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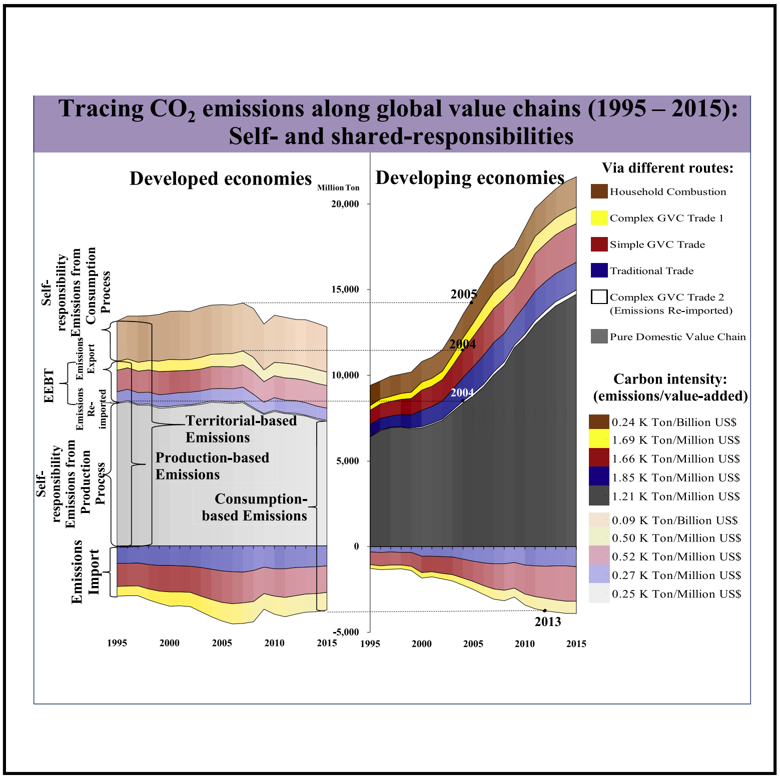
Developing countries’ responsibilities for CO_2 emissions in value chains are larger and growing faster than those of developed countries

Graphical abstract



Highlights

- Bilateral country-sector CO_2 emissions are traced along GVCs
- GVC accounting approach helps identify self- and shared emission responsibility
- Developing countries’ increasing emission responsibility requires more attention
- Climate negotiation must carefully review responsibility sharing along GVCs

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In brief

A recurring challenge of international climate change negotiations centers on how responsibility for global warming should be shared across countries, especially in the era of global value chains (GVCs) characterized by massive and complex cross-border trade. We propose a new method to identify self- and shared emission responsibilities along GVCs and illustrate that developing countries’ responsibilities for global CO_2 emissions are larger and increasing faster than those of developed countries. We argue that international discussions of climate change mitigation should take account of GVC-based responsibility sharing.

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Developing countries' responsibilities for CO_2 emissions in value chains are larger and growing faster than those of developed countries

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SCIENCE FOR SOCIETY Global trade has resulted in multiple socioeconomic benefits including employment, knowledge transfers, and innovations. However, CO_2 emissions associated with trade activities continue to rise, resulting in an intense debate on "who should be responsible for what degree of emissions reduction?" This debate is particularly fierce between developing and developed countries that are often recognized as *producers* and *consumers.* The rise of massive global value chains (GVCs), however, makes it increasingly complex to differentiate producers from consumers: e.g., China-mined metals are exported to Japan where vehicles are produced before being imported and sold in China. This has imposed great challenges in formulating effective policies that clearly identify and allocate responsibilities for emissions along GVCs. We have designed a new method to separate self-responsibility (CO_2 embodied in purely domestic value chains) from shared responsibilities (CO_2 embodied in GVCs). We show that developing countries' GVC-based responsibility for global CO_2 emissions has surpassed that of developed countries since 2012 and is increasing quickly. Our study offers scientific-based new evidence to global climate policy discussions via the lens of trade-related responsibility sharing.

SUMMARY

Carbon emissions associated with international trade are significant. The emergence of complex global value chains (GVCs) in recent decades, in which a country can operate as both a consumer and producer simultaneously, has led to a further rise in emissions. The complexity of these GVCs makes it increasingly difficult to determine what country is responsible for the emissions embodied within them. Here, we propose a new method based on input-output analysis to identify and distinguish self- and shared responsibility for CO_2 emissions along GVCs, where self-responsibility describes emissions embodied in purely domestic value chains. Our results show that developing countries' self-responsibility for CO_2 emissions has been the largest driver in the growth of total GVC embodied emissions since 2001. Even considering the shared responsibility for emission transfers via GVCs, developing countries' total responsibility has exceeded that of developed countries since 2012. We argue that climate negotiations should seriously consider GVC-based responsibility sharing to enable more effective climate policies.

INTRODUCTION

The world has witnessed an increasing amount of CO_2 emissions related to international trade over the last two to three decades. One of the most important driving forces has been considered the rapid economic globalization characterized by the rise and spreading of global value chains (GVCs).[1–5] GVCs refer to the creation, transfer, and distribution of value along global production networks. With the rise of GVCs, the ''Made in'' label that typically applied to manufactured goods attributing them to a specific country has become an archaic symbol of a bygone era, because most manufactured goods are now ''Made in the World''[4]—i.e., they are produced in stages in a number of different countries, with value-added increasing at each stage. The phenomenon of GVCs, which enabled great gains in the economic efficiency of global firms,[6,7] has significantly changed the nature and structure of international trade.[8,9] A report by the United Nations Conference on Trade and Development stated that 80% of trade takes place in ''value chains'' linked to transnational corporations.[1] Meanwhile, the increasing complexity and uncertainty of GVCs has also created considerable difficulty in understanding ''who generates emissions or pollution for whom'' and in formulating policies that enable countries, industries, and firms to clearly identify their environmental responsibilities along GVCs.[10]

Regarding the connection between international trade and carbon emissions, a large body of literature has explored the concept of ''consumption-based accounting,''[11–15] with a heavy emphasis on carbon emissions transfers induced by developed countries' consumption of goods produced in developing countries via international trade. Similar applications can be found in relation to numerous environmental issues, including climate change,[16–18] energy use,[19] air pollution,[20,21] material use,[22] land use,[23] biomass,[24] water quality,[25–27] and biodiversity.[28] This accounting has considerable methodological and conceptual overlap with studies on ''trade in value-added'' in relation to GVCs.[29–31] However, to date, few formal attempts to consistently link these two independent lines of research have been made for the purpose of identifying emissions responsibility in the context of both climate change and GVCs. Currently, the Paris Agreement is focused on territorial-based emissions (which are easy to monitor), while consumption-based emissions are used as a reference point in designing possible transnational financial support mechanisms to enable developed countries to help developing countries reduce their emissions. Unfortunately, neither territorial- nor consumption-based accounting (both of which allocate full responsibility to either the producers or the consumers) provides sufficient incentive for countries to pursue emissions reduction efforts because of a lack of consensus regarding responsibility sharing. Although several pioneering studies have discussed the topic of producers and consumers sharing responsibility for emissions,[32–40] two significant problems still need to be addressed. One is how to identify a country's self-responsibility for emissions. Without an accurate measure, we are unable to even determine the amount of emissions for which responsibility should be shared among the various related parties. The other problem is how to determine the appropriate weights to enable proper distribution of responsibility for emissions among the various producers and consumers along GVCs.

Here, we introduce a suitable accounting framework to trace both value-added and emissions at each stage from the perspectives of production, consumption, and trade. Within this framework, international trade-related emissions are further divided into traditional trade (i.e., classical Ricardian-type trade such as ''French wine in exchange for English cloth,'' in which there is no international production sharing), simple GVC trade (in which factor contents cross national borders once), and complex GVC trade (in which factor contents cross national borders more than once).[41,42] Using this framework, we can clearly distinguish self-responsibility-based emissions (i.e., emissions generated in a purely domestic value chain for domestic final use that does not involve international trade). Then, we develop a double-weights-based approach to enable responsibility for international trade-related emissions to be shared among various producers and consumers depending on their contributions to carbon leakage (i.e., one country's strict climate policy leads to an increase in carbon emissions in another country) both horizontally (i.e., comparing producers' and consumers' contributions to carbon leakage within a specific country) and vertically (i.e., comparing a specific country's contributions to carbon leakage as both producers and consumers with those of all other countries). Our results show that developing countries' self-responsibility-based carbon dioxide (CO_2) emissions from their production processes more than doubled between 1995 and 2015 and accounted for 42.8% of global CO_2 emissions in 2015, almost twice the amount emitted by developed countries. Considering emissions transfers as a result of international trade, using our proposed emissions responsibility sharing approach, we find that developing and developed countries were responsible for 43.2% and 56.8%, respectively, of cumulative global CO_2 emissions from 1995 to 2015, while developing countries' responsibility for global CO_2 emissions has exceeded that of developed countries since 2012. At the country level, the US, China, Russia, Japan, Germany, and India were responsible for 23.4%, 18.8%, 6.8%, 5.0%, 3.9%, and 3.1%, respectively, of cumulative global CO_2 emissions from 1995 to 2015. Our work provides valuable information to improve concerted climate action and formulate more efficient carbon mitigation strategies. In conclusion, we argue that climate change negotiations that can help developing countries set a more ambitious timeline toward achieving peak emissions and/or carbon neutrality in terms of their self- and shared responsibility along GVCs should be seriously considered in the Paris Agreement era.

RESULTS

GVC-based accounting framework for tracing emissions

Following the most recent studies,[41,42] we trace CO_2 emissions along GVCs by introducing the following accounting framework based on a multiregional input-output (MRIO) model (see ''building a GVC-based accounting to trace emissions'' in experimental procedures for further details and Note S1 for more detailed methods). Our accounting framework traces emissions from upstream to downstream, as illustrated in Figure 1. The logic behind this framework is that a country or sector's production-based emissions are both directly and indirectly embodied in all downstream countries and sectors via numerous value chain routes and are eventually absorbed by domestic or foreign final

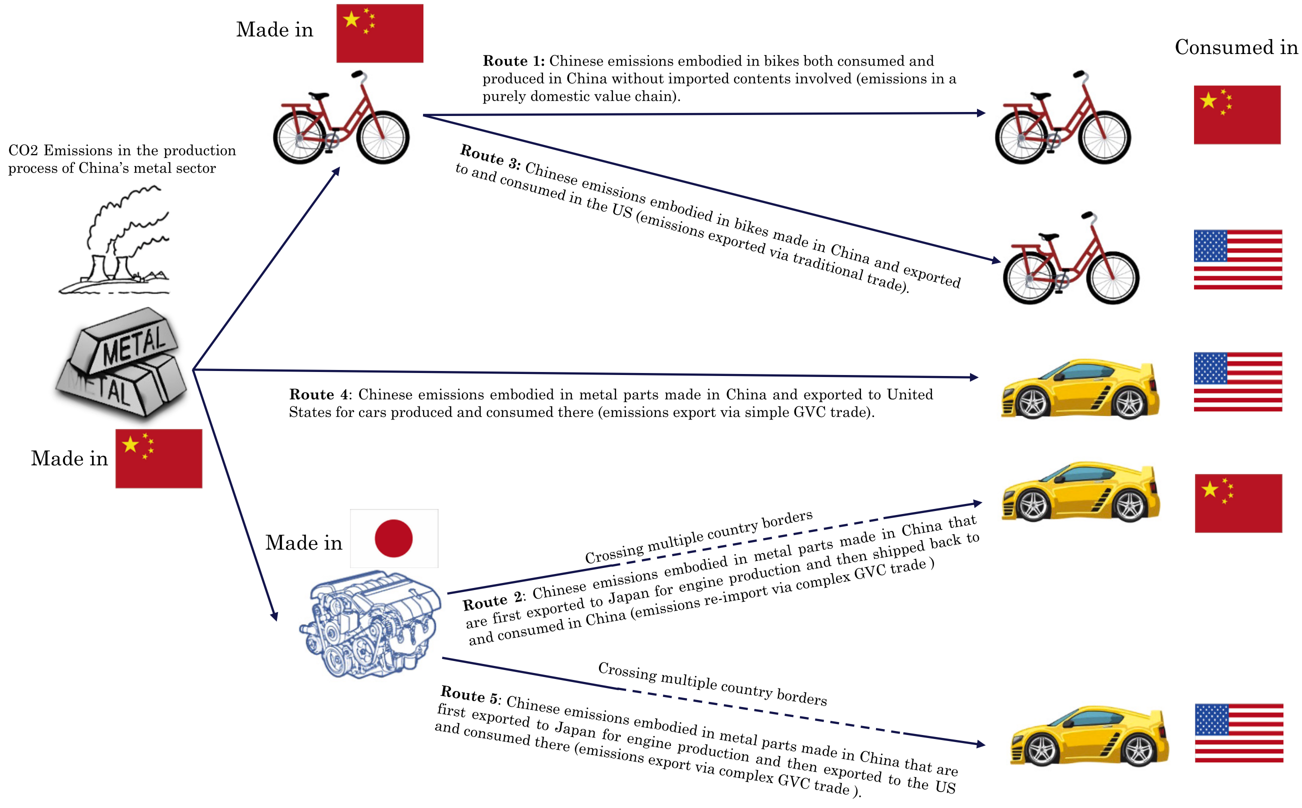


Figure 1. GVC-based accounting framework for tracing CO_2 emissions

CO_2 emissions are traced along GVCs from upstream to downstream at country/sector/bilateral levels via different routes. For example, emissions that happen in the production process of China-made metal can be embodied in international trade of final or intermediate goods crossing multiple country borders, and eventually meet China's or the US's final demand on bikes or cars via five routes according to the pattern of international production sharing. Note:a detailed explanation is presented in "building a GVC-based accounting to trace emissions" (experimental procedures). Dotted lines indicate that intermediate goods might cross multiple borders.

demand (when tracing from downstream to upstream, they are defined as consumption-based emissions). To facilitate the analysis of these complex flows, which might cross multiple borders multiple times, we divide these routes into five categories, as shown in Figure 1.

