Allocating China's CO_2 Emissions based on Economic Welfare Gains from Environmental Externalities

Yiyi Cao,[1, 2] Shen Qu,[1, 2, *] Heran Zheng,[3] Jing Meng,[3] Zhifu Mi,[3] Weiming Chen,[1, 2] and Yi-Ming Wei[1, 2]
1 School of Management and Economics, Beijing Institute of Technology, Beijing, 100081, China
2 Center for Energy & Environmental Policy Research, Beijing Institute of Technology, Beijing, 100081, China
3 The Bartlett School of Sustainable Construction, University College London, London WC1E6BT, UK
*Email: squ@bit.edu.cn

ABSTRACT

To achieve carbon neutrality (i.e., net zero carbon emissions) by 2060, China must make significant changes in its socioeconomic systems, including appropriately allocating emissions responsibility. Traditional methods of delineating responsibilities (such as production-based and consumption-based accounting) can lead to double counting when applied simultaneously and therefore difficulty in determining responsibilities of different agents. An alternative approach based on economic welfare gains from environmental externalities has been refined, ensuring that the responsibilities of consumers and producers add up to the total emissions. The application of this approach to 48 countries and 31 Chinese provinces reveals that regions with less elastic supply and demand, such as Hebei in China and Russia, have higher responsibilities. Furthermore, larger externalities associated with unitary product value shifts the burden of obligations from producers to consumers. Regions with high levels of wealth and carbon-intensive imports, such as Zhejiang and Guangdong in China, as well as the United States, typically have higher CBA emissions than PBA emissions and, as a result, redistributed responsibilities between PBA and CBA emissions. The new distribution results vary significantly from PBA or CBA emissions, indicating opportunities for more comprehensive and accessible policy goals.

Keywords: Emissions responsibility; Economic welfare; Price elasticities; Externalities; Input-output analysis; Carbon mitigation

Synopsis: The allocation of responsibility for carbon emissions is a key step in mitigating climate change. By sharing responsibility in accordance with the cost-benefit rule, the efficiency of environmental policies is increased. This study aims to allocate China's provincial emissions based on economic welfare and investigate how supply and demand price elasticities, as well as environmental externalities, can influence the allocation of emission responsibility.

INTRODUCTION

Global climate change has become a threat to both humans and other natural species, accelerating extinction risks for a significant number of species and affecting human health[1,2,3] and economic development.[4,5,6,7] Therefore, stricter low-carbon policies are needed to stabilize the global climate.[8,9] So far, a host of regions in the world have taken action on setting low-carbon goals, which contribute to the 1.5 °C goals.[10] China has promised to reach carbon neutrality before 2060, meaning that the country needs to achieve net zero carbon emissions by 2060 when anthropogenic CO_2 emissions are balanced by anthropogenic CO_2 removals over a specified period.[11] However, challenges also exist during the course of reaching carbon neutrality. Compared to other developed countries, China has a shorter interim period from peak carbon to neutrality.[12] As a developing country, China has a great dependency on heavy industries with the discharge of massive emissions into the atmosphere. Therefore, achieving carbon neutrality needs a profound and fast social transformation, with bottom-up measures coordinated with top-down policies.[13,14,15,16] The appropriate accounting and distribution of responsibility for emissions should be the first step of greenhouse gases (GHG) mitigation.[17]

Not only local consumption but also external demand drive GHG emissions.[18,19] The *Paris Agreement* has urged countries to manage to achieve their low-carbon goals, but without efficient schemes to conduct climate policies, this could lead to carbon leakage among different countries[20,21,22] or different industries in one country.[23] The situation has occurred where emissions are transferred from one department which has reduced emissions to another less-strict department; therefore, assigning responsibility between producers and consumers can contribute to a more efficient global climate policy.[24,25,26] Two of the most traditional and basic accounting methods for emissions include production-based accounting (PBA) and consumer-based accounting (CBA). PBA measures carbon emissions from industrial production and household energy use in a region, while CBA accounts for carbon emissions resulting from final consumption of the region. Under the current accounting scheme, the responsibility allocation among countries is sometimes unfair.[27] According to previous research,[28,29] PBA fails to provide a complete description of emissions because it ignores the role of interregional and international trade. Furthermore, accounting for responsibilities solely from the production perspective ignores the driving force of consumption on emissions.[30] On the other hand, CBA also suffers from some shortcomings. The most evident one is that it solely allocates responsibilities to consumers.[31,32,33] Also, other factors such as limitations in data availability or quality, incomplete knowledge of key variables or relationships, or simplifying assumptions made to facilitate modeling may affect the accuracy and reliability of the estimates obtained [34,35,36,37,38] Given the unequal distribution of political willingness and transaction costs for climate change mitigation,[39] assigning responsibility to both producers and consumers based on their economic welfare ensure a balanced distribution of costs and benefits, and increase the engagement of agents in the supply chain for mitigation actions.

Here, we adopt and improve upon a new method[40] that allocates trade-related emissions from different provinces in China based on economic welfare. We improve the resolution of the original method by extending it to trade flows between region and sectors rather than regions. We also improve the computation of the model by solving for the exact price and welfare changes for consumers and producers under a new carbon price. The application of this method to China's case is critical since a unified framework to clarify producer and consumer environmental responsibilities can induce more stakeholders to take climate actions, reduce interregional carbon leakages and increase resource efficiencies. This is critical for a large country with urgent climate mitigation goals and complex industrial networks like China. Specifically, the method sets up a hypothetical situation where externalities are internalized by a carbon tax. We use the differences in economic welfare between reality and the hypothetical situation as agents' welfare gains from CO_2 emissions. We then allocate emission responsibilities in proportion to such producer and consumer welfare gains from environmental externalities. Specifically, we embed China's multi-regional input-output (MRIO) table into a global one and estimate emissions embodied in bilateral trade flows. Following the above method, we redistribute emission responsibilities associated with interprovincial and international trade based on economic welfare. In this way, we construct new emission accounts of provinces and sectors in China and other countries in the world for emissions directly generated in China. The comparison between traditional allocation schemes and economic welfare-based allocation reveals policy opportunities for emission mitigation.

MATERIALS AND METHODS

We adopt an economic welfare-based accounting to reassign emissions responsibilities, inspired by the previous research by Jakob et al.[40]. Compared with the previous research, we improve spatial resolution and extend the parameter space. First, we insert a Chinese MRIO table into a global MRIO table to connect provincial trade flows to global trade. Then we take the heterogeneity of price elasticities into consideration by including elasticities of each sector in China. This paper also introduces an implicit function into the model to extend parameter space. The following three sections explain our method in detail.

