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DOI:
10.1016/j.ecolecon.2024.108162

Ecological Economics 220 (2024) 108162

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

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ARTICLE INFO

Keywords:
Shared responsibility
Trade-embodied carbon emissions
Economic benefit
Input-output analysis

ABSTRACT

The distribution of trade-embodied carbon emissions has frequently been a contestation in international climate negotiations. The proposed shared responsibility approach developed by Jakob et al. (2021) is based on economic benefits derived from generating emissions without paying for associated social costs, which are represented by the carbon price. The impacts of the real tariffs on economic benefits were not considered. Here, we improve the proposed approach by introducing the real import and export tariffs and using tariff and elasticity data specified at both country- and sector-level. We re-investigate the responsibility for trade-embodied carbon emissions sharing between 141 economies for 2017. Results show that the improved shared responsibility approach leads to a less extreme distribution of responsibility among countries. The top three emitters, China, the EU27, and the USA, were allocated 939, 761, and 702 million tons of trade-embodied carbon emissions that are 32% below, 39% above, and 50% above production-based emissions and 62% above, 17% below, and 33% below consumption-based emissions, respectively. Furthermore, we investigate the impacts of introducing tariffs and raising carbon prices on responsibility distribution and find that both will increase import-embodied responsibility and decrease export-embodied responsibility and thus favor net exporters of carbon emissions.

1. Introduction

Under the United National Framework Convention of Climate Change (UNFCCC), countries are requested to submit National Emissions Inventories (NEIs) and Nationally Determined Contributions (NDCs) to benchmark reductions in greenhouse gas (GHG) emissions and outline climate actions, respectively (Peters, 2008). While NDCs are designed separately by countries based on their development priorities, emissions reduction potentials, and historical emissions volumes, it has been argued that it is difficult to achieve the 2 °C target through the joint effects of the independent national emission reduction targets (Liu and Raftery, 2021). Additionally, the distribution of emission responsibilities among countries is an essential basis when estimating NEIs and proposing NDCs, as the mitigation options change according to the system boundary of the NEIs (Peters, 2008).

The allocation of emission responsibility among countries has been a

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https://doi.org/10.1016/j.ecolecon.2024.108162
Received 9 September 2023; Received in revised form 14 February 2024; Accepted 3 March 2024
Available online 13 March 2024

focus of academic debate because of the diversity of available approaches regarding the attribution of emissions embodied in import and export (e.g., Ferng, 2003). International climate change agreements are generally based on production-based accounting (PBA). Under the principle of PBA, emissions within a territory are allocated to the emitting country, including emissions associated with the production of exports (or emissions embodied in exports) and excluding emissions embodied in imports. However, researchers have criticized that under PBA, a country could meet commitments by outsourcing high-pollution and high-energy-consumption industries abroad, which leads to carbon leakage and affects the degree of achieving the NDCs (Chang, 2013; Cadarso et al., 2012; Munksgaard et al., 2005; Peters and Hertwich, 2008a; Csutora, and Vetőné mózner, Z., 2014).

Thus, researchers proposed consumption-based accounting (CBA) which reallocates all emissions along global supply chains to the consumer (Barrett et al., 2013; Peters and Hertwich, 2008b). Under the principle of CBA, export-embodied emissions are excluded while import-embodied emissions are included in the emission responsibility of a country's consumption (Lenzen et al., 2007). Although it has advantages in avoiding carbon leakage, CBA has a number of shortcomings: jurisdictional transgression of national power (Peters, 2008); reduced incentives for cleaner production (Kander et al., 2015); and unequal trade restrictions or adjustments (Jakob and Marschinski, 2013), e.g., a border tax adjustment would put exporters at a comparative disadvantage (Kander et al., 2015). For these reasons, an increasing number of researchers argued that full responsibility principles that allocate trade-embodied emissions to one actor, i.e., producers as in PBA or consumers as in CBA, as being too extreme (Liu et al., 2020).

As such, combating climate change requires global cooperation. More importantly, effective climate action requires the recognition of shared responsibility for emissions related to multiple actors (Ferng, 2003; Bastianoni et al., 2004; Gallego and Lenzen, 2005; Lenzen et al., 2007; Botzen et al., 2008). According to the common but differentiated responsibilities formalized in the UNFCCC in 1992, different ways to split the responsibility between producers and consumers have been proposed: for example, a simple 50:50 (Gallego and Lenzen, 2005), based on economic benefits, e.g. income (Marques et al., 2012) or value-added (Xu et al., 2021; Liu et al., 2020; Guo et al., 2020; Lenzen et al., 2007; Pinero et al., 2019; Andrew and Forgie, 2008), distance of producers from primary input providers and final users (Temursho and Miller, 2020), carbon intensity (Zhu et al., 2018), best available technologies (Berzosa et al., 2014), border tax adjustments (Chang, 2013), benefits of producers from production versus benefits of consumers from enjoying the products (Csutora, and Vetőné mózner, Z., 2014), and seven mixed approaches (Zhang, 2015). Having an idea of shared responsibility was further demonstrated to be necessary (Khajehpour et al., 2021), fair (Xu et al., 2021), and effective (Liu et al., 2020) for international climate negotiations.

An essential principle of assigning the emission responsibilities between each actor is that the responsibilities should not be decoupled from associated benefits of producing or consuming a product (Csutora, and Vetőné mózner, Z., 2014). Jakob et al. (2021) proposed an economic benefit-based shared responsibility approach by conducting a what-if counterfactual analysis. They assumed that there are no economic costs for releasing emissions in a factual scenario, which is the status quo of most countries. While if an emission price, i.e. a global carbon price, was in place, economic benefits for producers and consumers would both decrease, which means both producers and consumers gain economic benefits because of the nonexistent emission price. Thus, Jakob et al. split emission responsibilities between producers and consumers in proportion to the economic benefits derived from releasing emissions but not being required to pay for the associated economic costs. Referring to this approach, Cao et al. (2023) discussed the allocation of emissions responsibilities embodied in interprovincial trade in China. Whereas this classic economic benefit-based shared responsibility approach did not consider the impacts of real tariffs on economic benefits, and the data used were only country-specific but not sector-specific which requires a strong sector-homogeneity assumption, so the evaluated economic benefits are less in line with reality.

Here, we improve the aforementioned proposed economic benefit-based shared responsibility approach to re-investigate the shared responsibility for trade-embodied carbon emissions of 141 countries and regions worldwide in 2017, contributing about 95% of the world's total GDP. We improve the framework in two aspects: first, we take actual import and export tariffs into account; second, we use the most up-to-date country-specific and sector-specific tariff data and elasticity data. The approach used in this study is based on a solid theoretical foundation. In this study, we answer the following research questions: first, how much emission responsibility is assigned to each country under the improved shared responsibility approach? Second, how does such an approach differ from emission responsibilities under 'extreme' approaches (i.e. PBA and CBA) that allocate full responsibility to one actor? Third, how does the introduction of import and export tariffs affect countries' assigned emission responsibilities? Fourth, how will the emission responsibility assigned to each country change as the global carbon price rises from 10 to 1000 USD/ton CO_2?