Emissions along route 1 are generated through the creation of a country's gross domestic product (GDP) to satisfy the country's final demand for domestically produced goods and services (i.e., a purely domestic value chain). In this case, the country has "self-responsibility" for these emissions. Emissions along route 2 are generated and absorbed solely within a country, but also involve international trade in which factor contents cross national borders more than once, and thus belong to the category of re-imported emissions via complex GVC trade. Emissions along routes 3, 4, and 5 refer to emissions exports via traditional trade, simple GVC trade, and complex GVC trade, respectively. The sum of emissions along routes 2, 3, 4, and 5 in each bilateral trade yields emissions embodied in bilateral trade (EEBT).[12,14] Therefore, our GVC-based accounting approach consistently integrates existing production-based emissions, consumption-based emissions, emissions exports, emissions imports, emissions re-imports, and EEBT under a single unified framework. Emissions from direct household combustion are not included in this framework because they do not belong to the production process involved in the creation of GDP, but rather are considered part of the consuming country's self-responsibility-based emissions.

Production- vs. consumption-based emissions via GVCs

By applying this accounting framework to MRIO data (from the two versions of the World Input-Output Database 1995–2014[43] and the Asian Development Bank's 2015 Multiregional Input-Output Tables), we cannot only estimate production-based and consumption-based emissions from 1995 to 2015 for both developed countries and developing countries (see Note S2 for the country list and groupings), but also demonstrate how the international transfer of emissions occurs through various routes with different carbon intensities (e.g., emissions per US dollar of GDP created).

Figure 2 shows that territorial-based CO_2 emissions by developed countries increased slightly during the period 1995–2007 (peaking in 2007), decreased slightly after 2008, and reached 12.8 Gt in 2015, slightly lower than the 1995 level of 13.1 Gt. During this period, emissions exports for the purpose of satisfying foreign final demand were the main driver of the increasing trend from 1995 to 2007, self-responsibility-based emissions

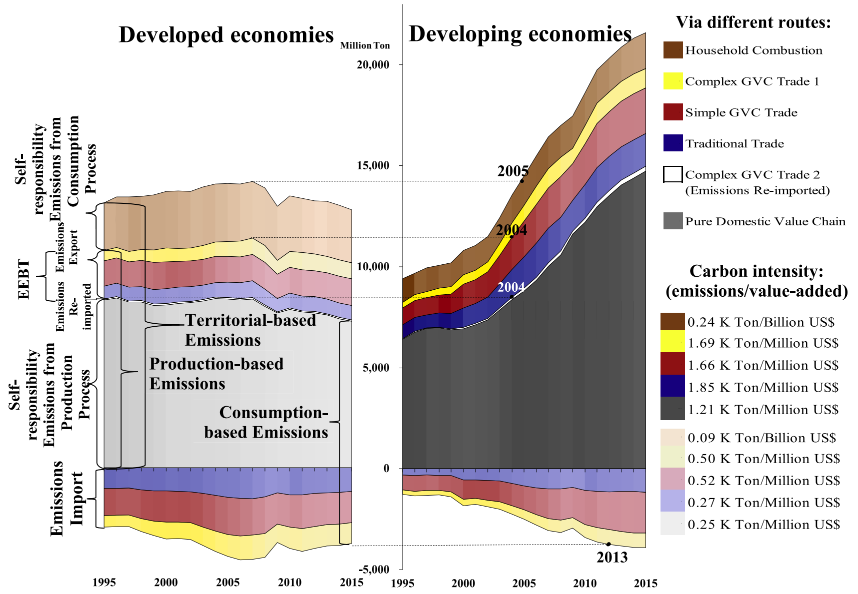


Figure 2. Production-based vs. consumption-based CO_2 emissions and emission transfers via international trade routes

The GVC-based accounting approach consistently integrates the existing production-based emissions, consumption-based emissions, emissions exports, emissions imports, emissions re-imports, and emissions embodied in bilateral trade under a single unified framework. Developing countries' both purely domestic value-chain-based (self-responsibility) emissions and emissions transfers via international trade have surpassed those of developed countries and are increasing rapidly with high carbon intensity. Note: territorial-based emissions, emissions from fossil fuel combustion inside a country's territory; production-based emissions, emissions from the production process inside a country; consumption-based emissions, global emissions induced by a country's final demand; self-responsibility-based emissions from the production process, emissions generated by the creation of a country's gross domestic product (GDP) to satisfy that country's final demand for domestically produced goods and services; self-responsibility-based emissions from household combustion, emissions generated by household combustion; emissions exported from country r to country s, country r's emissions induced by country s's final demand; emissions re-imported, emissions from a country's production of intermediate goods that are exported and then re-imported for final demand; EEBT, emissions embodied in bilateral trade. Given the above definitions, in our accounting, territorial-based emissions are the sum of production-based emissions and emissions from household combustion. The darkness of the color represents the carbon intensity of each route measured by CO_2 emissions per US dollar of GDP created or per US dollar of household consumption at 1995 constant prices along different trading routes.

generated by the production process were the main driver of the decreasing trend during the period 2008–2015, and self-responsibility-based emissions generated through individual household combustion were stable over the entire period. Consumption-based emissions by developed countries increased during the period 1995–2007 as a result of rising emissions imports and decreased during the period 2008–2015, mainly because of a decrease in self-responsibility-based emissions from production processes. Developing countries showed larger increases in both self-responsibility-based emissions and emissions trade than developed countries, and self-responsibility-based emissions from production, production-based emissions, and territorial-based emissions by developing countries during the period 2004–2005 exceeded the peak levels in developed countries that occurred in 2007. Furthermore, developing countries' self-responsibility-based emissions from production processes were approximately twice those of developed countries in 2015. Meanwhile, developing countries' imported emissions increased and had exceeded those of developed countries by 2013. Looking at the structure of increasing emissions trade based on different GVC routes for developing countries, both emissions exports and imports more than doubled between 1995 and 2015, with GVC trade-related emissions accounting for the majority (70%).

The main information about carbon intensity and its evolution shown in Figure 2 can be summarized as follows: carbon intensity shows a decreasing trend in both developed and developing countries via all routes between 1995 and 2015. However, the carbon intensity of developing countries in 2015 remained much higher than that of developed countries in 1995. In addition, the ever-increasing territorial-based emissions in developing countries implies that the decrease in carbon intensity in these countries cannot offset the increased emissions, probably because of rapid economic and population growth.[44]

Sharing CO_2 emissions responsibility along GVCs

As shown previously, self-responsibility-based emissions are well defined in relation to both the production and direct household combustion processes. Thus, the remaining issue is how to allocate responsibility for carbon emissions transfers among various producers and consumers along GVCs. Here, we propose a new approach to measuring carbon leakage from both producers' and consumers' perspectives based on the following logic. If a country wants to maintain its current final demand level in relation to domestically produced goods and services (in monetary terms) under a no-trade (NT) scenario (i.e., a form of economic self-sufficiency or autarky), its emissions are defined as NT emissions. Under this NT scenario, it is self-evident that a country's production-based emissions are equal to its consumption-based emissions at the country level. Thus, the difference between practical production-based emissions and NT emissions can be defined as production-based carbon leakage, and the difference between practical consumption-based emissions and NT emissions can be defined as consumption-based carbon leakage. This could be a new way to measure "avoided emissions" based on the Greenhouse Gas Protocol for Project Accounting.[45,46] Given the definition of carbon leakage from both the production and consumption sides, we can then develop two kinds of weights for sharing emissions responsibility in both the horizontal and vertical dimensions. One is the ratio of production-based

Table 1. GVC-based responsibility for global CO_2 emissions

Unit: $MtCO_2$	Producers take all responsibility for emission transfer (2015)	Consumers take all responsibility for emission transfer (2015)	Shared responsibility between producers and consumers (2015)	Shared responsibility for emission transfer by three trading routes (2015)				Total responsibility on 1995–2015 cumulative global CO_2 emissions
				Total trade	Traditional trade	Simple GVC trade	Complex GVC trade	
China	9,372.7 (27.3%)	8,335.8 (24.2%)	9,205.4 (26.8%)	1,687.3 (21.2%)	494.9 (6.2%)	756.0 (9.5%)	436.4 (5.5%)	112,309.2 (18.8%)
US	5,274.3 (15.3%)	6,118.2 (17.8%)	6,610.0 (19.2%)	1,732.1 (21.7%)	508.0 (6.4%)	776.1 (9.7%)	448.0 (5.6%)	139,617.6 (23.4%)
Russia	1,574.5 (4.6%)	1,045.8 (3.0%)	1,914.1 (5.6%)	969.9 (12.2%)	284.5 (3.6%)	434.6 (5.5%)	250.9 (3.1%)	40,331.2 (6.8%)
Japan	1,326.7 (3.9%)	1,470.4 (4.3%)	1,330.6 (3.9%)	294.6 (3.7%)	86.4 (1.1%)	132.0 (1.7%)	76.2 (1.0%)	29,851.0 (5.0%)
India	2,358.1 (6.9%)	2,169.7 (6.3%)	1,320.9 (3.8%)	649.3 (−8.2%)	−190.4 (−2.4%)	−290.9 (−3.7%)	−168 (−2.1%)	18,194.3 (3.1%)
Germany	881.4 (2.6%)	899.1 (2.6%)	978.9 (2.8%)	417.8 (5.2%)	122.5 (1.5%)	187.2 (2.3%)	108.1 (1.4%)	22,984.8 (3.9%)
UK	453.2 (1.3%)	615.4 (1.8%)	690.5 (2.0%)	342.4 (4.3%)	100.4 (1.3%)	153.4 (1.9%)	88.6 (1.1%)	16,334.9 (2.7%)
Brazil	639.3 (1.9%)	654.2 (1.9%)	608.6 (1.8%)	73.0 (0.9%)	21.4 (0.3%)	32.7 (0.4%)	18.9 (0.2%)	9,577.8 (1.6%)
Indonesia	568.4 (1.7%)	557.9 (1.6%)	545.1 (1.6%)	106.0 (1.3%)	31.1 (0.4%)	47.5 (0.6%)	27.4 (0.3%)	7,749.4 (1.3%)
Mexico	495.1 (1.4%)	521.9 (1.5%)	536.9 (1.6%)	179.9 (2.3%)	52.8 (0.7%)	80.6 (1.0%)	46.5 (0.6%)	8,863.6 (1.5%)
RoW	11,434.4 (33.3%)	11,989.7 (34.9%)	10,637.0 (30.9%)	2,813.3 (35.3%)	825.1 (10.4%)	1,260.5 (15.8%)	727.7 (9.1%)	190,312.3 (31.9%)
World	34,378.1 (100%)	34,378.1 (100%)	34,378.0 (100%)	7,967.0 (100.0%)	2,336.6 (29.3%)	3,569.6 (44.8%)	2,060.7 (25.9%)	596,126.1 (100.0%)
Developed countries	12,791.1 (37.2%)	13,713.8 (39.9%)	14,972.5 (43.6%)	5,074.9 (63.7%)	1,488.4 (18.7%)	2,273.8 (28.5%)	1,312.7 (16.5%)	338,302.3 (56.8%)
Developing countries	21,587.0 (62.8%)	20,664.2 (60.1%)	19,405.5 (56.4%)	2,892.1 (36.3%)	848.2 (10.6%)	1,295.8 (16.3%)	748.1 (9.4%)	257,823.8 (43.2%)

carbon leakage to total carbon leakage (production-based carbon leakage + consumption-based carbon leakage) for a specific country. This weight is used to measure the relative importance of a country's carbon leakage as both a producer and a consumer (i.e., a form of horizontal comparison). The other weight is the ratio of a country's production-based carbon leakage to global production-based carbon leakage. This weight is used to measure the importance of a specific country in relation to global production-based carbon leakage (i.e., a form of vertical comparison). These weights can also be applied to consumption-based carbon leakage in the same manner. Because self-responsibility-based emissions from production processes can be directly measured using our accounting framework, the responsibility that should be shared from the production (or consumption) side can be defined as the difference between production-based emissions (or consumption-based emissions) and self-responsibility-based emissions. Finally, by simultaneously applying these two types of weights (horizontal and vertical), a country's total responsibility as both a producer and a consumer can be estimated step-by-step based on our algorithm, which can be mathematically proven to be a convergent function when the steps iteratively approach infinity (see "sharing emissions responsibility along GVCs" in experimental procedures).

