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The short-term impact of US-China trade war on global GHG emissions from the perspective of supply chain reallocation

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ABSTRACT

Changes in trading relationships including trade wars can have a large impact on the distribution of GHG emissions across supply chains, and thus resulting in the changes of global emissions. One such example is the US-China trade conflict after 2017. Although previous studies have examined the emission impacts resulting from tariff adjustments during China-US trade wars, they did not investigate what would happen when goods in supply chains are reallocated to other countries. This is important due to complex global trading interconnections and different emission intensities for goods in different regions. We examine the multi-regional and multi-sectoral changes in GHGs from a shift in China-US trading relationships between 2010 and 2017. We develop four scenarios to explore how emissions change under an extreme scenario if China-US trade was reallocated to other regions. We find that an absence of China-US trade would decrease emissions from those products and services by 1.2% but when these products and services are reallocated to the rest of the world, global emissions increase on net by 0.3–1.8%. This increase is mainly driven by increased domestic production within China, contributing a 5–8.7% increase in China's emissions due to higher emission intensities. The reallocation of the excluded products in the US-China relationship would lead to large shifts of embodied emission to other regions, especially for other Asian countries which see an increase of 1.2–5.7% compared to 2017 levels.

1. Introduction

China and the US comprise the world's largest bilateral trade partnership and the relationship plays a vital role in the global trade network (Xin et al., 2019; Shi et al., 2022; Zheng et al., 2022; Jiang et al., 2022). China's accession to the World Trade Organization (WTO) in 2001 deepened the economic ties between China and the US, which resulted in a growth of China-US bilateral trade. This trade reached USD 657.4billion by 2017, accounting for 2.3% globally (WTO, 2022). As large amounts of greenhouse gas emissions (GHGs) are involved in the production of goods (Usman and Balsalobre-Lorente, 2022; Balsalobre-Lorente et al., 2022), the development of this bilateral relationship represents a large shift in the embodied emissions of products (Davis and Caldeira, 2010; Hoekstra and Wiedmann, 2014; Acquaye et al., 2017). Any shift in the China-US relationship also impacts other nations as products are often imported and re-exported in complex supply chains (Peters et al., 2011; Su and Ang, 2014; Zhang et al., 2019).

Due to large trade imbalances and geopolitical tensions, rhetoric surrounding trade has increased in recent years. A good example is the US "301" investigation of "unfair trade practices" into US-China trading arrangements in 2017 (Cui and Li, 2021). In 2020, China and the US concluded with an agreement on these conflicts but long-term disagreements over trade were not eased (He et al., 2020; Li et al., 2020; Xie and Wu, 2021). Political commentators have suggested that China-US trade relations are moving from a period of "cooperation over competition" to "competition over cooperation," and that trade disagreements are here to stay (Li et al., 2018, Kim, 2019).

Researchers have quantified the embodied emissions in US-China trade (Meng et al., 2018a, 2018b, Liu et al., 2019, Sun et al., 2020) and shown how China is mainly downstream in the global value chain while the US is mainly upstream (Du et al., 2011; Lin et al., 2014; Zhao et al., 2016). Dai et al. (2021), Wang and Han (2021) and Xiong and Wu (2021) systematically analyzed the economic benefits and environmental costs of China-US trade and found that China had a large trade surplus but a considerable environmental deficit with the US during

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Nomenclature

US	United States
WTO	World Trade Organization
GHG	Greenhouse Gas
MRIO	Multi-regional Input-Output
GMRIO	Global multi-regional Input-Output
RoW	Rest of World
E_{cu}	The emissions embodied in US's exports to China
E_{uc}	The emissions embodied in China's exports to US
F	Direct emission coefficients of industries
L	Leontief inverse matrix
Y	Final demand matrix
DF_{uc}	The embodied emissions in China's final exports to US
IF_{uc}	The embodied emissions in China's intermediate exports to US
II_{uc}	The embodied emissions in intermediate products of China's indirect exports to US
Z	Intermediate flow matrix
V	Primary input flow matrix
X	Total output
ER	The emissions from industries
EH	The emissions from final demand categories
A	Total technical coefficients
AY	Total consumption coefficients
B	Value-added coefficients
YT	Total final demand
FY	Direct emission coefficients of final demand categories
VT	Total value-added
AYV	The coefficients between value-added and final demand
AP	Pure technical coefficients
AT	Trade technical coefficients
AYP	Pure consumption coefficients
AYT	Trade consumption coefficients
dir	Direct effect
fb	Expenditure feedback effect

