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The inequality impacts of the carbon tax in China

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Previous research has acknowledged that climate change is likely to expand the wealth gap, and climate policies may further increase inequality. Nevertheless, little research has focused on how climate policies affect inequality. To address this, we employ a Computable General Equilibrium (CGE) model to quantify the inequality impacts of the Chinese carbon taxes. Our CGE model results show that tax impacts on inequality are influenced by distribution of climate damages, tax payments, and recycling of tax revenues. Specifically, a positive correlation between income and climate damage induces lower inequality, compared to a zero or negative correlation. Tax payments by high-income households induce lower inequality than tax payments proportional to or independent from income. Recycling tax revenues to low-income households only induces lower inequality than the other recycling schemes. The results imply that relative utility is determined by absolute income, whereas income inequality only has a slight impact on it. In other words, governments could reduce negative feelings about inequality under a climate policy by increasing national income, even if the climate policy may induce higher inequality.

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Introduction

How climate change influences generational inequality has received a great deal of attention in recent years (Burke et al., 2015; Moore and Diaz, 2015). This is because energy inaccessibility of the poor in the content of climate change "can decisively hamper the political feasibility of respective reforms and provoke public resistance" (Dorband et al., 2019).

Considering the accelerating global warming recently, many researchers (Yahoo and Othman, 2017; Chen et al., 2017; Bi et al., 2019) claimed for more climate policies to effectively address climate change by curbing anthropogenic emissions. Unexpectedly, higher energy price, induced by climate policies, is likely to undermine energy access, especially for the poor, and trap them in their current patterns of energy use (Jakob and Steckel, 2014). This is because the poor spend a higher share of their income on pollution-intensive goods than the rich (Klenert et al., 2018). Hence, climate policies are likely to disproportionally affect the lifestyles of the poor; hence, most simulated climate policies in literature appeared regressive (Berry, 2019). Nevertheless, less attention has been given to potential inequality impacts of climate policies (Markkanen and Anger-Kraavi, 2019). Omitting inequality impacts is unlikely to simulate optimal climate policies, because a complex and multi-layered relationship exists between income inequality and greenhouse gas emissions (Rao and Min, 2018). Such omissions may also lead to biased policy evaluations, as inequality could weaken effectiveness of climate policies (Bae, 2018).

Inequality impacts of climate policies are also related to changes of subjective well-being. People have negative feelings at the sight of another's good fortune (Bosmans and Ozturk, 2018). Such feelings can be measured by relative utility, which postulates that individuals compare their income to a reference level (Pham, 2008). In other words, individual utility not only depends on own income but also is related to reference groups (Michalos, 1985; Hagerty and Veenhoven, 2003). Indeed, a reference group's income could be as important as own income for individual happiness (Ferrer-i-Carbonell, 2005). Previously, different terminologies were used to define the scope of relative utility, including happiness (Hagerty and Veenhoven, 2003; Clark et al., 2008), satisfaction level of workers (Clark and Oswald, 1996), and personal life satisfaction (Georgellis et al., 2009). Although it is extremely hard to prove that human psychology measures utility, "the acceptance of subjective well-being measures as a direct proxy for utility has consequently opened up a wide range of opportunities to further inform theory and policy design" (Clark et al., 2008). Hence, human psychology can be meaningfully denoted by relative utility.

Previous research has agreed that relative utility is negatively correlated with subjective well-being (Hagerty and Veenhoven, 2003; Clark et al., 2008; Clark and Oswald, 1996; Georgellis et al., 2009). Because of social inequity, raising overall income may not necessarily increase average happiness for the whole society (Hagerty and Veenhoven, 2003). As climate policies affect national income as well as income inequality, people's psychological states could vary considering policy effects. Nevertheless, to our best knowledge, almost no research was performed to study psychological effects of climate policies. This paper narrows the research gap by measuring changes of subjective welfare, denoted by relative utility, under the designed carbon taxes. The main innovations of this paper are listed as follows:

① Inequality impacts of climate policies are innovatively linked to a previous behaviour study.

② Welfare impacts of tax-induced inequality is innovatively measured by relative utility.

③ How tax revenue recycling affects inequality is analysed in the designed scenarios.

This paper is divided into five sections. Section "Introduction" introduces the research background, main targets, and research gap. Section "Methods" describes the research method, including the CGE model structure, scenario designs, and definition of relative utility. Section "Results" presents the model results in graphs. Section "Discussion" discusses the main findings in comparison with the literature. Section "Conclusion" shows the main conclusions of this paper.

Methods

CGE model. In this paper, a Computable General Equilibrium (CGE) model, originating from the pioneering work of Johansen (1960), is used to analyse inequality impacts of carbon taxes. Stemming from the general equilibrium theory of Walras, a CGE model reaches equilibrium when aggregated supplies and demands are equalised across all the interconnected markets (Xie et al., 2018).

In this paper, the social accounting matrix (SAM) of the CGE model is based on the 2015 China Input-Output (IO) Table. The detailed SAM is shown in Table S1 in Supplementary Information. The sector division of the Chinese economy is based on Guo et al. (2014), shown in Table S2 in Supplementary Information. According to Table S2, there are 42 sectors in the input-output Table, but only 29 sectors are left through the aggregation and disaggregation process. Noticeably, the Production and Distribution of Electric Power and Heat Power sector is divided into the electricity sector and heat sector first. Then the electricity sector is disaggregated into nine subsectors following Lindner et al. (2013) who disaggregated the Chinese electricity sector in the 2007 Input-Output Table. Electricity disaggregation is necessary, because with very few anthropogenic emissions, electricity subsectors exploiting renewables should not be regulated by climate policies. Detailed electricity disaggregation can be found in the equations in Section B of Supplementary Information.

The CGE model is formed by the top-down method, with two regions (China and the rest of the world) and four economic entities (household, enterprise, foreigner, and government). As the CGE model is dynamic recursive, a dynamic block is introduced, and the research period is 2015–2030. The equations of the CGE model are presented in Section B of Supplementary Information.

Production block. In this block, the top level is formed by a Leontief function, while the other levels are formed by constant elasticity of substitution (CES) functions. The elasticity parameters in the CES functions are from Guo et al. (2014). Noticeably, the elasticity parameters of the electricity subsectors are assumed to be the same as the elasticity parameter of the electricity sector given in Guo et al. (2014). The default values of the elasticity parameters are shown in Table S3 in Supplementary Information.

A sensitivity analysis is performed to test how the given values of the elasticity parameters influence the model results, namely the robustness of the results to the exogenous elasticity parameters. In the sensitivity analysis, the elasticity parameters are assumed to change by ±10, ±20, and ±50% to analyse how parametric values affect model equilibrium. This is because in the range of ±50%, inputs in some sectors may turn from poor (good) substitutes to good (poor) substitutes (Lu and Stern, 2016). In general, low (high) elasticity parameters denote flexible (stringent) economy.

