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The effects of carbon taxation in China: An analysis based on energy input-output model in hybrid units

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ABSTRACT

This paper evaluates the economy-wide effects of carbon taxation in China. To this end, we build a price model based on an energy input-output table in hybrid units that ensures the consistency of the analysis. The results indicate that carbon taxation has small negative impact on GDP. There are, however, relatively substantial emissions reductions. To explore whether the impacts are *spatially blind*, in the sense of having similar impacts on urban and rural residents, the results of the distributional effects show that the impacts of carbon taxation on different urban household groups reveal small differences and are slightly regressive. Yet for rural residents, carbon taxation may be significantly regressive. In addition, rural residents are found to be affected much more than urban residents. Furthermore, the paper explores a policy intervention to investigate the effects of redistributing the carbon tax paid by households. The main results reveal that reallocating the carbon tax to the groups with low income levels can offset the negative distributional effects significantly. Moreover, the results of Miyazawa-style interrelational income multiplier analysis indicate that the household groups with high income would benefit significantly from the income increases in those with low income levels, but not vice versa.

1. Introduction

It has been argued that one of the main causes of the increase in the average temperature observed since the mid-twentieth century is the greenhouse gas (GHG) emissions generated by human activities (IPCC, 2007). Emissions from production and the supply of energy have contributed considerably to the ever-increasing atmospheric GHG concentrations (IPCC, 2011). Therefore, the worldwide efforts have been made to tackle climate change. The recent development is that, under the United Nations Framework Convention on Climate Change (UNFCCC), the Paris Agreement was reached at the end of 2015, and came into effect in November 2016. Its long-term goal is to limit the global average temperature rise to below 2 °C above pre-industrial levels and pursue efforts to keep the increase to 1.5 °C. For this purpose, countries are encouraged to submit their emission targets in the form of Intended Nationally Determined Contributions (INDCs). Many countries have made plans to reduce GHG in order to help avert the worst impacts of global warming and climate change (Meinshausen et al., 2009; Liu et al., 2017; Rogelj et al., 2016).

As a large developing country, China has been under significant pressure to reduce GHG emissions. According to the World Input–Output Database (WIOD), China accounted for 24% of the global total GHG emissions in 2009 (Genty et al., 2012; Timmer et al., 2015). The Chinese government continues to make great efforts to contribute to the global emissions reduction. In 2009, the Chinese government announced its emission–reduction target noting a goal to reduce CO2 emissions per unit of GDP by 40–45% in 2020 compared to the 2005 level. More recently, when the Paris Agreements took effect, the State Council of China issued the Work Plan for the Control of Green-house Gas Emissions during the 13th Five-Year Period (The State Council of China, 2016). The main goals plan for peak CO2 emissions by around 2030 but strive to achieve it as soon as possible, and to reduce CO2 per unit of GDP by 60–65% over the 2005 level by 2030.

To attain these emission reductions goals, a series of economic instruments will be required; environmental taxes and tradable permits are considered most frequently. In China, although the carbon market based on regional pilot projects has started and the cap-and-trade policy will be extended to more industries and regions, there are a number of challenges and difficulties for constructing an effective national carbon market originating from its complication and uncertainty, such as lagging legislation, uncertain emissions cap, improper quota allocation, imperfect trading mechanism, etc. Compared with tradable permits, a carbon tax is also a measure with potential feasibility for emission mitigation especially considering its advantages, which include its

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simplicity, cost certainty and its clear signaling. In addition, carbon taxation can increase the prices of the fossil fuels, relative to renewable energies. It should be noted that it does not imply that cap-and-trade policy would not increase the prices of the fossil fuels, but a carbon tax would affect the prices in a direct and explicit way. First, this relative price increase may encourage the enterprises that use fossil fuels as inputs, such as thermal power plants, to improve their energy efficiency. Secondly, it may cause the substitution between fossil fuels and renewable energies, and promote a more sustainable energy mix. Therefore, a carbon tax could be an effective policy instrument for CO_2 mitigation, as advocated by the Nobel Laureate Nordhaus (2013). Moreover, a carbon tax is much easier to implement across the country, considering the complete taxation system. Additionally, from January 1st, 2018, China has started levying an environmental tax on various sources of pollution, including air pollutions, which also increases the feasibility of a carbon tax. For carbon taxation, what should be discussed further are its possible negative effects on economic growth and income distribution; these are the issues to be addressed in this paper and some policy interventions are explored.

The paper is organized as follows. The next section reviews the relevant literature on carbon taxes while Section 3 builds the model we use in this paper, and describes how the input-output database in hybrid units is organized and the other databases used in this paper. Section 4 presents the simulation results, and Section 5 investigates the policy options for redistributing the carbon tax income to offset the negative distributional effects of carbon taxation. Finally, conclusions are provided in Section 6.

2. The relevant carbon tax literature

There has been a great deal of discussion centered on the effects of a carbon tax. As a method that can consider both direct and indirect effects, the input-output model is used frequently in such discussions. For example, Cornwell and Creedy (1996) investigate the orders of magnitude of a carbon tax required to reduce carbon dioxide emissions in Australia, such that the Toronto target is met, and further considered the distributional implications of carbon taxation. Labandeira and Labeaga (1999) explore the effects of a tax levied on Spanish energy-related CO2 emissions, employing an input–output demand model. They find a limited short-run reaction to the carbon tax, hampering its environmental success. However, the carbon tax burden is significant with a proportional distribution across households. Grainger and Kolstad (2010) use the 2003 Consumer Expenditure Survey and emissions estimates from an input-output model based on the 1997 US economy to estimate the incidence of a price on carbon induced by a cap-and-trade program or carbon tax in the context of the US. Gemechu et al. (2014) investigate the direct and indirect effects of CO2 taxation on Spanish products, using environmental input-output (EIO) and price models. They find that, in general, the environmental and economic goals cannot both be met at the same time through environmental taxation, unless there is a way in which the public revenues could be used to compensate those who are negatively affected by the tax. da Silva Freitas et al. (2016) investigate the impact of a policy of taxing GHG emissions on the Brazilian economy as a whole and on different household groups based on income levels in 2009, also using an input-output model. Their main results show that, for Brazil, the taxation system was slightly regressive and had a small negative impact on output, but generated significant emissions reductions. Renner (2018) explores the welfare effects of different carbon tax rates on the income distribution by simulating an input-output model coupled with household survey data. The results indicate that higher simulated tax rates show a slight progressivity but welfare losses remain moderate, and by widening the tax base to include natural gas and the other greenhouse gases, welfare losses, regressivity and poverty rise more.

For China, Brenner et al. (2007) find that the introduction of carbon charges on the use of fossil fuels in China would have a progressive impact on income distribution. Sun and Ueta (2011) examine the scenario presented in a report on the necessity and feasibility of imposing carbon taxes in China, and measure the potential distributional impacts of carbon tax. They find that a carbon tax would be regressive in urban areas, but progressive in rural areas. Liang et al. (2013) find that a carbon tax could have a weakly progressive effect within the rural areas, and would widen the income and welfare gap between urban and rural households, and within urban groups. Jiang and Shao (2014) take Shanghai as a case study and estimate the distributional effects of a carbon tax on households across various income groups by using an input–output model and the Suits index, an index that is based on the principle of the concentration curve and is widely adopted to examine the progressivity or regressivity of taxes. Their results indicate that the comprehensive distributional effect of the carbon tax is regressive. Wang et al. (2011) provided a detailed analysis of short-term impacts of carbon tax on sectoral competitiveness, based on the Chinese 2007 input–output table. They found that a high tax level (100yuan/tCO2) may necessitate compensatory measures for certain highly affected industries, and that a low tax rate (10yuan/tCO2) would generate few competitiveness problems for all industries.