1996–2015. Given that the trade flow is overwhelmingly from China to the US and that emissions from production varies across China, detailed provincial analyses are important (Liu et al., 2016; Zhang et al., 2018; Yan et al., 2020; Sinha et al., 2022). Weitzel and Ma (2014), Wang et al. (2017) and Mi and Sun (2021) also have shown that the imbalance of economic development in China leads to the regional heterogeneity of exports, which would impact China-US trade. However, existing studies have not investigated the emissions embodied in China-US trade from a multi-regional and multi-sectoral perspective.

There are few studies examining the impact of new US-China trade relations on global emissions. He and Hertwich (2019) analyzed the environmental impacts of China-US soybean trade barriers and found the change in international soybean trade caused by the US-China trade barrier would lead to an increase in global environmental costs in the short term. This is because that the need for soybean in China would encourage Brazil and Argentina to expand their soybean-planting areas, which increased the transport costs. Liu et al. (2020) used a global computable general equilibrium model to investigate the environmental effects of trade friction and found that the China-US trade war decreases global GHG emissions by 5% but is harmful for the development of clean energy in less-developed regions. Guo et al. (2021) used a global multi-regional computable general equilibrium model and designed three scenarios to estimate the impact of China-US trade conflicts on changes in the global shipping carbon emissions, finding that imposing 5–25% tariff increases shipping emissions by 0.25–0.33%. However, most studies tend to analyze the environmental effects of tariffs adjustments, and there are no studies focusing on the effects of China-US trade conflicts from the perspective of trade distribution among global supply chains.

Here we address the gaps in the literature outlined above by linking China's latest multi-regional input-output (MRIO) table (from 2010 to 2017) with the EXIOBASE global MRIO to analyze how provincial and sectoral heterogeneity impact embodied emissions (we stop our analysis in 2017 as the point at which trade conflicts start rising sharply). Moreover, we develop four scenarios to simulate China-US embodied emissions changes in which the exchanged products between China and US are lost and replaced by the domestic production or the trade with the Rest of World (ROW). We aim to answer the question: what would happen to global/national emissions, especially in major economies and important US-China trade partners if trade between the US and China would stop? The core of the four scenarios is the reallocation of the excluded supply chain-wide inputs embodied the China-US trade and constrained by constructing the new equilibrium of final demand with value-added and assuming the same total final demand. We are interested in identifying the supply-chain importance of trade openness and globalization in emissions to help decision makers strengthen multilateral collaborations.

Compared with existing studies, we have the following contributions. (1) From the aspect of data, we compile a detailed global MRIO (GMRIO) table in 2010 and 2017 by linking China's MRIO table with EXIOBASE database, which improve the delicacy of data. Accordingly, we comprehensively analyze the characteristics of the embodied GHG emissions flows in the China-US trade from multi-regional and multi-sectoral perspectives. This helps us identify which countries/provinces and sectors are major emitters in the production of goods traded between China and the US. (2) From the perspective of method, to the best of our knowledge, no existing MRIO approach based on trade reallocation has been used to evaluate the impact of China-US trade war on global emissions. We provide a GHG emissions analysis from the perspective of supply chain reallocation. With the MRIO framework, we design four scenarios in which we assume that no trade occurs between China and the US, to capture the changes of emissions due to China-US trade war throughout the full supply chain. Previous studies have highlighted the impact of trade policy on emissions considering the change of tariffs. However, the impact of trade war is not only transmitted through price mechanism but also through trade pattern reallocation along supply chains. Thus, from the practical perspective, our analysis helps obtain some valuable insights into the contribution of the China-US trade on global GHG emissions from a new perspective. (3) From the theoretical perspective, no studies have investigated the allocation mechanism through which China-US trade conflicts propagate across nations in the world. We creatively develop four scenarios in which we assume that no trade occurs between China and the US, with different descriptions of how excluded trade would be reallocated among domestic production and the trade with the RoW. Moreover, we divide the changes in emissions in the last three scenarios (i.e., allocation scenarios) into two parts, those are the direct substitution effect and expenditure feedback effect. The direct substitution effect reflects the emissions changes due to the changes in the pure technical and consumption coefficients, while the expenditure feedback effect reflects the emissions changes due to the changes of final demand from reallocation. These can help us to study the mechanism of global supply chain reallocation, as well as the emissions impacts of the technological and structural bases.