Income-expenditure block. A representative household and enterprise are introduced to represent the entire Chinese households and enterprises. The household consumes domestic or foreign goods, while its income source is labour, capital, and money transfers. The enterprise earns its income from capital only, whereas its expenditure includes labour wages, economic taxes, carbon taxes, and money transfers to the household.

Government block. A representative government is used to represent all the Chinese central and local governments. Governmental income comes from taxes imposed on consumption, production, international trade, and carbon emissions. The government spends its income on consumption of goods, money transfers, and savings with a CES utility function quantifying its spending.

Trade block. In this block, a representative foreigner is introduced to represent the worldwide countries except China. The foreigner produces goods consumed by the household, meanwhile it consumes goods exported by the enterprise. Trade balance is assumed when monetary value of export equals that of import. International trade is based on the Armington (1969) assumption that goods produced in different regions are imperfect substitutes.

Dynamic block. In this paper, the exogenously determined dynamic parameters are the population, price, energy consumption growth rate, output growth rate, and capital accumulation. The projected Chinese population is from the medium variant scenario in 2017 World Population Prospects (WPP) by UN (2017). The export price is assumed to change proportionally to the price projection of the total OECD countries by OECD (2014). The GDP deflator, domestic commodity price, and import price are assumed to change proportionally to the price projection of China by OECD (2014). The projected energy consumption growth rate is from the reference scenario in 2017 International Energy Outlook by EIA (2017). The output growth of the energy sectors follows the projected growth of the Chinese energy consumption (OECD, 2018), while the output growth of the nonenergy sectors follows the Chinese GDP projection in the regional GDP long-term forecast (OECD, 2018). The projected physical capital stock follows Long and Herrera (2016), while the projected human capital stock is based on the annual China Human Capital Report published by China Centre for Human Capital and Labour Market Research (CHLR, 2018). The detailed variations of the dynamic parameters in this paper are shown in Section C of Supplementary Information.

Household disaggregation. Based on income, the representative household of the CGE model is divided into three household groups, namely low-income, mid-income, and high-income households. Low-income households are the lowest 40% income households; high-income households are the highest 10% income households; the other households belong to mid-income households. The household division is based on the 2013 Chinese Household Income Project (CHIP) conducted by China Institute for Income Distribution (CIID, 2013). The compiled data are summarised in Table 1.

In this paper, ratios of income sources for household groups are assumed to be time-invariant. As a carbon tax may have various impacts on different income sources, household income distribution is likely to vary in tax scenarios.

$$\mathrm{HGI}_{\mathrm{gt}} = \sum\nolimits_{\mathrm{f}} \left(\mathrm{INS}_{\mathrm{fgt}} \times \mathrm{YH}_{\mathrm{ft}} \right) \quad (1)$$

We have defined household income distribution in Eq. (1), where the subscripts f, g, and t denote factor (labour, capital, and transfer), household group, and time (year). $\mathrm{HGI}_{\mathrm{gt}}$ stands for the gross income of a household group. $\mathrm{YH}_{\mathrm{ft}}$ refers to household factor income; $\mathrm{INS}_{\mathrm{fgt}}$ is ratios of income sources displayed in Table 1.

Table 1 Ratios of income sources for household groups.

Income source	Labour	Capital	Transfer	Overall
Low-income	10.03%	18.26%	23.38%	14.38%
Mid-income	57.43%	49.76%	57.67%	55.39%
High-income	32.55%	31.97%	18.95%	30.23%

The 2013 CHIP data also include consumption distribution of the surveyed households, shown in Table 2. A carbon tax may have various impacts on different consumption goods; hence, it is likely to affect household consumption distribution. Like income source ratios, commodity consumption ratios are assumed to be time-invariant.

$$\mathrm{HGC}_{\mathrm{gt}} = \sum\nolimits_{c} \left(\mathrm{INC}_{\mathrm{cgt}} \times \mathrm{YC}_{\mathrm{ct}} \right) \quad (2)$$

Equation (2) shows household consumption distribution, where the subscript c represents a kind of commodity. $\mathrm{HGC}_{\mathrm{gt}}$ stands for the monetary value of total consumption for a household group. $\mathrm{YC}_{\mathrm{ct}}$ is household consumption on a certain commodity; $\mathrm{INC}_{\mathrm{cgt}}$ is ratios of consumed commodities displayed in Table 2.

Distribution of climate damages. To analyse the effects of climate change on inequality, in this paper, we have studied climate damage distribution among household groups. According to Dennig et al. (2015), the relationship between climate damages and income distribution can be denoted by the income elasticity of damage parameter (ξ). A positive ξ value means that climate damages are proportional to income; in other words, high-income households suffer the most welfare loss, while low-income households suffer the least welfare loss under climate change. Hence, this assumption induces the lowest inequality among the ξ assumptions.

A zero ξ value means that climate damages are independent from income. This assumption implies that uncertainties exist in equity issues of climate change. For example, distributive criterion may be relevant to income distribution influenced by climate change; hence, there is less agreement on how equity considerations should inform future action on climate change (Matto and Subramanian, 2012).

A negative ξ value means that climate damages are inversely related to income. This is the case that most previous researchers were concerned about. For example, Mendelsohn et al. (2006) examined worldwide impacts of climate change, arguing that poor countries suffered bulks of damages from climate change; in other words, global temperature rise from anthropogenic emissions causes impacts that fall more heavily on low-income countries (Taconet et al., 2020). Hence, this assumption induces the highest inequality among the ξ assumptions.

In this paper, damage distribution among household groups is based on the ξ assumptions. Under the positive ξ assumption, household damage distribution is defined in Eq. (3a). $\mathrm{HGD}_{\mathrm{gt}}$ refers to climate damages suffered by a household group. $\mathrm{HTC}_{\mathrm{t}}$ is total household consumption. $\mathrm{Dam}_{\mathrm{t}}$ denotes aggregated climate damages suffered by households. dr_{t} is proportion of household consumption that is deducted by climate damages.

$$\mathrm{HGD}_{\mathrm{gt}} = \mathrm{HGC}_{\mathrm{gt}}/\mathrm{HTC}_{\mathrm{t}} \times \mathrm{Dam}_{\mathrm{t}} = \mathrm{HGC}_{\mathrm{gt}} \times \mathrm{dr}_{\mathrm{t}} \quad (3a)$$

$$\mathrm{HGD}_{\mathrm{gt}} = \mathrm{PR}_{\mathrm{g}} \times \mathrm{Dam}_{\mathrm{t}} \quad (3b)$$

$$\mathrm{HGD}_{\mathrm{gt}} = \mathrm{dr}_{\mathrm{g}}^{*} \times \mathrm{Dam}_{\mathrm{t}} \quad (3c)$$

When ξ equals zero, climate damages are assumed to be independent from household income. Hence, damage distribution is only related to the size of a household group, shown in Eq. (3b). PR_{g} refers to the occupied population ratio of a household group, namely 40%, 50%, and 10% for low, mid, and high-income households, respectively.