2. Methods

2.1. The improved economic benefit-based shared responsibility approach

The original economic benefit-based shared responsibility approach (Jakob et al., 2021) suggested dividing trade-embodied carbon emissions between producers and consumers in proportion to the economic benefits derived from releasing emissions but not being required to pay for the associated economic costs. While the economic benefits were measured by the changes in the economic surplus of producers and consumers when the social cost of emissions was in place. This approach is based on a solid theoretical foundation and provides a new perspective regarding the allocation of emission responsibilities. While one of the limitations is that it fails to consider the import and export tariffs that exist in the real world in the factual scenario. Additionally, the import and export elasticity data used in that study were only country-specific and not sector-specific. Considering the elasticity of import and export varies widely by sector, the essential information on the relationship between prices and quantities associated with imports and exports is less detailed. Both limitations lead to the concern of biased estimates of changes in producer and consumer surplus and thus lead to less accurate responsibility assignment.

Jakob et al. (2021) assumed that neither producers nor consumers need to pay for the social costs of emissions in the factual scenario. The interaction between supply (export) and demand (import) in the international market would lead to an equilibrium price p_0 and quantity q_0 (see Fig. 1 in Jakob et al., 2021). While if the social costs of emissions were correctly evaluated in for example a global carbon price in the counterfactual scenario, the benefits of producers and consumers would both decline because producers would receive a lower price p_s and consumers would pay a higher price p_c, which are known as the change in producer surplus and the change in consumer surplus, respectively. Consequently, the authors proposed to allocate the responsibility between producers and consumers according to the proportion of their economic benefits derived from releasing emissions without paying for the associated social costs.

We improve this method by introducing import and export tariffs. For most commodities, producers and consumers are required to pay tariffs for export and import in real life. According to economic benefit theory, tariffs will lead to changes in producer surplus and consumer surplus as well as the deadweight loss of welfare. Thus, in the factual scenario with tariffs taken into account, producers would receive a lower price p_{s1} and consumers would pay a higher price p_{c1}, compared with the equilibrium price p_0 in the factual scenario without tariffs (Fig. 1a). As counterfactual when a global carbon price is in place, producers would

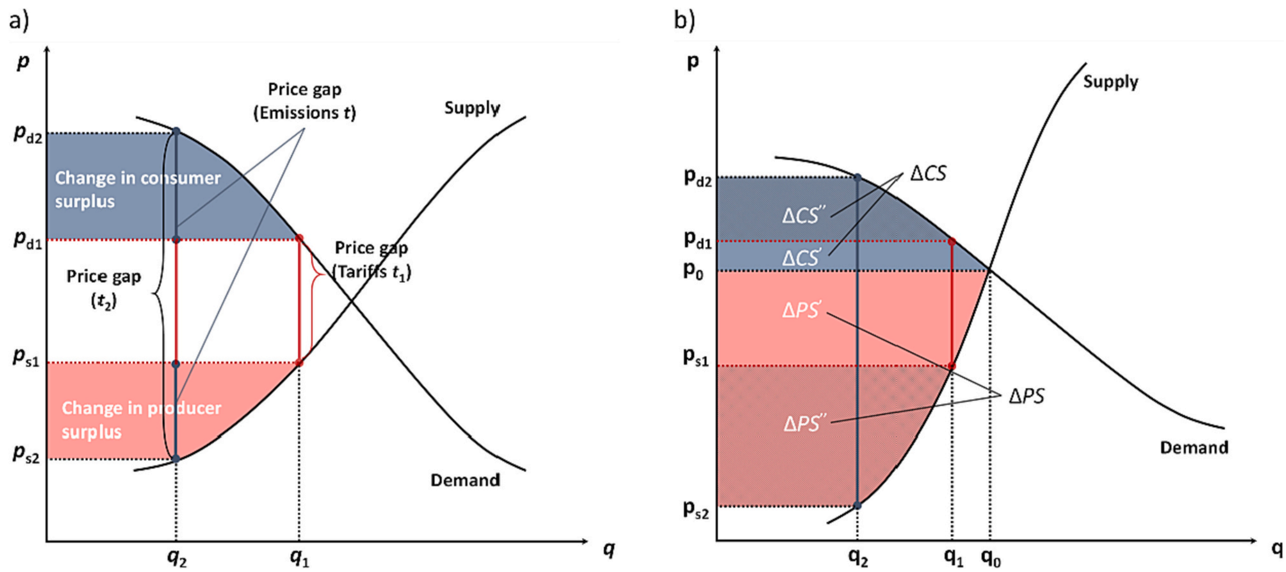


Fig. 1. Schematic diagram of the economic theory behind the shared responsibility framework based on economic benefits. a) Improved theory proposed in this study. b) An example of the effect of elasticities on the distribution of emission responsibilities. X-axis and y-axis indicate quantity and price, respectively.

receive a much lower price p_{s2} and consumers would pay a much higher price p_{c2}, compared with the prices in the factual scenario with tariffs. In this case, the proportion used to allocate emission responsibility, i.e. the ratio of change in producer surplus to change in producer surplus, changes to the ratio of the area comprised by p_{s1}, p_{s2}, q_1, q_2, and the supply curve to the area comprised by p_{d1}, p_{d2}, q_1, q_2, and the demand curve.

Fig. 1b shows how elasticities of supply curve and demand curve affect the distribution of emission responsibilities. The introduction of a carbon price would lead to producers receiving a lower price and consumers paying a higher price, leading to reductions in the benefits of both producers and consumers, known as changes in producer surplus (ΔPS) and changes in consumer surplus (ΔCS). This indicates both producers and consumers benefit from the current non-carbon-price state and their responsibilities are assigned based on the proportion of their benefits. When tariffs are considered, the benefits of producers and consumers would first decline because of introducing tariffs, known as $\Delta PS^{'}$ and $\Delta CS^{'}$, respectively, and would further reduce because of introducing a carbon price, known as $\Delta PS^{''}$ and $\Delta CS^{''}$, respectively. There exists $\Delta PS^{'} + \Delta PS^{''} = \Delta PS$ and $\Delta CS^{'} + \Delta CS^{''} = \Delta CS$. If the supply curve is inelastic and the demand curve is elastic (shown in Fig. 1b), the reduced magnitude of the benefit driven by tariffs is higher for the producer than for the consumer, which is $\Delta PS^{'}/\Delta PS > \Delta CS^{'}/\Delta CS$. Consequently, the ratio of the reduced benefits caused by carbon price between producer and consumer will decrease when considering tariffs, compared to that without tariffs, which is $\Delta PS^{''}/\Delta CS^{''} < \Delta PS/\Delta CS$. That means fewer emissions are allocated to producers (exporters) and more emissions are allocated to consumers (importers) compared with the no-tariff scenario when supply curve is less elastic than the demand curve.