Table 1 shows the results of shared global CO_2 emissions by producers and consumers for the 10 largest emitters in 2015. In the extreme case in which all responsibility for emissions transfers is assigned to producers, China accounted for 27.3% of all emissions, followed by the US (15.3%). If all responsibility for emissions transfers is assigned to consumers, China accounted for 24.2% of all emissions, followed by the US (17.8%). On the basis of our shared-responsibility model, China accounted for 26.8% of all emissions, followed by the US (19.2%). In total, developing countries' share of responsibility for emissions has exceeded that of developed countries since 2012. Looking at the shared responsibility for emissions transfer by route, obviously GVC trade accounts for the majority (70.7%, of which 44.8% was from simple GVC trade and 25.9% was from complex GVC trade). Developed and developing countries' shares of responsibility for global emissions for the period 1995–2015 were 56.8% and 43.2%, respectively, whereas at the country level, the US's share of responsibility (23.4%) was greater than that of China (18.8%), Russia (6.8%), Japan (5.0%), Germany (3.9%), and India (3.1%). The above result clearly differs from the results obtained using existing methods (as shown in Figure 3), which assign responsibilities based on either a linear combination of production-based and consumption-based emissions,[36] or along the demand and supply chains based on the production process[37,38] with a weight by value-added gain, or the volume of emissions that are saved globally because of trade.[39] Our purpose is in line with those of the above-mentioned pioneering works, but our method (idea) goes further by explicitly considering the role of GVC-based emissions accounting (see "sharing emissions responsibility along GVCs" in experimental procedures). The inherent innovation of our method is that we assign responsibility to producers and consumers based on their contribution (using both horizontal and vertical weights) to GVC-based carbon leakage as defined by the difference between their emissions under the

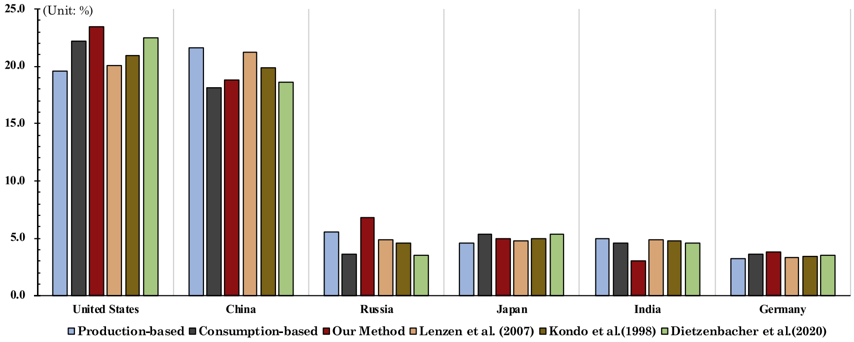


Figure 3. Share of responsibility for selected countries in global cumulative CO_2 emissions for the period 1995–2015 under different methods

Different responsibility sharing methods applied to selected countries are compared. Our method fully considers the role of a country as both producer and consumer in GVCs when carbon leakages via international trade happen, thus can assign responsibility across countries more reasonably. In this sense, the existing methods that assign responsibilities based on a linear combination of production-based and consumption-based emissions, or along the demand and supply chains based on the production process, or with a weight by value-added gain, or according to the volume of emissions that are saved globally because of trade might yield over- or underestimations of emissions responsibility.

NT scenario (where by definition production-based emissions are equal to consumption-based emissions at the country level) and their actual production-based and consumption-based emissions. This makes our results systematically more reasonable (see Table 3 in experimental procedures for more results by country).

DISCUSSION

Numerous countries have become increasingly involved in GVCs, resulting in the rapid growth of CO_2 emissions associated with international production sharing. The GVC phenomenon, in which intermediate-goods trade crosses national borders several times, potentially poses a challenge to the terms of the Paris Agreement because it comprises a patchwork of national policies. Our approach involving shared carbon emissions responsibility is based on a consistent GVC accounting framework in which both value-added and emissions, as well as a type of environmental cost (value-added gain per unit of CO_2 emissions or emissions per unit of value-added) can be systematically traced at the country/sector/bilateral level through various trading routes for selected individual countries. Furthermore, developing a double-weights-based method under a non-trade scenario in this GVC framework helps us overcome the unsolved problems in the existing methods, such as the ad hoc and arbitrary selection of weights, the endogeneity problem, and the use of strong technical assumptions. Therefore, our method can allocate responsibility for emissions between producers and consumers across countries more reasonably than existing methods. There are also some limitations that might bring some uncertainties to our results. First, the MRIO datasets that we used follow different International Standard Industrial Classification versions, which may have led to some statistical bias in our results. Second, both direct purchases by non-residents and international transportation services are not fully endogenized in the WIOD database because of a lack of detailed information. In addition, the rest of the world accounts for the second-largest share of global production-based emissions, but its original dataset is modeled due to a lack of detailed input-output (IO) data for some countries involved.

Our results show that self-responsibility-based emissions from production processes in developing countries have contributed a significant proportion of global emissions growth since 2001. This should be of great concern because most developing countries have relatively weak environmental regulations and lower levels of enforcement. Therefore, urgent action must be taken to reduce these emissions, which are growing rapidly, as an integral component of a credible and competent international governance framework for addressing climate change. Although there was a decreasing trend in the environmental cost of GVCs, as measured by carbon intensity in both developed and developing countries between 1995 and 2015, creating GDP through international trade is still a high-carbon-intensity process. One of the main drivers of this is the carbon emissions transfers that occur through

Table 2. Layout of a conventional multiregional input-output table

		Intermediate use				Final demand				Total output
		1	2	⋯	G	1	2	⋯	G	
Intermediate inputs	1	Z^{11}	Z^{12}	⋯	Z^{1g}	Y^{11}	Y^{12}	⋯	Y^{1g}	X^1
	2	Z^{21}	Z^{22}	⋯	Z^{2g}	Y^{21}	Y^{22}	⋯	Y^{2g}	X^2
	⋮	⋮	⋮	⋱	⋮	⋮	⋮	⋱	⋮	⋮
	G	Z^{g1}	Z^{g2}	⋯	Z^{gg}	Y^{g1}	Y^{g2}	⋯	Y^{gg}	X^g
Value-added		Va^1	Va^2	⋯	Va^g					
Total input		$(X^1)'$	$(X^2)'$	⋯	$(X^g)'$					
Emissions		E^1	E^2	⋯	E^g					

Table 3. GVC-based responsibility for global CO_2 emissions calculated using the iterative algorithm[a]

2015 Unit: $MtCO_2$	Territory-based emissions	Self responsibility emissions from consumption process	Production-based emissions	Consumption-based emissions	No-trade scenario emissions	Production-based carbon leakage	Consumption-based carbon leakage	Responsibility weight for producer (%)	Responsibility weight for consumer (%)	Self responsibility emissions from production process	Production-based emissions to be shared	Consumption-based emissions to be shared	Shared production-based emissions	Shared consumption-based emissions	Responsibility on carbon leakage	Total responsibility on global emissions	Total responsibility on global emissions by Lenzen method	Total responsibility on global emissions by Kondo method	Total responsibility on global emissions by Dietzenbacher method	Total responsibility on global emissions (%)	Total responsibility based on pure producer (%)	Total responsibility based on pure consumer (%)
Countries[b]	TE	SEC	PE	CE	NT	PCL = PE-NT	CCL = CE-NT	ω = PCL/(PCL + CCL)	1-ω = CCL/(PCL + CCL)	SEP	PES = PE-SEP	CES = CE-SEP	FSP	FSC	FS = FSP + FSC	TS = FS + SEP + SEC	Lenzen et al.	Kondo et al.	Dietzenbacher et al.	TS/ΣTS	(PE + SEC)/Σ(PE + SEC)	(CE + SEC)/Σ(CE + SEC)
AUS	406.5	42.4	364.1	407.4	334.8	29.2	72.6	28.7	71.3	276.6	87.5	130.8	17.0	104.6	121.6	440.6	371.3	385.7	407.9	1.3	1.2	1.3
AUT	67.2	12.9	54.3	91.9	66.3	−12.1	25.6	32.0	68.0	28.2	26.1	63.7	−7.8	35.2	27.3	68.4	69.7	73.1	86.6	0.2	0.2	0.3
BEL	108.5	18.2	90.3	114.9	66.9	23.4	47.9	32.8	67.2	31.3	59.0	83.6	15.5	65.2	80.7	130.2	97.8	102.6	113.6	0.4	0.3	0.4
BGR	45.8	2.7	43.1	36.7	34.9	8.2	1.8	81.7	18.3	23.7	19.4	13.1	13.5	0.7	14.2	40.5	42.1	39.9	33.5	0.1	0.1	0.1
BRA	639.3	55.6	583.7	598.6	556.7	27.0	41.9	39.2	60.8	480.0	103.8	118.7	21.4	51.6	73.0	608.6	576.7	591.2	596.2	1.8	1.9	1.9
CAN	518.9	75.6	443.3	434.5	361.0	82.2	73.5	52.8	47.2	263.6	179.7	170.9	87.9	70.1	158.0	497.2	441.2	438.9	435.4	1.4	1.5	1.5
CHN	9,372.7	369.5	9,003.2	7,966.4	8,067.7	935.5	−1,01.3	90.2	9.8	7,148.7	1,854.5	817.7	1,707.3	−20.0	1,687.3	9,205.4	8,887.5	8,484.8	8,060.2	26.8	27.3	24.2
CYP	12.9	2.0	10.9	7.5	10.0	0.9	−2.5	26.9	73.1	3.0	7.9	4.4	0.5	−3.7	−3.2	1.8	7.4	9.2	−3.8	0.0	0.0	0.0
CZE	103.5	10.7	92.8	79.2	68.5	24.4	10.8	69.3	30.7	43.2	49.6	36.1	34.1	6.7	40.8	94.7	88.2	86.0	76.8	0.3	0.3	0.3
DEU	881.4	167.6	713.8	731.5	516.4	197.3	215.0	47.9	52.1	393.4	320.3	338.0	191.0	226.8	417.8	978.9	707.6	722.6	706.1	2.8	2.6	2.6
DNK	51.7	8.2	43.5	40.7	15.7	27.8	25.0	52.6	47.4	9.8	33.7	30.9	29.6	24.0	53.6	71.7	40.9	42.1	33.3	0.2	0.2	0.1
ESP	280.7	68.6	212.1	230.2	277.7	−65.7	−47.5	58.0	42.0	124.9	87.1	105.3	−77.0	−40.4	−117.4	76.1	208.7	221.1	225.6	0.2	0.8	0.9
EST	18.8	1.6	17.1	14.1	12.5	4.6	1.6	74.6	25.4	9.6	7.6	4.5	7.0	0.8	7.8	19.0	16.2	15.6	11.4	0.1	0.1	0.0
FIN	45.6	3.1	42.5	51.0	34.0	8.5	17.0	33.3	66.7	24.6	17.9	26.4	5.7	22.9	28.6	56.3	45.2	46.7	46.5	0.2	0.1	0.2
FRA	322.5	72.9	249.6	369.3	239.4	10.2	129.9	7.3	92.7	152.9	96.7	216.4	1.5	243.6	245.1	470.9	274.9	309.4	357.6	1.4	0.9	1.3
GBR	453.2	98.6	354.6	516.8	326.9	27.7	189.9	12.7	87.3	249.5	105.1	267.3	7.1	335.3	342.4	690.5	388.2	435.7	514.5	2.0	1.3	1.8
GRC	136.3	21.5	114.8	64.8	55.3	59.5	9.5	86.2	13.8	44.0	70.8	20.7	103.9	2.6	106.5	172.0	100.4	89.8	60.3	0.5	0.4	0.3
HUN	46.2	9.3	36.8	38.6	30.3	6.5	8.3	44.0	56.0	18.0	18.8	20.6	5.8	9.4	15.2	42.5	40.2	37.7	35.1	0.1	0.1	0.1
IDN	568.4	53.8	514.6	504.1	457.5	57.1	46.6	55.1	44.9	385.4	129.2	118.7	63.6	42.4	106.0	545.1	507.9	509.3	504.8	1.6	1.7	1.6
IND	2,358.1	182.9	2,175.2	1,986.7	2,371.4	−196.2	−384.7	33.8	66.2	1,787.3	387.9	199.5	−134.0	−515.3	−649.3	1320.9	2,128.5	2,081.0	1,998.9	3.8	6.9	6.3
IRL	48.4	10.4	38.0	40.2	21.1	16.9	19.1	47.0	53.0	14.4	23.6	25.7	16.1	20.4	36.5	61.3	36.7	39.1	21.6	0.2	0.1	0.1
ITA	354.9	66.6	288.3	358.1	277.7	10.6	80.4	11.7	88.3	200.9	87.5	157.2	2.5	143.6	146.1	413.6	312.4	323.2	342.8	1.2	1.0	1.2
JPN	1,326.7	206.4	1,120.3	1,264.0	1,107.5	12.7	156.4	7.5	92.5	829.6	290.7	434.4	1.9	292.6	294.6	1,330.6	1,162.6	1,192.1	1,270.7	3.9	3.9	4.3
KOR	643.9	56.1	587.8	550.8	920.4	−332.6	−369.6	47.4	52.6	354.7	233.1	196.1	−318.7	−393.5	−712.2	−301.3	608.4	569.3	543.6	−0.9	1.9	1.8
LTU	14.8	6.4	8.4	15.7	4.6	3.8	11.1	25.5	74.5	3.2	5.2	12.5	1.9	16.7	18.6	28.3	10.3	12.0	13.2	0.1	0.0	0.1
LUX	9.5	2.0	7.5	8.6	3.7	3.8	4.8	44.1	55.9	1.3	6.2	7.2	3.4	5.5	8.8	12.1	5.9	8.0	5.7	0.0	0.0	0.0
LVA	10.0	3.2	6.9	9.1	4.3	2.6	4.8	34.6	65.4	3.0	3.8	6.1	1.8	6.4	8.2	14.4	7.5	8.0	6.3	0.0	0.0	0.0
MEX	495.1	98.0	397.2	424.0	323.7	73.4	100.3	42.3	57.7	259.1	138.0	164.9	62.8	117.1	179.9	536.9	398.5	410.6	456.0	1.6	1.4	1.5
MLT	2.8	0.4	2.4	4.0	2.1	0.3	1.9	12.5	87.5	1.6	0.8	2.4	0.1	3.3	3.4	5.4	3.7	3.2	1.7	0.0	0.0	0.0
NLD	173.6	21.6	152.0	147.3	80.7	71.3	66.6	51.7	48.3	55.9	96.1	91.4	74.6	65.1	139.7	217.2	147.9	149.7	144.9	0.6	0.5	0.5
POL	296.3	38.1	258.2	241.9	213.0	45.2	28.9	61.0	39.0	163.7	94.5	78.2	55.8	22.9	78.6	280.5	259.9	250.1	239.4	0.8	0.9	0.8
PRT	60.7	7.5	53.2	54.0	54.1	−0.9	−0.1	86.6	13.4	32.2	21.0	21.8	−1.6	0.0	−1.7	38.0	50.9	53.6	50.4	0.1	0.2	0.2
ROM	71.3	9.1	62.2	73.8	67.2	−5.0	6.6	43.3	56.7	41.8	20.4	32.0	−4.4	7.6	3.1	54.0	66.0	68.0	70.5	0.2	0.2	0.2
RUS	1,574.5	150.3	1,424.2	895.5	920.1	504.1	−24.6	95.3	4.7	793.9	630.3	101.6	972.2	−2.3	969.9	1,914.1	1,249.1	1,159.8	864.3	5.6	4.6	3.0
SVK	31.3	2.8	28.5	35.9	26.7	1.8	9.2	16.4	83.6	15.0	13.5	20.9	0.6	15.6	16.2	34.1	31.9	32.2	32.8	0.1	0.1	0.1
SVN	15.1	5.6	9.5	12.2	6.4	3.1	5.8	34.9	65.1	4.1	5.5	8.2	2.2	7.7	9.9	19.5	10.1	10.9	9.7	0.1	0.0	0.1
SWE	42.9	8.5	34.4	65.3	23.3	11.1	42.0	20.9	79.1	15.0	19.4	50.3	4.7	67.1	71.8	95.3	42.5	49.9	58.9	0.3	0.1	0.2
TUR	378.0	69.5	308.5	295.6	262.1	46.4	33.5	58.1	41.9	206.2	102.3	89.3	54.5	28.4	82.9	358.6	313.1	302.0	288.9	1.0	1.1	1.1
TWN	290.5	26.5	264.0	198.8	187.2	76.8	11.6	86.9	13.1	122.3	141.7	76.5	135.1	3.1	138.1	287.0	248.7	231.4	193.5	0.8	0.8	0.7
US	5,274.3	1,481.7	3,792.7	4,636.5	3,713.5	79.2	923.0	7.9	92.1	3,396.3	396.4	1,240.3	12.6	1,719.5	1,732.1	6,610.0	3,953.3	4,214.6	4,702.5	19.2	15.3	17.8