We organized the paper as follows. Section 2 presents theoretical foundation, methods, and data. Section 3 provides main results. Section 4 discusses, and Section 5 presents conclusions.

2. Methods

2.1. Theoretical foundation and methods framework

Theoretically, trade barriers limit resource allocation efficiency, decreasing the access to clean technologies and potentially leading to emission increases (Aklin, 2016; Nemati et al., 2019; Xu et al., 2019; Balsalobre-Lorente et al., 2021; Jahanger et al., 2022). This is because that the technique effect, which is reflected by an update of production technologies, tend to lower emissions through trade liberalization. Removing the trade between China and the US is not simple, as in the short-term, the global final demand and supply could not be adjusted in time. This would push China and the US to search alternative trade partners for satisfying the total demand and production. The alternative supply chains may grow, leading to a new distribution of inputs and demand, especially in emerging countries with large labor force and high emissions intensities (Kander et al., 2015; Yang et al., 2020; Wang et al., 2021a, 2021b). Along with the changes in inputs and demand, the emissions from the production processes would change their locations and scales (Liu et al., 2016, Meng et al., 2018a, 2018b, Wiedmann and Lenzen, 2018). Some work has explored the emissions impact of trade openness by comparing the actual global/national emissions with those hypothetical emissions under a 'no trade' scenario (Arce et al., 2016; Costa and Moreau, 2019). For example, Huang et al., 2020 developed three hypothetical scenarios to simulate the changes in the CO_2 emissions embodied in the China-Australia trade, finding that the China-Australia trade reduces global CO_2 emissions. However, the impact of China-US trade conflicts from the perspective of reallocation along supply chains has not been addressed.

The IO method can investigate inter-sectoral linkages and interdependence of production and consumption activities (Miller and Blair, 2009). The MRIO model is an extension of the IO model, which can further analyze transnational sectoral relationships (Su and Ang, 2010). Thus, the MRIO model is widely applied to trace economic activities along global supply chains. When the MRIO model is related with the environmental topic, the emissions embodied in the trade is analyzed by using the Environmental-Extended Input-Output (EEIO) model (Xu et al., 2017). Many previous studies have analyzed emissions embodied in trade and investigated its driving factors, which have provided clear knowledge about the impacts of trade on environment. However, few studies applied the counterfactual scenario approach to the MRIO system and analyze the impact of China-US trade war on global GHG footprints.

Thus, we first link the Chinese provincial-level MRIO database to the global MRIO database EXIOBASE, such that an overview of GHG emissions embodied in the China-US trade from both multi-regional and multi-sectoral perspectives can be obtained. Given that US-China tensions ramped-up after 2017 we take the historical emission relationships in 2017 as the baseline against which scenarios are evaluated. To analyze the emissions impact of an extreme situation in which the exchanged products between China and US are replaced by domestic production and trade with the RoW, we develop four scenarios:

S1) A "no trade" scenario that assumes that there is no trade between China and the US.

S2) Goods lost in the China-US trade are substituted by domestic production instead of imported (given that China and the US are the large manufacturing nations (Ratchford and Blanpied, 2008)). This reflects an extreme case corresponding to regional resilience and onshoring of manufacturing and material capacities.