2.2. Formula derivation

The supply curve and the demand curve are assumed to be in power function, with the power representing elasticities (Jakob et al., 2021).

$$\text{Supply curve}: q_s = p_s^{\sigma} \tag{1}$$

$$\text{Demand curve}: q_d = p_d^{\delta} \tag{2}$$

where q and p indicate quantity and price, respectively. σ and δ indicate producer elasticity and consumer elasticity, respectively. Jakob et al. (2021) verified that the results are robust for the selection of elasticity by conducting a sensitivity analysis for elasticities by halving and doubling import and export elasticities. Results show that except for doubling all elasticities of one kind while halving the others, changing the value of import and export elasticities has almost no significant effect on the results. Given that in a scenario without tariffs and carbon price, prices received by producers are equal to prices paid by consumers thus the equilibrium price can be normalized to $p_0 = 1$ (for more detailed information, please see Jakob et al., 2021). While import and export tariffs will lead to a price gap (t_1) between the price received by producers and the price paid by consumers. The relation between the price received by producers and the price paid by consumers in the tariff scenario can be formulized as

$$p_{d1} = (1 + t_1) \bullet p_{s1} \tag{3}$$

where p_{s1}, p_{d1}, and t_1 indicate the price received by producers, the price paid by consumers, and the price gap between producers and consumers in the tariff scenario. Based on Eqs. (1), (2), and (3), we can derive supply price and demand price that are expressed by elasticities and price gap under equilibrium in the tariff scenario.

$$\text{Supply price}: p_{s1} = (1 + t_1)^{\delta/(\sigma-\delta)} \tag{4}$$

$$\text{Demand price}: p_{d1} = (1 + t_1)^{\sigma/(\sigma-\delta)} \tag{5}$$

Assuming prices in the supply curve are pre-export-tariff-prices and prices in the demand curve are post-import-tariff-prices, then the price gap in the tariff scenario can be formulized as

$$p_{d1} = (1 + ITR)(1 + ETR) \bullet p_{s1} \tag{6}$$

where ITR and ETR represent import tariff rate and export tariff rate, respectively. Then, there is $t_1 = ITR + ETR + ITR \cdot ETR$.

Similarly, the relation between the price received by producers and the price paid by consumers in the carbon price scenario can be formulized as

$$p_{d2} = (1 + t_2) \bullet p_{s2} \tag{7}$$

where p_{s2}, p_{d2}, and t_2 indicate the price received by producers, the price paid by consumers, and the price gap between producers and consumers in the carbon price scenario. Based on Eqs. (1), (2), and (7), we can derive supply price and demand price that are expressed by elasticities and price gap under equilibrium in the carbon price scenario.

$$\text{Supply price}: p_{s2} = (1+t_2)^{\delta/(\sigma-\delta)} \tag{8}$$

$$\text{Demand price}: p_{d2} = (1+t_2)^{\sigma/(\sigma-\delta)} \tag{9}$$

Assuming that the impacts of the global carbon price on each trade flow are determined by the embodied carbon emissions per unit of embodied value added, the price gap caused by carbon price (t) can be written as

$$t_{r1}^{r2} = \frac{CO2_{r1}^{r2}}{VA_{r1}^{r2}} \bullet T \tag{10}$$

where CO_2 and VA indicate the carbon emissions and value-added embodied in the trade flow from region r_1 to region r_2, which are measured using the environmentally extended input-output analysis (for more detailed information, please see Jakob et al., 2021). Environmentally extended input-output analysis is widely used for capturing environmental effects embodied in input and output relations among multiple sectors and economies (Wang et al., 2018; Wang et al., 2020). T is the global carbon price used to quantify the social costs of emissions. Note that t is the price gap caused by the carbon price and t_2 is the total price gap in the carbon price scenario, including the price gap caused by import and export tariffs (t_1) and the price gap caused by carbon price (t). Here, we use the ratio between embodied carbon emissions and embodied value added to distinguish the differentiated impacts of a globally unified carbon price on the price gap t between different trade flows. The economic intuition is that for a less clean trade flow, the exporter (i.e. producer) is directly responsible for unclean production, leading to an increase in global carbon emissions, while the importer (i.e. consumer) is indirectly responsible for that due to choosing trade partners with lower costs but more carbon-emitting. Thus, compared with a relatively clean trade flow, the economic benefits of both exporter and importer of a less clean trade flow that embodied more carbon emissions per value added would be more affected by the carbon price. Then the price gap in the carbon price scenario can be formulized as

$$t_2 = t_1 + t = ITR + ETR + ITR \cdot ETR + \frac{CO_2}{VA} \bullet T \tag{11}$$

The relation between the price received by producers and the price paid by consumers in the carbon price scenario can also be written as

$$p_{d2} = [(1+ITR)(1+ETR)+t] \bullet p_{s2} \tag{12}$$

The change in producer surplus (ΔPS) and the change in consumer surplus (ΔCS) between the tariff scenario and the carbon price scenario can be expressed as Eqs. (13) and (14).

$$\Delta PS = \int_{p_{s2}}^{p_{s1}} p_s^{\sigma} dp = \frac{1}{\sigma+1} p_s^{(\sigma+1)} \Big|_{p_{s2}}^{p_{s1}} = \frac{1}{\sigma+1}\left(p_{s1}^{(\sigma+1)} - p_{s2}^{(\sigma+1)}\right)$$

$$= \frac{1}{\sigma+1}\left[(1+t_1)^{\frac{\delta(\sigma+1)}{(\sigma-\delta)}} - (1+t_2)^{\frac{\delta(\sigma+1)}{(\sigma-\delta)}}\right] \tag{13}$$

$$\Delta CS = \int_{p_{d1}}^{p_{d2}} p_d^{\delta} dp = \frac{1}{\delta+1} p_d^{(\delta+1)} \Big|_{p_{d1}}^{p_{d2}} = \frac{1}{\delta+1}\left(p_{d2}^{(\delta+1)} - p_{d1}^{(\delta+1)}\right)$$

$$= \frac{1}{\delta+1}\left[(1+t_2)^{\frac{\sigma(\delta+1)}{(\sigma-\delta)}} - (1+t_1)^{\frac{\sigma(\delta+1)}{(\sigma-\delta)}}\right] \tag{14}$$

Therefore, emission responsibilities allocated to producers (R_p) and consumers (R_c) are calculated by the proportion of change in producer surplus and change in consumer surplus.

$$\text{Responsibility allocated to producer } R_p = \frac{\Delta PS}{\Delta PS + \Delta CS} \bullet CO_2 \tag{15}$$

$$\text{Responsibility allocated to demander } R_d = \frac{\Delta CS}{\Delta PS + \Delta CS} \bullet CO_2 \tag{16}$$

2.3. *Data*

The global multi-regional input-output table used to measure bilateral trade relations is obtained from the Global Trade Analysis Project (GTAP) database (Aguiar et al., 2023). We use the latest version of the GTAP database (version 11) for 2017. GTAP includes 140 major economies and one "rest of the world" region and 65 sectors. Data on carbon emissions is also obtained from the environmental satellite of GTAP. Import and export tariff rates are obtained from the Program folder of GTAP. The global carbon price is assumed to be 50 USD per ton of CO_2 in this study, which is proposed to achieve the climate targets (Carbon Pricing Leadership Coalition, 2017) and is consistent with Jakob et al. (2021).