(*Continued on next page*)

Table 3. *Continued*

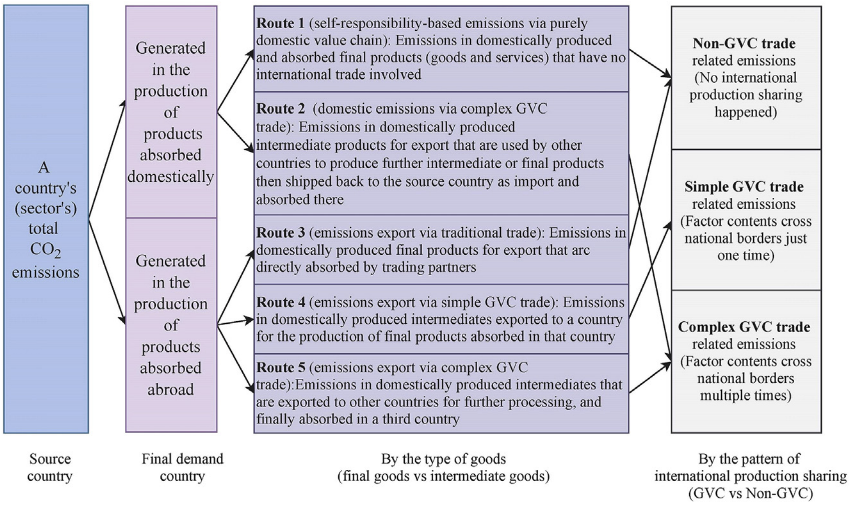
2015 Unit: $MtCO_2$	Territory-based emissions	Self responsibility emissions from consumption process	Production-based emissions	Consumption-based emissions	No-trade scenario emissions	Production-based carbon leakage	Consumption-based carbon leakage	Responsibility weight for producer (%)	Responsibility weight for consumer (%)	Self responsibility emissions from production process	Production-based emissions to be shared	Consumption-based emissions to be shared	Shared production-based emissions	Shared consumption-based emissions	Responsibility on carbon leakage	Total responsibility on global emissions	Total responsibility on global emissions by Lenzen method	Total responsibility on global emissions by Kondo method	Total responsibility on global emissions by Dietzenbacher method	Total responsibility on global emissions (%)	Total responsibility based on pure producer (%)	Total responsibility based on pure consumer (%)
RoW	6,825.3	866.1	5,959.2	6,347.5	5,211.4	747.8	1,136.1	39.7	60.3	3,984.8	1,974.4	2,362.7	600.4	1,385.8	1,986.2	6,837.1	6,003.5	6,153.3	6,345.8	19.9	19.9	21.0
Total	34,378.0	4,414.5	29,963.6	29,963.6	27,334.9	2,628.6	2,628.6	50.0	50.0	21,996.6	7,967.0	7,967.0	3,772.1	4,194.9	7967.0	34,378.0	34,378.0	34,378.0	34,378.0	100.0	100.0	100.0

[a] Calculations are based on the data for 2015.

[b] AUS, Australia; AUT, Austria; BEL, Belgium; BGR, Bulgaria; BRA, Brazil; CAN, Canada; CHN, China; CYP, Cyprus; CZE, Czech Republic; DEU, Germany; DNK, Denmark; ESP, Spain; EST, Estonia; FIN, Finland; FRA, France; GBR, United Kingdom; GRC, Greece; HUN, Hungry; IDN, Indonesia; IND, India; IRL, Ireland; ITA, Italy; JPN, Japan; KOR, South Korea; LTU, Lithuania; LUX, Luxembourg; LVA, Latvia; MEX, Mexico; MLT, Malta; NLD, the Netherlands; POL, Poland; PRT, Portugal; ROM, Romania; RUS, Russia; SVK, Slovakia; SWE, Sweden; TUR, Turkey; TWN, Taipei,China; US, United States; RoW, rest of the world.

international trade, which might be caused by differences in environmental regulation levels among countries.[47,48] Another driver is the increasing cross-border fragmentation of production, which requires more international shipping (which is a high-carbon-intensity activity) across multiple borders.[49,50] In this sense, introducing carbon pricing along GVCs at the country/sector/bilateral level based on each country's share of responsibility for carbon emissions in the context of a trade-investment-environment nexus to promote the establishment of green value chains should be fully considered in the GVC and Paris Agreement era.

Although consensus has been reached on "common but differentiated responsibilities" (CBDR) among the international community, many challenges remain regarding the effective implementation of CBDR. Using our proposed GVC-based emissions accounting framework as a reference point, it might be easier to achieve consensus regarding the control of self-responsibility-based emissions in advance. Given the increasing difficulty of limiting global warming to 1.5°C and the fact that most developing countries have no absolute emissions reduction targets and relatively weak environmental regulations, helping these countries to set an appropriate, ambitious target for an emissions peak and/or achieving carbon neutrality in terms of current self-responsibility-based emissions could be a constructive means of curbing the current rapid increase in global carbon emissions. The Paris Agreement allows countries to work from very different starting points and with different ambitions toward their own carbon neutrality goal, and uses production-based accounting to measure their emissions (e.g., the original idea of carbon neutrality at the individual country level means taking full responsibility for all of one's direct and indirect emissions), without explicit consideration of the responsibility sharing of carbon leakage across countries between producers and consumers. This implies that a net carbon exporting country might take more responsibility in the process of achieving its own carbon neutrality goal, while a net carbon importing country might take less responsibility than is required. In this sense, negotiation about responsibility sharing regarding carbon leakage across countries is inevitably going to be unavoidable if we are to achieve the global goal of net-zero emissions. Regarding emissions that are not self-responsibility based, our GVC-based sharing approach provides a useful reference point for future negotiations. One policy application involves monitoring the difference between the Nationally Determined Contributions or carbon neutrality agenda (or level of achievement) nominated by countries for the purpose of achieving their Paris Agreement target and their responsibility, thereby helping more countries to clearly recognize how far away they currently are from achieving their goal. Another policy application involves developing climate funds that can be used to support not only renewable energy projects in developing countries but also innovations that reduce the cost of carbon capture and storage.[51] These funds could be obtained through, for example, GVC responsibility-sharing-based carbon border adjustment taxes. In summary, substantially increasing the charges levied for carbon emissions by both producers and consumers at any point along GVCs in a fair and efficient manner is very important because unless some



Route 1 (self-responsibility-based emissions via purely domestic value chain): Emissions in domestically produced and absorbed final products (goods and services) that have no international trade involved

Route 2 (domestic emissions via complex GVC trade): Emissions in domestically produced intermediate products for export that are used by other countries to produce further intermediate or final products then shipped back to the source country as import and absorbed there

Route 3 (emissions export via traditional trade): Emissions in domestically produced final products for export that arc directly absorbed by trading partners

Route 4 (emissions export via simple GVC trade): Emissions in domestically produced intermediates exported to a country for the production of final products absorbed in that country

Route 5 (emissions export via complex GVC trade):Emissions in domestically produced intermediates that are exported to other countries for further processing, and finally absorbed in a third country

Figure 4. GVC-based accounting framework for tracing CO_2 emissions

The GVC-based accounting framework classifies the GVCs into five routes. Route 1: production of domestically produced and absorbed emissions. Route 2: domestic emissions embodied in intermediate exports that are finally absorbed domestically. Route 3: production of domestic emissions embodied in final product exports. Route 4: domestic emissions absorbed by the trading partner country without further border-crossing activity. Route 5: the emissions of country s that are absorbed by country r via third countries (factor contents move across country borders at least twice).

of the largest emitting countries or regions, such as the US, China, and the European Union can achieve consensus, no scheme will raise sufficient funds to reduce global carbon emissions by the necessary amount.[51]

As for application of our research findings beyond value-added and CO_2 emissions, if the necessary data are available, the potential environmental costs and responsibility in relation to income (measured in terms of both labor and capital) and any other externality (e.g., emissions into the atmosphere, pollution, and waste production) could also be monitored along GVCs.[52–54] Regarding further improvement of the emissions responsibility sharing method, some recent innovative studies have introduced capital formation to the consumption-based accounting approach[55–58] and the activities of multinationals to the control-based accounting approach[59–64] (see Note S3 for endogenizing capital), and have allocated emissions between co-products[65] and supply chains from a game-theory perspective,[66,67] all of which provide useful information for future research. It is of particular interest to share responsibility at the sector level, combining a bottom-up approach with our proposed top-down approach (see Note S4 for sector level results). In addition, considering that a considerable amount of emissions are associated with the production of capital goods, it is also important to share the emissions responsibilities under a dynamic model with endogenized capital formation.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Yuning Gao (gao_yuning@mail.tsinghua.edu.cn).

