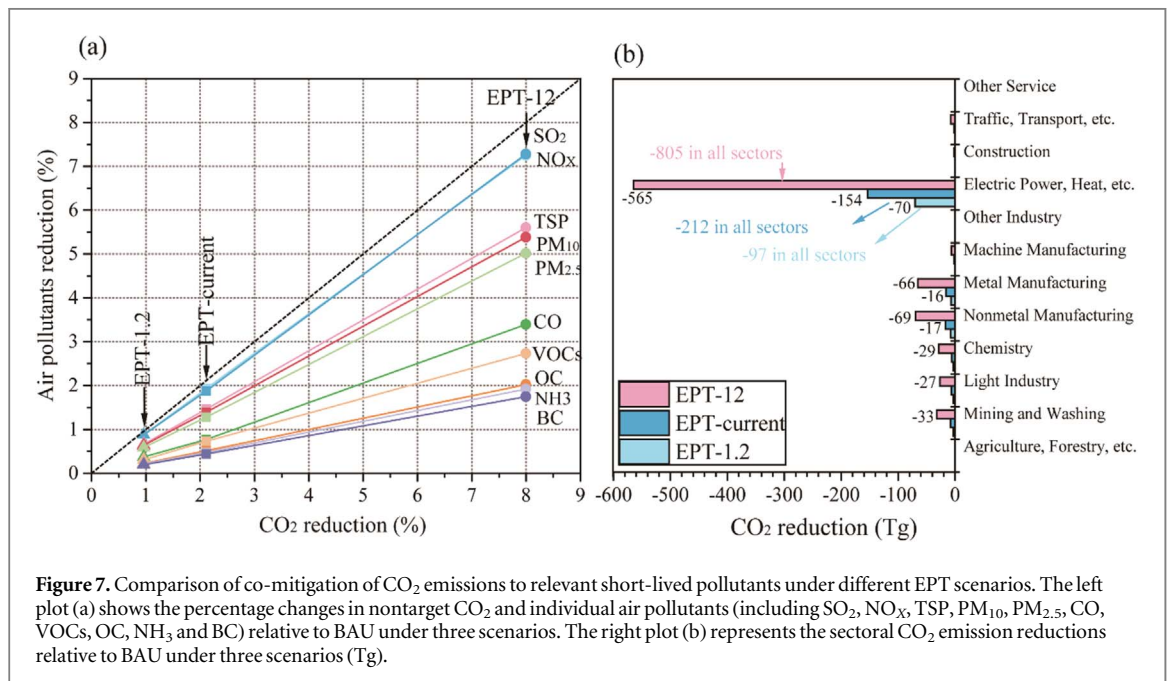
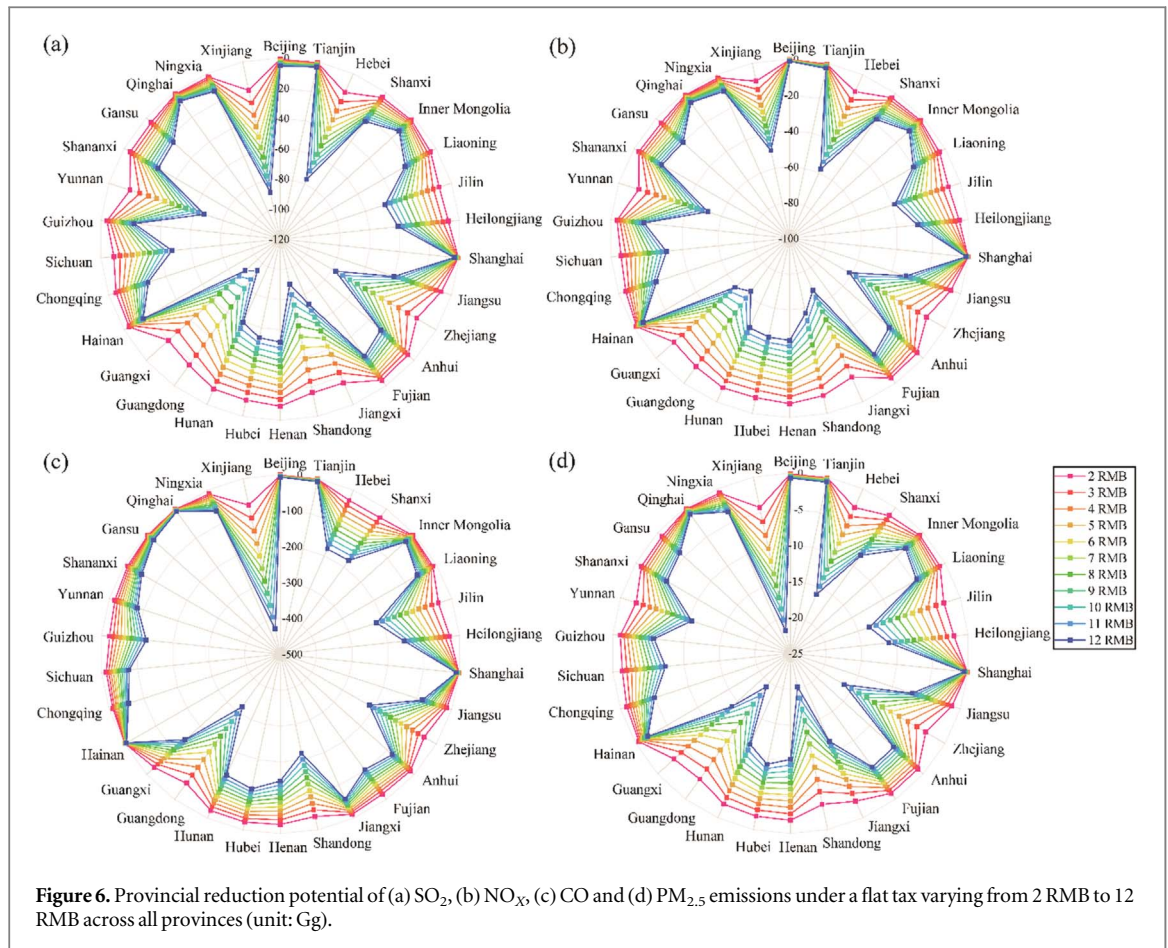