Import and export elasticities are based on our calculation which specify 141 regions and 65 sectors. The methods we use are quite different from previous studies. From the existing literature, there are two main types of methods that are often used, one is the econometric modeling approach (Mata et al., 2021). This type of method is mainly based on historical data acting as an econometric model for regression estimation of elasticity. The problem with the econometric approach is that elasticity estimation can be affected by the representativeness of the historical data and the choice of the measurement method, and it is also unrealistic to estimate elasticities for 141 regions and 65 sectors for this study. The other category is based on formula and system of joint equations calculation methods (Suanin, 2021; Tokarick, 2014). This type of method is based on trade data and economic theory formula to derive the value of elasticity. The estimation of this type of elasticity is more of the impact of the calculated direct partial equilibrium, and it is difficult to portray the complex interaction between different economic agents.

Different from the previous methods, this study uses the General Equilibrium (CGE) approach to simulate the method of calculating elasticity. This approach, on the one hand, can address the problem of historical data dependence of the measurement method, and on the other hand, can capture the general equilibrium impact of the interaction of various economic agents to be fully considered, so this study applies ORANI-G (A Generic Single-Country Computable General Equilibrium Model) model. This model is a standard national CGE model developed by the Cops (Centre of Policy Studies) Center at the University of Victoria, Australia (Horridge, 2000). The database is mainly from the latest eleventh edition of the database published by GTAP. We use the simulation method to calculate the elasticity, specifically, by shocking the price of imports or exports by 1% to obtain x% change in the quantity demanded of imports or the quantity supplied of exports, and x % is actually the elasticity of the quantity demanded of imports or the quantity supplied of exports. One problem is that in the simulation, the elasticity can only be simulated for one product in one country at a time because the simulation of multiple products will have an interactive effect, which will interfere with the accurate calculation of the elasticity. To solve this problem, we also developed a program to achieve batch large-scale simulation calculation. Based on the above methodology, this study calculates the import demand elasticity and export supply elasticity of 65 sectors corresponding to the benchmark year 2017 of the eleventh edition of GTAP data, respectively.

In this study, the calculated import elasticities range between −7 (sector "extraction of natural gas" of Brunei Darussalam) and −0.002 (sector "oil seeds and oleaginous fruit" of Brunei Darussalam), while export elasticities range between 0.003 (sector "extraction of natural gas" of Nigeria) and 3.452 (sector "manufacture of other non-metallic mineral products" of Madagascar). The shape of the demand curve and the supply curve changes with different values of import elasticity and export elasticity (please see Fig. A.1 in the appendix), yet the derivation principle of the formula remains unchanged.

2.4. Limitations

One of the limitations of this study is that the implemented carbon prices in some regions are not taken into account. We note that some regions have implemented carbon taxes or carbon emissions trading systems, but with carbon prices lower than 50 USD per ton of CO_2, except Uruguay, Liechtenstein, Sweden, Switzerland, Norway, the UK, Finland, New Zealand, and the EU ETS (World Bank, 2022; Ji et al., 2021). In addition, carbon prices also vary significantly across sectors. Hence, further study could allocate emissions responsibilities considering the implemented sector-specific carbon prices. Additionally, this study is a static analysis, ignoring adjustments in production and consumption due to carbon pricing, further study could take the interaction of price changes and strategy choices into consideration by constructing a dynamic model. Moreover, referring to Jakob et al. (2021), we assume the functional form of the supply curve and the demand curve are in power function with the power equaling elasticity, further study could investigate the impacts of different functional forms of the supply and demand curves on the allocation of emissions responsibilities.

3. Results

3.1. Responsibility for trade-embodied carbon emissions shared between countries and their trade partners

Fig. 2a shows how global carbon emissions embodied in trade are distributed among countries or regions under the improved economic benefits-based shared responsibility approach. In 2017, the global total trade-embodied carbon emissions were 5805 million tons (Mt). China (CHN), the European Union (EU27), and the United States of America (USA) were the largest three countries with emissions responsibilities, with 939, 761, and 702 Mt of trade-embodied carbon emissions, respectively, followed by India (229 Mt), Japan (221 Mt), Russia (214 Mt), Canada (191 Mt), Mexico (112 Mt), Australia (109 Mt), and Brazil (99 Mt).

Moreover, we select ten developed and emerging economies with relatively high GDP and large emission volumes. The total carbon emissions in the selected ten economies were 24 Gigaton (Gt) in 2017, contributing over 70% of the global total. Fig. 2b displays how much emissions are embodied in import and export of each economy and how the corresponding responsibilities are shared between each economy and its trade partners. Among the total responsibilities for trade-