Materials availability

This study did not generate new unique materials.

Data and code availability

We obtained our MRIO data from three sources: the WIOD11 from 1995 to 2009, the WIOD16 from 2010 to 2014[43] (https://www.rug.nl/ggdc/valuechain/wiod/?lang=en), and the ADB MRIO in 2015[68] (https://mrio.adbx.online). Although the techniques used to construct those MRIO data are similar, the structures of these three MRIOs differ: the WIOD11 covers 40+1 economies and 35 sectors, the WIOD16 covers 43+1 economies and 56 sectors, and the ADB covers 62+1 countries and 35 sectors. As one of the handbooks provided by the developers of the ADB MRIO notes, the core of the ADB MRIO is the WIOD, which facilitates consistency between the two series of tables. To obtain world IO tables that were consistent in terms of countries and industries, we aggregated these countries and sectors to create a series of world IO tables consisting of 41 countries and 34 industries from 1995 to 2015. All code and data have been deposited at Zonodo Deposit: https://doi.org/10.5281/zenodo.7455938.

Building a GVC-based accounting to trace emissions

The method used to build our GVC-based accounting framework is based on the work of Leontief,[69] who showed that the complex linkages among different industries and across countries could be expressed as inter-industry, cross-country transactions organized into chessboard-type matrices known as IO tables, in which each column represents the inputs required from other industries (including imports and direct value-added) to produce a given amount of the product represented in each column. After normalization, the technical coefficient table shows the amounts and types of intermediate inputs needed for the production of one unit of gross output. Using these coefficients, the gross output at all stages of production that is required to produce one unit of final product can be estimated via the Leontief inverse. When the output associated with a particular level of final demand is known, the total emissions from the global economy can be estimated by multiplying these output flows by the emissions-intensity coefficient (i.e., the amount of emissions per unit of gross output) in each country/industry. Furthermore, following previous studies on GVCs,[16,41,42] a country, or sector's production-based emissions (**PE**) can be thoroughly traced through various domestic and international trade routes based on the location of the final user.

Without loss of generality, let us consider an MRIO table including G countries and N sectors, as shown in Table 2.

In this example, $\mathbf{Z}^{sr}$ is an N × N matrix of intermediate input flows that are produced in country s and used in country r, $\mathbf{Y}^{sr}$ is an N × 1 vector representing the final products produced in country s and consumed in country r, $\mathbf{X}^{s}$ is also an N × 1 vector representing the gross outputs in country s, and $\mathbf{Va}^{s}$ and $\mathbf{Em}^{s}$ denote a 1 × N vector of direct value-added and emissions, respectively, in country s. In this MRIO table, the input coefficient matrix can be defined as $\mathbf{A} = \mathbf{Z}\widehat{\mathbf{X}}^{-1}$, where $\widehat{\mathbf{X}}$ denotes a diagonal matrix with the output vector $\mathbf{X}$ on its diagonal. The value-added and emissions coefficient vectors can be defined as $\mathbf{V} = \mathbf{Va}\widehat{\mathbf{X}}^{-1}$ and $\mathbf{E} = \mathbf{Em}\widehat{\mathbf{X}}^{-1}$, respectively. The gross output production and use balance, or the row balance condition, of the above MRIO table can be written as:

$$\mathbf{AX} + \mathbf{Y} = \mathbf{X}. \qquad \text{(Equation 1)}$$

Rearranging Equation 1, we obtain the classical Leontief equation:

$$\mathbf{X} = \mathbf{BY}, \qquad \text{(Equation 2)}$$

where $\mathbf{B} = (\mathbf{I} - \mathbf{A})^{-1}$ is the well-known global Leontief inverse matrix representing the output induced by one unit of final demand through the entire global production network. Equation 2 can also be expressed in the following matrix form:

$$\begin{bmatrix} \mathbf{X}^{11} & \cdots & \mathbf{X}^{1G} \\ \vdots & \ddots & \vdots \\ \mathbf{X}^{G1} & \cdots & \mathbf{X}^{GG} \end{bmatrix} = \begin{bmatrix} \mathbf{B}^{11} & \cdots & \mathbf{B}^{1G} \\ \vdots & \ddots & \vdots \\ \mathbf{B}^{G1} & \cdots & \mathbf{B}^{GG} \end{bmatrix} \begin{bmatrix} \mathbf{Y}^{11} & \cdots & \mathbf{Y}^{1G} \\ \vdots & \ddots & \vdots \\ \mathbf{Y}^{G1} & \cdots & \mathbf{Y}^{GG} \end{bmatrix}, \qquad \text{(Equation 3)}$$

where $\mathbf{X}^{sr}$ is an N×1 vector representing the output induced in country **s** by final demand in country **r**. This can be stated as follows:

$$\mathbf{X}^{sr} = \sum\nolimits_{t}^{G} \mathbf{B}^{st}\mathbf{Y}^{tr}. \qquad \text{(Equation 4)}$$

Thus, each country's output vector can be rewritten as:

$$\mathbf{X}^{s} = \sum\nolimits_{r}^{G} \mathbf{X}^{sr} = \mathbf{X}^{ss} + \sum\nolimits_{r \neq s}^{G} \mathbf{X}^{sr}. \qquad \text{(Equation 5)}$$

Multiplying both sides of Equation 3 by $(\mathbf{I} - \mathbf{A})$ yields:

$$\begin{bmatrix} \mathbf{I} - \mathbf{A}^{11} & \cdots & -\mathbf{A}^{1G} \\ \vdots & \ddots & \vdots \\ -\mathbf{A}^{G1} & \cdots & \mathbf{I} - \mathbf{A}^{GG} \end{bmatrix} \begin{bmatrix} \mathbf{X}^{11} & \cdots & \mathbf{X}^{1G} \\ \vdots & \ddots & \vdots \\ \mathbf{X}^{G1} & \cdots & \mathbf{X}^{GG} \end{bmatrix} = \begin{bmatrix} \mathbf{Y}^{11} & \cdots & \mathbf{Y}^{1G} \\ \vdots & \ddots & \vdots \\ \mathbf{Y}^{G1} & \cdots & \mathbf{Y}^{GG} \end{bmatrix}. \qquad \text{(Equation 6)}$$

Each element on the right-hand side of Equation 6 can be rewritten in the following form:

$$(\mathbf{I} - \mathbf{A}^{ss})\mathbf{X}^{sr} - \sum\nolimits_{t \neq s}^{G} \mathbf{A}^{st}\mathbf{X}^{tr} = \mathbf{Y}^{sr}. \qquad \text{(Equation 7)}$$

Multiplying both sides of Equation 7 by $\mathbf{L}^{ss} = (\mathbf{I} - \mathbf{A}^{ss})^{-1}$, which represents the domestic Leontief inverse of country **s** (output of domestic products induced by one unit of final demand), we obtain:

$$\mathbf{X}^{sr} = \mathbf{L}^{ss}\sum\nolimits_{t \neq s}^{G} \mathbf{A}^{st}\mathbf{X}^{tr} + \mathbf{L}^{ss}\mathbf{Y}^{sr}. \qquad \text{(Equation 8)}$$

Without loss of generality, when **r** = **s** in Equation 8, we obtain:

$$\mathbf{X}^{ss} = \mathbf{L}^{ss}\sum\nolimits_{t \neq s}^{G} \mathbf{A}^{st}\mathbf{X}^{ts} + \mathbf{L}^{ss}\mathbf{Y}^{ss}. \qquad \text{(Equation 9)}$$

Using Equation 8 and Equation 9, Equation 5 can be rewritten as:

$$\begin{aligned} \mathbf{X}^{s} &= \mathbf{X}^{ss} + \sum\nolimits_{r \neq s}^{G} \mathbf{X}^{sr} \\ &= \left(\mathbf{L}^{ss}\sum\nolimits_{t \neq s}^{G} \mathbf{A}^{st}\mathbf{X}^{ts} + \mathbf{L}^{ss}\mathbf{Y}^{ss}\right) + \sum\nolimits_{r \neq s}^{G}\left(\mathbf{L}^{ss}\sum\nolimits_{t \neq s}^{G} \mathbf{A}^{st}\mathbf{X}^{tr} + \mathbf{L}^{ss}\mathbf{Y}^{sr}\right). \\ &= \mathbf{L}^{ss}\mathbf{Y}^{ss} + \mathbf{L}^{ss}\sum\nolimits_{r \neq s}^{G} \mathbf{Y}^{sr} + \mathbf{L}^{ss}\sum\nolimits_{t \neq s}^{G} \mathbf{A}^{st}\mathbf{X}^{ts} + \mathbf{L}^{ss}\sum\nolimits_{r \neq s}^{G}\sum\nolimits_{t \neq s}^{G} \mathbf{A}^{st}\mathbf{X}^{tr} \end{aligned} \qquad \text{(Equation 10)}$$

Using Equation 4, Equation 10 can be rewritten as:

$$\begin{aligned} \mathbf{X}^{s} &= \mathbf{L}^{ss}\mathbf{Y}^{ss} + \mathbf{L}^{ss}\sum\nolimits_{r \neq s}^{G} \mathbf{Y}^{sr} + \mathbf{L}^{ss}\sum\nolimits_{t \neq s}^{G} \mathbf{A}^{st}\mathbf{X}^{ts} + \mathbf{L}^{ss}\sum\nolimits_{r \neq s}^{G}\sum\nolimits_{t \neq s}^{G} \mathbf{A}^{st}\mathbf{X}^{tr} \\ &= \mathbf{L}^{ss}\mathbf{Y}^{ss} + \mathbf{L}^{ss}\sum\nolimits_{r \neq s}^{G} \mathbf{Y}^{sr} + \mathbf{L}^{ss}\sum\nolimits_{t \neq s}^{G} \mathbf{A}^{st}\sum\nolimits_{u}^{G} \mathbf{B}^{tu}\mathbf{Y}^{us} + \mathbf{L}^{ss}\sum\nolimits_{r \neq s}^{G}\sum\nolimits_{t \neq s}^{G} \mathbf{A}^{st}\sum\nolimits_{u}^{G} \mathbf{B}^{tu}\mathbf{Y}^{ur} \\ &= \mathbf{L}^{ss}\mathbf{Y}^{ss} + \mathbf{L}^{ss}\sum\nolimits_{r \neq s}^{G} \mathbf{Y}^{sr} + \mathbf{L}^{ss}\sum\nolimits_{r \neq s}^{G} \mathbf{A}^{sr}\mathbf{L}^{rr}\mathbf{Y}^{rr} + \mathbf{L}^{ss}\sum\nolimits_{t \neq s}^{G} \mathbf{A}^{st}\sum\nolimits_{u}^{G} \mathbf{B}^{tu}\mathbf{Y}^{us} \\ &\quad + \mathbf{L}^{ss}\left(\sum\nolimits_{r \neq s}^{G}\sum\nolimits_{t \neq s}^{G} \mathbf{A}^{st}\sum\nolimits_{u}^{G} \mathbf{B}^{tu}\mathbf{Y}^{ur} - \sum\nolimits_{r \neq s}^{G} \mathbf{A}^{sr}\mathbf{L}^{rr}\mathbf{Y}^{rr}\right). \end{aligned} \qquad \text{(Equation 11)}$$

Multiplying both sides of Equation 11 by the emissions diagonal matrix and rearranging the results, we obtain:

$$\begin{aligned} (\mathbf{Em}^{s})' = \widehat{\mathbf{E}}^{s}\mathbf{X}^{s} = &\underbrace{\widehat{\mathbf{E}}^{s}\mathbf{L}^{ss}\mathbf{Y}^{ss}}_{\text{Route 1:producer's self – responsibility – based emissions}} \\ &+ \underbrace{\widehat{\mathbf{E}}^{s}\mathbf{L}^{ss}\sum\nolimits_{r \neq s}^{G} \mathbf{A}^{sr}\sum\nolimits_{u}^{G} \mathbf{B}^{ru}\mathbf{Y}^{us}}_{\text{Route 2:emissions re – import via complex GVC trade}} \\ &+ \underbrace{\widehat{\mathbf{E}}^{s}\mathbf{L}^{ss}\sum\nolimits_{r \neq s}^{G} \mathbf{Y}^{sr}}_{\text{Route 3:emissions export via simple GVC trade}} \\ &+ \underbrace{\widehat{\mathbf{E}}^{s}\mathbf{L}^{ss}\sum\nolimits_{r \neq s}^{G} \mathbf{A}^{sr}\mathbf{L}^{rr}\mathbf{Y}^{rr}}_{\text{Route 4:emissions export via simple GVC trade}} \\ &\underbrace{+ \widehat{\mathbf{E}}^{s}\mathbf{L}^{ss}\left(\sum\nolimits_{r \neq s}^{G}\sum\nolimits_{t \neq s}^{G} \mathbf{A}^{st}\sum\nolimits_{u}^{G} \mathbf{B}^{tu}\mathbf{Y}^{ur} - \sum\nolimits_{r \neq s}^{G} \mathbf{A}^{sr}\mathbf{L}^{rr}\mathbf{Y}^{rr}\right).}_{\text{Route 5:emissions export via complex GVC trade}} \end{aligned} \qquad \text{(Equation 12)}$$

Clearly, a country's domestic emissions can be decomposed into five types of production activities, as shown below and in Figure 4.