S3) Goods lost in the China-US trade are reallocated to imports from the RoW, as in the context of globalization and growing cross-border transactions, China and the US may have to import products from other countries to fulfill lost inputs.

S4) A scenario where the excluded products for the China-US trade are replaced with both domestic production and imported products from the RoW. We term this a "shared import replacement" scenario.

2.2. Data sources

National and provincial GHG emission inventories for China are not directly available. We use data from national/provincial statistics to estimate China's GHG emissions. The details of estimating all types of emissions can be found in the Yuan and Wang (2021). The China's MRIO table for 2010 and 2017 are from Liu et al. (2014) and CEADs database. We use global MRIO database EXIOBASE v3.4 for 2010 and 2017 (https://www.exiobase.eu/) to link the Chinese MRIO database. The consolidation process for the linked GMRIO table was described in the Yuan and Wang (2021). To be consistence with the sectoral energy data from Chinese Energy Statistic Yearbook, we aggregate original 30 economic sectors in Chinese MRIO table (See Table S1) and original 163 economic sectors in EXIOBASE (See Table S2) into 27 sectors. The deflators of China's 30 provinces are from China Provincial Statistical Yearbook. The WIOD and World Bank provides deflator for the 48 regions of EXIOBASE, and the details can be seen in the Yuan et al. (2022).

2.3. MRIO model and calculation of embodied emissions

We assume that there are m countries, and each country has n sectors within a MRIO model as (Leontief, 1986):

$$\begin{bmatrix} X_{11} & X_{12} & \dots & X_{1m} \\ X_{21} & X_{22} & \cdots & X_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ X_{m1} & X_{m2} & \cdots & X_{mm} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & \dots & A_{1m} \\ A_{21} & A_{22} & \cdots & A_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ A_{m1} & A_{m2} & \cdots & A_{mm} \end{bmatrix} \begin{bmatrix} X_{11} & X_{12} & \dots & X_{1m} \\ X_{21} & X_{22} & \cdots & X_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ X_{m1} & X_{m2} & \cdots & X_{mm} \end{bmatrix} + \begin{bmatrix} Y_{11} & Y_{12} & \dots & Y_{1m} \\ Y_{21} & Y_{22} & \cdots & Y_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ Y_{m1} & Y_{m2} & \cdots & Y_{mm} \end{bmatrix} \tag{1}$$

where X_{rr} represents the output column vector produced and consumed in region r, X_{rs} represents the output column vector exported from region r to region s, A_{rr} represents the input coefficient matrix between sectors in the same region, A_{rs} represents the input coefficient matrix between sectors in different regions. Y_{rr} represents the domestic production of domestic final products. Y_{rs} represents the exports of region r which is used for satisfying region s's final demand.

Based on Eq. (1), the expression of domestic consumption and the total import and export between regions can be obtained through conversion:

$$\begin{bmatrix} X_{11} & X_{12} & \dots & X_{1m} \\ X_{21} & X_{22} & \cdots & X_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ X_{m1} & X_{m2} & \cdots & X_{mm} \end{bmatrix} = \begin{bmatrix} I-A_{11} & -A_{12} & \dots & -A_{1m} \\ -A_{21} & I-A_{22} & \cdots & -A_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ -A_{m1} & -A_{m2} & \cdots & I-A_{mm} \end{bmatrix}^{-1} \begin{bmatrix} Y_{11} & Y_{12} & \dots & Y_{1m} \\ Y_{21} & Y_{22} & \cdots & Y_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ Y_{m1} & Y_{m2} & \cdots & Y_{mm} \end{bmatrix} \tag{2}$$