All the studies discussed above that are based on input-output models use the monetary input-output framework. However, there are some related works using hybrid methods to estimate the embodied emissions pollutants in final consumption or exports (see in Casler and Blair, 1997; Machado et al., 2001; Lindner and Guan, 2014). According to Bullard and Herendeen (1975), Miller and Blair (1985, 2009) and Casler and Blair (1997), when using an input-output model to analyze energy consumption, there is a high probability that the model in monetary units may not satisfy the energy conservation conditions, and the results will be inconsistent when using this kind of model. However, a model in hybrid units would always ensure consistency with the energy conservation conditions. As Miller and Blair (2009) mentioned, energy conservation conditions "turn out to be equivalent analytically to ensuring the internal consistency of accounting for physical energy flows in the economy." Pollutant emissions estimation has a similar problem (Casler and Blair, 1997). We know that when sectoral carbon emission intensities are required in analysis, they should be estimated by the sectoral energy intensities. Therefore, if the sectoral energy intensities cannot ensure the internal consistency, there will be some errors in the corresponding sectoral carbon intensities. As discussed by Casler and Blair (1997), the problem of the direct coefficient formulation based on input-output model in monetary unit is that it introduces errors in the estimations if the structure of the new, simulated final demand vectors significantly different from the base-year final demand vector. When considering part of the final demand, for example the household consumption vector in this paper, its structure definitely differs significantly compared with the *total* final demand vector. Therefore, when investigating the carbon tax burden of households, the model in hybrid units would be a better option.

Therefore, in this paper, we employ the method based on an energy input-output model in hybrid units to investigate the effects of carbon taxation on the Chinese economy. First, we examine the price impacts of a carbon tax on different sectors, and then estimate the effects on economic growth and carbon emissions. Secondly, the distributional effects on different household groups based on income levels are estimated. Finally, for a complete investigation of the policy, the effects of redistributing the carbon tax generated by households to different household groups with various income levels are analyzed through an integration of a quadratic programming solution with Miyazawa's extended input-output model.

3. Methodology and database

3.1. Methodology

In this section, we mainly describe the methodology of evaluating the effects of carbon taxation on GDP and carbon emissions, and the distributional effects on households. The models used in this paper for the policy agenda to offset the possible negative distributional effects are given in the following part (Section 5), because it would be much clearer to put it in the context of the empirical results of the distributional effects of a carbon tax.

3.1.1. The energy input-output model in hybrid units

According to Miller and Blair (2009), the energy input-output model in hybrid units can be expressed by:

$$A^*X^* + f^* = X^* \tag{1}$$

where X^* is the vector of output in hybrid unit, and $X^* = [x_i^*] = \begin{cases} x_i & \text{nonenergy} \\ g_k & \text{energy} \end{cases}$, x_i is the output of non-energy sector i with monetary unit (for example, RMB yuan), and g_k is the output of energy sector k in physical units (for example, tons of standard coal). f^* denotes the vector of final demand, also in hybrid unit, and $f^* = [f_i^*] = \begin{cases} f_i & \text{nonenergy} \\ q_k & \text{energy} \end{cases}$, where f_i is the final demand of non-energy sector i in monetary unit, and q_k is the final demand of energy sector k in physical unit. A^* is the matrix of direct input coefficients, and $A^* = Z^*(\hat{X}^*)^{-1}$. $Z^* = [z_{ij}^*] = \begin{cases} z_{ij} & \text{nonenergy} \\ e_{kj} & \text{energy} \end{cases}$, where similarly, z_{ij} is the inter industrial transaction (in monetary unit) from non-energy sector i to any sector j, and e_{kj} is the transaction (in physical unit) from energy sector k to any sector j. Therefore, a_{ij}^* indicates quantity of the input i required (monetary unit for nonenergy input, and physical unit for energy input) to produce per unit (also monetary unit for nonenergy input, and physical unit for energy input) of output in sector j. Suppose the first m sectors are for energy products, and the last n-m sectors for non-energy industries, we can see that the units of A^* will be $\begin{bmatrix} \text{physical/physical} & \text{physical/monetary} \\ \text{monetary/physical} & \text{monetary/monetary} \end{bmatrix}$. What should be emphasized is that the first m rows of A^* present the direct energy intensities, with each row corresponded to a specific energy. Further details of the hybrid methodology can be found in Casler and Wilbur (1984).

Solving for X^* by Eq. (1), we have:

$$X^* = (I - A^*)^{-1}f^* \tag{2}$$

Let $L^* = (I{-}A^*)^{-1}$, then L^* represents Leontief inverse matrix, or total requirement matrix. Clearly, L^* has the same units as A^*. Also, the first m rows of L^* present the total energy intensities, and l_{kj}^* indicates the amount of the k th energy required (in physical unit) in order to provide one unit of final demand of sector j (in monetary units for nonenergy final demand, and physical units for energy final demand).

3.1.2. The Leontief price model based on the energy IO model in hybrid units

Using Eqs. (1) and (2), we obtain the Leontief price model, which assumes that variations in production costs are converted into price increases. Thus, price (p) is equal to the sum of input cost to the value added (v) components.

$$p' = p'A^* + v \tag{3}$$

where v is the row vector of value added rates, with v_i indicating the primary input cost (in monetary unit) in producing one unit of output in sector i (monetary units for non-energy output, and physical units for energy output). Then, the price vector of the hybrid energy IO model is given by:

$$p' = vL^* \tag{4}$$

Eq. (4) is similar with the price model based on the monetary input-output framework. However, they are significant differences. First, they have very different implications; for example, in the monetary input-output price model, an element of p shows the price index of a certain sector (da Silva Freitas et al., 2016). Comparatively, in the hybrid input-output price model as presented in Eq. (4), an element in p for the energy sector definitely shows the price of a certain energy commodity, for example, how much RMB yuan per tec, and, for non-energy sector, a certain element in p gives the price index of that sector according to its monetary output. Secondly, for a price model based on the monetary input-output framework, it can be proven that $p' = vL = i'$, where $i' = (1 \ \cdots \ 1)$ (Miller and Blair, 2009). Yet, for a price model based on the hybrid IO framework, $p' = vL^* \neq i'$, even for non-energy sectors.

The carbon taxation will generate an extra cost on each sector, including both energy and non-energy sectors. In order to introduce a carbon tax, let δ be the matrix of direct energy intensity in the hybrid model, which refers to the first m rows of the matrix of direct input coefficients, A^*. Let $\theta = (\theta_1 \ \cdots \ \theta_m)'$ be the vector of emission factors of the m energies, and φ be the carbon tax rate per ton of CO2 equivalent, for example, 50 yuan per ton of CO_2, we have

$$\tau = \varphi\theta\delta \tag{5}$$

where τ denotes the vector of carbon tax intensity, and τ_i represents the quantity of carbon tax paid to produce one unit of output in sector i. Then, the price model will become:

$$\bar{p}' = \bar{p}'A^* + v + \tau \tag{6}$$

The price after introducing a carbon tax will be:

$$\bar{p}' = (v + \tau)L^* \tag{7}$$

yielding the price index after introducing a carbon tax:

$$P = \bar{p}\,(\hat{p})^{-1} \tag{8}$$

3.1.3. The effects on distribution, emissions and GDP

Assuming that households maximize their utilities using a Leontief function, and their income and savings are unchanged, none of each representative household could afford the same basket of goods. Therefore, using price changes derived from the model, it is possible to calculate the income variation necessary to compensate households for the loss of welfare. Formally, household welfare change for group k is the following:

$$\Delta w_k = \sum_i c_{ik}P_i - \sum_i c_{ik} \tag{9}$$

where c_{ik} is the expenditure on the final consumption for sector i by the kth group, and P_i is the price index of sector i induced by Eq. (8). It should be noted that given the fossil fuel consumed by households, we can take the carbon tax directly paid by households for final energy consumption into consideration as well.

Following Gemechu et al. (2014) and Llop (2008), suppose that before and after tax, the monetary values of the sectoral total input are constant, which means the budget restrictions are constant, and there is no extra capital source for sectoral productions. Therefore, the monetary values of sectoral output are held constant, before and after tax, then the sectoral output becomes:

$$x_j^{*1} = \frac{p_j}{\bar{p}_j}x_j^{*0} \tag{10}$$

where superscript "0" and "1" denote the variables before and after tax respectively.