Route 1: production of domestically produced and absorbed emissions. This represents domestic emissions that are embodied in domestic final demand not related to international trade, and for which no cross-country production sharing occurs.

Route 2: domestic emissions embodied in intermediate exports that are finally absorbed domestically. This represents emissions of country s embodied in intermediate exports that are used by importing country r to produce either intermediate (possibly via a third country in the production chain) or final goods and services that are ultimately shipped back to the source country s as imports and consumed there. In this case, production sharing via intermediate trade occurs between the home and foreign countries and results in two or more cross-border transactions.

Route 3: production of domestic emissions embodied in final product exports. This represents domestic emissions embodied in products used to satisfy foreign final demand that do not involve any cross-country production activities. These products cross a national border for consumption, and thus this is similar to the traditional Ricardian-type trade, or "French wine in exchange for English cloth."

Route 4: domestic emissions absorbed by the trading partner country without further border-crossing activity. This represents emissions of country s embodied in intermediate exports that are used by a trading partner to produce its domestic final products, which are then consumed in the direct importing country, r. In this case, domestic factor contents cross a national border only once, with no indirect exports via third countries or re-exporting activity involved.

Route 5: this category includes two parts, as shown in Equation 12. The first part represents the emissions by country s that are induced by the final demand of country r for imports from a third country u. This implies that the emissions by country s need to first be embodied in its intermediate products exported directly to country t (including country r), which will then be directly and indirectly used by country u (including country r) to produce final products for satisfying the final demand of country r. With the second part, which equals to minus route 3, it is easy to see that route 5 represents the emissions of country s that are absorbed by country r via third countries (factor contents move across country borders at least twice).

By removing the summation for r in Equation 12, routes 3, 4, and 5 can be expressed bilaterally as the emissions of country s that are absorbed by a part of the final demand of country r. Thus, the sum of routes 3, 4, and 5 can be expressed bilaterally as the emissions of country s that are absorbed by the total final demand of country r. This is consistent with the definition of trade in value-added at the bilateral level proposed by Johnson and Noguera.[29]

Sharing emissions responsibility along GVCs

One-step algorithm

Here, we share the responsibility for emissions among various producers and consumers along GVCs using a one-step algorithm. Under the NT scenario, if a country wants to maintain its current level of final demand for domestically produced goods and services, its emissions based on the MRIO table can be calculated as follows:

$$\mathbf{NT}^s = \mathbf{E}^s\overline{\mathbf{L}}^s\mathbf{Y}^{ss}, \qquad \text{(Equation 13)}$$

where $\mathbf{NT}^s$ represents the emissions level for country s using only domestic contents for its production processes to fulfill its current level of final demand for domestically made products. $\mathbf{E}^s$ is a $1 \times N$ vector (where n represents the number of sectors) of carbon intensity by sector (i.e., emissions per unit of output), $\overline{\mathbf{L}}^s = (\mathbf{I} - \sum_r \mathbf{A}^{rs})^{-1}$, in which $\sum_r \mathbf{A}^{rs}$ is the Leontief's technical coefficient (similar to a noncompetitive national IO table in which the domestic input matrix is merged with intermediate import matrices), and $\mathbf{Y}^{ss}$ is an $N \times 1$ vector representing final goods and services by sector produced in country s and consumed in country s. Comparing this $\mathbf{NT}^s$ with both production-based emissions ($\mathbf{PE}^s = \mathbf{Em}^s \cdot \mathbf{u}$; $\mathbf{u}$ is an $N \times 1$ unit vector) and consumption-based emissions ($\mathbf{CE}^s = \sum_t \sum_r \mathbf{E}^t\mathbf{B}^{tr}\mathbf{Y}^{rs}$), we obtain $\mathbf{PCL}^s$ and $\mathbf{CCL}^s$. Clearly, $\mathbf{PCL}^s$, the production-based emissions minus the emissions under the NT scenario, can be considered as the carbon leakage for which country s should take responsibility as a producer, and $\mathbf{CCL}^s$, the consumption-based emissions minus the emissions under the NT scenario, is the carbon leakage for which country s should take responsibility as a consumer:

$$\mathbf{PCL}^s = \mathbf{PE}^s - \mathbf{NT}^s \qquad \text{(Equation 14)}$$

$$\mathbf{CCL}^s = \mathbf{CE}^s - \mathbf{NT}^s. \qquad \text{(Equation 15)}$$

Then, the contribution of country s to worldwide total carbon leakage from producer and consumer perspectives can be calculated as follows:

$$\mathbf{SPCL}^s = \frac{\mathbf{PCL}^s}{\sum_s \mathbf{PCL}^s} \qquad \text{(Equation 16)}$$

$$\mathbf{SCCL}^s = \frac{\mathbf{CCL}^s}{\sum_s \mathbf{CCL}^s}. \qquad \text{(Equation 17)}$$

The emissions responsibilities to be shared by the producers and consumers of country s are its production-based emissions or consumption-based emissions minus its self-responsibility-based emissions. Given that its self-responsibility-based emissions $\mathbf{SEP}^s$ can be directly measured using our accounting framework, the responsibilities that should be shared by the production and consumption sides, respectively, are calculated as follows:

$$\mathbf{PES}^s = \mathbf{PE}^s - \mathbf{SEP}^s \qquad \text{(Equation 18)}$$

$$\mathbf{CES}^s = \mathbf{CE}^s - \mathbf{SEP}^s. \qquad \text{(Equation 19)}$$

The remaining responsibilities to be shared by producers and consumers worldwide can be calculated as follows:

$$\mathbf{TES} = \sum_s \mathbf{PES}^s = \sum_s \mathbf{CES}^s. \qquad \text{(Equation 20)}$$

Following Kondo et al.,[36] we assume that country s's total responsibility for carbon leakage consists of 50% of its shared **PE** and 50% of its shared **CE**. That is, its responsibility **FS** in relation to carbon leakage is given by:

$$\mathbf{FS} = 0.5 \cdot \mathbf{SPCL}^s \cdot \mathbf{TES} + 0.5 \cdot \mathbf{SCCL}^s \cdot \mathbf{TES}. \qquad \text{(Equation 21)}$$

Thus, the total responsibility of country ***s***, **TS**, in terms of global emissions is given by:

$$\mathbf{TS} = \mathbf{FS} + \mathbf{SEC} + \mathbf{SEP}, \qquad \text{(Equation 22)}$$

where **SEC** represents self-responsibility-based emissions from the consumption process, that is, emissions directly generated by household fuel combustion, such as fuel for road transportation, natural gas for heating/cooking, and other household fuel usage.

Iterative algorithm. Assuming that sharing production-side responsibilities and sharing consumption-side responsibilities are of equal importance to country **s** might be an oversimplification because it seems reasonable that there should be a difference between the importance of country s's role as a producer and that of its role as a consumer. This is the main reason for developing a multi-step method to share the responsibilities.

We can define the producers' and consumers' responsibility weights, which reflect the importance of country s's role as a producer and a consumer, respectively, as follows:

$$\omega^s = |\mathbf{PCL}^s| / (|\mathbf{PCL}^s| + |\mathbf{CCL}^s|) \qquad \text{(Equation 23)}$$

$$(1 - \omega^s) = |\mathbf{CCL}^s| / (|\mathbf{PCL}^s| + |\mathbf{CCL}^s|). \qquad \text{(Equation 24)}$$

The responsibilities that should be shared are still defined as:

$$\mathbf{PES}^s = \mathbf{PE}^s - \mathbf{SEP}^s \qquad \text{(Equation 25)}$$

$$\mathbf{CES}^s = \mathbf{CE}^s - \mathbf{SEP}^s. \qquad \text{(Equation 26)}$$

Thus, the remaining responsibilities to be shared by producers and consumers worldwide can be calculated as follows:

$$\mathbf{TES} = \sum_s \mathbf{PES}^s = \sum_s \mathbf{CES}^s. \qquad \text{(Equation 27)}$$

The total shared responsibilities should be the sum of the production-side shared responsibilities and the consumption-side shared responsibilities, weighted by the relative importance of the country's roles as a producer and as a consumer, represented by ω^s and $(1 - \omega^s)$, respectively. In the process of sharing responsibility with weights of ω^s and $(1 - \omega^s)$, there is no guarantee that total world responsibilities **TES** will be fully shared by all countries in the first step. If we denote the responsibilities that have already been shared by all countries up until the n-th step as $\mathbf{SPCE}_n$, the responsibilities that remain to be shared until the n-th step are given by $\mathbf{TES} - \mathbf{SPCE}_n$. Thus, the shared responsibilities from the production side and the consumption side, respectively, for country s at the n-th step are given by:

$$\mathbf{PES}^s_n = (\mathbf{TES} - \mathbf{SPCE}_n) \cdot \mathbf{SPCL}^s \qquad \text{(Equation 28)}$$

$$\mathbf{CES}^s_n = (\mathbf{TES} - \mathbf{SPCE}_n) \cdot \mathbf{SCCL}^s. \qquad \text{(Equation 29)}$$

Using an iterative algorithm to share responsibility step by step, we obtain the responsibilities shared between countries as follows:

$$\mathbf{SPCE}_1 = \sum_s \omega^s \cdot \mathbf{PES}^s_0 + \sum_s (1 - \omega^s) \cdot \mathbf{CES}^s_0$$

$$\cdots\cdots$$

$$\mathbf{SPCE}_n = \mathbf{SPCE}_{n-1} + \sum_s \omega^s \cdot \mathbf{PES}^s_{n-1} + \sum_s (1 - \omega^s) \cdot \mathbf{CES}^s_{n-1}. \qquad \text{(Equation 30)}$$

$$\mathbf{SPCE}_n = \mathbf{SPCE}_{n-1} + \sum_s \omega^s \cdot \mathbf{PES}^s_{n-1} + \sum_s (1 - \omega^s) \cdot \mathbf{CES}^s_{n-1}$$

After sufficient iterations, the responsibilities that have already been shared by all countries converge to the total responsibilities to be shared as follows:

$$\lim_{n\to\infty}\mathbf{SPCE}_n = \mathbf{TES}. \quad \text{(Equation 31)}$$

Using this method, the shared production-based emissions $\mathbf{FSP}^s$, shared consumption-based emissions $\mathbf{FSC}^s$, and responsibility for carbon leakage $\mathbf{FS}^s$, respectively, are given by:

$$\mathbf{FSP}^s = \sum_{n=0}^{\infty}\omega^s\cdot\mathbf{FSP}^s \quad \text{(Equation 32)}$$

$$\mathbf{FSC}^s = \sum_{n=0}^{\infty}(1-\omega^s)\cdot\mathbf{CES}_n^s \quad \text{(Equation 33)}$$

$$\mathbf{FS}^s = \mathbf{FSP}^s+\mathbf{FSC}^s. \quad \text{(Equation 34)}$$

Thus, the total responsibility for global emissions of country s is given by:

$$\mathbf{TS} = \mathbf{FS}+\mathbf{SEC}+\mathbf{SEP}. \quad \text{(Equation 35)}$$

Applying this iterative method to sharing emissions responsibility among countries, we arrive at the results shown in Table 3.