When ξ is negative, low-income households suffer disproportionally more climate damages than high-income households shown in Eq. (3c). According to Dennig et al. (2015), the

Table 2 Ratios of consumed commodities for household groups.

Consumption source	Food	Clothing	Transport	Service	Other goods	Overall
Low-income	24.90%	16.56%	15.72%	20.63%	15.22%	20.91%
Mid-income	55.08%	56.57%	53.47%	53.53%	50.11%	54.16%
High-income	20.02%	26.87%	30.81%	25.83%	34.68%	24.93%

exogenous given damage ratio (dr_g^*) is 69.7%, 27.8%, and 2.5% for low, middle, and high-income households. In this paper, the ratio for low-income households is the aggregation of the first and second quintiles in Dennig et al. (2015); the ratio for mid-income households is the aggregation of the third and fourth quintiles and the first half of the fifth quintile; the ratio for high-income households is the second half of the fifth quintile. The embedded assumption of dividing the fifth quintile is that climate damages are evenly distributed. Noticeably, the aggregation of the damage ratios is equal to 99%, and thus all the ratios have been amplified by 100/99% for mathematical balance.

Tax payments. In literature, the Gini coefficient is widely used to denote income inequality; however, it is oversensitive to changes in the middle of income distribution and less sensitive to changes at the extremes. Hence, the Gini coefficient is not an ideal tool to analyse current inequality patterns characterised by stable income share of middle classes and high fluctuations on tails (Campagnolo and Davide, 2019). In contrast, the Palma ratio focuses on top and bottom class of income distribution, and thus it is more appropriate to current inequality patterns (Cobham et al., 2016). The Palma ratio is defined as "the ratio of the top 10% of population's share of gross national income (GNI) divided by the poorest 40% of the population's share of GNI" (Campagnolo and Davide, 2019). In this paper, the Palma ratio is defined as net income of low-income households divided by that of high-income households.

Net income equals gross income subtracted by climate damages and tax payments; hence, the net income of a household group in this paper is related to who pays the carbon tax. The poor are less responsible for historical emissions but possess fewer resources to adapt to climate change; on the contrary, the rich have much higher per capita CO_2 emissions than the poor (Padilla and Serrano, 2006), and they have more resources to adapt to global temperature rise. Hence, carbon taxes should be paid by high-income households only (Markkanen and Anger-Kraavi, 2019).

$$HGNI_{gt} = HGI_{gt} \times (1 - dr_t) - \begin{cases} 0 & \text{(low and mid income households)} \\ YT_t \times (1 - dr_t) \times tax_t & \text{(high income households)} \end{cases} \quad (4a)$$

$$HGNI_{gt} = HGI_{gt} - YT_t \times dr_t \times PR_g - \begin{cases} 0 & \text{(low and mid income households)} \\ YT_t \times (1 - dr_t) \times tax_t & \text{(high income households)} \end{cases} \quad (4b)$$

$$HGNI_{gt} = HGI_{gt} - YT_t \times dr_t \times dr_g^* - \begin{cases} 0 & \text{(low and mid income households)} \\ YT_t \times (1 - dr_t) \times tax_t & \text{(high income households)} \end{cases} \quad (4c)$$

In Eqs. (4a, b), we have defined distribution of net income among household groups under tax payments by high-income households only; the three equations denote damage distribution under the positive, zero, and negative ξ assumptions. $HGNI_{gt}$ is the net income of a household group; YT_t is total household income; tax_t is tax payments.

$$HGNI_{gt} = HGI_{gt} \times (1 - dr_t) \times (1 - tax_t) \quad (5a)$$

$$HGNI_{gt} = \left(HGI_{gt} - YT_t \times dr_t \times PR_g\right) \times (1 - tax_t) \quad (5b)$$

$$HGNI_{gt} = \left(HGI_{gt} - YT_t \times dr_t \times dr_g^*\right) \times (1 - tax_t) \quad (5c)$$

When tax payments are proportional to income, we have defined distribution of net income among household groups on the positive, zero, and negative ξ assumptions of damage distribution in Eqs. (5a, c).

$$HGNI_{gt} = HGI_{gt} \times (1 - dr_t) - YT_t \times (1 - dr_t) \times tax_t \times PR_g \quad (6a)$$

$$HGNI_{gt} = HGI_{gt} - YT_t \times dr_t \times PR_g - YT_t \times (1 - dr_t) \times tax_t \times PR_g \quad (6b)$$

$$HGNI_{gt} = HGI_{gt} - YT_t \times dr_t \times dr_g^* - YT_t \times (1 - dr_t) \times tax_t \times PR_g \quad (6c)$$

By comparison, tax payments could be also independent from income, and thus payments are only related to the size of a household group. In this case, we have defined distribution of net income on the positive, zero, and negative ξ assumptions in Eqs. (6a, c).

Tax revenue recycling. Revenue recycling to complement carbon taxes could make a difference to tax policy effects, as it can stimulate economic growth or reduce mitigation costs (Sands, 2018). In addition, revenue recycling is a way to compensate or even offset welfare loss induced by climate policies, and thus it helps achieve social equity. The importance of revenue recycling has been already confirmed in literature. For example, Liu and Lu (2015) used a dynamic CGE model to study economic impacts of different revenue recycling schemes in China, arguing that revenue recycling was important in tax designs; Xiao et al. (2015) utilised a dynamic recursive multi-sector CGE model to explore policy effects of an environmental tax in China, concluding that governmental tax refunds could reduce negative effects of the tax on economy.

In this paper, tax revenue recipients are governments, enterprises, and households. Recycling tax revenues to governments is equivalent to no revenue recycling in previous research on carbon taxes (Li et al., 2019). Recycling tax revenues to enterprises is beneficial to production activity and international trade (Macaluso et al., 2018). By comparison, recycling tax revenues to households could be regarded as a kind of income redistribution. Specifically, tax revenues could be recycled to households evenly or low-income households only.

Table 3 shows the designed 12 scenarios based on distribution of climate damages, tax payments, and tax revenue recycling. In addition, a baseline scenario with no climate policies implemented is designed to act as the reference scenario in this paper.

Table 3 The designed scenarios in this paper.