1. Insert China MRIO into world MRIO table

We calculate the trade-related emissions based on the MRIO table from EXIOBASE[41]. The table contains 163 industries and 49 countries. To discuss both interprovincial and international results, we insert the Chinese MRIO model from China Emission Accounts and Data sets (CEADs)[42] into the world MRIO and create a new global MRIO model. Some previous studies have done similar connections. For instance, Mi et al. connected Chinese MRIO with the Global Trade and Analysis Project (GTAP) database in their research in 2017.[43] We first reorganize the Chinese industries in the world MRIO table into 42 industries, consistent with the Chinese MRIO table (Supplemental Table.S3-S4). Then we disaggregate imports and exports for each province among other 48 countries, assuming that the imports and exports of each industry in each province follow the same distribution among other countries as each industry of China in the world MRIO table does. In order to balance the new input-output table while retaining the original structure of the input-output table to the maximum extent, we use RAS technique, in other words, biproportional method, to adjust the elements of the imports, exports, and final demands for each province so as to make the row and column sums consistently with original sums of EXIOBASE table. The new elements in the matrix of intermediate inputs after linking China MRIO to the world MRIO are given by Eq.1-2:

$$\bar{Z}_{p_1,i}^{r_2,j} = \frac{Z_{CHN,i}^{r_2,j}}{EX_{CHN,i}} \cdot EX_{p_1,i} \tag{1}$$

$$\bar{Z}_{r_2,j}^{p_1,i} = \frac{Z_{r_2,j}^{CHN,i}}{IM_{CHN,i}} \cdot IM_{p_1,i} \tag{2}$$

where $\bar{Z}_{p_1,i}^{r_2,j}$ indicates the new flow from industry i in Chinese province p_1 to industry j in another country r_2. EX and IM represent imports and exports of the certain region from (to) another country. We compute the new elements in the matrix of final demands as follows:

$$\bar{y}_{p_1,i}^{r_2} = \frac{y_{CHN,i}^{r_2}}{y\_EX_{CHN}} \cdot EX_{p_1,i} \tag{3}$$

$$\bar{y}_{r_2,j}^{p_1} = \frac{y_{r_2,j}^{CHN}}{y\_IM_{CHN}} \cdot y\_IM_{p_1} \tag{4}$$

Similar to the first two equations, $\bar{y}^{r_2}_{p_1,i}$ is the final demand for industry i in province p_1 of the country r_2. y_IM and y_EX indicate the total final demand of China (a province) for imports from other countries and the summation of final demands of other countries for imports from China (a province), respectively. The new global MRIO table has 48 countries, each with 163 industries, and 31 provinces, each with 42 industries.

2. Derive trade-related emissions

We compute trade-related emissions based on an IO model. The IO table is composed with a flow matrix Z and final demand y. The horizontal summation of the IO table is the total output x. In the following equations (5) and (6), we derive the Leontief inverse matrix *L* to portray the economic system:

$$A^{r_2,j}_{r_1,i} = Z^{r_2,j}_{r_1,i} / x_{r_2,j} \tag{5}$$

$$L = (I - A)^{-1} \tag{6}$$

where *A* is the technology matrix indicating the coefficients of direct consumption. The element $Z^{r_2,j}_{r_1,i}$ reflects the monetary flow from sector i in region r_1 to sector j in region r_2. The total emissions associated with bilateral trades, CO_2eq, are given by:

$$f_{r_1,i} = CE_{r_1,i} / x_{r_1,i} \tag{7}$$

$$CO_2eq = fLy \tag{8}$$

CE stands for the direct carbon emissions for each industry of each region. EXIOBASE provides satellite accounts for direct carbon emissions for each industry of each country. CEADs also provides the carbon emission inventory for each industry of each province. The vector *f* is the industrial emission intensity of each region. In this research, we account for the major GHG emissions (i.e., carbon dioxide, methane, and nitrous oxide) and convert them to CO_2 equivalents according to their global warming potentials listed by IPCC.[44]

3. Responsibility sharing between producers and consumers

By vertically summing the Z matrix, we can derive the total input matrix *IN*. The element $V_{r_1,i}$ in the matrix V is the difference between the total output and input of industry i in the region r_1 as shown in Eq.9. In Eq.10, we define BTR as bilateral trade relations, indicating the value added embodied in bilateral trades and V is the matrix of value added. To estimate the ratio of externalities to product value for each bilateral trade, we adopt the general carbon price of 50 USD per tonne of CO_2 proposed by Carbon Pricing Leadership Coalition in order to achieve the 2℃ goal minimally,[45] and compute externalities in Eq.11. T_G is the general carbon price given by IPCC and *T* is the matrix of external costs per unit of value. Here $T_{r_1,i}^{r_2,j}$ suggests the external cost per unit of value embodied in trading from region r_1 to r_2. From Eq.11, we have omitted the subscripts i and j, which represent industries in different regions, for ease of reading. Actually, we focus on the trade flow between the products of one region and another region and calculate at the product level.

$$V_{r_1,i} = x_{r_1,i} - IN_{r_1,i} \tag{9}$$

$$BTR = VLy \tag{10}$$

$$T_{r_1}^{r_2} = CO_2eq_{r_1}^{r_2} \cdot T_G / BTR_{r_1}^{r_2} \tag{11}$$

The allocation according to economic welfare is based on the basic supply-demand model. We first construct demand and supply functions, q_s and q_d in Eq.12. σ and δ are the price elasticities of export supply and import demand. We adopted the elasticities from recent research by Tokarick et al.[46] and Fan et al.[47] Due to limited data, we applied overall industrial price elasticities of China to each province. Applying carbon prices will cause an increase of consumer prices relative to producer prices and the increase rate is set as *t*. Hence, we can deduce that $p_d = (1+t)p_s$. The new equilibrium is set where q_s equals q_d, which leads to Eq.13. and Eq.14.

$$q_s = p_s^{\sigma} \quad q_d = p_d^{\delta} \tag{12}$$

$$p_s = (1+t)^{\delta/(\sigma-\delta)} \tag{13}$$

$$p_d = (1+t)^{\sigma/(\sigma-\delta)} \tag{14}$$

To internalize the externality caused by economic activities, the usual practice is to set the carbon prices equal to the externalities per unit of product value, as shown in Eq.15. Therefore, T is connected with the increasing rate t through price elasticities of supply and demand. Based on that, we can derive t from Eq.16 by solving the implicit function of externalities and elasticities.

$$T_{r_1}^{r_2} = p_d - p_s = t_{r_1}^{r_2} \cdot p_s = t_{r_1}^{r_2}(1+t_{r_1}^{r_2})^{\delta_{r_2}/\sigma_{r_1}-\delta_{r_2}} \tag{15}$$

$$t_{r_1}^{r_2} = f(T_{r_1}^{r_2}, \delta_{r_2}, \sigma_{r_1}) \tag{16}$$

After enforcing the carbon price on the emissions, consumers and producers will suffer a decreased trade volume and higher prices needed to pay. This will cause the economic surplus to decline, and the change in surplus is the economic welfare from emitting GHG into atmosphere without regulation. For each bilateral trade, producers' and consumers' welfare can be derived based on the supply-demand model, as shown in Eq.17 and Eq.18:

$$\Delta PS_{r_1}^{r_2} = \int_{p_s}^{p_0} p^{\sigma} dp = \frac{1}{1+\sigma_{r_1}}[1-(1+t)^{\delta_{r_2}(1+\sigma_{r_1})/\sigma_{r_1}-\delta_{r_2}}] \quad (17)$$

$$\Delta CS_{r_1}^{r_2} = \int_{p_0}^{p_d} p^{\delta} dp = \frac{1}{1+\delta_{r_2}}[(1+t)^{\sigma_{r_1}(1+\delta_{r_2})/\sigma_{r_1}-\delta_{r_2}} - 1] \quad (18)$$

where $\Delta PS_{r_1}^{r_2}$ ($\Delta CS_{r_1}^{r_2}$) indicates the extra welfare that the region r_1 (r_2) generated from externalities associated with exports (imports) to (from) the region r_2 (r_1). Consumers and producers both benefit from free emissions to different extents. We can then employ the economic welfare in Eq.17-18 to divide the emissions responsibility between producers and consumers. The consumer and producer shares of trade-related emissions are then derived from Eq.19-20. And the consumer (R_c) and producer (R_p) responsibility are given by Eq. 21-22.