The total emissions after tax can be calculated as

$$e^1 = \hat{\theta}\delta X^{*1} \tag{11}$$

We can also compute the total value added after tax by

$$V^1 = vX^{*1} \tag{12}$$

The assumption used here is the constant sectoral total input in monetary terms before and after tax. However, considering the potential uncertainties, for example, the possible adjustments of product mix by the producers originated from the price changes, the monetary values of the sectoral output (or the budget restrictions) may be different before and after tax. Therefore, it is necessary to discuss the consequence of the uncertainties. Gemechu et al. (2014) analyze it by considering all the sector output changing at the same rate (10% increase or decrease), taking the assumption as benchmark. In this paper, we discuss the problem in two scenarios, sector output changing at a constant rate, and at different rates.

It should be noted that it would not affect the results of household welfare change addressed in Eq. (9), but would have influences on the results of the carbon emissions and the total value added after tax. We discuss the impacts in the two scenarios as follows.

First, if all the monetary sectoral outputs increase or decrease at the same rate, such as a 10% increase, the total emissions and the total value added would be affected in the same way.

For example, if monetary sectoral outputs increase at 10%, then:

$$\tilde{x}_j^{*1} = 1.1 \times \frac{p_j}{\bar{p}_j} x_j^{*0} = 1.1 x_j^{*1}$$

And we have:

$$\tilde{e}^1 = \hat{\theta}\delta\tilde{X}^{*1} = 1.1\hat{\theta}\delta X^{*1} = 1.1e^1$$
$$\tilde{V}^1 = v\tilde{X}^{*1} = 1.1vX^{*1} = 1.1V^1$$

It shows that the total carbon emissions and GDP would increase at the same percentage, and their relative differences would not be changed, for $\frac{1.1e^1}{1.1V^1} = \frac{e^1}{V^1}$. It means that the results would not be changed, since what we mainly focus on is the comparative change of emissions with regard to GDP change.

Secondly, if the monetary sectoral outputs change at different rates, (e.g., one at 10% and one at 5%), the total emissions and total value added would be affected differently, and their relative relationship would be changed. For a simplified investigation, suppose there are two sectors, and the monetary output of sector 1 increases 10%, that of sector 2 increases 5%, then we have:

$$\tilde{x}_1^{*1} = 1.1 \times \frac{p_j}{\bar{p}_j} x_1^{*0} = 1.1 x_1^{*1}$$

$$\tilde{x}_2^{*1} = 1.05 \times \frac{p_j}{\bar{p}_j} x_1^{*0} = 1.05 x_1^{*1}$$

And

$$\tilde{e}_1^1 = 1.1e_1^1, \quad \tilde{e}_2^1 = 1.05e_2^1$$
$$\tilde{V}_1^1 = 1.1V_1^1, \quad \tilde{V}_2^1 = 1.05V_2^1$$

Now the relative difference between the total emissions and the total value added is unequal to the benchmark:

$$\frac{\tilde{e}_1^1 + \tilde{e}_2^1}{\tilde{V}_1^1 + \tilde{V}_2^1} = \frac{1.1e_1^1 + 1.05e_2^1}{1.1V_1^1 + 1.05V_2^1} \neq \frac{e_1^1 + e_2^1}{V_1^1 + V_2^1}$$

Although the relative difference is not to the same as the benchmark, we could ignore the impact. The first reason is that the weights of sectoral emissions and sectoral outputs after tax are the same, and the gap between the scenario and the benchmark would not be large, shown as follows.

$$\frac{1.1e_1^1 + 1.05e_2^1}{1.1V_1^1 + 1.05V_2^1} - \frac{e_1^1 + e_2^1}{V_1^1 + V_2^1}$$
$$= \frac{(1.1e_1^1 + 1.05e_2^1)(V_1^1 + V_2^1) - (e_1^1 + e_2^1)(1.1V_1^1 + 1.05V_2^1)}{(1.1V_1^1 + 1.05V_2^1)(V_1^1 + V_2^1)}$$
$$= \frac{0.05(e_1^1 V_2^1 - e_2^1 V_1^1)}{(1.1V_1^1 + 1.05V_2^1)(V_1^1 + V_2^1)}$$

Generally, the absolute value of the numerator would be much smaller than the denominator, and the impact of different monetary sectoral outputs changes would not be large.

Table 1
The industrial carbon emissions in China 10,000 tons.

Industry	CO_2 emissions
Mining and washing of coal	108,200.70
Extraction of petroleum	1726.76
Extraction of natural gas	832.68
coke-making	2902.22
gasoline	4095.78
kerosene	972.61
diesel oil	7710.90
Fuel oil	854.69
Electric power and heat power	273,170.51
Agriculture	4049.14
Ferrous metal mineral mining	2637.09
Nonferrous metal mineral mining	1716.97
Non-metal mineral mining	2258.55
Building materials and other non-metal mineral products	838.97
Food products	3835.36
Liquor, beverages, and refined teas	1785.38
tobacco processing products	260.26
Textile	3605.11
Textile, wearing apparel, and accessories	675.48
Manufacture of leather, fur, feather and related products	754.80
Processing of timber, manufacture of wood, bamboo, rattan, palm and straw products	1675.39
Manufacture of Furniture	146.81
Manufacture of paper and paper products	7527.03
Printing, reproduction of recording media	295.84
Manufacture of articles for culture, education and sport activity	643.21
Manufacture of raw chemical materials and chemical products	95,059.99
Manufacture of medicines	1149.02
Manufacture of chemical fibers	5037.37
Manufacture of rubber	1701.38
Manufacture and plastics	3262.80
Manufacture of non-metallic mineral products	79,627.02
Smelting and pressing of ferrous metals	170,041.25
Smelting and pressing of non-ferrous metals	14,626.42
Manufacture of metal products	5355.93
Manufacture of general purpose machinery	2923.97
Manufacture of special	2760.15
Manufacture of special purpose machinery	1004.88
Manufacture of railway, shipping, aerospace and other transport equipment	669.50
Manufacture of electrical machinery and equipment	1106.83
Manufacture of communication equipment, computers and other electronic equipment	371.11
Manufacture of measuring instruments and machinery for cultural activity and office work	49.83
Manufacture of artwork and other manufacturing	2649.93
Recycling and disposal of waste	462.17
Repair of metal products, machinery and equipment	148.07
Production and distribution of gas	401.91
Production and distribution of water	71.75
Construction	8000.40
Transport, storage and post	26,011.25
Wholesale, retail trade and hotel, restaurants	882.13
Others	15,816.65
Household	25,491.85
Total	897,855.74

Note: the results are computed by the authors.

The second reason is that it is hard to take all possible uncertainties into consideration, if the monetary sectoral output changes at different percentages. For simplification, we use the benchmark assumption in our analysis, that is, the monetary sectoral outputs are constant before and after tax.

3.2. Database

3.2.1. The energy input-output table in hybrid units

We compile the energy input-output table in hybrid units based on the 2012 Chinese input-output table published by the National Bureau of Statistics (NBS). Considering the data availability, we disaggregate the energy industries into 9 sectors, and aggregate some non-energy sectors, yielding 50 sectors as shown in Table 1. The main steps of compiling the table are as follows.

3.2.1.1. Step 1. Sector aggregation based on 2012 Chinese input-output table with 139 sectors, according to the data about industry-specific energy consumption published by NBS. The sector classification in the data of industry-specific energy consumption is more aggregated than that of input-output table. Therefore, we aggregate the 139 sectors into 46 sectors.

3.2.1.2. Step 2. Disaggregation of energy sectors. In order to account for energy sectors in a more detailed level, we disaggregate the 5 energy sectors to 9 sectors, when compiling the energy input-output table. We used the industry-based technology assumption in the disaggregation process implying that all the commodities produced in a certain industry have the same technology. For the energy sectors that were decomposed, including oil and gas and oil refining products, this assumption is reasonable because the products are extracted or manufactured using similar technological processes.