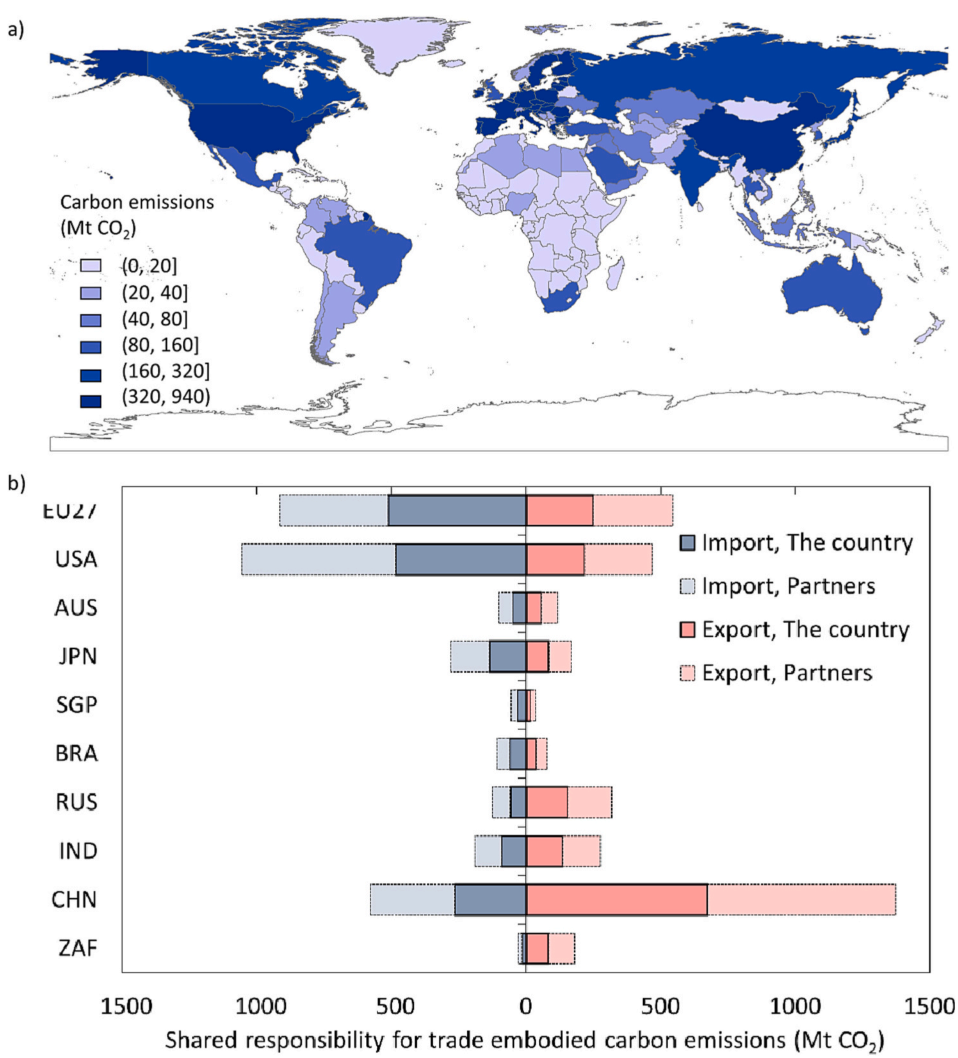


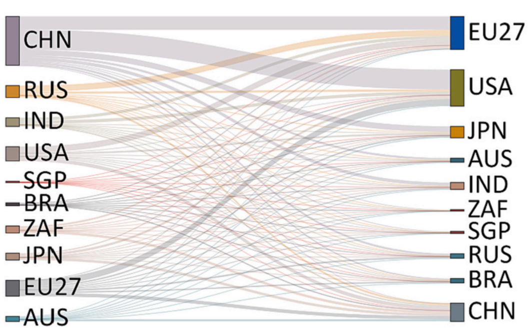
Fig. 2. Responsibilities for trade-embodied carbon emissions under the improved economic benefit-based shared responsibility approach. a) Responsibilities of countries. b) Responsibilities for import- and export-embodied carbon emissions that are shared by a country and its trade partners. Note: EU27, USA, AUS, JPN, SGP, BRA, RUS, IND, CHN, and ZAF indicates the European Union which consists of 27 member countries without the United Kingdom, the United States of America, Australia, Japan, Singapore, Brazil, Russia, India, China, and South Africa, respectively.

embodied carbon emissions, the EU27, the USA, Japan, Singapore, and Brazil were dominated by import with import-embodied responsibilities accounted for 61% (Brazil) to 69% (the USA) of the total emission responsibility of the respective country. The above economies are considered as net trade-embodied carbon emissions consumers. While Australia, Russia, India, China, and South Africa were dominated by export with export-embodied responsibilities accounted for 54% (Australia) to 84% (South Africa) of the total. In other words, those economies are net trade-embodied carbon emissions producers.

For the above export-dominated economies (i.e. net producers), their trade partners took a larger share of export-embodied responsibility. The improved shared responsibility approach allocates less than half (from 46% in South Africa to 50% in Australia) of the embodied emissions to them. China, as the largest exporter of carbon emissions, exported 1373 Mt carbon emissions in 2017 with 49% of the export-embodied emissions assigned to itself and the remaining 51% assigned to its trade partners. For the import-dominated economies (i.e. net consumers), the improved shared responsibility approach allocated more than half of the import-embodied emissions to the EU27 (56%), Singapore (61%), and Brazil (55%). Whereas the USA and Japan were assigned less than half of the import-embodied carbon emissions, which were 46% for the USA and 49% for Japan.

We further explore the flows of carbon emissions embodied in bilateral trade between the ten economies (Fig. 3). The emissions embodied in each trade flow are split according to the corresponding proportion of the economic benefits gained by the exporter and the importer. The largest volumes of flows were found among China, the EU27, and the USA. In 2017, 316 Mt of carbon emissions were exported from China to the USA, ranking top in the bilateral trade flows among the ten economies (Fig. 3a). The improved shared responsibility approach distributed 55% of the responsibility for the 316 Mt carbon emissions to China (exporter) and the remaining 45% to USA (importer) (Fig. 3b). For the 55 Mt of embodied carbon emissions exported from the USA to China, the USA and China should take the responsibilities in the proportions of 53% and 47%, respectively. The trade flows between

a)



b)

	EU27	USA	AUS	JPN	SGP	BRA	RUS	IND	CHN	ZAF
EU27		49 51	44 56	45 55	33 67	43 57	49 51	45 55	51 49	46 54
USA	43 57		49 51	48 52	36 64	45 55	52 48	50 50	53 47	47 53
AUS	42 58	53 47		44 56	44 56	41 59	55 45	52 48	57 43	44 56
JPN	44 56	56 44	52 48		41 59	47 53	54 46	52 48	56 44	52 48
SGP	40 60	57 43	50 50	55 45		47 53	47 53	54 46	61 39	55 45
BRA	43 57	54 46	52 48	47 53	32 68		54 46	46 54	58 42	48 52
RUS	45 55	54 46	54 46	49 51	42 58	43 57		51 49	54 46	50 50
IND	46 54	56 44	54 46	56 44	43 57	47 53	56 44		57 43	52 48
CHN	44 56	55 45	53 47	53 47	42 58	44 56	54 46	53 47		50 50
ZAF	43 57	52 48	49 51	52 48	43 57	39 61	51 49	50 50	52 48	

Fig. 3. Responsibilities for carbon emissions embodied in bilateral trade between the ten economies under the improved economic benefit-based shared responsibility approach. A) Flows of the import- and export-embodied carbon emissions. B) Share of the responsibilities that are assigned between producers and consumers (unit: %). Economies in rows and columns stand for exporters and importers, respectively. Segments in light grey and dark grey indicate the proportion of responsibility assigned to exporters and importers, respectively.

China and the EU27 also embodied massive emissions. In 2017, 203 Mt of carbon emissions were exported from China to the EU27 while 52 Mt of carbon emissions were exported from the EU27 to China. Under the improved shared responsibility approach, the EU27 would receive a larger share of responsibility than China in both directions, receiving 51% of the responsibility for exporting carbon emissions to China and 56% of the responsibility for importing carbon emissions from China. Regarding trade flows between the EU27 and the USA, the exporter would receive 43% and 49% of the responsibility for exporting from the USA to the EU27 (97 Mt) and from the EU27 to the USA (99 Mt), respectively. For the remaining flows, China constituted the largest destination related to exports from Australia, Japan, Brazil, and South Africa, with less than half of the responsibilities (from 42% to 48%) assigned to China. In terms of imports, China's responsibility was less than half when the trade partners were the EU27 (44%), Singapore (42%), and Brazil (44%), yet over than half when the trade partners were the USA (55%), Australia (53%), Japan (53%), Russia (54%), India (53%), and 50% when exporting to South Africa.