$$ProducerShare_{r_1}^{r_2} = \Delta PS_{r_1}^{r_2} / (\Delta CS_{r_1}^{r_2} + PS_{r_1}^{r_2}) \quad (19)$$

$$ConsumerShare_{r_1}^{r_2} = \Delta CS_{r_1}^{r_2} / (\Delta CS_{r_1}^{r_2} + PS_{r_1}^{r_2}) \quad (20)$$

$$R_p = ProducerShare_{r_1}^{r_2} \cdot CO_2eq_{r_1}^{r_2} \quad (21)$$

$$R_c = ConsumerShare_{r_1}^{r_2} \cdot CO_2eq_{r_1}^{r_2} \quad (22)$$

Producers' and consumers' shares of responsibility are proportional to their economic welfare. We assign the total emissions embedded in the supply chain to both producers and consumers, thus avoiding double-accounting of responsibility.

4. Data sources

The global and Chinese input-output data is available at EXIOBASE[41] and China Emission Accounts and Data sets (CEADs)[42], respectively. The MRIO tables were constructed using current prices from 2017, therefore, both tables remain consistent with each other, despite the absence of a base year adjustment. Apart from CO_2 emissions, other GHG have also shown great impacts on climate change. Therefore, we calculate the major GHG emissions (i.e., carbon dioxide, methane, and nitrous oxide) in this research and converted them to CO2 equivalents according to their global warming potentials listed by IPCC.[44] The general carbon price we use is derived from *Report of the High-Level Commission on Carbon Prices* released by Carbon Pricing Leadership Coalition.[45] This report assessed the price of carbon required to meet the 2ºC target in baseline scenarios and 50 USD/tCO_2eq is the lowest price to assure the probability of achieving the 2ºC target over 66%. To build the supply-demand model, we adopt price elasticities measured by Tokarick et al.[46] and Fan et al.[47] who computed price elasticities of countries and industries in China, respectively. Since we lack elasticities of each industry in countries, we elect trade flows from each industry in each province to consumers and trade flows from each country to consumers so that we only need to adopt price elasticities of countries and industries of each province. It's also noticeable that the research by Fan et al. provides national industrial price elasticities so we assume that they are the same for all Chinese provinces.

RESULTS

1. Allocation of provincial emissions responsibility based on the economic welfare

Figure 1 displays emissions associated with trade flows among major Chinese provinces, which account for 44% of China's total emissions. Jiangsu province generates the most trade-related emissions, 0.95 Gt, among all provinces in China, with over 50% of responsibility in all bilateral trades with other places. Emissions from exports to Zhejiang and Guangdong make up a significant portion of Jiangsu's total emissions, with 54.7% and 70.9% of responsibilities in bilateral trades assigned to Jiangsu under the economic welfare accounting scheme.

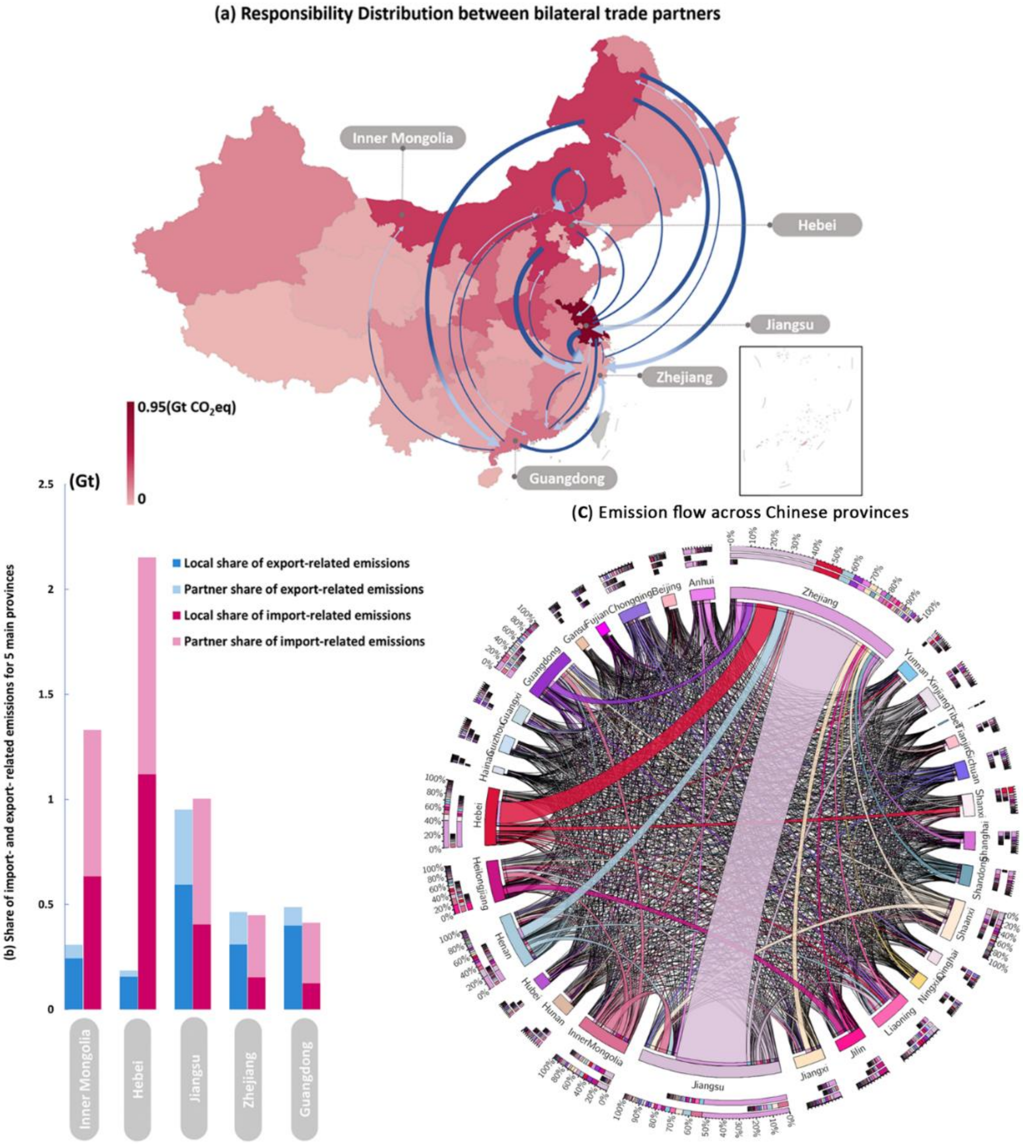


Figure 1. Responsibility distribution among major provinces in China. **a** Mapping the provincial emission allocation. The magnitude of export-related emissions is ranked by the shades of colors. The blue arrows represent the emissions associated with trade flows. The dark area is the share of exporters and the light area represents importer shares. **b** Quantification of main provinces' share of import- and export-related emissions under the economic welfare accounts. **c** The Circos depicts the overall emission flows across provinces with relative ratios indicating components of each province's PBA and CBA emissions within China.