3.2.1.3. Step 3. Adjustment of the industry-specific energy consumption in physical units. The data adopted were obtained from the China Energy Statistical Yearbook published by National Bureau of Statistics (NBS). The energy classification is consistent with the energy sectors in the input-output table completed in step 2. It should be noted that, Chinese input-output table is commodity-by-commodity, while the data of the industry-specific energy consumption is classified by industry. Therefore, we do some adjustment for the data by using the structure information provided by the monetary transactions of the energy sectors in the input-output table.

The non-energy sector classification is still not consistent with the input-output table; thus, some further adjustment for the data was necessary essentially resulting in the aggregation of some sectors.

3.2.1.4. Step 4. Using the adjusted industrial energy consumption data we obtained from step 3 as the energy transaction matrix in the input-output table, we finally complete the energy input-output table in hybrid units.

3.2.2. The estimation of industrial carbon emissions

The industrial carbon emissions are estimated from the industrial energy transactions in the 2012 energy input-output table in hybrid units by using the method and related parameters proposed by IPCC (2007). The results are shown in Table 1.

In 2012, the amount of estimated total CO_2 emissions in China is 8979 million tons. Among all the industries, the emission from Electric Power and Heat Power contributes 2732 million tons, accounting for 30% of the total emissions. The industry with the second highest emission is Smelting and Pressing of Ferrous Metals, 1700 million tons, approximately 19% of the total emissions. Mining and Washing of Coal also has high emissions, 1082 million tons, 12% of the total emissions while Manufacture of Raw Chemical Materials and Chemical Products and Manufacture of Non-Metallic Mineral Products also contribute significantly to total emissions.

3.2.3. The expenditure data of different household groups

In order to analyze the distributional effects of carbon taxation on different household groups based on income levels, data are required for household income and expenditure for detailed categories for various income deciles. Such data are provided by the Household Sample Survey conducted and published by National Bureau of Statistics (NBS). In order to be consistent with the 2012 input-output table, the year of the survey data used in this paper is 2012. The data for urban households are from "*China City Statistical Yearbook 2012*" (National Bureau of Statistics of China, 2013) and "*China Statistical Yearbook 2016*" (National Bureau of Statistics of China, 2017), and the data for rural households are from "*China Statistical Yearbook 2016*" (National Bureau of Statistics of China, 2017). In the survey, there are 66,000 households selected in urban area, and 74,000 households selected in the rural area.

For each group, there are 8 main consumption items, including: (1) Food, tobacco, and liquor, (2) Clothing, (3) Residence, (4) Household facilities, articles and services, (5) Transport and communications, (6) Education, cultural and recreation, (7) Health care and medical services, (8) Miscellaneous goods and services. For urban groups, more detailed sub-items are also provided in each main item. Yet for rural groups, there is no detailed information provided for different household groups.

The definitions of the urban and rural household groups are also from the publication of NBS. For urban households groups, as explained by NBS, "All households in the sample are grouped, by per capita disposable income of the household, into groups of lowest income, low income, lower middle income, middle income, upper middle income, high income and highest income, each group consisting of 10%, 10%, 20%, 20%, 20%, 10% and 10% of all households respectively. The lowest 5% of households are also referred to as poor households" (*China Statistical Yearbook 2016*). For rural households, the households in the sample are grouped by per capita annual net income into Low Income Households, Lower Middle Income Households, Middle Income Households, Upper Middle Income Households, and High Income Households, each group consisting of 20% of all households (*China Statistical Year book 2016*).

We need to merge the household expenditure data with the input-output table for the purpose of simulations. In the second quadrant of Chinese input-output table, the household consumptions consist of urban household consumption and rural household consumption. Based on the information of urban household expenditure data and rural household expenditure data, using the RAS method, the urban household consumption in input-output table is decomposed into 8 groups (8 columns), and the rural household consumption is decomposed into 5 groups (5 columns). The steps of the decomposition are as follows.

3.2.3.1. Step 1. Estimate the total consumption of each urban and rural group, based on the information of the expenditure per capita, the percentage of each group, and the population, using the subtotal of urban household consumptions and rural household consumptions as controls respectively. It is to compute the subtotals of the corresponding decomposed columns (or the corresponding groups), which are used as column controls in the decomposition process. The row controllers for urban and rural households are already provided in the input-output table(the sectoral final demand of urban household and rural household consumption).

3.2.3.2. Step 2. Transfer the consumption items of each household group into the sectors of the input-output table, according to the given information of the expenditures of urban and rural households on the consumption items. In this step, we obtain the estimation of sector-specified per capita consumption of each household group, for urban and rural residents.[1]

3.2.3.3. Step 3. Compute the sector-specified expenditure structure of each household group based on the estimated sector-specified per capita consumption and then, using the estimated total consumption of each group obtained in step 1, compute the initial values of the consumption vectors of urban and rural household groups.

[1] The preferred procedure of assigning consumption to the input-output table sectors does not follow the more careful allocations suggested in Kim et al. (2015) and Amores (2018) since, for example, wholesale and retail trade margins and transportations margins were not available.

Table 2
The effects of carbon tax on emissions and GDP.

Tax rate (yuan/ton)	The decrease of carbon emissions(%)	The decrease of GDP(%)	The elasticity[a]
10	−0.6722	−0.1834	3.6650
15	−1.0042	−0.2746	3.6573
20	−1.3334	−0.3653	3.6496
30	−1.9837	−0.5458	3.6345
40	−2.6235	−0.7248	3.6195
50	−3.2530	−0.9024	3.6048
60	−3.8726	−1.0786	3.5903
70	−4.4825	−1.2535	3.5761
80	−5.0830	−1.4270	3.5620
90	−5.6743	−1.5992	3.5481
100	−6.2566	−1.7702	3.5344
200	−11.6326	−3.4139	3.4075

[a] The elasticity is calculated by dividing the decrease of carbon emissions with the decrease of GDP.

3.2.3.4. Step 4. Apply the RAS procedure to adjust and balance the urban and rural consumption vectors respectively, based on the controls obtained in step 1 (columns) and those (rows) provided in the input-output table.

Finally, the urban household and rural household consumption in the input-output table are decomposed into 8 groups and 5 groups respectively.

4. The simulations results of a carbon tax: differential impacts on urban and rural households

4.1. The effects of carbon tax on CO2 emissions and GDP

The simulations are conducted for various carbon tax rates, from 10 yuan to 200 yuan per ton CO_2. The results are shown in Tables 2–4. In Table 2, the effects of carbon tax on carbon emissions and GDP are presented.

Table 4
The distributional effects of carbon tax on different rural household groups.

Tax rate (yuan/ton)	Rural low income households	Rural lower middle income households	Rural middle income households	Rural upper middle income households	Rural high income households
Expenditure growth rate after tax(%)					
10	0.2760	0.2795	0.2890	0.3018	0.2974
15	0.4140	0.4192	0.4335	0.4519	0.4467
20	0.5520	0.5590	0.5780	0.6021	0.5959
30	0.8280	0.8385	0.8669	0.9024	0.8943
40	1.1040	1.1180	1.1559	1.2028	1.1927
50	1.3800	1.3975	1.4449	1.5031	1.4911
60	1.6560	1.6769	1.7339	1.8034	1.7896
70	1.9320	1.9564	2.0229	2.1038	2.0880
80	2.2080	2.2359	2.3118	2.4041	2.3864
90	2.4840	2.5154	2.6008	2.7044	2.6848
100	2.7600	2.7949	2.8898	3.0048	2.9832
200	5.5199	5.5898	5.7796	6.0081	5.9675
Proportion of carbon tax to income(%)					
10	0.4459	0.2595	0.2229	0.2060	0.1608
15	0.6689	0.3893	0.3343	0.3085	0.2414
20	0.8919	0.5191	0.4457	0.4111	0.3221
30	1.3378	0.7786	0.6686	0.6161	0.4834
40	1.7837	1.0382	0.8915	0.8212	0.6447
50	2.2296	1.2977	1.1144	1.0262	0.8060
60	2.6756	1.5572	1.3372	1.2312	0.9673
70	3.1215	1.8168	1.5601	1.4363	1.1287
80	3.5674	2.0763	1.7830	1.6413	1.2900
90	4.0133	2.3359	2.0059	1.8464	1.4513
100	4.4593	2.5954	2.2287	2.0514	1.6126
200	8.9186	5.1908	4.4575	4.1018	3.2257

The results of the effects of a carbon tax on emissions and GDP indicate that when there is a carbon tax, both the carbon emissions and GDP decrease. However, the degree of decrease in emissions is always higher than the decrease of GDP. Most importantly, as the tax rate goes up, the mitigation rate of carbon emission decreases much faster than the decreasing rate of GDP, an outcome that is presented in Fig. 1. The

Table 3
The distributional effects of carbon tax on different urban household groups.