Scenarios	Recipients of tax revenues	Tax payments
SCRO1	Governments	High-income households only
SCRO2	Governments	Proportional to income
SCRO3	Governments	Independent from income
SCRO4	Households evenly	High-income households only
SCRO5	Households evenly	Proportional to income
SCRO6	Households evenly	Independent from income
SCRO7	Low-income households only	High-income households only
SCRO8	Low-income households only	Proportional to income
SCRO9	Low-income households only	Independent from income
SCRO10	Enterprises	High-income households only
SCRO11	Enterprises	Proportional to income
SCRO12	Enterprises	Independent from income

Relative utility. According to Johansson-Stenman et al. (2002), we have defined relative utility (RU) for each household group in Eq. (7). $HRGU_{gt}$ denotes the average relative utility of a household group. $HGANI_{gt}$ is the average net income of a household group. $ANYT_t$ is average net income, and it equals aggregated net household income divided by population.

$$HGRU_{gt} = \frac{1}{1-\gamma_2}\left(HGANI_t \times ANYT_t^{-\gamma_1}\right)^{1-\gamma_2} \quad (7)$$

In Eq. (7), the parameter γ_1 is a weight that an individual attaches to relative income (Johansson-Stenman et al., 2002). γ_1 lies between 0 and 1, with the extreme value 0, meaning that RU does not depend on relative income, and the extreme value 1, meaning that RU only depends on positional effects of individual income relative to average income in the society (Johansson-Stenman et al., 2002). By default, in this paper, γ_1 is assumed to equal 0.35, which was the median value of the positional experiment by Johansson-Stenman et al. (2002).

The parameter γ_2 measures the rate at which RU falls as income rises (Howarth and Kennedy, 2016). By default, in this paper, γ_2 is assumed to equal 1.72, which was the median value of the risk (inequality) aversion experiment (Johansson-Stenman et al., 2002); this value is quite close to 1.8 given by Howarth and Kennedy (2016). As rising income inequality decreases RU (Howarth and Kennedy, 2016), γ_2 is assumed to be larger than one. This assumption is rational as most of the experimental participants in Johansson-Stenman et al. (2002) had relative risk aversions larger than one. As γ_2 is larger than one, RU is negative in this paper, implying that if national income is fixed, a rise in income inequality increases RU absolute value.

$$ORU_t = \sum_g \left(HGRU_{gt} \times PR_g\right) \times POP_t \quad (8)$$

Hence, we have defined overall relative utility (ORU_t) as the weighted summation of each group's relative utility in Eq. (8), where POP_t refers to population.

Carbon tax. In the baseline scenario of this paper, with no climate policies implemented, the Chinese anthropogenic emissions will grow continuously over the research period 2015–2030 under the current production and consumption patterns. Nevertheless, China has committed in its Nationally Determined Contribution (NDC) target (NDRC, 2015) to peak the emissions before 2030. To achieve this NDC target, the Chinese governments should implement climate policies to abate the anthropogenic emissions.

In literature, carbon taxes and emission trading schemes (ETS) are the most popular climate policies to mitigate carbon emissions (Li and Jia, 2017; Bi et al., 2019). Implementation of a carbon tax requires governments to play important roles in economy, while ETS implementation requires a solid carbon market to be established (Liu and Lu, 2015). Considering strong governmental powers and undeveloped carbon markets in China, a carbon tax is preferable to an ETS. This is because China's nationwide ETS market has been established very recently, and the seven ETS pilots encountered problems. For example, too many allocated carbon quotas led to a low and unstable carbon price and thus induced an ineffective carbon market (Li and Jia, 2016). Compared to an ETS, a carbon tax promotes energy-saving technologies and optimises energy consumption structure, and its negative effect on GDP is small (Chi et al., 2014). Therefore, "a carbon tax is recognised as one of the most cost-effective economic instruments to control carbon emissions" (Li et al., 2018). Hence, it is worthwhile to study socioeconomic impacts of the Chinese carbon taxes.

In literature, most carbon taxes were implemented as fixed carbon prices on anthropogenic emissions (Li and Jia, 2016; Li and Jia, 2017; Dong et al., 2017). In a dynamic study over time, a fixed tax price achieves a larger proportion of emission reduction when emissions are lower, but it achieves a lower proportion of emission reduction at higher anthropogenic emissions. Hence, carbon taxes based on fixed percentage tax rates are more meaningful as they regulate emissions evenly over time.

In this paper, three carbon taxes are designed with the fixed tax rates at 1%, 2%, and 3%, imposed on consumption of non-renewable energy; in other words, tax base is monetary value of consumed non-renewable energy. Noticeably, the designed carbon taxes directly regulate electricity generation, because combustion of fossil fuels in electricity generation emits enormous quantities of greenhouse gases; in contrast, the designed taxes do not directly curb end use of electricity, because electricity consumption induces very few anthropogenic emissions. In China, electricity price is determined by governmental commands; however, in this paper, the representative enterprise is assumed to be economically rational: it shifts rising costs of electricity generation, under carbon taxes, to end-users by increasing electricity price. Hence, household consumption of fossil fuels is directly regulated by carbon taxes, while household electricity consumption is indirectly affected by carbon taxes.

The 1, 2, and 3% tax in this paper are equivalently to 2.4–4.9, 3.6–7.8, and 4.4–9.8 \$/t CO_2 over the research period. According to National Development and Reform Commission (NDRC) and Ministry of Finance of China (Li and Jia, 2017), the guided carbon tax rates, which are China's attempts to incentivise taxpayers to lower non-renewable energy consumption (RIFS, 2009), are ~1.7, 4.2, and 6.7 \$/t CO_2 for low, medium, and high tax, respectively. In comparison with the guided taxes, the 1% tax in this paper lies between the low and medium tax; the 2% tax lies between the medium and high tax; the 3% tax is closer to the high tax.

Carbon taxes could complement ETS policies, and such complementary roles were proved in literature (Lin and Jia, 2020). Nevertheless, this paper has focused on policy effects of carbon taxes only, and thus the designed taxes are not related to the current Chinese nationwide ETS policy. The current ETS price is ~60 CNY/t CO_2 (Huanbao EN-IN, 2022) or 9 \$/t CO_2, which is higher than the designed tax rates, except for a few years at the 3% tax. Different tax rates and ETS prices are rational because carbon taxes regulate anthropogenic emissions by direct governmental commands (Bruvoll and Larsen, 2004), while ETS policies indirectly abate emissions through market mechanisms (Crossland et al., 2013). Indeed, tax rates could be lower than ETS prices (Li and Jia, 2017), because emission reduction of carbon taxes could be higher than that of ETS policies under the same

Fig. 1 Impacts of climate damage distribution (ξ) on the Palma ratio. Shows impacts of climate damage on the Palma ratio: the legends "Positive", "Zero", and "Negative" denote the positive, zero, and negative ξ assumptions.