The convergence in Equation 31 can be proved as follows:

$$\mathbf{SPCE}_n = \mathbf{SPCE}_{n-1}+\sum_s\omega^s\cdot(\mathbf{TES}-\mathbf{SPCE}_{n-1})\cdot\mathbf{SPCL}^s+\sum_s(1-\omega^s)\cdot(\mathbf{TES}-\mathbf{SPCE}_{n-1})\cdot\mathbf{SCCL}^s, \quad \text{(Equation 36)}$$

that is,

$$\mathbf{SPCE}_n = \mathbf{SPCE}_{n-1}+\sum_s\omega^s\cdot\mathbf{TES}\cdot\mathbf{SPCL}^s-\sum_s\omega^s\cdot\mathbf{SPCE}_{n-1}\cdot\mathbf{SPCL}^s+\sum_s(1-\omega^s)\cdot\mathbf{TES}\cdot\mathbf{SCCL}^s-\sum_s(1-\omega^s)\cdot\mathbf{SPCE}_{n-1}\cdot\mathbf{SCCL}^s. \quad \text{(Equation 37)}$$

Simplifying the above expressions, we get:

$$\mathbf{TES} = \sum_s\mathbf{PES}^s = \sum_s\mathbf{CES}^s = \alpha \quad \text{(Equation 38)}$$

$$\sum_s\omega^s\cdot\mathbf{TES}\cdot\mathbf{SPCL}^s+\sum_s(1-\omega^s)\cdot\mathbf{TES}\cdot\mathbf{SCCL}^s = \sum_s\omega^s\cdot\alpha\cdot\mathbf{SPCL}^s+\sum_s(1-\omega^s)\cdot\alpha\cdot\mathbf{SCCL}^s = \beta \quad \text{(Equation 39)}$$

$$\sum_s\omega^s\cdot\mathbf{SPCL}^s+\sum_s(1-\omega^s)\cdot\mathbf{SCCL}^s = \beta\Big/\alpha \quad \text{(Equation 40)}$$

$$\sum_s\mathbf{PCL}^s = \sum_s\mathbf{CCL}^s = \gamma \quad \text{(Equation 41)}$$

$$\sum_s\omega^s\cdot\mathbf{PCL}^s+\sum_s(1-\omega^s)\cdot\mathbf{CCL}^s = \theta \quad \text{(Equation 42)}$$

$$\frac{\theta}{\gamma} = \frac{\beta}{\alpha}. \quad \text{(Equation 43)}$$

We can simplify Equation 37 as follows:

$$\mathbf{SPCE}_n = \mathbf{SPCE}_{n-1}+\beta-\mathbf{SPCE}_{n-1}\sum_s\omega^s\cdot\mathbf{SPCL}^s-\mathbf{SPCE}_{n-1}\sum_s(1-\omega^s)1-\omega^s\cdot\mathbf{SCCL}^s = \mathbf{SPCE}_{n-1}+\beta-\mathbf{SPCE}_{n-1}\cdot\frac{\sum_s\omega^s\cdot\mathbf{PCL}^s+\sum_s(1-\omega^s)\cdot\mathbf{CCL}^s}{\gamma} = \mathbf{SPCE}_{\mathbf{n-1}}+\beta-\mathbf{SPCE}_{\mathbf{n-1}}\cdot\frac{\theta}{\gamma}. \quad \text{(Equation 44)}$$

Eliminating α from both sides, we have:

$$\mathbf{SPCE}_n-\alpha = \mathbf{SPCE}_{n-1}+\beta-\mathbf{SPCE}_{n-1}\cdot\frac{\beta}{\alpha}-\alpha = \left(1-\frac{\beta}{\alpha}\right)(\mathbf{SPCE}_{n-1}-\alpha) \quad \text{(Equation 45)}$$

$$\mathbf{SPCE}_n-\alpha = \left(1-\frac{\beta}{\alpha}\right)^2(\mathbf{SPCE}_{n-2}-\alpha) = \ldots = \left(1-\frac{\beta}{\alpha}\right)^{n-1}(\mathbf{SPCE}_1-\alpha). \quad \text{(Equation 46)}$$

Given that $0\le\omega^s\le1$, we have:

$$-1<\frac{\beta}{\alpha}<1. \quad \text{(Equation 47)}$$

This provides the sufficient condition for obtaining converged results at the conclusion of the above process. That is, when $n\to\infty$, $\left(1-\frac{\beta}{\alpha}\right)^{n-1}$ converges to 0 and $\mathbf{SPCE}_n$ converges to $\mathbf{TES} = \sum_s\mathbf{PES}^s = \sum_s\mathbf{CES}^s = \alpha$.

Comparison of one-step and iterative algorithms

Two methods for sharing responsibilities for emissions along GVCs are proposed. A one-step algorithm describes a one-step responsibility-sharing method, which is simple, intuitive, and easy to calculate. It only needs one kind of weight index to share the emissions, which is each country's contribution to worldwide total carbon leakage from producers' and consumers' perspectives ($\mathbf{SPCL}^s$ and $\mathbf{SCCL}^s$). An iterative algorithm describes an iterative responsibility-sharing method, which is more logically reasonable, but more complex. The iterative method includes two types of weight index to share the emissions. One is each country's contribution to worldwide total carbon leakage from producers' and consumers' perspectives ($\mathbf{SPCL}^s$ and $\mathbf{SCCL}^s$), estimated across countries, while the other is estimated by comparing each country's own production-side leakage and consumption-side leakage, which reflect the importance of the country's role as a producer and a consumer (ω^s), respectively. These two algorithms are similar because they both share the emissions along GVCs by a country's contribution to worldwide total carbon leakage from producers' and consumers' perspectives. The main difference is that the iterative algorithm also supposes the differing importance of each country's role as a producer and a consumer.

An example of the responsibility sharing process

Here, we take China, one of the world's largest CO_2 emitters, as an example to illustrate how emissions responsibilities are shared across countries.

First, we use the one-step algorithm to estimate China's emissions responsibilities. In 2015, on the production side, China's total production-based emissions or territorial-based emissions were 9,372.7 $MtCO_2$ (TE), consisting of 369.5 $MtCO_2$ of self-responsibility emissions from consumption processes generated through households' direct combustion of fuels (SEC) and 9,003.2 $MtCO_2$ of production-based emissions generated through the production process (PE). On the consumption side, China's total consumption-based emissions were 7,966.4 $MtCO_2$ (CE), which is the counterpart of PE. Under an NT scenario, which is a form of economic self-sufficiency, China's emissions were 8,067.7 $MtCO_2$ (NT). Thus, the difference between practical production-based emissions and NT emissions can be defined as production-based carbon leakage, which was 935.5 $MtCO_2$ (PCL = PE − NT), accounting for 35.6% of total global production-based carbon leakage (SPCL) of 2,628.4 $MtCO_2$. Similarly, the difference between practical consumption-based emissions and NT emissions can be defined as consumption-based carbon leakage, which was −101.3 $MtCO_2$ (CCL = CE − NT), accounting for −3.9% of total global consumption-based carbon leakage (SCCL) of 2,628.4 $MtCO_2$. These shares of SPCL and SCCL represent the relative importance of China in relation to global production-based emissions and consumption-based emissions, respectively, and provide a reference point for how carbon emissions should be shared across countries. How many emissions should be shared? This is derived from our GVC-based results. Self-responsibilities, which do not need to be shared, are the emissions from Route 1, or 7,148.7 $MtCO_2$ for China (SEP). Production-based and consumption-based emissions that need to be shared are 1,854.5 $MtCO_2$ (PES) and 817.7 $MtCO_2$ (CES), respectively, which are the emissions from routes 2 and 5 on the production side and consumption side, respectively. Summing the figures for all countries, we obtain the total global production-based and consumption-based emissions to be shared, or 7,967.1 $MtCO_2$ (SUM(PES) and SUM(CES)). Considering the above-mentioned coefficients SPCL and SCCL, China should be responsible for 35.6% and −3.9% of emissions on the production side and the consumption side, respectively. If the production-side and consumption-side shared responsibilities are equally important, China's share of production-based and consumption-based emissions would be 50% × 35.6% × 7,967.1 = 1,417.8 $MtCO_2$ (FSP) and 50% × (−3.9%) × 7,967.1 = −153.5 $MtCO_2$ (FSC), respectively. Thus, China's share of total emissions is 8,782.5 $MtCO_2$ (TS), consisting of 369.5 $MtCO_2$ of self-responsibility emissions from households' direct consumption of fuel, 7,148.7 of self-responsibility emissions that need no sharing (SEP), 1,417.8 $MtCO_2$ of production-side shared emissions (FSP), and −153.5 $MtCO_2$ of consumption-side shared emissions (FSC).

Next, we use the iterative algorithm to estimate China's emissions responsibilities. All steps remain the same as those used in relation to the one-step algorithm if the production-side shared responsibilities and the consumption-side shared responsibilities are equally important. However, under this iterative algorithm, the production-side and consumption-side shared responsibilities are not of equal importance, which is more reasonable. For instance, China's PCL is 935.5 $MtCO_2$, while its CCL is −101.3 $MtCO_2$. We can obtain more reasonable results if we use another weight ω to reflect how shared production-based emissions and consumption-based emissions should be reflected in total emissions responsibilities (TS). By comparing the sizes of PCL and CCL, we obtain weight ω ($\omega = |PCL^s| / (|PCL^s| + |CCL^s|)$), which was 90.2% for China in 2015. Then, we conduct the iterative process. In the first-round sharing process, China is allocated 90.2% × 35.6% × 7,967.1 $MtCO_2$ from the production side and 9.8% × (−3.9%) × 7,967.1 $MtCO_2$ from the consumption side. After the first round, not all of the global emissions that should be shared are accounted for. Thus, we sum the global emissions that remain to be shared and undertake a second round of the sharing process. This process continues until the n-th round, at which point all global emissions have been shared.

SUPPLEMENTAL INFORMATION

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AUTHOR CONTRIBUTIONS

B.M., Y.G., Z.W., and J.X. conceived the original idea. B.M., Z.W., Y.L., Y.G., and M.L. developed the theoretical model. B.M. and M.L. developed the responsibility sharing algorithm. M.L. conducted the model calculation, data arrangement, compilation of figures and tables, and literature review. B.M., M.L., Y.G., Y.L., and R.A. wrote the main text and worked on the responses to editor and reviewers' comments. K.F. provided the emissions data. Y.Q., K.F., Y.S., H.S., and K.W. advised on the model, data construction works, and provided comments and revision suggestions on the preliminary draft of the research. All authors discussed the results and revised the paper.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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REFERENCES

1. United Nations Conference on Trade and Development (2013). World Investment Report 2013: Global Value Chains: Investment and Trade for Development (UN).
2. Degain, C., Meng, B., and Wang, Z. (2017). Recent trends in global trade and global value chains. In the World Bank Group. In Global Value Chain Development Report 2017: Measuring and Analyzing the Impact of GVCs on Economic Development, pp. 37–68.
3. Li, X., Meng, B., and Wang, Z. (2019). Recent patterns of global production and GVC participation. In Global Value Chain Development Report 2019: Technological Innovation, Supply Chain Trade, and Workers in a Globalized World, D. Dollar, E. Ganne, V. Stolzenburg, and Z. Wang, eds., pp. 9–43.
4. WTO.; IDE-JETRO (2011). Trade Patterns and Global Value Chains in East Asia: From Trade in Goods to Trade in Tasks (WTO iLibrary). https://doi.org/10.30875/6a810f38-en.
5. Antràs, P., and Gortari, A. (2020). On the geography of global value chains. Econometrica *88*, 1553–1598. https://doi.org/10.3982/ECTA15362.
6. Melitz, M.J., and Trefler, D. (2012). Gains from trade when firms matter. J. Econ. Perspect. *26*, 91–118. https://doi.org/10.1257/jep.26.2.91.
7. Bloom, N., Sadun, R., and Reenen, J.V. (2012). Americans do IT better: US multinationals and the productivity miracle. Am. Econ. Rev. *102*, 167–201. https://doi.org/10.1257/aer.102.1.167.
8. Gereffi, G., and Fernandez-Stark, K. (2016). Global Value Chain Analysis: A Primer, 2nd Edition. https://hdl.handle.net/10161/12488.
9. Baldwin, R., and Lopez-Gonzalez, J. (2015). Supply-chain trade: a portrait of global patterns and several testable hypotheses. World Econ. *38*, 1682–1721. https://doi.org/10.1111/twec.12189.