To make the equation more concise, we replace the inverse matrix of Eq. (2) with the Leontief inverse matrix to obtain Eq. (3):

$$\begin{bmatrix} X_{11} & X_{12} & \dots & X_{1m} \\ X_{21} & X_{22} & \cdots & X_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ X_{m1} & X_{m2} & \cdots & X_{mm} \end{bmatrix} = \begin{bmatrix} L_{11} & L_{12} & \dots & L_{1m} \\ L_{21} & L_{22} & \cdots & L_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ L_{m1} & L_{m2} & \cdots & L_{mm} \end{bmatrix} \begin{bmatrix} Y_{11} & Y_{12} & \dots & Y_{1m} \\ Y_{21} & Y_{22} & \cdots & Y_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ Y_{m1} & Y_{m2} & \cdots & Y_{mm} \end{bmatrix}$$

$$= \begin{bmatrix} \sum_{i=1}^{m} L_{1i}Y_{i1} & \sum_{i=1}^{m} L_{1i}Y_{i2} & \dots & \sum_{i=1}^{m} L_{1i}Y_{im} \\ \sum_{i=1}^{m} L_{2i}Y_{i1} & \sum_{i=1}^{m} L_{2i}Y_{i2} & \cdots & \sum_{i=1}^{m} L_{2i}Y_{im} \\ \vdots & \vdots & \vdots & \vdots \\ \sum_{i=1}^{m} L_{mi}Y_{i1} & \sum_{i=1}^{m} L_{mi}Y_{i2} & \cdots & \sum_{i=1}^{m} L_{mi}Y_{im} \end{bmatrix} \tag{3}$$

where L is the Leontief inverse matrix, representing the total economy-wide requirements from row sector j to produce a unit of output from column sector i. We introduce the emission factor F to calculate GHG emissions, where F expresses GHG emissions produced by each unit of input, calculated using the GHG emissions in the environmental account and the total input in the MRIO table. The factor F is total GHG emissions divided by total input. Hence, F can be expressed as:

$$\begin{bmatrix} F_1 & 0 & \dots & 0 \\ 0 & F_2 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \cdots & F_m \end{bmatrix} \tag{4}$$

Combined with the above equation, we obtain global GHG emissions (E) as follows:

$$E = \begin{bmatrix} E_{11} & E_{12} & \dots & E_{1m} \\ E_{21} & E_{22} & \cdots & E_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ E_{m1} & e_{m2} & \cdots & E_{mm} \end{bmatrix} = FLY$$

$$= \begin{bmatrix} F_1\sum_{i=1}^{m} L_{1i}Y_{i1} & F_1\sum_{i=1}^{m} L_{1i}Y_{i2} & \dots & F_1\sum_{i=1}^{m} L_{1i}Y_{im} \\ F_2\sum_{i=1}^{m} L_{2i}Y_{i1} & F_2\sum_{i=1}^{m} L_{2i}Y_{i2} & \cdots & F_2\sum_{i=1}^{m} L_{2i}Y_{im} \\ \vdots & \vdots & \vdots & \vdots \\ F_m\sum_{i=1}^{m} L_{mi}Y_{i1} & F_m\sum_{i=1}^{m} L_{mi}Y_{i2} & \cdots & F_m\sum_{i=1}^{m} L_{mi}Y_{im} \end{bmatrix} \tag{5}$$

where E_{rr} represents domestic emissions caused by domestic consumption, and E_{rs} represents emissions embodied in region r's exports to region s. Here, we focus on emissions and value-added flows embodied in China-US trade, so regions except for China and US are considered as one region and labelled as 'RoW'. China, US and RoW are labelled as C, U and R, respectively. Therefore, we calculate the emissions embodied in US's exports to China (E_{UC}) and China's exports to US (E_{CU}) as:

$$E_{CU} = [F_C \ \ 0 \ \ 0] \begin{bmatrix} L_{CC} & L_{CU} & L_{CR} \\ L_{UC} & L_{UU} & L_{UR} \\ L_{RC} & L_{RU} & L_{RR} \end{bmatrix} \begin{bmatrix} 0 & Y_{CU} & 0 \\ 0 & Y_{UU} & 0 \\ 0 & Y_{RU} & 0 \end{bmatrix} \tag{6-1}$$
$$= F_C L_{CC} Y_{CU} + F_C L_{CU} Y_{UU} + F_C L_{CR} Y_{RU}$$
$$= DF_{CU} + IF_{CU} + II_{CU}$$