Tax rate (yuan/ton)	First five percent group	First decile group	Second decile group	Second quintile group	Third quintile group	Fourth quintile group	Ninth decile group	Tenth decile group
Expenditure growth rate after tax (%)								
10	0.1412	0.1373	0.1275	0.1231	0.1206	0.1180	0.1157	0.1145
15	0.2119	0.2059	0.1913	0.1846	0.1808	0.1771	0.1735	0.1717
20	0.2825	0.2745	0.2550	0.2461	0.2411	0.2361	0.2314	0.2289
30	0.4237	0.4118	0.3826	0.3692	0.3617	0.3541	0.3471	0.3434
40	0.5650	0.5491	0.5101	0.4922	0.4822	0.4722	0.4627	0.4579
50	0.7062	0.6864	0.6376	0.6153	0.6028	0.5902	0.5784	0.5724
60	0.8475	0.8236	0.7651	0.7383	0.7234	0.7083	0.6941	0.6868
70	0.9887	0.9609	0.8927	0.8614	0.8439	0.8263	0.8098	0.8013
80	1.1300	1.0982	1.0202	0.9844	0.9645	0.9444	0.9255	0.9158
90	1.2712	1.2354	1.1477	1.1075	1.0851	1.0624	1.0412	1.0302
100	1.4125	1.3727	1.2752	1.2305	1.2056	1.1804	1.1568	1.1447
200	2.8250	2.7454	2.5505	2.4610	2.4112	2.3609	2.3137	2.2894
Proportion of carbon tax to income (%)								
10	0.1433	0.1339	0.1100	0.1017	0.0963	0.0902	0.0879	0.0802
15	0.2150	0.2009	0.1650	0.1525	0.1445	0.1353	0.1319	0.1203
20	0.2867	0.2679	0.2199	0.2033	0.1926	0.1804	0.1758	0.1604
30	0.4300	0.4018	0.3299	0.3050	0.2889	0.2706	0.2637	0.2407
40	0.5733	0.5358	0.4399	0.4067	0.3853	0.3608	0.3516	0.3209
50	0.7167	0.6697	0.5498	0.5083	0.4816	0.4510	0.4395	0.4011
60	0.8600	0.8037	0.6598	0.6100	0.5779	0.5412	0.5274	0.4813
70	1.0034	0.9376	0.7698	0.7116	0.6742	0.6314	0.6153	0.5615
80	1.1467	1.0716	0.8797	0.8133	0.7705	0.7216	0.7032	0.6418
90	1.2900	1.2055	0.9897	0.9150	0.8668	0.8118	0.7911	0.7220
100	1.4334	1.3395	1.0997	1.0166	0.9631	0.9020	0.8790	0.8022
200	2.8667	2.6790	2.1994	2.0333	1.9263	1.8040	1.7580	1.6044

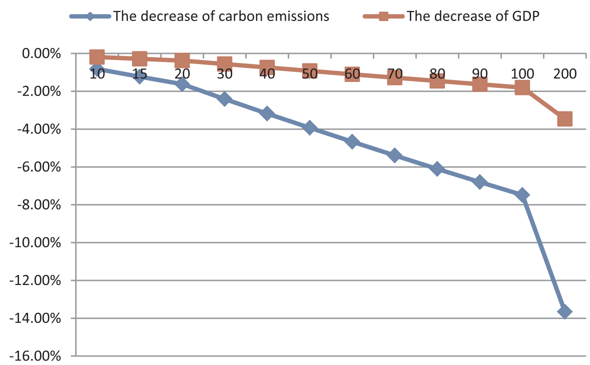

Fig. 1. The effects of CO_2 tax on carbon emissions and GDP.

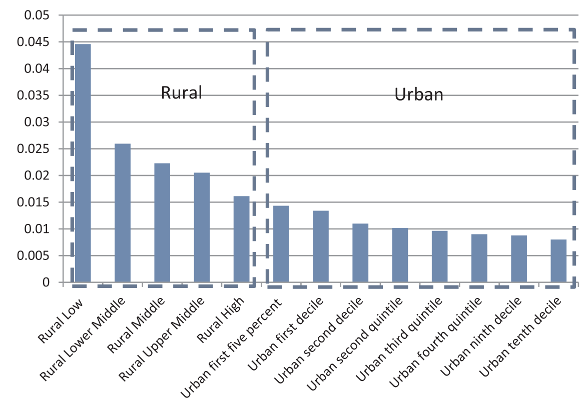

Fig. 2. The distributional effects of carbon tax on different household groups.

elasticity of emissions is large; for example, if the tax rate is 100 yuan/ton, the elasticity is 3.53, indicating that the amount of CO_2 emissions will be reduced 3.53% while GDP decreases 1%. If the tax rate is 200 yuan/ton, the elasticity is 3.41, which is also large. The results reveal that the taxation policy is capable of achieving its main goal of mitigating carbon emissions, with a relatively small negative effect on economic growth.

The impacts of the tax on CO_2 emissions on different industries are different. Among the fifty sectors, the industries with large volumes of emissions have relatively significant reductions. The effect on Electric Power and Heat Power is the most significant; for example, when the tax rate is 100 yuan/ton, the emissions of the sector will decrease 10%, and when the tax rate is 200 yuan/ton, the emission reduction percentage of the sector will be 18%. The reduction of emissions in Mining and Washing of Coal is large as well, a decrease of 6.6% for a tax rate of 100 yuan/ton, and 12.5% for a tax rate of 200 yuan/ton. For the sector of Smelting and Pressing of Ferrous Metals, when the tax rate is 100 yuan/ton or 200 yuan/ton, a 5.6% or 10.5% decrease in its carbon emissions has been estimated respectively. For Manufacture of Non-Metallic Mineral Products, the reductions are 4.4% for the tax rate of 100 yuan/ton and 8.5% for the tax rate of 200 yuan/ton. For Manufacture of Raw Chemical Materials and Chemical Products, the reduction percentage will be4.2% and 8.1% respectively.

4.2. The distributional effects of carbon tax on different household groups

Although the results reveal that the carbon tax is a promising policy instrument for the purpose of reducing carbon emissions, it also has some negative distributional effects on different household groups based on income levels. We analyze the distributional effects on urban and rural household separately, according to the data available (see Tables 3 and 4). The direct and indirect carbon taxes paid by households are both considered. Here carbon tax directly paid by households refers to the carbon tax generated by the energy consumed by households, and indirect carbon tax refers to the carbon tax embodied in the energy and non-energy products consumed by households, originating from the production chains of the products.

The results in Tables 3 and 4 show that, for all household groups whether for urban or for rural households, as the tax rate increases, both the expenditure growth rate after tax and the proportion of carbon tax to income increases in a linear form. If the tax rate doubles, the negative distributional effects are also doubled.

For urban household groups, the results reveal that, no matter the tax rate, the effects of a carbon tax on different household groups based on income level are slightly regressive. The group with higher income has the lower expenditure growth rate after tax, and a lower percentage of tax expenditure to the corresponding income. For example, when the tax rate is 100 yuan/ton, for the household with the lowest income, the proportion of carbon tax to the income is 1.43%, while the ratio is 0.80% for the household with the highest income. (The effects are both doubled when the tax rate is 200 yuan/tons.) Thus, the effect on the poorest households is 1.8 times of that on the richest ones. Although the degree of regressivity is slight, it cannot be ignored and requires consideration of some compensation policy to offset the negative effects.