3.2. Comparison of the emission responsibility between PBA, CBA, and the improved shared responsibility approach

Fig. 4 shows how emissions allocated to countries under the improved shared responsibility approach differ from those under PBA and CBA. Except for a few countries, the improved shared responsibility approach yields a more moderate outcome between PBA and CBA for most economies (Fig. 4a and Fig. 4b). The exceptions include Brunei Darussalam, Mexico, Chile, Belarus, Azerbaijan, Kuwait, and Tunisia. These countries would receive the largest emission responsibilities under the improved shared responsibility approach, which are larger than those under both PBA and CBA.

Moreover, the improved shared responsibility approach distributes responsibilities for trade-embodied carbon emissions more evenly across economies (Fig. 4c). Regarding the trade-embodied carbon emissions in 2017, China was the largest emitter under PBA with 1373 Mt carbon emissions exported from China, which was more than twice those of the second-largest exporter, i.e. 546 Mt in the EU27. While the largest two emitters under CBA, the USA and the EU27, imported 1056 Mt and 915 Mt carbon emissions in 2017, respectively, which were 1.5 times as much as the third-largest importer, i.e. 579 Mt in China. In comparison, the largest three emission economies, namely China, the EU27, and the USA, shared more even responsibilities in more similar amounts under the improved shared responsibility approach. Under the improved shared responsibility approach, 939, 761, and 702 Mt of carbon emissions were assigned to China, the EU27, and the USA, respectively. It is because PBA and CBA are two extreme ways that attribute full responsibility for exported emissions to producers (PBA) and attribute full responsibility for imported emissions to consumers (CBA). In comparison, the improved shared responsibility approach makes a compromise between producers and consumers based on their economic benefits gained from the nonexistent carbon price by assigning a certain part of both the imported emissions and the exported emissions to the country and the other part to its trade partners.

Regarding allocating emissions responsibilities, what is disputed is the part of the emissions measured by PBA that exceeds that measured by CBA (net exporter) or vice versa (net importer), that is, the difference between the results of the two extreme approaches. The improved economic benefit-based shared responsibility approach allocates a portion of the above-mentioned difference to each economy, rather than reckoning in whole or no emissions of that part. Specifically, for the five net importers in Fig. 4c, the improved shared responsibility approach allocates 58%, 40%, 48%, 81%, and 68% of the disputed part (i.e. the difference between the results of PBA and CBA) to the EU27, the USA, Japan, Singapore, and Brazil, respectively. For the five net exporters, 47%, 46%, 45%, 45%, and 45% of the disputed parts are assigned to Australia, Russia, India, China, and South Africa, respectively.

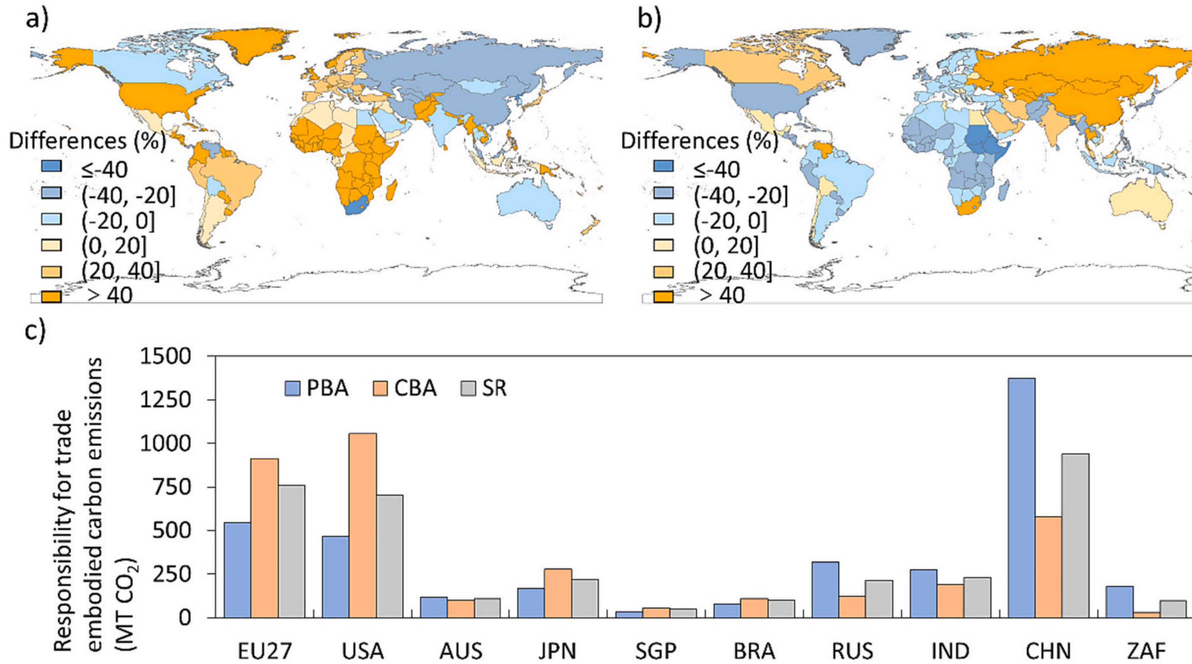


Fig. 4. Comparison of the responsibility for trade-embodied carbon emissions measured by PBA, CBA, and the improved economic benefit-based shared responsibility approach. a) Percentage changes of responsibility under the improved shared responsibility approach compared with PBA. b) Percentage changes of responsibility under the improved shared responsibility approach compared with CBA. c) Responsibilities for trade-embodied emissions under PBA, CBA, and the improved shared responsibility approach in ten economies.

3.3. *Impacts of introducing tariffs on responsibility allocation*

Considering that import and export tariffs imposed on goods and services traded across borders will change the economic benefits of both importers and exporters and thus change the responsibility distribution, we introduce the import and export tariffs in this study and investigate the corresponding impacts. Fig. 5 shows the differences in the responsibility for trade-embodied carbon emissions with and without the tariffs considered. After introducing import and export tariffs, the assigned responsibilities for trade-embodied carbon emissions decreased significantly in China by 5.88 Mt, India (0.33 Mt), Russia (3.05 Mt), Kazakhstan (0.4 Mt), and South Africa (0.58 Mt), while increased in Japan by 0.57 Mt, Pakistan (0.35 Mt), the USA (2.51 Mt), the EU27 (1.92 Mt), and Iran (0.41 Mt), respectively (Fig. 5a).