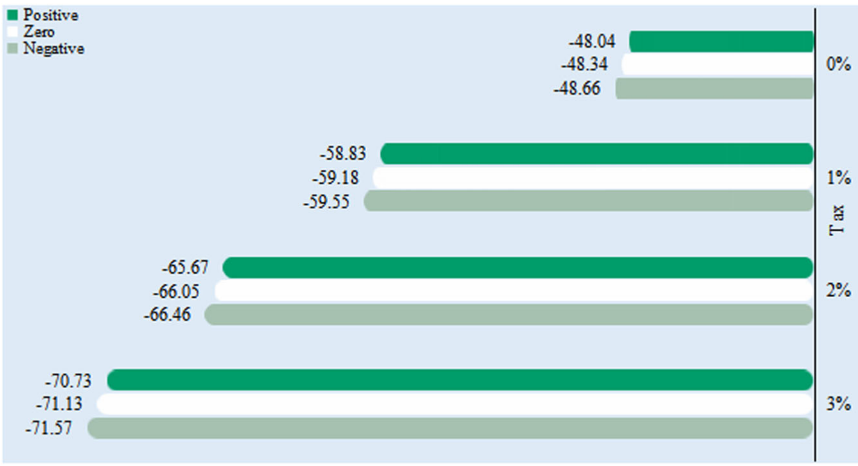

Fig. 2 Impacts of climate damages (ξ) on relative utility (unit: 10^9 CNY). Shows impacts of climate damage on relative utility: the legends "Positive", "Zero", and "Negative" denote the positive, zero, and negative ξ assumptions.

GDP effect (Jia and Lin, 2020). Hence, it is meaningful to design the tax rates lower than the current ETS price in this paper.

Results

Damage distribution. The Palma ratios in all the 12 scenarios are shown in Table S4–S15 in Supplementary Information. According to Fig. 1, the ξ assumptions influence inequality: a positive ξ value induces the lowest inequality, while a negative ξ value induces the highest inequality among the ξ assumptions. Figure 1 also shows that carbon taxes reduce inequality on all the ξ assumptions. This is because high-income households earn more income from energy sectors than low-income households, and thus carbon taxes decrease net income of high-income households disproportionately more than average level. This finding is contrary to the previous research showing that the simulated French carbon tax appeared regressive (Berry, 2019). The result differences are caused by the taxation scopes: Berry (2019) simulated the tax levied on household energy consumption only, whereas the taxes in this paper are imposed on sectoral and household energy consumption.

Figure 2 shows the relative utility (RU) in SCRO1, while Fig. S1–S11 in Supplementary Information shows the RU in the other scenarios. According to Fig. 2, tax rate is positively related to RU absolute value. Under fixed tax rate, RU absolute value is the lowest when ξ is positive; it is the highest when ξ is negative. Although carbon taxes reduce inequality shown in Fig. 1, however, Fig. 2 shows that taxes increase RU absolute value. This result implies that absolute income is the main RU determinant even though inequality does affect relative utility. Higher RU absolute values mean more negative feelings about inequality, and thus this finding agrees with Georgellis et al. (2009) who used the European Social Survey data to show that reference or comparison income exerted a negative influence on life satisfaction.

Tax payments. Because of zero tax payments, the Palma ratio in the baseline scenario is equal to 2.63 on the zero ξ assumption, shown in Fig. 1. Hence, Fig. 3 only shows the Palma ratio under the designed carbon taxes.

According to Fig. 3, tax payments by high-income households only induce the lowest inequality among the tax payment schemes. In this case, carbon taxes induce lower inequality than that in the baseline scenario, implying that taxes are progressive. When carbon taxes are paid proportionally to income, they have small impacts on the Palma ratio, compared to the baseline scenario, implying that taxes are neutral. This is because in this case, low-income and high-income households bear the same proportion of tax payments to income, which minimally affects inequality, according to the definition of the Palma ratio. If tax payments are independent from income, inequality is the highest

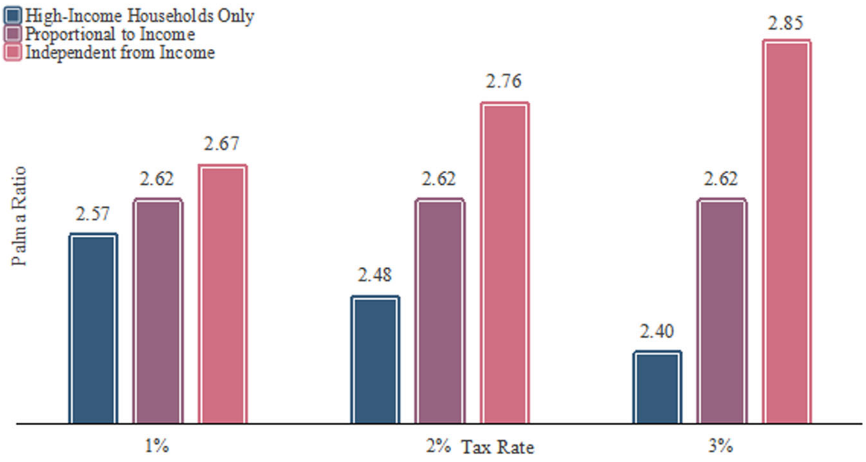

Fig. 3 Impacts of tax payments on the Palma ratio. Shows impacts of tax payments on the Palma ratio: the legends "High-income Households Only", "Proportional to Income", and "Independent from Income" refer to tax payments by high-income households, proportional to income, and independent from income.

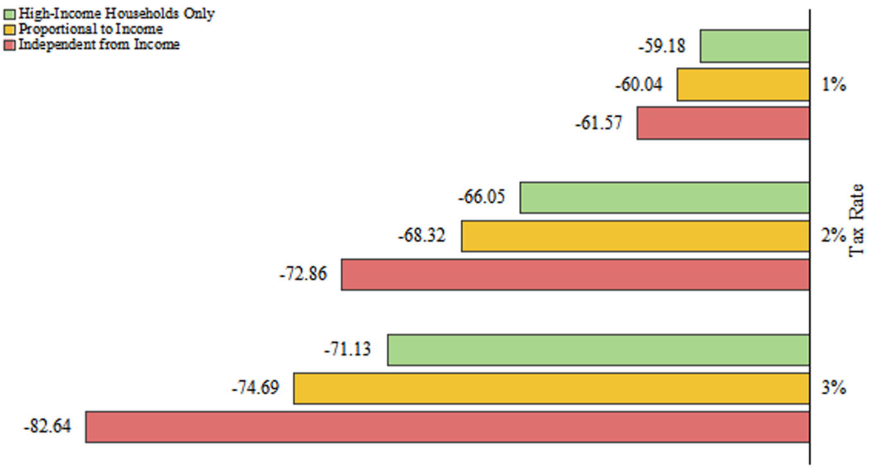

Fig. 4 Impacts of tax payments on relative utility (unit: 10^9 CNY). Shows impacts of tax payments on relative utility: the legends "High-income Households Only", "Proportional to Income", and "Independent from Income" refer to tax payments by high-income households, proportional to income, and independent from income.

among the tax payment schemes and higher than that in the baseline scenario, implying that taxes are regressive.