The map also indicates Hebei as the second important source of emissions associated with trading. Out of 0.46 Gt trade-related emissions in Hebei, Zhejiang (0.1Gt) and Inner Mongolia (3.9Mt) are two major targets of export. Under the new scheme of accounting responsibilities, Hebei usually needs to undertake around half of the total responsibility less than other resource-dependent cities. Compared with other provinces, trade-related emissions in Inner Mongolia are split relatively evenly to different targets instead of concentrating on one or two important regions, which is due to the abundant exporting resources and mature shipping networks of Inner Mongolia, and these make the region a strong trade partner for many provinces. The share of Inner Mongolia in trade with Jiangsu and Guangdong is 83.8% and 89.5%, respectively. That Inner Mongolia has a markedly higher share of responsibilities for export emissions results from its lower price elasticities of supply, which indicates that Inner Mongolia is more dependent on export trading for its economic prosperity.

Guangdong (0.1Gt) and Zhejiang (28.9Mt) have generated relatively low emissions from exporting but Zhejiang is the biggest import-related emissions recipient with 2.0Gt GHG emissions. Guangdong takes more responsibility than its trade partners based on economic welfare. Zhejiang is the biggest target of Guangdong with 32.3Mt emissions, of which 63.3% is accrued to Guangdong. The emission associated with imports of Zhejiang is very large (See Supplemental Figure. S1). Similar to Inner Mongolia, Zhejiang splits its exports among several regions. Out of 2.0 Gt, 330 and 203Mt of emissions come from imports from Jiangsu and Hebei, only accounting for 17% and 5%. Another large share of the emissions results from international trade. However, opposite to Inner Mongolia, Zhejiang has relatively higher demand elasticities facing Hebei and Jiangsu and is thus assigned a smaller share of responsibilities. Zhejiang undertakes 46.8% responsibilities for emissions generated from importing from Hebei and 45.3% of responsibilities for importing from Jiangsu.

2. Emissions flow and responsibility allocation in the international trade

In Figure 2, we present the redistribution of emissions responsibilities based on economic welfare, which differs significantly from the results of PBA and CBA. We expand our analysis to other countries worldwide, taking into account major provinces involved in international trade. The regions we consider represent a significant proportion of global export-related and import-related emissions. Some provinces, like Zhejiang and Guangdong, are non-negligible targets of trade-related emissions. These two provinces account for 11.9% of emissions embodied in exports from Japan, making them the second and third largest targets of Japanese export-related emissions. In addition, emissions embodied in exports to Zhejiang and Guangdong also rank third and fourth for the US, second and fourth for India, and third and fifth for Russia. Japan constitutes the largest share of export emissions from the US, with 0.15 Gt, up to 38.4% of emissions embodied in bilateral trades between the US and the other eight regions.

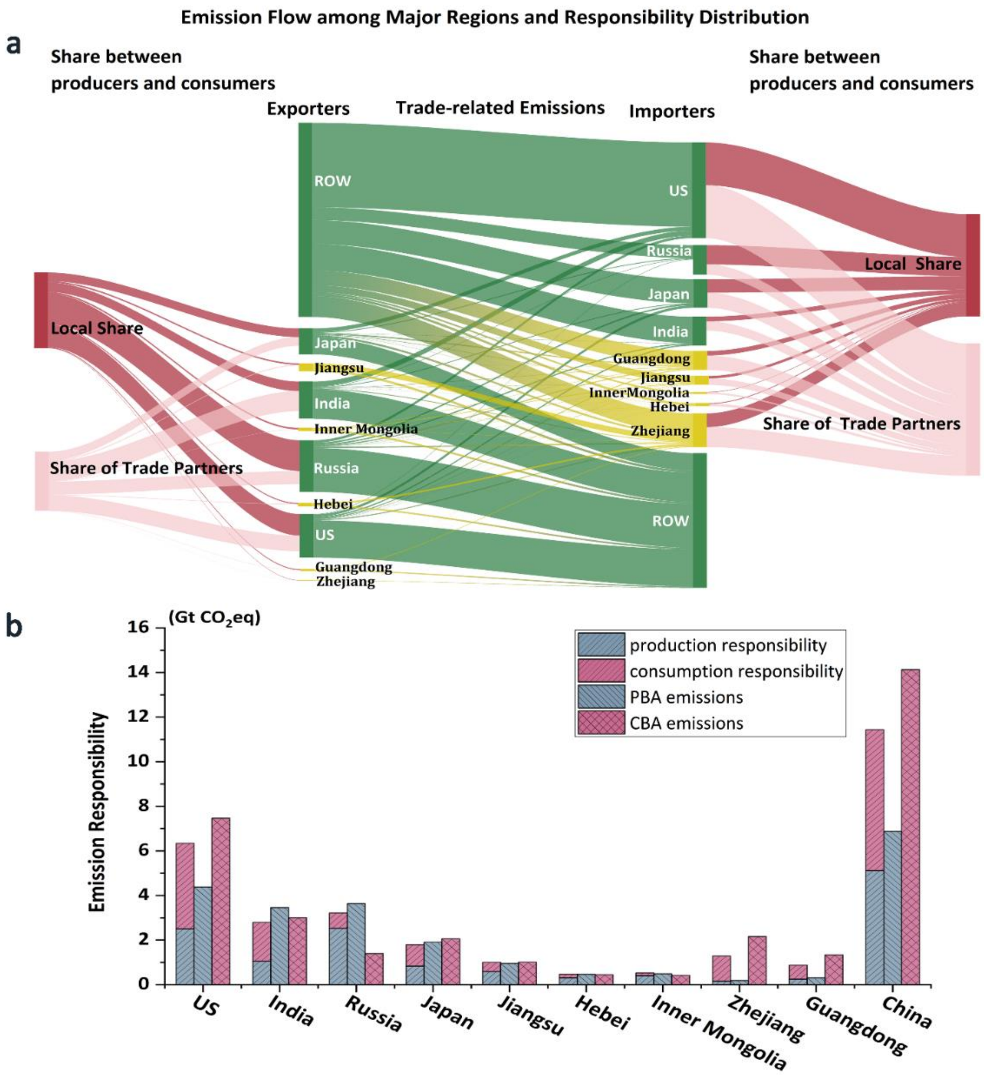


Figure 2. Allocation of emissions to major regions based on economic welfare. **a** Total responsibility shares of major countries and provinces. The figure contains five major Chinese provinces and four countries. ROW means the other regions of the world. The nodes indicate the magnitude of emissions. The links denote emissions embodied in trade flows from exporters (left) to importers (right). The red bars represent the local share of the emissions while pink bars represent emissions assigned to its trade partners. **b** Sensitivity analysis of the scheme based on price elasticities.