Moreover, we explored the differences in the import- and export-embodied carbon emissions that were assigned to each economy when introducing tariffs (Fig. 5b). Specifically, among the ten economies, China, Russia, India, and South Africa as net exporters, benefit the most from introducing tariffs, with responsibilities for export-embodied emissions decreasing by 8.6, 3.6, 1.9, and 0.7 Mt, respectively, and responsibilities for import-embodied emissions increased by 2.7, 0.6, 1.5, and 0.2 Mt, respectively. Whereas the USA, the EU27, and Japan, as net importers, need to take more responsibilities, with responsibilities for export-embodied emissions decreasing by 0.7, 1.0, and 0.5 Mt, respectively, and responsibilities for import-embodied emissions increasing by 2.5, 1.9, and 0.6 Mt, respectively. Although Singapore and Brazil are net importers of embodied carbon emissions, introducing tariffs decreased 0.01 and 0.02 Mt emissions responsibilities for these two countries, respectively, with export-embodied responsibilities decreased 0.07 and 0.59 Mt and import-embodied responsibilities increased 0.06 and 0.57 Mt, respectively. Similarly, although Australia is a net exporter of embodied carbon emissions, introducing tariffs increased 0.01 Mt emissions responsibilities for it, with export-embodied responsibilities decreased 0.29 Mt and import-embodied responsibilities increased 0.30 Mt.

Furthermore, we found that introducing tariffs raises import-

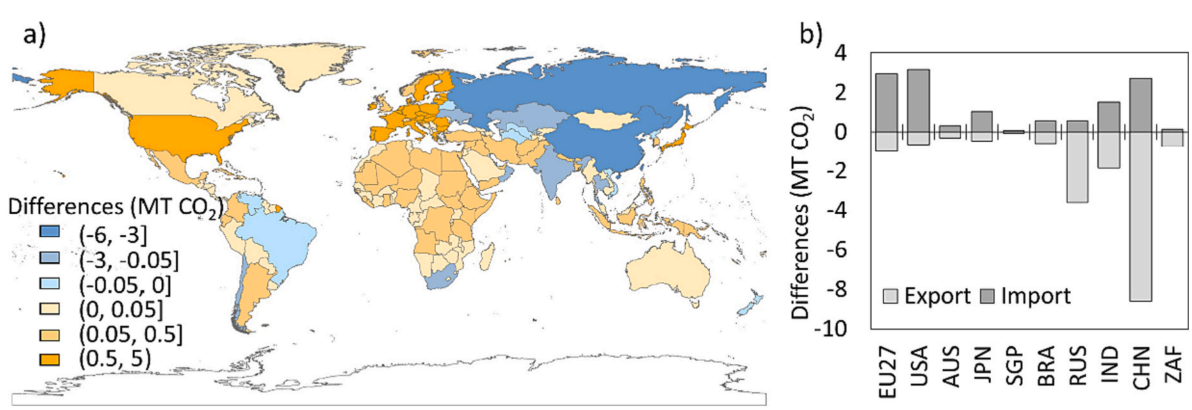


Fig. 5. Comparison of the responsibility for trade-embodied carbon emissions before and after introducing import and export tariffs. a) Differences in trade-embodied emission responsibility among countries. b) Differences in emissions related to export and import in ten economies.

embodied responsibility yet reduces export-embodied responsibility for all economies. It is because if tariffs are not considered, the losses of economic benefits of both producers and consumers (i.e. changes in producer surplus and changes in consumer surplus) are only caused by carbon price. After considering tariffs, the total losses of economic benefits caused by carbon price remain unchanged, but some losses are converted into government income due to tariffs with the remaining losses still taken by producers and consumers. That is to say, tariffs bear some of the loss of benefits for producers and consumers. Because for those dominant trade flows with large embodied carbon emissions, exporting countries and sectors are more inelastic than importing countries and sectors, in other words, producers are more reliant on trade, the proportion of the loss of benefits avoided by tariffs is higher for producers. Thus, after taking tariffs into account, the producer's responsibility is reduced (for a detailed explanation, please see the Methods section).

3.4. Impacts of changes in global carbon prices on responsibility allocation

Considering that under the improved shared responsibility approach, the allocation of trade-embodied emissions is based on the proportion of changes in the economic benefits of producers and consumers if the socio-economic cost of emissions would be paid, and that proportion of changes is affected by not only the shape of supply and demand curves determined by the elasticities of exports and imports but also the price gap between producers and consumers determined by the global carbon price. Therefore, we further explore the impacts on responsibility for each economy when the global carbon price increase per 10 USD/ton CO_2 from 10 to 1000 USD/ ton CO_2 (Fig. 6).

The assigned responsibilities increase with the rising carbon price in the EU27 (from 51% to 55%), the USA (from 45% to 50%), Japan (from 48% to 52%), Singapore (from 56% to 58%), and Brazil (from 52% to 56%). While the assigned responsibilities decrease in Russia (from 50% to 43%), India (from 50% to 46%), China (from 50% to 44%), and South Africa (from 51% to 40%). The economic intuition of this disparity is that the elasticities of supply curves and demand curves are different, indicating the degrees of dependence on trade are different for producers and consumers. When the carbon price rises, the change ratio of the export volume and the import volume is different. In other words, the decline rate of producer surplus and consumer surplus will change with different carbon prices. Therefore, some economies' emission responsibilities change in the same direction as the carbon price, while others change in the opposite direction.

For the above nine economies, regardless of whether the assigned responsibility increases or decreases, the changes in responsibility with the increase in carbon price are larger at low carbon prices. When the global carbon price is at a relatively high level (for example higher than 500 USD/ton CO_2), the effect of each ten-USD increase in carbon price on the distribution of responsibility becomes less pronounced. Australia is an interesting case, the assigned responsibility first goes up (from 49.705% to 49.803%) and then goes down (from 49.802% to 49.157%) with the global carbon price increase from 10 to 40 USD/ton CO_2 and from 50 to 1000 USD/ton CO_2, respectively. Additionally, from the view of changes in the share of responsibility when the global carbon price increases from 10 to 1000 USD/ ton CO_2, South Africa, Russia, China, the USA, and Brazil are significantly affected, with the share of responsibility decreasing by 11% in the case of South Africa, 7% for Russia and 6% for China and an increase by 5% for the USA 5% for Brazil.