Figure 5. Air pollution emission reductions in individual provinces in China (unit: Gg) under different EPT scenarios (i.e. EPT-1.2, left; EPT-current, middle; EPT-12, right) for SO₂ (top), NO_x (second row), CO (third row) and PM_{2.5} (bottom).

reduction potential (shown in figure 8(b)) is slightly different from those of short-lived pollutants. As the tax increases, provinces with large economic scales, such as Guangdong, Zhejiang, Shandong and Hebei, along with the regions that have a high emission intensity, such as Guangxi and Jiangxi, own higher CO₂ reduction potential.

4. Discussions

This study builds a multiregion multisectoral CGE model to analyze the impacts of the EPT Law, which intends to comprehensively understand the regional and sectoral responses to the implementation of EPT law. Our study suggests several insights for



policy-makers regarding China's EPT system. The results indicate that more stringent policies are necessary to achieve the goal of air pollution abatement in China. The percentage changes in air pollutants are all estimated less than 2% under current EPT policy in this study. However, according to the 13th Five-Year Plan, SO₂ and NO_x must be reduced by 15%

by 2020 compared to 2018. Even if air pollutants decrease 2% each year, the goal cannot be achieved in 2020. Thus, policy-makers should either establish a more progressive EPT policy or combine the EPT with other pollution control measures to reach their mitigation goal. In addition, current EPT policy consider only the first three items of pollutants ranked