$$E_{UC} = [0 \ \ F_U \ \ 0] \begin{bmatrix} L_{CC} & L_{CU} & L_{CR} \\ L_{UC} & L_{UU} & L_{UR} \\ L_{RC} & L_{RU} & L_{RR} \end{bmatrix} \begin{bmatrix} Y_{CC} & 0 & 0 \\ Y_{UC} & 0 & 0 \\ Y_{RC} & 0 & 0 \end{bmatrix} \tag{6-2}$$
$$= F_U L_{UU} Y_{UC} + F_U L_{UC} Y_{CC} + F_U L_{UR} Y_{RC}$$
$$= DF_{UC} + IF_{UC} + II_{UC}$$

where in Eq. (6-1), the first term, DF_{CU}=$F_C L_{CC} Y_{CU}$, is the embodied emissions in China's final exports to US; the second term, IF_{CU}=$F_C L_{CU} Y_{UU}$, is the embodied emissions in China's intermediate exports to US; and the last term, II_{CU}=$F_C L_{CR} Y_{RU}$, is the embodied emissions in intermediate products of China's indirect exports to US, which are initially exported to other regions and finally exported to US. A similar interpretation can be applied to Eq. (6-2). Detailed calculation of emissions and value-added embodied in trade about is elaborated in *SI Appendix*, Section 2.

2.4. Scenario design

2.4.1. Framework and notation

Let nR, nS, nP and nQ be number of regions, sectors per region, final demand categories per region, and primary factors per region. Let indices r, s and m denote regions, and i and j denote sectors, p denotes final demand categories; and q denotes primary factors of value-added. The GMRIO table describes the intermediate flows Z_{ij}^{rs} (r = source region, s = target region, i = target sector, j = target sector), final demand flows$Y_{i,\ p}^{rs}$ (p = target final demand category, other indices as in Z), primary input flows $V_{q,\ j}^{s}$ (q = target primary factor, other indices as in Z), total outputX_i^r. The basic monetary quantities follow the constraints (Leontief, 1986):

$$\sum_s \sum_j Z_{ij}^{rs} + \sum_s \sum_m Y_{i,p}^{rs} = X_i^r \tag{7-1}$$

$$\sum_r \sum_i Z_{ij}^{rs} + \sum_q V_{q,j}^{s} = X_j^s \tag{7-2}$$

The baseline data are used to calibrate the model, which consists in a series of coefficients that are assumed to be fixed, and external control variables in the scenarios (see Table 1).

We also assume that there are coefficients between value-added $AY_{i,\ p}^{rs}$, to a certain degree, could reflect consumption structure, but which is different from the traditional definition of consumption structure. Because the consumption structure always reflects the share of a given consumption category in the total consumption without considering the specific origin of production place.

Table 1
Explanation of baseline data.

Name	Equation	Meaning
Total technical coefficients	$A_{ij}^{rs} = Z_{ij}^{rs}/X_j^s$	How many inputs from sector *i* of region *r* are used to generate output of sector *j* of region *s*.
Total consumption coefficients	$AY_{i,\ p}^{rs} = Y_{i,\ p}^{rs}/YT_p^s$	How many inputs from sector *i* of region *r* are used to one unit of consumption of final demand category *p* in region *s*.
Value-added coefficients	$B_{q,\ j}^{s} = V_{q,\ j}^{s}/X_j^s$	How many inputs from primary factor *q* are used in one unit of production of sector *j* of region *s*.
Total final demand expenditure	$YT_p^s = \sum_r \sum_i Y_{i,p}^{rs}$	Total final demand expenditure of final demand category *p*, which is a control variable.
Direct emission coefficients of industries	$F_i^r = \frac{ER_i^r}{X_i^r}$	The ratio between direct emissions and total output of activity sector *i* in region *r*.
Direct emission coefficients of final demand categories	$FY_i^r = \frac{EH_i^r}{YT_i^r}$	The ratio between direct emissions and total final demand expenditure of sector *i* in region *r*.