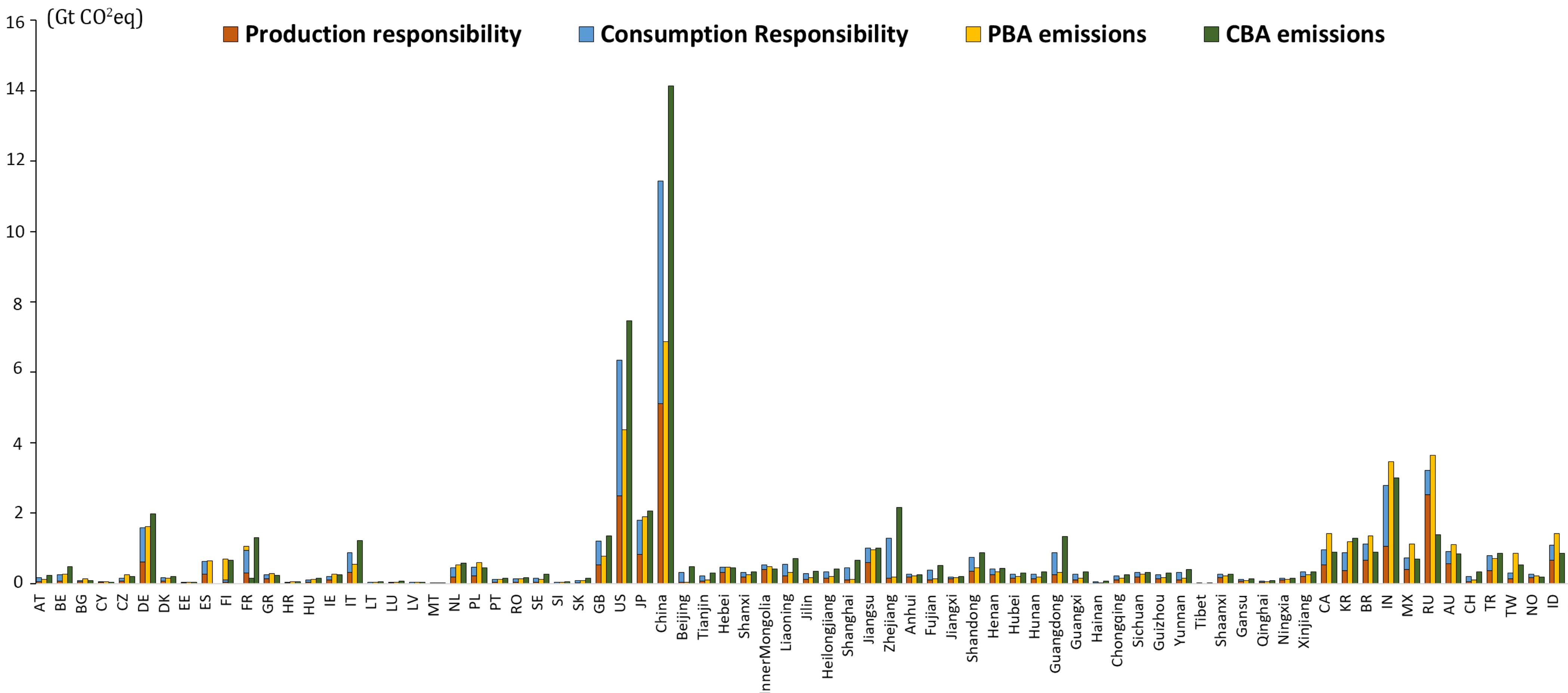
The new results of sharing responsibilities can be different due to price elasticities of supply and demand. For import-related emissions, all these nine regions share around 50% of the total responsibilities (The full results of overall sharing proportions are in Supplemental Table S1.). The US is allocated to a large amount of emission under the CBA scheme, but the method concerning economic welfare only assigns 58.11% of emissions associated with imports in the US. This indicates that the US actually did not gain much welfare through importing from other countries to avoid emissions taking place domestically.

On the other hand, almost all regions share more than half of the export-related emissions except for Japan (49.48%) and India (32.40%). For instance, it is clear that Russia is attributed the majority of the emissions released in the region to fulfil the imports of other trade partners. With a supply elasticity lower than the other eight regions, Russia is assigned 70.40% of total emissions associated with exports to other countries. The relatively even distribution of responsibility between Russia and Chinese provinces, compared to that of responsibility between Russia and other countries, can be attributed to the lower import elasticities of the provinces. This causes Russia's proportional share of production emissions to decrease, as the country receives less economic welfare.

Similarly, the price elasticity of export supply of Inner Mongolia is 0.6918, while the elasticity of import for other regions is relatively higher. Inner Mongolia shares 82.1% of total export-related emissions, and also a large share of emissions embodied in certain exports to other regions. Compared to Russia, Inner Mongolia earns more welfare from not paying prices for emissions from producing exports, that is, Inner Mongolia relies more on export trading. Although the export elasticity of Russia is much smaller than that of Inner Mongolia, the responsibility sharing under the economic welfare scheme still allocates more responsibilities to Inner Mongolia, taking into consideration other factors (see Supplemental Table S2. for proportions of producers' responsibility in bilateral trades among 9 regions.).

We tested our accounting scheme by running a check with extremely inelastic producers and consumers and found that responsibility sharing increases with decreased elasticity. The results aligned with PBA and CBA so they can be considered to allocate emissions assuming producers or consumers are inelastic on supply or demand. However, few countries are actually extremely inelastic on bilateral trade, emphasizing the importance of mutual responsibility sharing. Economic welfare accounting gives a different result of responsibility accounting, as it combines a region's share of both production- and consumption-related emissions.