Figure 4 shows how relative utility (RU) is affected by tax payments. RU absolute value is the lowest under tax payments by high-income households; it becomes higher under payments proportional to income; tax payments independent from income induce the highest RU absolute value. Figure 4 implies that given absolute income, RU absolute value is inversely related to inequality. This finding agrees with Clark and Oswald (1996) who explored the data of 5000 British workers to conclude that workers' satisfaction was inversely related to satisfaction of reference group. Similarly, Clark et al. (2008) discussed the relation between happiness and utility, arguing that income gap reduced happiness.

Tax revenue recycling. In Figs. 1–4, we have not considered tax revenue recycling; in other words, tax revenues are kept in governmental budgets (Li et al., 2019).

Figure 5 shows how recycling of tax revenues affects inequality. At a lower tax rate, revenue recycling has a small impact on inequality; however, at a higher tax rate, this impact is larger. Revenue recycling to enterprises induces similar inequality to the case without revenue recycling. In contrast, revenue recycling to households induces lower inequality than recycling to other recipients. This finding agrees with Davies et al. (2014) who tested possibilities of eliminating global inequality by tax revenues, concluding that redistributing tax revenues reduced the Gini coefficient. In addition, revenue recycling to low-income households only rather than households evenly further reduces inequality. This finding complies with Grottera et al. (2017) who used a Brazilian SAM to analyse tax effects on income distribution, showing that recycling of tax revenues to lower income class contributed the most to inequality reduction in Brazil.

Figure 6 shows how recycling of tax revenues affects relative utility (RU). Revenue recycling to enterprises induces the largest RU absolute value, closely followed by revenue recycling to governments. Revenue recycling to households induces lower RU absolute value than recycling to other recipients; particularly, revenue recycling to low-income households only induces the lowest RU absolute value among the recycling schemes.

Sensitivity analysis. Table S16 in Supplementary Information shows that if the elasticity parameters change by −50 to 50%, the Palma ratio will change by <0.1%. Similarly, Table S17 in Supplementary Information shows that the relative utility will change by <10% under the parametric changes by −50 to 50%. Hence, the results of the sensitivity analysis imply that the defined Palma

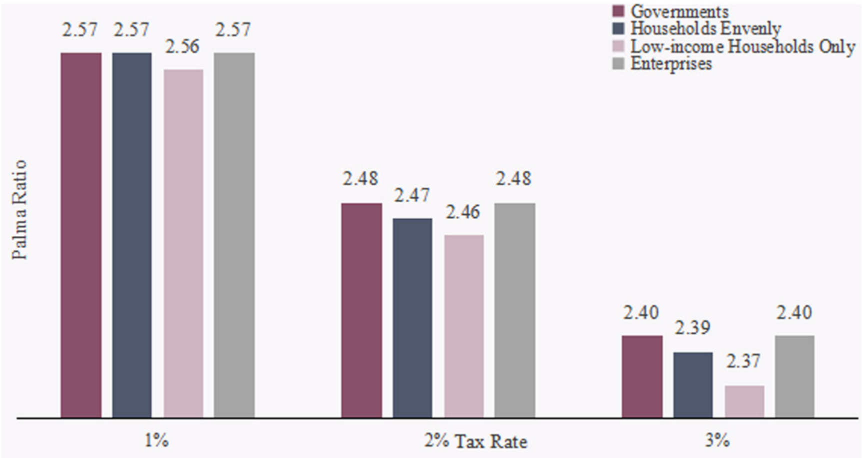

Fig. 5 Impacts of tax revenue recycling on the Palma ratio. Shows impacts of tax revenue recycling on the Palma ratio: the legends “Governments”, “Households Evenly”, “Low-income Households Only”, and “Enterprises” refer to revenue recipients are governments, entire households, low-income households, and enterprises.

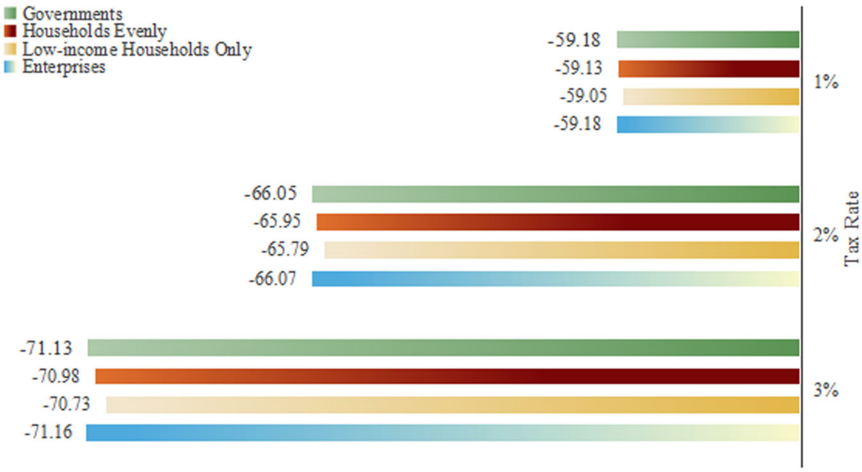

Fig. 6 Impacts of tax revenue recycling on relative utility (unit: 10^9 CNY). Shows impacts of tax revenue recycling on relative utility: the legends “Governments”, “Households Evenly”, “Low-income Households Only”, and “Enterprises” refer to revenue recipients are governments, entire households, low-income households, and enterprises.

ratio and relative utility, in this paper, are quite insensitive to the exogenous elasticity parameters; in other words, the CGE model results are reliable.

Discussion

This paper shows that inequality is affected by the income elasticity of damage parameter (ξ). A negative ξ value induces higher inequality than a positive or zero ξ value. This finding is compatible with Winsemius et al. (2018) who argued that the poor were often disproportionally exposed to climate damages. Hence, climate change exacerbates inequality (Beck, 2010).

If tax payments are independent from income, carbon taxes increase inequality. This finding agrees with Markkanen and Anger-Kraavi (2019) who synthesised evidence of inequality impacts of climate policies in literature, arguing that a carbon tax usually increased inequality because of rising energy price, even if tax revenues were recycled to the poor. Similarly, Freitas et al. (2016) also analysed economic and distributional effects of emission taxation in Brazil, concluding that a Brazilian tax increased inequality.

A decrease in national income, caused by a rise of tax rate, always results in an increase in RU absolute value even if a carbon tax decreases inequality. This result implies that compared to relative income, absolute income has a more influential impact on relative utility. Similarly, Clark et al. (2008) also argued for positive correlations between individual income and individual measures of subjective well-being even though happiness was indeed negatively related to others' income and own income in the past.

Keeping revenues in governmental budgets is equivalent to the case with no revenue recycling in literature (Li et al., 2019). Without revenue recycling, carbon taxes are usually regressive as tax burdens on the poor are higher than that on the rich (Wang et al., 2019). Conversely, carbon taxes may decrease inequality if tax revenues are recycled as uniform lump-sum transfers (Klenert and Mattauch, 2016). Revenue recycling to households induces lower inequality than recycling to other recipients. This finding is compatible with Montenegro et al. (2019) who found that redistributing revenues from carbon certificates decreased income inequality in EU.