Unlike the situation of urban residents, the results for rural household groups indicate that, for different groups with different income levels, their expenditure growth rates after tax remain relatively unchanged. There is a small increase as the income goes up, and the highest expenditure growth rate shows up in the group with upper middle income.

However, most importantly, the results reveal that, according to the proportion of carbon tax to income, the effects of the carbon tax on rural residents are significantly regressive, compared with those on urban residents (Fig. 2 provides an example for the case when the tax rate equals 100 yuan/ton). For example, when the tax rate is 100 yuan/ton, for rural low-income households, the proportion of carbon tax to income is 4.46%, while for rural high-income households, the proportion is 1.61%. (The percentages are doubled when the tax rate is 200 yuan/ton.) The former is 2.76 times of the latter, which is a large gap. It means that the carbon tax may aggravate income inequality in rural China.

In addition, Fig. 2 also shows that generally, the rural households are negatively affected more than the urban households. For example, if the tax rate is 100 yuan/ton, for the first five percentile urban groups, the proportion of carbon tax to income is 1.43%, which is smaller than that for the rural High Income Households. It indicates that the carbon tax may increase the rural-urban inequality as well.

The main reason for the differences in the distributional effects on different urban and rural household groups is not the direct emissions, but the indirect emissions. The various effects originate from the price change in the sectors, the consumption structure and the consumption propensity.

In all the sectors, the price of Electric Power and Heat Power increases the most; the sector with the second greatest price increase is Mining and Washing of Coal. For example, when the tax rate is 100 yuan/ton, the price index of the sector of Electric Power and Heat Power is 1.11, which is the largest among all the sectors, and the price index of the sector of Coal products is 1.07. The two sectors affect primarily the household consumption item “Residence”.

For urban households, the consumption structures show that the poorer the households group is, the higher the share of expenditure on Electric Power and Heat Power. For the poorest urban group, the first five percent group, the ratio of the expenditure on Electric Power and Heat Power is 2.6%, while for the urban group with the highest income level, the tenth decile group, the share of the expenditure on Electric Power and Heat Power is 0.8%. Therefore, the poor groups are affected more through the emission of the sector of Electric Power and Heat Power than the richer groups. This item accounts for 20% of the total carbon tax paid by the poorest urban group, but only 9% of the tax paid by the richest urban group. Besides the sector of Electric Power and Heat Power, the sector of Food products and the sector of other services are also the main sources of the effects on urban poor groups, since purchases from these sectors accounts for a high proportions of their total consumption. For the rich urban groups, the main sources of the effects are the sectors of other services, Manufacture of Special Purpose Machinery, and Electric Power and Heat Power. Another important factor of the regressivity of carbon tax in urban area is the different consumption propensities of the household groups. The consumption propensity decreases as the income of the households increases; for example, the average consumption propensity of the lowest income group is 0.79, while that of the group with highest income level is only 0.54.

For rural households, the main reason for the regressivity is the difference of consumption propensities of the household groups. The sectors of Electric Power and Heat Power, and Mining and Washing of Coal are the two main sources of carbon tax for rural households, and account for over 40% of the total tax. Meanwhile, the consumption structures show that the ratio of expenditure on the two sectors goes up as the income increases. Therefore, with the increase of income level, the gap in the magnitude of the effects on the two sectors increases. While for the richer rural groups, the ratio of carbon tax to total expenditure is higher, the impact is offset by the fact that with higher income, the lower the consumption propensity. For example, for the rural low-income household group, the average consumption propensity is greater than 1, because the expenditure of the group exceeds the income, decreasing to 0.93 for the lower middle income group, while the consumption propensity of the group with high income level is 0.54. The great difference in average consumption propensity contributes significantly to the regressivity of carbon tax in rural area.

5. Redistribution of carbon tax to different household groups: the policy agenda

Most policies promulgated at the national level are implicitly assumed to be spatially blind (see Hewings, 2014); hence, different parts of the country should experience the same negative/positive impacts from, in this case, the carbon tax policy. Section 4 revealed that the national policy would have a significantly different impact on rural as opposed to urban households – the carbon tax policy would not be spatially blind. In addition, the impacts on household groups of different income levels need to be considered and, as a further exploration, the interdependence between changes in income among these groups also should be explored – in essence, considering income multiplier effects. This section will focus on outcomes from policies that address the differential impacts on households in two senses – (1) the rural/urban distinction and (2) on those different income levels that is complemented with a further exploration of the *income interdependence* between households of different income levels. In essence, the carbon tax is assumed to be *revenue-neutral* in that all the revenues are re-allocated

As revealed earlier, the most important negative effect of carbon tax is its regressivity that would aggravate income inequality. Redistributing the carbon tax to different household groups most affected by the tax might be considered as an important policy option to offset this negative effect. In this section, we discuss the impact of re-allocating the carbon tax paid by households in two scenarios. In the first scenario, the carbon tax *directly* paid by households is redistributed, where carbon tax directly paid by households refers to the carbon tax generated by the energy consumed by households, and in the second scenario the total carbon tax (*directly and indirectly*) paid by household is reallocated. Indirect carbon tax refers to the carbon tax embodied in the energy and non-energy products consumed by households, originating from the production chains of the products.

5.1. The effect of redistribution in scenario 1

In scenario 1, the carbon tax directly paid by households is redistributed among different household groups with various income levels. In this scenario, the objective of the redistribution is to reduce the regressivity of the carbon tax; it is assumed that the central government would be the main proponent of such a redistribution since it will be the recipient of the carbon tax revenues. The scheme of the reallocation is determined by solving a quadratic programming as follows:

$$\min \sum_{i \in \Phi} (r_i - \bar{r}_h)^2$$
$$\text{s.t.} \quad r_i = \frac{t_i - y_i}{m_i}, \quad i = 1, 2, \dots, q$$
$$\textstyle\sum_{i=1}^{q} y_i = T$$
$$y_i \geq 0, \; i = 1, 2, \dots, q$$

where Φ is the set of household groups with low income, including all the rural groups and the urban groups with income under the lower middle income level; r_i denotes the proportion of "net" carbon tax paid by group i to the income of group i, where "net" carbon tax means carbon tax less compensation; $\bar{r}_h$ represents the average proportion of "net" carbon tax to income for households with high income levels, t_i is the amount of carbon tax directly paid by group i, y_i denotes the amount of compensation given to group i, m_i is the total income of group i, T is the amount of carbon tax directly paid by households, and q is the number of household groups. The objective of the quadratic programming is to minimize the gaps between the proportion of "net" carbon tax to income for household groups with lower income levels and the average proportion of net carbon tax to income for household groups with higher income. The purpose of the redistribution is to reduce the difference of the proportion of net carbon tax to income between lower and higher income, in order to reduce the regressivity of the incidence of the carbon tax. The restrictions are the amount of direct tax paid by all households, and the non-negative restrictions on the subsidies received by different household groups. The results are shown in Table 5.

The results indicate that to reduce the regressivity of the carbon tax, almost all the compensation should be given to rural households. The percentage of compensation shared by rural low income households, the group with the lowest income and highest proportion of carbon tax to income, is 47.94%. Rural lower middle households and rural middle income households would receive 30.63% and 17.09% of the total compensation respectively. The share of the compensation for rural upper middle income households would be 2.64%. For urban households, the first five percentile group should have 1.54% of the total compensation. The simulation results show that after the redistribution, the regressivity of carbon tax is alleviated significantly; this is shown more clearly in Fig. 3.

5.2. The effect of redistribution in scenario 2

Scenario 1 only captures the direct effects on income by households in different locations and with different income levels. We can also evaluate the system-wide impacts of the changes in income in the sense that the redistribution will enhance the income of lower income groups especially those located in rural areas. In scenario 2, the total amount of carbon tax paid directly and indirectly by households is reallocated among household groups with various income levels. The total amount of carbon tax paid by households is much greater than the direct amount paid by households. Therefore, in contrast to scenario 1, the objective of the redistribution in scenario 2 is to reduce the income inequality through minimizing the difference between the income levels of poorer households and the average income level. The following quadratic program is used:

Table 5
The effect of redistributing the carbon tax directly paid by households.