3. Comparison of responsibility based on economic welfare with PBA and CBA emissions

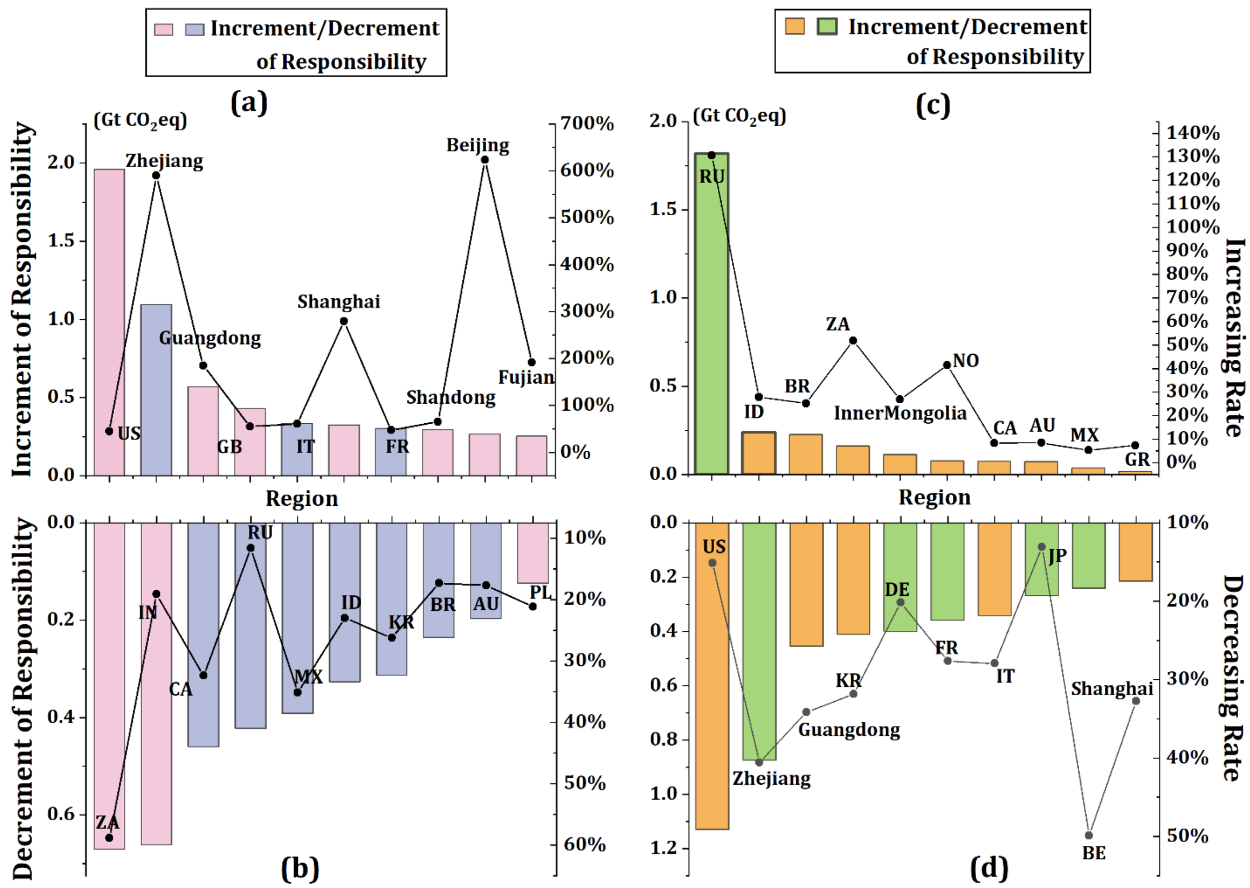


Abbreviation list:

AT: Austria; BE: Belgium; BG: Bulgaria; CY: Cyprus; CZ: Czech Republic; DE: Germany; DK: Denmark; EE: Estonia; ES: Spain; FI: Finland; FR: France; GR: Greece; HR: Croatia; HU: Hungary; IE: Ireland; IT: Italy; LT: Lithuania; LU: Luxembourg; LV: Latvia; MT: Malta; NL: Netherlands; PL: Poland; PT: Portugal; RO: Romania; SE: Sweden; SI: Slovenia; SK: Slovakia; GB: United Kingdom; US: United States; JP: Japan; CA: Canada; KR: Korea; BR: Brazil; IN: India; MX: Mexico; RU: Russia; Russian Federation; AU: Australia; CH: Switzerland; TR: Turkey; TW: Taiwan; NO: Norway; ID: Indonesia; ZA: South Afrika

Figure 3. Comparison among three emissions accounting schemes.

For most regions, accounting based on economic welfare yields a result between PBA and CBA. This also accords with full results of other provinces and countries in Figure 3. For instance, the US and Russia both have either CBA emissions or PBA emissions markedly higher than the other and a sharing responsibility based on economic welfare in between. For India and Japan, the economic welfare accounting scheme allocates fewer emission responsibilities than either PBA or CBA. These two countries do not rely on imports to satisfy domestic needs, thus taking on a small part of emissions associated with international trade. It can be noticed that China's share of PBA emissions is higher than that of CBA emissions. This new distribution of responsibility aligns with the patterns observed across most provinces in China. However, the figure also highlights significant heterogeneity in trading and technological practices across Chinese provinces, with Inner Mongolia, for instance, exhibiting higher emissions than both PBA and CBA. This results from Inner Mongolia's higher PBA emissions and an extremely large share of that. For regions with larger economies, their responsibilities from exports and imports are relatively more balanced. This is partly because of their moderate price elasticities. Larger economies have multiple trading channels and thus don't rely on single trade partners. However, many undeveloped or developing regions with smaller economies tend to undertake a large number of external orders to make economic growth. This explains why they are responsible for the majority of production-related responsibility and a total responsibility exceeding PBA and CBA emissions based on economic welfare. It also should be noted that some developed regions such as Korea will undertake less responsibility than PBA and CBA based on the economic-welfare accounting scheme. These regions fulfill the domestic need through imports from many other regions. Most of these countries have a tertiary sector share of over 60%,[48] which makes their externalities per unit of value added usually less than developing and underdeveloped regions. That's why their new responsibility decrease compared to PBA or CBA.



(a) (b): Compared to PBA emissions; (c) (d): Compared to CBA emissions

Figure 4. Top 10 regions with greatest responsibility changes after applying economic-welfare-based accounting. **a, b** Top 10 increases and decreases compared to PBA emission; **c, d** Top 10 increases and decreases compared to CBA emission.

Economic-welfare-based accounting causes great changes in the allocation of emissions either in positive or negative ways. And the changing rates vary a lot. Figure 4 depicts the top 10 regions with the greatest increment or decrement compared to PBA or CBA emissions. Most regions with the greatest increment compared to PBA emissions have the greatest decrement compared to CBA as well. The greatest increments or decrements compared to PBA and CBA reach up to 1.96 Gt, 0.67 Gt, 1.82 Gt, and 1.13 Gt. And the corresponding change rates are 44.8%, 58.9%, 130.6%, and 15.1%, respectively. The US ranks first among regions with the greatest increment compared to PBA and those with the largest decrement compared to CBA. Russia has the highest increment compared to CBA emissions and South Africa has the most decrement compared to PBA accounting. Beijing and Russia represent two opposite economic situations. They both have the highest increasing rates of PBA or CBA emissions. As a developed city, Beijing has a great import demand and fewer heavy industries, which causes a much heavier emission responsibility from the consumption perspective. Russia depends on heavy industries and thus accrued higher PBA responsibility. But Russia doesn't rely on imports from other countries to fulfill domestic consumption. The accounting results based on the economic welfare make their responsibility grow substantially more than before. Therefore, Figure 4 indicates that current PBA or CBA accounting doesn't match the economic welfare well. This new allocation reveals the weakness of traditional responsibility sharing: they don't take economic welfare into account but determine production or consumption as the sole cause of emission, which is not fair for producers or consumers. The large increasing or decreasing rates also emphasize that local regions' share of import- and export-related emissions can vary a lot, which causes significant differences from PBA or CBA emissions. For most regions in the world, this novel accounting method helps avoid the situation where they take all the guilt of carbon emissions.