In addition, revenue recycling to low-income households only induces the lowest inequality among the recycling schemes. By providing the best means for sheltering the poorest, revenue recycling as income transfers is the most equitable way to use tax revenues (Jorgenson et al., 2018). This finding agrees with the previous research showing that revenue recycling to low-income households was the cheapest option to offset regressivity of the French carbon tax (Berry, 2019).

In summary, this paper implies that inequality impacts of carbon taxes are affected by distribution of climate damages, tax payments, and tax revenue recipients. Distribution of climate damages may not be easily influenced by governmental policies; however, governments can take measures to reduce inequality induced by climate policies. A desirable carbon tax should include tax payments by high-income households instead of payments proportional to or independent from income; tax revenues should be recycled to low-income households rather than enterprises or governments.

Conclusion

In this paper, the representative household of the CGE model is divided, based on income, into three household groups to quantify inequality impacts of carbon taxes. The model results show that inequality varies in the designed tax scenarios, compared to the baseline scenario. Inequality impacts of carbon taxes are influenced by distribution of climate damages, tax payments, and recycling of tax revenues. More specific results are summarised below:

Climate damage distribution affects inequality because it is linked to distribution of welfare loss under climate change. If climate damages are positively related to income, inequality is the lowest among the distribution assumptions. If climate damages become independent from income, low-income households suffer more welfare loss, and thus inequality is higher than that on the positive distribution assumption. If climate damages are negatively related to income, low-income households suffer the most welfare loss, and thus inequality is the highest among the distribution assumptions.

Tax payments are burdens on taxpayers and thus affect inequality. Inequality is the lowest under tax payments by high-income households. Payments proportional to income induce higher inequality than payments by high-income households. If tax payments are independent from income, inequality is the highest among the payment schemes. A carbon tax is progressive under payments by high-income households; it is neutral if payments are proportional to income; it is regressive if payments are independent from income.

Revenue recycling is a way to compensate welfare loss of economic entities induced by climate policies, and thus it affects inequality. Among the recycling schemes, revenue recycling to low-income households induces the lowest inequality. By comparison, revenue recycling to enterprises or governments induces higher inequality than revenue recycling to households.

Different from the Palma ratio, the defined relative utility in this paper is determined by absolute income, even though relative income does have an impact on it. In other words, variations of income inequality, owing to distribution of climate damages, tax payments, and tax revenue recycling, only slightly affect relative utility. When tax rate increases, absolute value of relative utility becomes higher even if an increase in tax rate may reduce inequality. This is because higher tax rate induces lower household absolute income irrespective of tax effects on income distribution.

Data availability

The data that support the findings of this paper are available on request. The data in this paper were derived from the following public domain resources: https://www.eia.gov/outlooks/archive/ieo17/; https://stats.oecd.org/; https://data.oecd.org/gdp/gdp-long-term-forecast.htm; https://www.un.org/development/desa/publications/world-population-prospects-the-2017-revision.html; The access of 2013 Chinese Household Income Project (CHIP) data permission must be obtained from the owners: http://www.ciidbnu.org/chip/chips.asp?year=2013.

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References

Armington PS (1969) A theory of demand for products distinguished by place of origin. Staff Papers (International Monetary Fund) 16(1):159–178

Bae JH (2018) Impacts of income inequality on CO_2 emission under different climate change mitigation policies. Korean Econ Rev 34(2):187–211

Beck U (2010) Remapping social inequalities in an age of climate change: for a cosmopolitan renewal of sociology. Glob Netw 10(2):165–181

Berry A (2019) The distributional effects of a carbon tax and its impact on fuel poverty: a microsimulation study in the French context. Energy Policy 124:81–94

Bi HM, Xiao H, Sun KJ (2019) The impact of carbon market and carbon tax on green growth pathway in China: a dynamic CGE model approach. Emerg Market Finan Trade 55(6):1312–1325

Bosmans K, Ozturk ZE (2018) An axiomatic approach to the measurement of envy. Soc Choice Welf 50(2):247–264

Bruvoll A, Larsen BM (2004) Greenhouse gas emissions in Norway: do carbon taxes work? Energy Policy 32(4):493–505

Burke M, Hsiang SM, Miguel E (2015) Global non-linear effect of temperature on economic production. Nature 527(7577):235

Campagnolo L, Davide M (2019) Can the Paris deal boost SDGs achievement? An assessment of climate mitigation co-benefits or side-effects on poverty and inequality. World Dev 122:96–109

Chen W et al. (2017) Effects of an energy tax (carbon tax) on energy saving and emission reduction in guangdong province-based on a CGE model. Sustainability 9:5

Chi YY et al. (2014) Scenarios analysis of the energies' consumption and carbon emissions in China based on a dynamic CGE Model. Sustainability 6(2):487–512

CHLR (2018) Human capital in China, in China human capital report series. Central University of Finance and Economics, Beijing

CIID (2013) Chinese Household Income Project. [cited 08/11/2021]; Available from: http://www.ciidbnu.org/chip/chips.asp?year=2013

Clark AE, Frijters P, Shields MA (2008) Relative income, happiness, and utility: an explanation for the Easterlin paradox and other puzzles. J Econ Lit 46(1):95–144

Clark AE, Oswald AJ (1996) Satisfaction and comparison income. J Public Econ 61(3):359–381

Cobham A, Schlogl L, Sumner A (2016) Inequality and the tails: the Palma proposition and ratio. Glob Policy 7(1):25–36

Crossland J, Li B, Roca E (2013) Is the European Union Emissions Trading Scheme (EU ETS) informationally efficient? Evidence from momentum-based trading strategies. Appl Energy 109:10–23

Davies JB, Shi XJ, Whalley J (2014) The possibilities for global inequality and poverty reduction using revenues from global carbon pricing. J Econ Inequal 12(3):363–391

Dennig F et al. (2015) Inequality, climate impacts on the future poor, and carbon prices. Proc Natl Acad Sci USA 112(52):15827–15832

Dong HJ et al. (2017) Exploring impact of carbon tax on China's CO2 reductions and provincial disparities. Renew Sustain Energy Rev 77:596–603

Dorband II et al. (2019) Poverty and distributional effects of carbon pricing in low- and middle-income countries—A global comparative analysis. World Dev 115:246–257

EIA (2017) International Energy Outlook 2017 [cited: 08/11/2021]; Available from: https://www.eia.gov/outlooks/archive/ieo17/

Ferrer-i-Carbonell A (2005) Income and well-being: an empirical analysis of the comparison income effect. J Public Econ 89(5-6):997–1019

Freitas LFD et al. (2016) The distributional effects of emissions taxation in Brazil and their implications for climate policy. Energy Econ 59:37–44

Georgellis Y, Tsitsianis N, Yin YP (2009) Personal values as mitigating factors in the link between income and life satisfaction: evidence from the European Social Survey. Soc Indic Res 91(3):329–344