Household groups	Shares in the compensation (%)	Proportion of carbon tax to income pre-redistribution(%)	Proportion of carbon tax to income after redistribution(%)
Rural Low Income Households	47.94	4.46	1.56
Rural Lower Middle Income Households	30.63	2.60	1.66
Rural Middle Income Households	17.09	2.23	1.86
Rural Upper Middle Income Households	2.64	2.05	2.01
Rural High Income Households	0.00	1.61	1.61
First five percent group	1.54	1.21	1.21
First decile group	0.16	1.43	1.43
Second decile group	0.00	1.10	1.10
Second quintile group	0.00	1.02	1.02
Third quintile group	0.00	0.96	0.96
Fourth quintile group	0.00	0.90	0.90
Ninth decile group	0.00	0.88	0.88
Tenth decile group	0.00	0.80	0.80

Note: The tax rate is 100yuan/ton CO_2. We also simulated the effects for various tax rates, e.g. 200 yuan/ton. The results are similar.

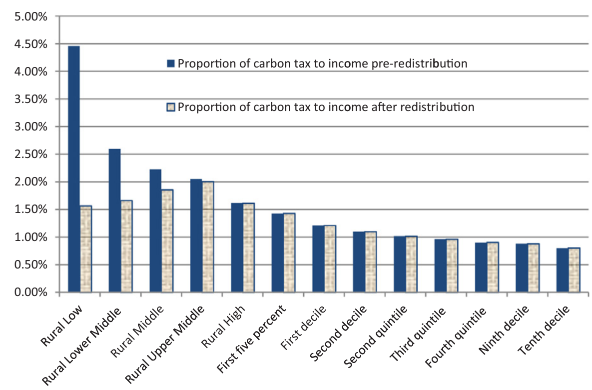

Fig. 3. Proportion of carbon tax to income after redistribution.

$$\min \sum_{i\in\Phi} (m_i^c - \bar{m}^c)^2$$
$$\text{s.t. } m_i^c = \frac{m_i - t_i + y_i}{N_i},\ \ i = 1,\ 2,\dots,q$$
$$\sum_{i=1}^{q} y_i = T^t$$
$$y_i \geq 0,\ \ i = 1,\ 2,\dots,q$$

where m_i^c represents the income per capita for group i, $\bar{m}^c$ is the average income per capita for all groups, N_i is the population of group i, and T^t is the amount of carbon tax directly and indirectly paid by households. The objective of the quadratic programming is to minimize the income gaps between the low income groups and the average income level. The restrictions are the amount of total carbon tax directly and indirectly paid by all households, and the non-negative restrictions on the compensations received by different household groups. The results are shown in Table 6.

The results in Table 6 show that the total carbon tax is mainly reallocated to the poorest household groups in both rural and urban areas. The group of rural low income households would have the largest part of the compensation, 59.7% of the total amount. A further 22.5% of the compensation would be given to the first five urban percentile groups. The first decile urban group, the group of rural lower middle income households, and rural middle income households should receive 8.18%, 6.02% and 3.60% respectively.

The income per capita of each of these poorer groups would thus be increased and the income inequality reduced. The results show that for the rural low income households, the increase of income per capita would be 42.73%, and the first percentile urban group would have a 23.27% increase in its income per capita.

In both scenarios 1 and 2, most of the compensation should be given to the groups with low income levels. However, there are many interactions among the different household groups. An income increase in one group will affect other groups and cause income increases for them. In next section, we investigate how income increases in poorer household groups influence incomes of other groups.

5.3. The effects of income increase in poorer household groups

Miyazawa's extended input-output model (Miyazawa, 1968) is used to analyze the interactions of the different household groups in this paper. It is a simple yet very powerful framework that facilitates analyzing the relations of endogenous, heterogeneous households groups. The Miyazawa system is specified as the follows:

$$\begin{bmatrix} x_{n\times1} \\ \cdots \\ y_{q\times1} \end{bmatrix} = \begin{bmatrix} A_{n\times n} & \vdots & C_{n\times q} \\ \cdots & \cdots & \cdots \\ V_{q\times n} & \vdots & 0_{q\times q} \end{bmatrix} \begin{bmatrix} x_{n\times1} \\ \cdots \\ y_{q\times1} \end{bmatrix} + \begin{bmatrix} \bar{f}_{n\times1} \\ \cdots \\ g_{q\times1} \end{bmatrix} \tag{13}$$

where n is the number of sectors; q is the number of household groups; y is a vector of total income; V is a labor income coefficient matrix; C is a consumption coefficient matrix; $\bar{f}$ is a vector of exogenous final demand; g is a vector of exogenous income.

Solving Eq. (13) for x and y yields:

$$\begin{bmatrix} x \\ \cdots \\ y \end{bmatrix} = \begin{bmatrix} B(I + CKVB) & \vdots & BCK \\ \cdots & \cdots & \cdots \\ KVB & \vdots & K \end{bmatrix} \begin{bmatrix} f^* \\ \cdots \\ g \end{bmatrix} \tag{14}$$

where B is a traditional Leontief inverse matrix, i.e., $B = (I - A)^{-1}$; $K = (I - L)^{-1}$ for $L = VBC$. The K matrix is the "interrelational income multiplier" matrix, indicating how much income in one group is generated by a unit income increase in the income of other groups. The matrix of "multi-sector income multipliers," KVB, indicates how much income in one group is generated by a unit increase of final demand in each sector.

In order to obtain the coefficient matrices of C and V, data from urban and rural Household Sample Surveys and the survey report on migrant workers, we construct the matrices of consumption and labor income by various household groups (5 rural household groups and 8 urban groups, as described earlier). The interrelational income multiplier matrix has been computed, and shown in Table 7.

A column in Table 7 indicates that given a labor income shock in one household group, how much additional income would be received by each of the other groups. It shows that a 100 yuan increase of income in rural low income households induces 21.9 yuan in the group with the highest income level, the tenth decile urban group. The fourth quintile urban group receives 19.9 yuan, and the rural high income households receives 17.5 yuan induced income. It means that the income increase of the household group with the lowest income level is expected to induce the largest income increase in the groups with high income levels. This is also the case for other groups with lower income levels.

Table 6
The effect of redistributing total carbon tax paid by households.

Household groups	Shares in the compensation(%)	Income per capita pre-tax (yuan)	Income per capita after redistribution (yuan)	Increase of income per capita (%)
Rural Low Income Households	59.70	2316	3306	42.73
Rural Lower Middle Income Households	6.02	4808	4810	0.05
Rural Middle Income Households	3.60	7041	6972	−0.98
Rural Upper Middle Income Households	0.00	10,142	9956	−1.83
Rural High Income Households	0.00	19,009	18,734	−1.44
First five percent group	22.50	7521	9271	23.27
First decile group	8.18	9210	9486	3.00
Second decile group	0.00	13,725	13,585	−1.02
Second quintile group	0.00	18,375	18,198	−0.96
Third quintile group	0.00	24,531	24,306	−0.92
Fourth quintile group	0.00	32,759	32,478	−0.86
Ninth decile group	0.00	43,471	43,110	−0.83
Tenth decile group	0.00	69,877	69,352	−0.75

Note: The tax rate is 100yuan/ton CO2. Again, we simulated the effects for various tax rates, e.g. 200 yuan/ton, and got similar results.

The column sums in Table 7 show that the income increases in the household groups with lower income levels have higher effects in inducing income economy-wide. A 100-yuan increase of income in rural low income households induces 232 yuan income increase in total; given a 100-yuan increase in rural lower middle income group, there would be 191 yuan income increase. The effect of the first five percentile group would be 183 yuan.

The row sums in Table 7 indicate that the household groups with higher income are expected to receive much larger induced income from the increases of income in all groups. Given a 100-yuan increase in each group, the tenth decile urban group will receive 264 yuan, the third and fourth quintile group will have 200 yuan and 248 yuan respectively. The group of rural High Income Households will have 211 yuan, which is a large contribution.