4. Influencing factors of economic welfare-based accounting

To better examine the influencing factors of the accounting scheme based on economic welfare, we simulated the allocation under different ratios of externalities to the product value. We found that export supply and import demand elasticities and externalities per unit of product value are three parameters affecting the producer and consumer share. Price elasticities indicate the reliability of regions in foreign trade. The ratio of externalities to the product value suggests the projected environmental cost per unit of production, indicating the extent to which bilateral trades have caused environmental degradation. In Fig. 5 a-c, we depict the producer share under different trade price elasticities and externalities per unit of the product value. It can be seen from the figure that the producer share will decrease while the supply elasticity increases relative to the demand elasticity of the consumer, ceteris paribus. The price elasticity of export (import) supply (demand) reveals the extent to which producers (consumers) rely on external trades to contribute to economic development and consumption needs. A relatively higher export elasticity implies that the producer will switch to other trade partners easily once the price changes, while a relatively lower supply elasticity means that the producers usually stick with their trade partners even if the prices change. Likewise, suppose that the price elasticity of supply remains constant; a higher price elasticity of import demand will lead to a larger share of responsibilities accrued to the producer because the relative decrease of the price elasticity of supply means the producer is more reliable on the bilateral trades than its partner. Therefore, the economic welfare accounting scheme discerns whether the producers (consumers) benefit more from trading and allocates more emissions responsibility to this side.

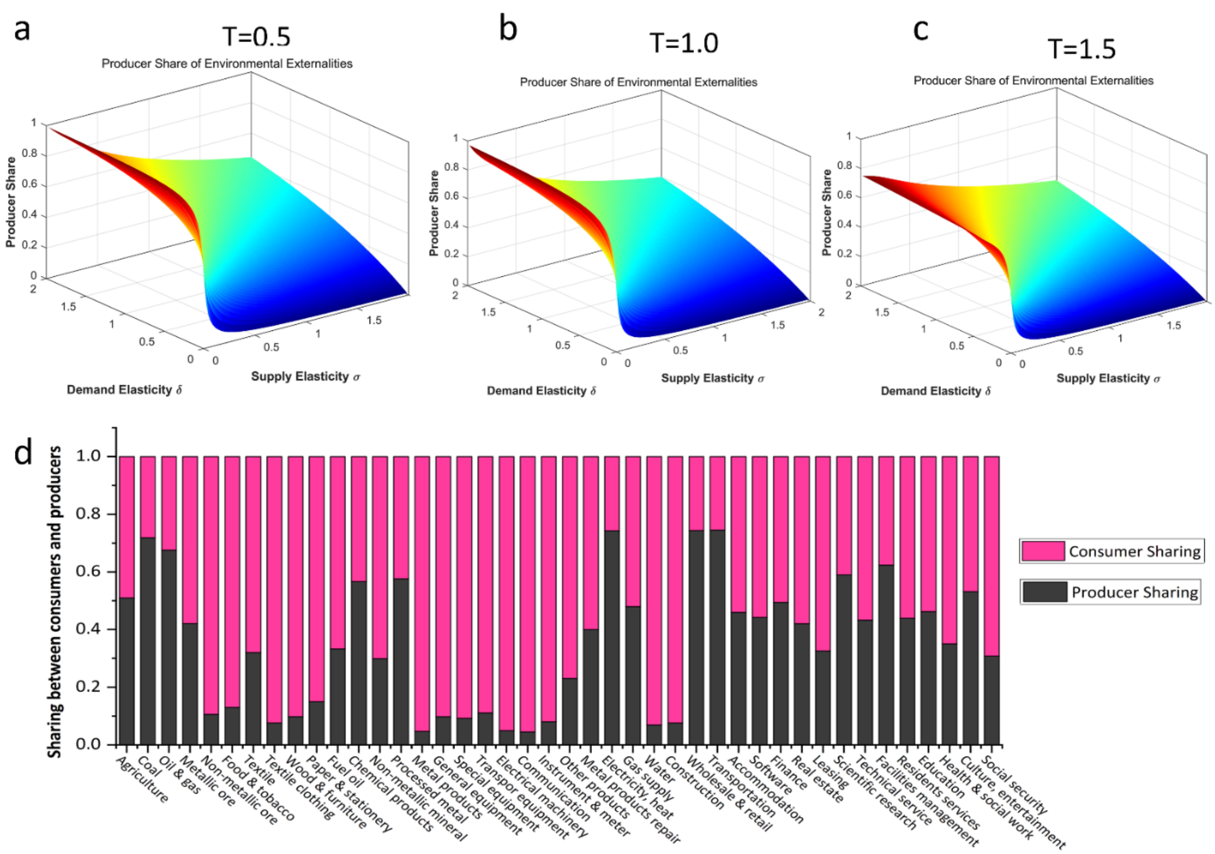


Figure 5. The mechanism of allocation based on economic welfare. **a-c** Influencing factors of the producer and consumer share. T is the externalities per unit of the product value. **d** Responsibility sharing between consumers and producers of industries.

However, simply assigning responsibility according to elasticities will cause confusion when considering regions with different levels of technological evolution. Figure 5.a-c shows that the corresponding cost of emissions per unit of value traded also affects the allocation of responsibility. Comparing the producer share under different ratios of externalities to the product value, we can tell that as the ratio goes up, the producer share will go down. This can explain why Inner Mongolia with higher supply elasticity shares more responsibilities than Russia from trades with the same partner. As the ratio of externalities to the product value increases, the consumers' share increases too. After the ratio exceeds 1, the increase of consumer shares becomes more obvious. The ratio of externalities to product value associated with the trade between Inner Mongolia and any other regions is under 1 in all cases, much smaller than that of Russia. When the ratio keeps going up, it approaches the limit of emissions that can be released during a trade. When the ratio exceeds 1, it means that the cost of environmental degradation exceeds the economic welfare, which hinders sustainable development. In this case, consumers also need to pay the price for deliberately purchasing such carbon-intensive products because their welfare from not having to pay for the pollution also increases.

The virtual simulation we conducted revealed a rule that is consistent with real-world situations, as demonstrated in Figure S2. The figure tracks changes in producer shares among major provinces and countries, indicating that while the producer share of each region tends to increase with higher demand elasticities from trade partners, externalities per unit of product value can cause certain exceptions. Typically, underdeveloped regions experience greater production externalities than developed regions, due to the transfer of older technologies from richer regions and less stringent environmental regulations. Additionally, trade structures are determined by factors such as geographical characteristics and economic structures of each region, which can indirectly affect the value added that each region receives from the same product. As a result, highly industrialized but less developed regions often have smaller elasticities and higher unit externalities, leading to a higher share of local emissions than their more developed trade partners, but a lower share than less-industrialized peripheries.