Grottera C, Pereira AO, La EL (2017) Rovere, impacts of carbon pricing on income inequality in Brazil. Clim Dev 9(1):80–93

Guo ZQ et al. (2014) Exploring the impacts of a carbon tax on the Chinese economy using a CGE model with a detailed disaggregation of energy sectors. Energy Econ 45:455–462

Hagerty MR, Veenhoven R (2003) Wealth and happiness revisited— Growing national income does go with greater happiness. Soc Indic Res 64(1):1–27

Howarth RB, Kennedy K (2016) Economic growth, inequality, and well-being. Ecol Econ 121:231–236

Huanbao IN-EN (2022) The Daily Report of the Transaction Price of the Nationwide ETS Price in China on 25 February 2022 [cited: 28/02/2022]; Available from: https://huanbao.in-en.com/html/huanbao-2347746.shtml

Jakob M, Steckel JC (2014) How climate change mitigation could harm development in poor countries. Wiley Interdiscip Rev Clim Change 5(2): 161–168
Jia ZJ, Lin BQ. (2020) Rethinking the choice of carbon tax and carbon trading in China. Technol Forecast Soc Change 159:120187
Johansen L (1960) A multi-sectoral study of economic growth. Oxford, North-Holland, Amsterdam, p 177
Johansson-Stenman O, Carlsson F, Daruvala D (2002) Measuring future grandparents' preferences for equality and relative standing. Econ J 112(479):362–383
Jorgenson DW et al. (2018) The welfare consequences of taxing carbon. Clim Change Econ 9:1
Klenert D, Mattauch L (2016) How to make a carbon tax reform progressive: the role of subsistence consumption. Econ Lett 138:100–103
Klenert D et al. (2018) Environmental taxation, inequality and Engel's law: the double dividend of redistribution. Environ Resour Econ 71(3):605–624
Li ZL et al. (2018) Exploring the impacts of regional unbalanced carbon tax on CO2 emissions and industrial competitiveness in Liaoning province of China. Energy Policy 113:9–19
Li H et al. (2019) Scenario analysis of ETS revenue allocation mechanism of China: based on a dynamic CGE model. Environ Sci Pollut Res 26(27): 27971–27986
Li W, Jia ZJ (2017) Carbon tax, emission trading, or the mixed policy: which is the most effective strategy for climate change mitigation in China? Mitig Adapt Strateg Glob Change 22(6):973–992
Li W, Jia ZJ (2016) The impact of emission trading scheme and the ratio of free quota: a dynamic recursive CGE model in China. Appl Energy 174:1–14
Lin BQ, Jia ZJ (2020) Can carbon tax complement emission trading scheme? The impact of carbon tax on economy, energy and environment in China. Clim Change Econ 11:3
Lindner S, Legault J, Guan D (2013) Disaggregating the electricity sector of China's input-output table for improved environmental life-cycle assessment. Econ Syst Res 25(3):300–320
Liu Y, Lu YY (2015) The economic impact of different carbon tax revenue recycling schemes in China: a model-based scenario analysis. Appl Energy 141:96–105
Long ZM, Herrera R (2016) Building original series of physical capital stocks for China's economy methodological problems, proposals for solutions and a new database. China Econ Rev 40:33–53
Lu YY, Stern DI (2016) Substitutability and the cost of climate mitigation policy. Environ Resour Econ 64(1):81–107
Macaluso N et al. (2018) The impact of carbon taxation and revenue recycling on U.S. industries. Clim Change Econ 9:1
Markkanen S, Anger-Kraavi A (2019) Social impacts of climate change mitigation policies and their implications for inequality. Clim Policy 19(7):827–844
Matto A, Subramanian A (2012) Equity in climate change: an analytical review. World Dev 40(6):1083–1097
Mendelsohn R, Dinar A, Williams L (2006) The distributional impact of climate change on rich and poor countries. Environ Dev Econ 11:159–178
Michalos AC (1985) Multiple discrepancies theory (Mdt). Soc Indic Res 16(4): 347–413
Montenegro RC et al. (2019) Long-term distributional impacts of European cap-and-trade climate policies: a CGE multi-regional analysis. Sustainability 11:23
Moore FC, Diaz DB (2015) Temperature impacts on economic growth warrant stringent mitigation policy. Nat Clim Change 5(2):127–131
NDRC (2015) Enhanced actions on climate change: China's intended nationally determined contributions. Policy. Food and Agricultural Organization of the United Nations, Beijing
OECD (2014) Long-term baseline projections. OECD Economic Outlook: Statistics and Projections 2014 [cited: 28/10/2021]; Available from: https://stats.oecd.org/
OECD (2018) GDP long-term forecast. [cited: 28/10/2021]; Available from: https://data.oecd.org/gdp/gdp-long-term-forecast.htm
Padilla E, Serrano A (2006) Inequality in CO_2 emissions across countries and its relationship with income inequality: a distributive approach. Energy Policy 34(14):1762–1772
Pham TKC (2008) Consequences of relative utility hypothesis in economic analysis. Revue D Econ Polit 118(4):541–572
Rao ND, Min J (2018) Less global inequality can improve climate outcomes. Wiley Interdiscip Rev Clim Change 9:2
RIFS (2009) Research on levying carbon tax in China. [cited 26/02/2022]; Available from: https://max.book118.com/html/2015/0507/16555574.shtm
Sands RD (2018) U.S. carbon tax scenarios and bioenergy. Clim Change Econ 9:1
Taconet N, Mejean A, Guivarch C (2020) Influence of climate change impacts and mitigation costs on inequality between countries. Clim Change 160(1):15–34
UN (2017) World population prospects: The 2017 revision. [cited 16/10/2021]; Available from: https://www.un.org/development/desa/publications/world-population-prospects-the-2017-revision.html
Wang Q et al. (2019) Distributional impact of carbon pricing in Chinese provinces. Energy Econ 81:327–340
Winsemius HC et al. (2018) Disaster risk, climate change, and poverty: assessing the global exposure of poor people to floods and droughts. Environ Dev Econ 23(3):328–348
Xiao BW et al. (2015) The impacts of environmental tax in China: a dynamic recursive multi-sector CGE model. Energies 8(8):7777–7804
Xie Y, Dai HC, Dong HJ (2018) Impacts of SO2 taxations and renewable energy development on CO_2, NO_x and SO_2 emissions in Jing-Jin-Ji region. J Clean Prod 171:1386–1395
Yahoo M, Othman J (2017) Employing a CGE model in analysing the environmental and economy-wide impacts of CO_2 emission abatement policies in Malaysia. Sci Total Environ 584:234–243

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Competing interests

The author declares no competing interests.

Ethical approval

The author confirms that all research was performed in accordance with relevant guidelines/regulations.

Informed consent

This paper does not contain any studies with human participants performed by the author.

Additional information

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