10. Kander, A., Jiborn, M., Moran, D.D., and Wiedmann, T.O. (2015). National greenhouse-gas accounting for effective climate policy on international trade. Nat. Clim. Chang. *5*, 431–435. https://doi.org/10.1038/nclimate2555.
11. Hoekstra, A.Y., and Wiedmann, T.O. (2014). Humanity's unsustainable environmental footprint. Science *344*, 1114–1117. https://doi.org/10.1126/science.1248365.
12. Peters, G.P. (2008). From production-based to consumption-based national emission inventories. Ecol. Econ. *65*, 13–23. https://doi.org/10.1016/j.ecolecon.2007.10.014.
13. Tukker, A., and Dietzenbacher, E. (2013). Global multiregional input–output frameworks: an introduction and outlook. Econ. Syst. Res. *25*, 1–19. https://doi.org/10.1080/09535314.2012.761179.
14. Cadarso, M.Á., Monsalve, F., and Arce, G. (2018). Emissions burden shifting in global value chains – winners and losers under multi-regional versus bilateral accounting. Econ. Syst. Res. *30*, 439–461. https://doi.org/10.1080/09535314.2018.1431768.
15. Kander, A., Jiborn, M., Moran, D.D., and Wiedmann, T.O. (2016). Reply to 'Consistency of technology-adjusted consumption-based accounting. Nat. Clim. Chang. *6*, 730. https://doi.org/10.1038/nclimate3060.
16. Meng, B., Peters, G.P., Wang, Z., and Li, M. (2018). Tracing CO_2 emissions in global value chains. Energy Econ. *73*, 24–42. https://doi.org/10.1016/j.eneco.2018.05.013.
17. Jiborn, M., Kulionis, V., and Kander, A. (2020). Consumption versus technology: drivers of global carbon emissions 2000–2014. Energies *13*, 339. https://doi.org/10.3390/en13020339.
18. Davis, S.J., Peters, G.P., and Caldeira, K. (2011). The supply chain of CO_2 emissions. Proc. Natl. Acad. Sci. USA *108*, 18554–18559. https://doi.org/10.1073/pnas.1107409108.
19. Owen, A., Brockway, P., Brand-Correa, L., Bunse, L., Sakai, M., and Barrett, J. (2017). Energy consumption-based accounts: a comparison of results using different energy extension vectors. Appl. Energy *190*, 464–473. https://doi.org/10.1016/j.apenergy.2016.12.089.
20. Lin, J., Pan, D., Davis, S.J., Zhang, Q., He, K., Wang, C., Streets, D.G., Wuebbles, D.J., and Guan, D. (2014). China's international trade and air pollution in the United States. Proc. Natl. Acad. Sci. USA *111*, 1736–1741. https://doi.org/10.1073/pnas.1312860111.
21. Kanemoto, K., Moran, D., Lenzen, M., and Geschke, A. (2014). International trade undermines national emission reduction targets: new evidence from air pollution. Glob. Environ. Change *24*, 52–59. https://doi.org/10.1016/j.gloenvcha.2013.09.008.
22. Wiedmann, T.O., Schandl, H., Lenzen, M., Moran, D., Suh, S., West, J., and Kanemoto, K. (2015). The material footprint of nations. Proc. Natl. Acad. Sci. USA *112*, 6271–6276. https://doi.org/10.1073/pnas.1220362110.
23. Weinzettel, J., Hertwich, E.G., Peters, G.P., Steen-Olsen, K., and Galli, A. (2013). Affluence drives the global displacement of land use. Glob. Environ. Change *23*, 433–438. https://doi.org/10.1016/j.gloenvcha.2012.12.010.
24. Peters, G.P., Davis, S.J., and Andrew, R. (2012). A synthesis of carbon in international trade. Biogeosciences *9*, 3247–3276. https://doi.org/10.5194/bg-9-3247-2012.
25. Feng, K., Chapagain, A., Suh, S., Pfister, S., and Hubacek, K. (2011). Comparison of bottom-up and top-down approaches to calculating the water footprints of nations. Econ. Syst. Res. *23*, 371–385. https://doi.org/10.1080/09535314.2011.638276.
26. Lenzen, M., Moran, D., Bhaduri, A., Kanemoto, K., Bekchanov, M., Geschke, A., and Foran, B. (2013). International trade of scarce water. Ecol. Econ. *94*, 78–85. https://doi.org/10.1016/j.ecolecon.2013.06.018.
27. White, D.J., Hubacek, K., Feng, K., Sun, L., and Meng, B. (2018). The Water-Energy-Food Nexus in East Asia: a tele-connected value chain analysis using inter-regional input-output analysis. Appl. Energy *210*, 550–567. https://doi.org/10.1016/j.apenergy.2017.05.159.
28. Lenzen, M., Moran, D., Kanemoto, K., Foran, B., Lobefaro, L., and Geschke, A. (2012). International trade drives biodiversity threats in developing nations. Nature *486*, 109–112. https://doi.org/10.1038/nature11145.
29. Johnson, R.C., and Noguera, G. (2012). Accounting for intermediates: production sharing and trade in value added. J. Int. Econ. *86*, 224–236. https://doi.org/10.1016/j.jinteco.2011.10.003.
30. Koopman, R., Wang, Z., and Wei, S.-J. (2014). Tracing value-added and double counting in gross exports. Am. Econ. Rev. *104*, 459–494. https://doi.org/10.1257/aer.104.2.459.
31. Timmer, M.P., Erumban, A.A., Los, B., Stehrer, R., and de Vries, G.J. (2014). Slicing up global value chains. J. Econ. Perspect. *28*, 99–118. https://doi.org/10.1257/jep.28.2.99.
32. Andrew, R., and Forgie, V. (2008). A three-perspective view of greenhouse gas emission responsibilities in New Zealand. Ecol. Econ. *68*, 194–204. https://doi.org/10.1016/j.ecolecon.2008.02.016.
33. Bastianoni, S., Pulselli, F.M., and Tiezzi, E. (2004). The problem of assigning responsibility for greenhouse gas emissions. Ecol. Econ. *49*, 253–257. https://doi.org/10.1016/j.ecolecon.2004.01.018.
34. Cadarso, M.Á., López, L.A., Gómez, N., and Tobarra, M.Á. (2012). International trade and shared environmental responsibility by sector. An application to the Spanish economy. Ecol. Econ. *83*, 221–235. https://doi.org/10.1016/j.ecolecon.2012.05.009.
35. Ferng, J.-J. (2003). Allocating the responsibility of CO_2 over-emissions from the perspectives of benefit principle and ecological deficit. Ecol. Econ. *46*, 121–141. https://doi.org/10.1016/S0921-8009(03)00104-6.
36. Kondo, Y., Moriguchi, Y., and Shimizu, H. (1998). CO_2 Emissions in Japan: influences of imports and exports. Appl. Energy *59*, 163–174. https://doi.org/10.1016/S0306-2619(98)00011-7.
37. Gallego, B., and Lenzen, M. (2005). A consistent input–output formulation of shared producer and consumer responsibility. Econ. Syst. Res. *17*, 365–391. https://doi.org/10.1080/09535310500283492.
38. Lenzen, M., Murray, J., Sack, F., and Wiedmann, T. (2007). Shared producer and consumer responsibility-Theory and practice. Ecol. Econ. *61*, 27–42. https://doi.org/10.1016/j.ecolecon.2006.05.018.
39. Dietzenbacher, E., Cazcarro, I., and Arto, I. (2020). Towards a more effective climate policy on international trade. Nat. Commun. *11*, 1130. https://doi.org/10.1038/s41467-020-14837-5.
40. Rodrigues, J., Domingos, T., Giljum, S., and Schneider, F. (2006). Designing an indicator of environmental responsibility. Ecol. Econ. *59*, 256–266. https://doi.org/10.1016/j.ecolecon.2005.10.002.
41. Wang, Z., Wei, S.-J., Yu, X., and Zhu, K. (2017). Measures of Participation in Global Value Chains and Global Business Cycles (National Bureau of Economic Research). Updated version: Wang, Z., Wei, S.-J., Yu, X., and Zhu, K. (2022). Global value chains over business cycles. Journal of International Money and Finance 126, 102643. https://doi.org/10.3386/w23222.
42. Xiao, H., Meng, B., Ye, J., and Li, S. (2020). Are global value chains truly global? Econ. Syst. Res. *32*, 540–564. https://doi.org/10.1080/09535314.2020.1783643.
43. Timmer, M.P., Dietzenbacher, E., Los, B., Stehrer, R., and de Vries, G.J. (2015). An illustrated user guide to the world input-output database: the case of global automotive production: user guide to world input-output database. Rev. Int. Econ. *23*, 575–605. https://doi.org/10.1111/roie.12178.
44. Peters, G.P., Weber, C.L., Guan, D., and Hubacek, K. (2007). China's growing CO_2 emissions: a race between increasing consumption and efficiency gains. Environ. Sci. Technol. *41*, 5939–5944. https://doi.org/10.1021/es070108f.
45. Bhatia, P., Cummis, C., Rich, D., Draucker, L., Lahd, H., and Brown, A. (2011). Greenhouse Gas Protocol Corporate Value Chain (Scope 3) Accounting and Reporting Standard (Standard. World Resources Institute).
46. Rocchi, P., Serrano, M., Roca, J., and Arto, I. (2018). Border carbon adjustments based on avoided emissions: addressing the challenge of its design. Ecol. Econ. *145*, 126–136. https://doi.org/10.1016/j.ecolecon.2017.08.003.

47. Aichele, R., and Felbermayr, G. (2015). Kyoto and carbon leakage: an empirical analysis of the carbon content of bilateral trade. Rev. Econ. Stat. *97*, 104–115. https://doi.org/10.1162/REST_a_00438.
48. Dechezleprêtre, A., and Sato, M. (2017). The impacts of environmental regulations on competitiveness. Rev. Environ. Econ. Policy *11*, 183–206. https://doi.org/10.1093/reep/rex013.
49. Peters, G.P., Marland, G., Le Quéré, C., Boden, T., Canadell, J.G., and Raupach, M.R. (2012). Rapid growth in CO_2 emissions after the 2008–2009 global financial crisis. Nat. Clim. Change. *2*, 2–4. https://doi.org/10.1038/nclimate1332.
50. Wood, R., Stadler, K., Simas, M., Bulavskaya, T., Giljum, S., Lutter, S., and Tukker, A. (2018). Growth in environmental footprints and environmental impacts embodied in trade: resource efficiency indicators from EXIOBASE3: growth in environmental impacts embodied in trade. J. Ind. Ecol. *22*, 553–564. https://doi.org/10.1111/jiec.12735.
51. Wei, S.-J.. How to Make Climate Pledges Stick - Jackson Hole Economics. https://jheconomics.com/how-to-make-climate-pledges-stick-2/.
52. Duan, Y., and Yan, B. (2021). Has processing trade made China's exports cleaner? A regional level analysis. Energy Econ. *96*, 105150. https://doi.org/10.1016/j.eneco.2021.105150.
53. Duan, Y., Ji, T., and Yu, T. (2021). Reassessing pollution haven effect in global value chains. J. Clean. Prod. *284*, 124705. https://doi.org/10.1016/j.jclepro.2020.124705.
54. Meng, B., Gao, Y., Ye, J., Zhang, M., and Xing, Y. (2022). Trade in factor income and the US-China trade balance. China Econ. Rev. *73*, 101792. https://doi.org/10.1016/j.chieco.2022.101792.
55. Lenzen, M., and Treloar, G.J. (2004). Endogenising capital - a comparison of two methods. J. Appl. Input Output Anal. *10*, 1–11. http://www.gakkai.ne.jp/papaios/en/img/jaia2004_10-1.pdf.
56. Södersten, C.J.H., Wood, R., and Hertwich, E.G. (2018). Endogenizing capital in MRIO models: the implications for consumption-based accounting. Environ. Sci. Technol. *52*, 13250–13259. https://doi.org/10.1021/acs.est.8b02791.
57. Södersten, C.J., Wood, R., and Wiedmann, T. (2020). The capital load of global material footprints. Resour. Conserv. Recycl. *158*, 104811. https://doi.org/10.1016/j.resconrec.2020.104811.
58. Chen, Z.-M., Ohshita, S., Lenzen, M., Wiedmann, T., Jiborn, M., Chen, B., Lester, L., Guan, D., Meng, J., Xu, S., et al. (2018). Consumption-based greenhouse gas emissions accounting with capital stock change highlights dynamics of fast-developing countries. Nat. Commun. *9*, 3581. https://doi.org/10.1038/s41467-018-05905-y.
59. López, L.A., Cadarso, M.Á., Zafrilla, J., and Arce, G. (2019). The carbon footprint of the U.S. multinationals' foreign affiliates. Nat. Commun. *10*, 1672–1711. https://doi.org/10.1038/s41467-019-09473-7.
60. Ortiz, M., López, L.A., and Cadarso, M. (2020). EU carbon emissions by multinational enterprises under control-based accounting. Resour. Conserv. Recycl. *163*, 105104. https://doi.org/10.1016/j.resconrec.2020.105104.
61. Zhang, Z., Guan, D., Wang, R., Meng, J., Zheng, H., Zhu, K., and Du, H. (2020). Embodied carbon emissions in the supply chains of multinational enterprises. Nat. Clim. Chang. *10*, 1096–1101. https://doi.org/10.1038/s41558-020-0895-9.
62. Zhang, Z., Zhang, Z., and Zhu, K. (2020). Allocating carbon responsibility: the role of spatial production fragmentation. Energy Econ. *87*, 104491. https://doi.org/10.1016/j.eneco.2019.104491.
63. Li, M., Meng, B., Gao, Y., Wang, Z., Zhang, Y., and Sun, Y. (2022). Tracing CO_2 emissions in global value chains: multinationals vs. Domestically-owned firms. In Sustainable Global Supply Chains Discussion Papers, 2.
64. Li, M., Meng, B., Gao, Y., Guilhoto, J.J., Wang, K., and Geng, Y. (2023). Material footprints in global value chains with consideration of multinational enterprises. Resour. Conserv. Recycl. *190*, 106828.
65. Sunar, N., and Plambeck, E. (2016). Allocating emissions among Co-products: implications for procurement and climate policy. Manuf. Serv. Oper. Manag. *18*, 414–428. https://doi.org/10.1287/msom.2015.0572.
66. Gopalakrishnan, S., Granot, D., and Granot, F. (2021). Consistent allocation of emission responsibility in fossil fuel supply chains. Manag. Sci. *67*, 7637–7668. https://doi.org/10.1287/mnsc.2020.3874.
67. Gopalakrishnan, S., Granot, D., Granot, F., Sošić, G., and Cui, H. (2021). Incentives and emission responsibility allocation in supply chains. Manage. Sci. *67*, 4172–4190. https://doi.org/10.1287/mnsc.2020.3724.
68. Asian Development Bank. Multi-Regional Input-Output Tables. https://mrio.adbx.online.
69. Leontief, W.W. (1936). Quantitative input and output relations in the economic systems of the United States. Rev. Econ. Stat. *18*, 105. https://doi.org/10.2307/1927837.