Taxes or emission trading systems are two major ways to price carbon emissions. If we attach an extra carbon price on the market to internalize the externality, then part of the consumer responsibility will be shifted to the producers, thus increasing producer shares of emission responsibilities. For instance, India has supply elasticity close to that of Japan but shares 17% less export-related emissions. India has attracted much more foreign direct investment and exported quite a number of carbon-intensive products.[49] The externality of Indian production is much heavier than that of Japan; therefore, more responsibilities are transferred to India's trade partners compared to Japan. The ratio of externalities is correlated to technological innovation, as well as industrial characteristics. Figure 5d presents the responsibility sharing between consumers and producers for 42 industries in China. We aggregated the total emission and producers' share of emissions for each trade flow into those of 42 industries and computed the proportion of producer share and consumer share. The ratios vary across different industries, depending on whether they provide carbon-intensive goods or services.

The highest industrial producer share is 74.5% accrued to transportation, and the lowest industrial producer share is 4.5% accrued to the communications industry. Emissions responsibilities are relatively evenly split between producers and consumers in the industries of agriculture (49.0% to producers and 51.0% to consumers) and finance (50.5% to consumers and 49.5% to producers). Each of these two industries has similar supply and demand elasticities. The fuel oil and non-metallic mineral products industries show the importance of identifying externalities per unit of product value during the allocation of responsibilities. The supply and demand elasticities of fuel oil are 0.912 and 0.3805, and 0.67 and 0.36 for Non-metallic mineral products. Correspondingly, the producer's share of emissions responsibility for Fuel oil is 33.3% and that of Non-metallic mineral products is 29.9%. By comparison, the decrease in the supply elasticity of Non-metallic mineral products is relatively larger; thus, there should be more emissions accrued to producers. However, the ratio of externalities to product value of Non-metallic mineral products also increases to 1.01, nearly ten times that of fuel oil, which means that environmental degradation has exceeded the corresponding economic value, so consumers need to pay extra for what they should not have bought.

DISCUSSION

Sharing responsibilities for emissions has long been a source of disputes in climate change mitigation. In this paper, we adopted and improve upon a novel method based on economic welfare gains from environmental externalities. Emission responsibilities can be mutually shared between consumers and producers. We computed the responsibility distribution in bilateral trades and compared the results with PBA and CBA allocations.

The results indicate that producers or consumers more dependent on trade, as manifested by relatively low supply or demand elasticities, tend to generate more economic welfare from exporting (importing) to (from) other regions. Therefore, imposing a certain carbon price will cause a more obvious shock to the low-elasticity side. Furthermore, the ratios of externalities to product values affect how much responsibility consumers should share from producers due to the environmental characteristics of the traded goods. Higher externalities usually result in a shift from producer responsibilities to consumer responsibilities. The wealthier provinces with stricter environmental regulations, such as Beijing, Shanghai, Zhejiang, and Guangdong, purchase large amounts of carbon-intensive products from outside. The relatively high environmental externalities and low demand elasticities for these products results in responsibility transfers from the less well-off producers to more well-off consumers. In other words, the wealthy provinces have enjoyed much economic welfare from not paying for the carbon externalities associated with inter-provincial trading. If the government applies a carbon price to internalize the externalities, their economic surplus will also decline sharply. Such results accord well with policy discussions and economic intuitions for climate change mitigation. For instance, after British Columbia increased their carbon taxes, the price of fossil fuels increased accordingly, which led to higher prices for consumers and lower prices for producers, as well as a decrease in trading volume. The policy initially resulted in a reduction of people's economic surplus. However, over time, carbon emissions decreased and individuals began to purchase fuel-efficient vehicles, which did not destroy the local economy.

Previous studies have tried to attribute environmental impacts in China to either the consumption or production side. By comparing the responsibilities under the economic welfare accounting scheme and PBA/CBA, we find that the newly computed responsibility is usually between the results of PBA and CBA. This is a more moderate way to deal with emissions that can potentially mobilize the entire economic system. Interprovincial and international traders can replan the trade network according to price elasticities and externalities per unit of product value so that consumers and producers of bilateral trades can fairly share emissions responsibilities relative to their economic volume.

One key problem of PBA and CBA is that their summation does not equal the total emissions associated with relevant economic activities, preventing the setting of clear and comprehensive mitigation targets for consumers and producers. Based on the economic welfare gains from environmental externalities, the total emissions from economic activities are split between producers and consumers. The redistribution of responsibilities can contribute to decoupling GHG emissions from economic growth. Furthermore, current researches tend to focus on emission reduction from multi perspectives,[50,51,52] but the results from different perspectives are not interactive. With shared responsibilities under the economic welfare accounting, one can derive a more precise decoupling indicator between emissions and value added for each party in the economic activity. New mitigation policies can therefore avoid placing the mitigation burdens on only one side.

Assigning part of total emissions to consumers, the government can simultaneously encourage both green production and consumption-side revolutions. There are several policies targeted at producers before. Take the emission trade system as an example, the local government can also include local consumers in the cap-and-trade system by setting carbon consumption limits for consumers based on their responsibility. This will solve the major problem when implementing the polluter pays principle in nationwide that some producers avoid regulations by shifting their production to regions with weaker environmental legislation. Consumers will tend to choose cleaner products to lower their carbon consumption, which will urge producers to accelerate the technological transformation to compete for consumers. Based on the responsibility assessment in this research, the government can adjust carbon taxes to let consumers share the burden of industries. It can also serve as a macro-regulatory tool for shortages or surpluses in market economies since adjustments of carbon taxes will change consumer demands or producer supplies. Compared to CBA, more moderate individual carbon accounts can be built to urge consumers to purchase more environment-friendly products, choose a diet pattern with small environmental footprints, use renewable energy and also save electricity, choose greener transportation, and pay attention to recycling. The consumption and production behaviors can be regulated under an integrated and consistent scheme, relieving the tension between both sides about who should be charged with environmental degradation. Since the mitigation responsibility is shared, the government may also share part of the subsidy for green-producing companies with consumers to encourage their green consumption. In any case, all agents involved in emissions deserve welfare and responsibilities corresponding to their degree of participation.

CODE AVAILABILITY STATEMENT

The codes of economic-welfare-based accounting model is openly available at https://github.com/YCAO-Phillipa/Allocating-China-s-CO2-Emissions-based-on-Economic-Welfare-Gains-from-Environmental-Externalities.git.

SUPPORTING INFORMATION

The supporting information provides supplemental Figures and Tables supporting the main text.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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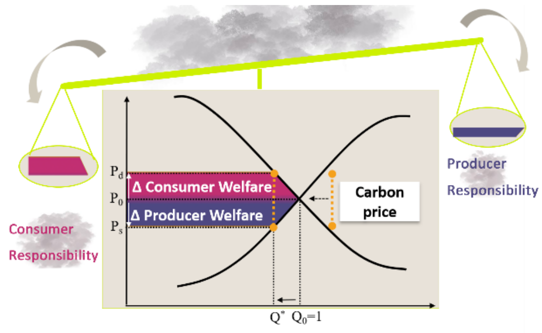

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