The results of the interrelational income multipliers indicate that the household groups with high income levels will benefit most from the income increases in household groups with lower income levels. Therefore, compensation to groups with low income is clearly a preferred choice for redistribution of the carbon tax but there needs to be a full accounting of the resulting *total effects* since the initial impacts on each income group provides only a partial assessment of the economy-wide effects. However, it requires further discussions on the ways of redistribution, such as combining the redistribution of carbon tax with a subsistence security system and other appropriate policy instruments that address life-cycle income dimensions. The interrelational income dynamics presented here turn out to be relatively typical; for example, recent research in Chicago has revealed similar asymmetries (spillovers from poor to rich are much higher than rich to poor) complicating the results from an reallocation program (Kim and Hewings, 2018).

6. Conclusions and policy implications

In this paper, we have implemented an energy input-output model in hybrid units, and with a Leontief price model constructed based on this hybrid framework, to investigate the potential effects of a CO_2 tax on Chinese economy. We first compiled the 2012 Chinese energy input-output table in hybrid units. Based on this table, we simulate the effects of a carbon tax on economic growth, CO_2 emissions, and the distributional effects on the different household groups based on income level.

The main results indicate that after a CO_2 tax, the decrease in emission is always larger than the decrease of GDP. Moreover, as the tax rate goes up, the mitigation rate of carbon emission decreases much faster than the decreasing rate of GDP. There is a large elasticity of emission, about 3.41 when the tax rate is 200 yuan/ton. It means that the amount of CO_2 emissions will be reduced 3.41% or so while GDP decreases 1%. Therefore, the results reveal that the taxation policy is capable of achieving its main goal of mitigating carbon emissions, with a relatively small negative effect on economic growth.

The policy implication of this result is that besides tradable permits, the carbon tax is also an effective and promising policy option for Chinese government to achieve its ambitious carbon reduction goals. Considering the completeness and effectiveness of the tax system, the option has high feasibility as well.

However, the analysis reveals that the carbon tax has a negative distributional effect on different household groups (disaggregated by income level); the negative effects are more pronounced for rural residents. For urban household groups with different income levels, there is a slight regressive impact. In urban areas, the effect on the lowest income quintile is around 1.8 times of that on the richest, but for the rural household groups, the carbon tax may be significantly regressive. In rural areas, the effect on the poorest is about 2.76 times that on the richest. The results indicate that a carbon tax may aggravate the income inequality in rural areas in China. Meanwhile, the results reveal that in general, the rural households are more negatively affected than the urban households, which means that the carbon tax may aggravate the rural-urban inequality as well.

Therefore, the policy implication is that if a carbon tax is implemented by the government, the negative effects cannot be ignored and some form of compensation policy would be required to offset such negative distributional effects. In order to discuss the proper direction of compensation, in this paper, we considered a revenue-neutral reallocation policy and simulated the results of redistributing the carbon tax loaded by households to household groups with different income levels by constructing quadratic programming models. The results reveal that in the first scenario, when the amount of carbon tax directly paid by households is spent on the groups with low income levels, the regressivity of carbon tax will be largely removed. Almost all the compensation should be given to the poorer rural households. The largest part of the tax, 47.9%, is allocated to the poorest group, the rural low income households. In the second scenario, if the total carbon tax directly and indirectly loaded by households is reallocated to the groups with low income levels, the inequality situation will be improved. The poorer groups in rural and urban areas should share the compensation. In summary, for both of the two sceneries, most of the compensation should be given to the groups with low income levels. However, it is important to consider the full economy-wide effects impacts of these redistributions. Using Miyazawa's extended input-output model, we computed interrelational income multipliers. The results indicate that the household groups with high income levels will benefit largely from the income increases in household groups with low income levels.

Therefore, the policy implication is that compensation to groups with low income will be a preferred choice for redistribution of carbon tax. It can not only offset the negative distributional effects of a carbon

Table 7
The interrelational income multipliers.

	Rural Low Income	Rural Lower Middle Income	Rural Middle Income	Rural Upper Middle Income	Rural High Income	First five percent group	First decile group	Second decile group	Second quintile group	Third quintile group	Fourth quintile group	Ninth decile group	Tenth decile group	Total
Rural Low Income	1.0320	0.0218	0.0177	0.0153	0.0115	0.0188	0.0172	0.0147	0.0136	0.0126	0.0113	0.0106	0.0089	**1.2061**
Rural Lower Middle Income	0.0581	1.0395	0.0319	0.0276	0.0207	0.0339	0.0309	0.0263	0.0242	0.0223	0.0200	0.0186	0.0154	**1.3693**
Rural Middle Income	0.0810	0.0552	1.0445	0.0385	0.0288	0.0472	0.0431	0.0367	0.0338	0.0311	0.0279	0.0259	0.0214	**1.5152**
Rural Upper Middle Income	0.1050	0.0715	0.0577	1.0499	0.0374	0.0612	0.0559	0.0476	0.0438	0.0404	0.0362	0.0336	0.0278	**1.6680**
Rural High Income Households	0.1750	0.1191	0.0962	0.0831	1.0623	0.1020	0.0932	0.0793	0.0729	0.0673	0.0603	0.0559	0.0463	**2.1131**
First five percent group	0.0107	0.0075	0.0063	0.0056	0.0045	1.0070	0.0066	0.0059	0.0056	0.0055	0.0053	0.0052	0.0049	**1.0805**
First decile group	0.0261	0.0183	0.0154	0.0138	0.0111	0.0170	1.0161	0.0143	0.0138	0.0134	0.0129	0.0128	0.0120	**1.1972**
Second decile group	0.0384	0.0269	0.0226	0.0202	0.0163	0.0250	0.0237	1.0211	0.0203	0.0197	0.0189	0.0188	0.0176	**1.2896**
Second quintile group	0.1030	0.0722	0.0607	0.0542	0.0438	0.0671	0.0634	0.0565	1.0545	0.0529	0.0507	0.0505	0.0472	**1.7769**
Third quintile group	0.1383	0.0969	0.0814	0.0728	0.0588	0.0901	0.0852	0.0758	0.0732	1.0710	0.0681	0.0678	0.0634	**2.0428**
Fourth quintile group	0.1989	0.1390	0.1165	0.1039	0.0836	0.1296	0.1221	0.1088	0.1047	0.1013	1.0968	0.0959	0.0889	**2.4898**
Ninth decile group	0.1340	0.0937	0.0785	0.0700	0.0563	0.0873	0.0823	0.0733	0.0706	0.0683	0.0652	1.0647	0.0599	**2.0041**
Tenth decile group	0.2192	0.1532	0.1284	0.1145	0.0921	0.1428	0.1346	0.1199	0.1154	0.1116	0.1066	0.1057	1.0979	**2.6417**
Total	**2.3197**	**1.9149**	**1.7578**	**1.6692**	**1.5273**	**1.8292**	**1.7745**	**1.6802**	**1.6463**	**1.6173**	**1.5803**	**1.5662**	**1.5115**	

tax, but there may be some further redistribution back to higher income groups when lower income groups receive additional income.

To summarize, the negative effects of carbon taxation on income distribution indicate that compensation policy would be quite necessary if a carbon tax is implemented. Our further investigation shows that redistribution of carbon tax would be a preferred policy to offset the negative effects. Since the goal of a carbon tax is not to increase tax revenue, but to mitigate carbon emissions, to use the carbon tax to compensate households should be a preferable option. Furthermore, reallocating should be more favorable than simply returning the tax, because redistribution can help to eliminate inequality.

The approach in this paper can be used in understanding the potential effects of various levels of CO_2 tax in achieving a target, and the results may help to find an appropriate CO_2 rate, according to the goal of emission reduction, and may help to find an effective compensation policy to offset the negative distributional effects as well. Furthermore, the framework in this paper can also be applied to analyzing the effects of pollution tax such as the one that was started in China in 2018. It should be noted that the effects analyzed in this paper are for the short term, because the parameters, such as the matrix of input coefficients and the matrix of consumption coefficients, are assumed to be fixed. Substitution of inputs and products should be considered if long-term effects of carbon tax are investigated.

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Appendix A. Supporting information

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