4. Discussion and conclusions

This study assigns responsibility for trade-embodied carbon emissions between exporters and importers according to the economic

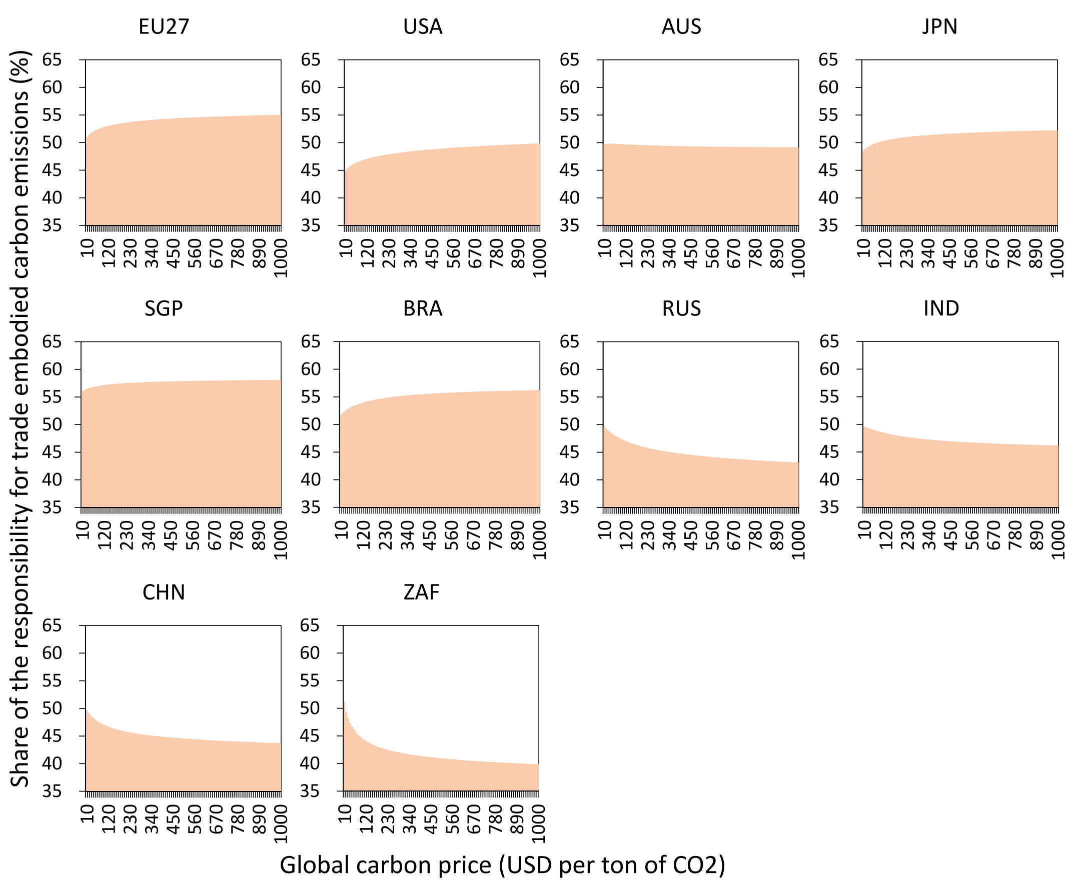


Fig. 6. Percentage of responsibilities for trade-embodied carbon emissions assigned to each economy under different global carbon prices.

benefits they gain from not being required to pay the associated costs. We demonstrate this approach for 141 economies in 2017 and further explore the impacts of introducing import and export tariffs and changes in the global carbon price on responsibility distribution. There are two aspects of improvements in this study compared with the original method: first, Jakob et al. (2021) calculated economic benefits derived by producers and consumers using country-specific elasticity data which might hide substantial sectoral details. In this study, we use highly detailed elasticity data for 141 economies and 65 sectors, enabling a more fine-grained analysis. Second, we introduce the import and export tariffs into the responsibility distribution model and make the theoretical foundation more comprehensive by considering changes in producers' and consumers' benefits caused by tariffs in the factual scenario.

Based on this improved shared responsibility approach, we map the trade-embodied responsibilities among various economies in 2017. We find that:

1) For most economies, sharing responsibility provides a compromise solution for international climate negotiations compared with the extreme ways that allocate full responsibility to one actor. Under the improved shared responsibility approach, trade-embodied emission responsibilities assigned to the top three emitters, i.e. China, the EU27, and the USA, were 939, 761, and 702 Mt in 2017, respectively, which are of the same order of magnitude. Specifically, China should account for 46% and 49% of its responsibilities for import-embodied and export-embodied carbon emissions, respectively. Responsibility for import-embodied emissions was 56% for the EU27 and 46% for the USA, while responsibility for export-embodied emissions was 46% for the EU27 and 46% for the USA.
2) Considering import and export tariffs is beneficial to net exporters whose price-quantity curves are usually more inelastic than importers. The logic is that import elasticities tend to be higher than export elasticities, indicating that exporters are more reliant on trade. When introducing tariffs, the proportion of economic losses caused by tariffs in the factual scenario to the economic losses caused by both tariffs and carbon prices in the counterfactual scenario is larger for exporters than for importers. In other words, tariffs bear more benefit loss for exporters than importers. Consequently, introducing tariffs decrease the responsibilities of exporters.
3) Raising the global carbon price will increase the responsibility of net import countries while decrease the responsibility of net export countries. Essentially, changes in carbon price affect the price gap between producers and consumers in the counterfactual scenario and further affect the ratio of economic benefits derived by producers and consumers, i.e. the ratio of changes in producer surplus to changes in consumer surplus, which is also determined by the shapes of the supply curve and the demand curve that based on elasticities. If an increase in the global carbon price increases the ratio of producer's benefit to consumer's benefit, then the responsibility assigned to producers would increase and thus the total responsibility for both export- and import-embodied carbon emissions would increase for export-oriented countries, and vice versa.

The approach for sharing responsibility demonstrated in this study allocates trade-embodied carbon emissions between exporters and importers in proportion to the economic benefits of releasing emissions without paying the associated costs. The proportion is highly related to the shapes of the supply curve and the demand curve which are decided by export elasticity and import elasticity, respectively. This kind of approach links emissions responsibilities to economic benefits and splits the responsibility between producers and consumers based on economic theory rather than allocating the entire responsibility to one party, so that might be more effective for encouraging all parties to take emission reduction actions.

CRediT authorship contribution statement

Jiayu Wang: Writing – original draft, Methodology, Investigation, Formal analysis. **Chang-Jing Ji:** Methodology, Investigation. **Yu Liu:** Validation, Methodology, Funding acquisition, Data curation. **Yuli Shan:** Visualization, Resources, Data curation. **Klaus Hubacek:** Visualization, Supervision. **Yi-Ming Wei:** Project administration, Conceptualization. **Ke Wang:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:
Ke Wang reports financial support was provided by National Natural Science Foundation of China.

Data availability

Data will be made available on request.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (Grant Nos. 72271026, 72293601, 71871022, 72125010, 72243011, 72243004, 71974186), the Joint Development Program of Beijing Municipal Commission of Education, the National Program for Support of Top-notch Young Professionals, the China Scholarship Council, the Fundamental Research Funds for the Central Universities (Peking University), The United Kingdom Research and Innovation (UKRI) Research England QR policy support fund (PSF-16), and the High-performance Computing Platform of Peking University.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2024.108162.

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