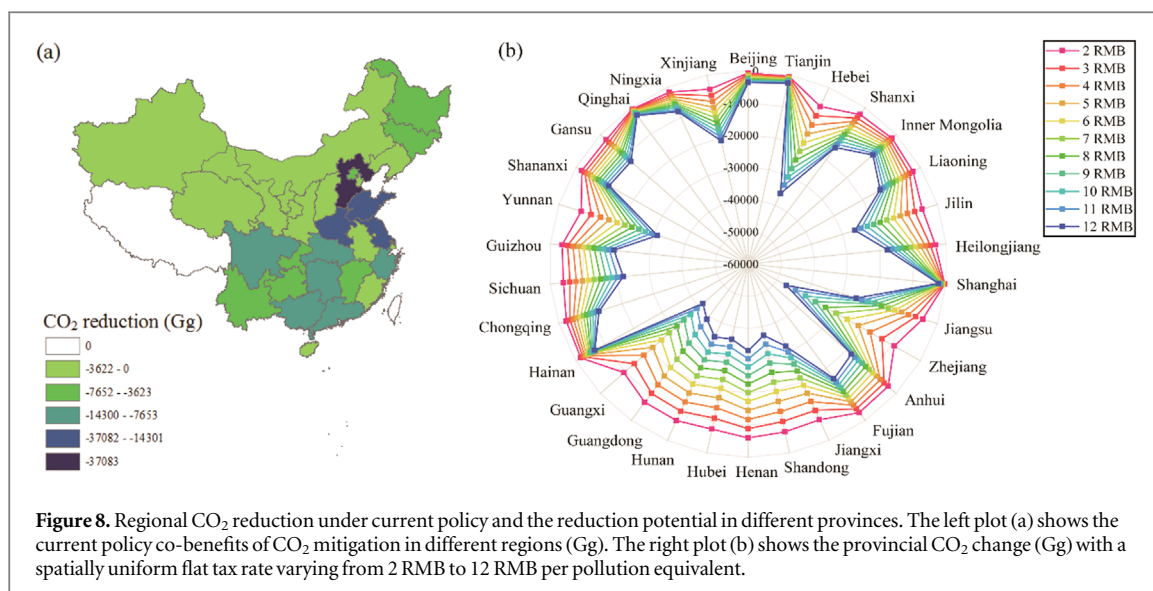


Figure 8. Regional CO₂ reduction under current policy and the reduction potential in different provinces. The left plot (a) shows the current policy co-benefits of CO₂ mitigation in different regions (Gg). The right plot (b) shows the provincial CO₂ change (Gg) with a spatially uniform flat tax rate varying from 2 RMB to 12 RMB per pollution equivalent.

in descending order of pollution equivalents shall be subject to the EPT. According to our analysis (see supplementary figure S12), extending EPT to four items (i.e. SO₂, NO_x, CO and PM) will result in additional emission reductions, which are beneficial to human health. Therefore, the EPT policy in China could consider to cover more items of pollutants in the future.

At sector level, the majority of pollution reduction comes from the electric power sector, the nonmetal manufacturing sector and the metal manufacturing sector, especially for SO₂, NO_x and PM (TSP, PM₁₀ and PM_{2.5}). Policymakers can mitigate the air pollution in a more effective way by prioritizing reductions from sectors with large reduction potential. As one of the largest contributors of emissions reduction, the electric power sector should make efforts to reduce air pollutants and CO₂. Both the nonmetal manufacturing sector and the metal manufacturing sector also have large potential for further air pollution mitigation. At the regional level, provinces with large economy scales (as they have large base emissions), such as Guangdong, Shandong, Zhejiang and Hebei, and those provinces with SO₂-intensive and NO_x-intensive industries, such as Xinjiang, Guangxi, and Jiangxi, could contribute a great deal to air pollution mitigation because these provinces have large air pollutant reduction potential.

We also find that there exist large indirect effects from the implementation of the EPT. Although the EPT law is mainly designed to mitigate SO₂ and NO_x emissions and for sectors without agriculture and transportation, its influence extends to almost all types of air pollutants (including CO₂, PM, BC, OC, VOCs, NH₃ and so on) and to all sectors having energy consumption (e.g. the CO emissions in transportation section) via the sectoral interactions in the dynamic market system. The increases of production prices stemmed from the EPT could influence the whole

market prices via variety of market activities. Therefore, policymakers in China should be aware of both the direct and indirect effects of the EPT law, and extend their pollution control targets to a broader and comprehensive context including both air quality improvement and climate change mitigation.

To illustrate the impacts of EPT-current induced emissions reduction on air quality, we conduct additional model simulations using a well validated chemical transport model (WRF-Chem). The simulations are based on the latest available emission inventories of 2015 (Tao *et al* 2015, 2017). As shown in figure S139 in the supplementary information, the changes of regional concentrations of PM_{2.5} and O₃ are largely proportional to their emissions reduction. The provinces with large emissions reduction, e.g. Zhejiang, Shandong and Jiangsu, usually have larger air quality benefits from the implementation of EPT than those provinces with lower emissions reduction. However, from the absolute reduction of PM_{2.5} and O₃ concentrations, current EPT policy only has a trivial effect on air quality improvement (see more discussions in the supplementary information).

As above mentioned, the current EPT has limited impacts on air pollutants reduction and air quality improvement. A more stringent tax should be imposed on these sectors and regions for more effective reduction, and technology and subsidy support should be provided at the same time to offset their costs. In addition, the EPT has substantial co-benefits to CO₂ mitigation. Therefore, it is necessary to better coordinate pollution control actions in the framework of climate change mitigation. By addressing both problems together, mitigations of both long-lived and short-lived pollutants can be managed more effectively, at less cost, and with greater overall benefits.

5. Uncertainties analysis

This study aims to fill the gap of projection evaluation on China's EPT for air pollution from the national, sectoral and provincial perspectives. However, limitations exist and need to be addressed in future works. The main limitations are embedded in primary economic data, the baseline emission inventories, technological assumptions and socioeconomic assumptions.

As the basic data for the CGE model, the regional SAM tables suffer from uncertainties caused by the inconsistent statistical methods and purposes of the regional input–output tables, the China Finance Yearbook, the China Taxation Yearbook and so on. However, in this model, the interactions among agents (households, government, enterprise and foreign accounts) in the SAM table have little impacts on the simulation and calibration of the model parameters. Although it is impossible to quantify uncertainty due to the complex data sources, we note that our results are generally consistent with those of recent studies (shown in the model validation in supplementary information).

There are also uncertainties associated to regional and sectoral air pollutant emissions. Neglecting residential emissions may underestimate the indirect impact of the tax. When attributing total emissions to sectors, the emissions factors of fossil fuel use in each sector are assumed to be homogeneous. For dynamic simulation from 2007 to 2018, the technology improvement is represented as the energy efficiency improvement and total productivity factor improvement. Though the simulated total emissions match well, this assumption might cause biases in specific regions or sectors. For example, it might overestimate the emissions for factories used air pollution control devices, but underestimate those with no pollution control devices. Additionally, the industrial process emissions divided by productions could overestimate the sectors using raw materials generated and transported from other industries. Since the life cycle analysis, like Kellens *et al* (2012), is beyond the scope of this study, we will address these issues in our follow-up studies.

The overachieving goal of study is to evaluate the short-term aggregated macroeconomic behavior in China's dynamic market system in response to an environmental tax shock. The detailed long-term optimization behavior for individual industries under the EPT including the technology improvement and installation of end-of-pipe emission control devices are not considered in this work and will be addressed in our follow-up studies. The assumptions in the CGE model also bring uncertainties to our results, mainly due to the input parameters. For instance, previous studies showed that the elasticity of substitution between different energy sources and the elasticity of substitution between capital and energy are the

primary parameters influencing energy demand and emissions (Abler *et al* 1999, Wang and Chen 2006). To understand the extent to which our results depend on these parameters, we conducted a sensitivity analysis to compare the emissions changes between these two substitution elasticities. The results in supplementary figure S14 indicate slightly differences, but the main conclusion is robust.

There are additional uncertainties that cannot be fully captured within this framework. These issues will further be addressed step by step in our follow-up studies as more data and measurements become available. We will also combine the bottom-up energy model into the CGE model to address issues of technology improvement and the cost of installation of end-of-pipe equipment. Finally, we will adopt logistics data and other economic data to simulate provincial heterogeneous elasticities.

Acknowledgments

This work was supported by funding from the National Natural Science Foundation of China under award nos. 41571130010, 41671491, 41390240 and 41821005; Newton Advanced Fellowship (NAFR2180104); National Key Research and Development Program of China 2016YFC0206202.

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