(which defines income) and total final demand expenditure, and these coefficients are a one-to-one correspondence. These values are determined using expert judgment: e.g., there is a coefficient between depreciation and fixed capital formation, and between wages and household consumption, which can be estimated as:

$$VT_q^s = AYV_{q,p}^s YT_p^s \tag{8}$$

where $VT_q^s = \sum_j V_{q,j}^s$ is total value-added of primary factor q in region s.

The above coefficients are connected in the model as:

$$ER_r = \sum_i \sum_j \sum_p \sum_s \sum_m F_i^r L_{ij}^{rs} AY_{j,p}^{sm} YT_p^m \tag{9-1}$$

$$EY_r = \sum_i FY_i^r YT_i^r \tag{9-2}$$

$$VT_q^r = \sum_i \sum_j \sum_p \sum_s \sum_m B_{q,i}^r L_{ij}^{rs} AY_{j,p}^{sm} YT_p^m \tag{9-3}$$

where ER_r is emissions from industries in a region r, EY_r is emissions from final demand categories in a region r,$VT_q^r$is the total value-added of category q in region r that results from final demand in every region m and final demand category p, through the purchase of product j from region s which in whose supply chain there may be inputs from industry i in region r.

We can describe the Eqs. (9) in a simplified notation without indices for coordinates to denote the baseline:

$$ER = F\ L\ AY\ YT \tag{10-1}$$

$$EY = FY\ YT \tag{10-2}$$

$$VT = B\ L\ AY\ YT \tag{10-3}$$

$$VT = AYV\ YT \tag{10-4}$$

where YT is the control variable, ER, EY and VT are the response variables. A (and so L), and AY are parameters that will change across scenarios. In the baseline scenario the two last equations yield the same value by default. These two parameter sets are further decomposed into pure technical/consumption coefficients, and trade coefficients. Thus:

$A_{ij}^{rs} = AP_{ij}^r AT_{ij}^{rs}$($AP$ = pure, AT = trade), such that

$$\sum_r AT_{ij}^{rs} = 1 \tag{11-1}$$

$AY_{i,p}^{rs} = AYP_{i,p}^s AYT_{i,p}^{rs}$($AYP$ = pure, AYT = trade), such that

$$\sum_r AYT_{i,p}^{rs}, = 1 \tag{11-2}$$

In the scenarios AP and AYP remain identical to the baseline scenario, but AT and AYT will change, such that

$$ER^* = F\ L^*\ AY^*\ YT^* \tag{12-1}$$

$$EY^* = FY\ \ YT^* \tag{12-2}$$

$$VT^* = B\ L^*\ AY^*\ YT^* \tag{12-3}$$

$$VT^* = AYV\ YT^* \tag{12-4}$$

We determine the new final demand (YT^*) for each region by cancelling the total value-added (VT^*) from the two last expressions Eqs. (12-3) and (12-4). Then we obtain a new equilibrium, which can be expressed as:

$$(B\ L^*\ AY^* - AYV)\ YT^* = 0 \tag{13}$$

Here we assume that B and AYV are fixed. Moreover, we assume that the total final demand of the world remained unchanged. This means that the total final demand, which is the sum of the three final component, for the world is exogenous. We argue that using an unchanged final demand is reasonable as we do not consider price factors which may affect final demand. Also, we construct counterfactual scenarios not projected scenarios, such that the population impacted by the total final demand does not change. We then solve to find YT^* in the new equilibrium. This modified total final demand expenditure reflects a new equilibrium which considers final demand changes due to altered trade patterns.

2.4.2. Building the scenarios

In the first scenario called 'no trade scenario' (S1), we consider that there is no trade between US and China, we estimate the impact of the total elimination of trade between US and China, the hypothetical situation in which China does not import/export any product to US (both intermediate inputs and final goods). To accomplish this, we adjust the matrix of the total technical coefficients A, and the matrix of final demand Y, taking into account direct and indirect effects of the trade generated between these two regions. Thus, the part of the matrix A and final demand Y that corresponds to product exchange between China and US is hypothetically extracted from the economic system (Dietzenbacher and Lahr, 2013; Temurshoev and Oosterhaven, 2013), that is, the blocks belong to China-US trade in the matrices are set to zero as:

$$A^* = \begin{bmatrix} A_{CC} & 0 & A_{CR} \\ 0 & A_{UU} & A_{UR} \\ A_{RC} & A_{RU} & A_{RR} \end{bmatrix} \tag{14-1}$$

$$Y^* = \begin{bmatrix} Y_{CC} & 0 & Y_{CR} \\ 0 & Y_{UU} & Y_{UR} \\ Y_{RC} & Y_{RU} & Y_{RR} \end{bmatrix} \tag{14-2}$$

where A^* and Y^* reflect there are no trade between China and US.

In the second scenario called "domestic scenario' (S2), we assume that there is no trade between China and US, but in this case, the goods are assumed to be produced domestically instead of been imported. Referring to Huang et al. 2020, here we assume that China's imports from US are allocated to China's 30 provinces according to the weight of each sector within each province, with respect to the total of that sector in the China's provincial bloc. For notational convenience, we assume that regions $r = 1, \ldots, nC$ are the different Chinese regions, let r be a Chinese region, m another Chinese region, and s a non-Chinese region other than USA, and thus the new trade coefficient in the domestic substitution scenario is identified as:

$$\begin{aligned} & AT_{ij}^{r,US*} = 0 \\ & AT_{ij}^{US,US*} = AT_{ij}^{US,US} + \sum_r AT_{ij}^{r,US} \end{aligned} \tag{15-1}$$

$$\begin{aligned} & AYT_{ij}^{r,US^*} = 0 \\ & AYT_{ij}^{US,US^*} = AYT_{ij}^{US,US} + \sum_r AYT_{ij}^{r,US} \end{aligned} \tag{15-2}$$

$$\begin{aligned} & AT_{ij}^{US,r^*} = 0 \\ & AT_{ij}^{mr^*} = AT_{ij}^{mr} + \left(AT_{ij}^{mr} \Big/ \sum_m AT_{ij}^{mr} \right) AT_{ij}^{US,China} \end{aligned} \tag{15-3}$$

$$\begin{aligned} & AYT_{ij}^{US,r^*} = 0 \\ & AYT_{ij}^{mr^*} = AYT_{ij}^{mr} + \left(AYT_{ij}^{mr} \Big/ \sum_m AYT_{ij}^{mr} \right) AYT_{ij}^{US,China} \end{aligned} \tag{15-4}$$

and otherwise $AT^* = AT$, $AYT^* = AYT$.

In the third scenario called 'distribution scenario (S3)', we assume import substitution of excluded imports. Thus, we assume that China-US trade is distributed among the production of the RoW. This means that, due to the elimination of China-US trade, China and US both increase their trade with the RoW, according to the weight of each sector within each region in 2017, with respect to the total of that sector in the corresponding China-US trade. Thus, we can construct a new technical coefficient matrix below:

$$\begin{aligned} &AT_{ij}^{r,US^*} = 0 \\ &AT_{ij}^{US,US^*} = AT_{ij}^{US,US} \\ &AT_{ij}^{s,US^*} = AT_{ij}^{s,US} \Big/ \sum_s AT_{ij}^{s,US}\left(1 - AT_{ij}^{US,US}\right) \end{aligned} \quad (16\text{-}1)$$

$$\begin{aligned} &AYT_{ij}^{r,US^*} = 0 \\ &AYT_{ij}^{US,US^*} = AYT_{ij}^{US,US} \\ &AYT_{ij}^{s,US^*} = AYT_{ij}^{s,US} \Big/ \sum_s AYT_{ij}^{s,US}\left(1 - AYT_{ij}^{US,US}\right) \end{aligned} \quad (16\text{-}2)$$

$$\begin{aligned} &AT_{ij}^{US,r^*} = 0 \\ &AT_{ij}^{mr^*} = AT_{ij}^{mr} \\ &AT_{ij}^{sr^*} = AT_{ij}^{sr} \Big/ \sum_s AT_{ij}^{sr}\left(1 - \sum_m AT_{ij}^{mr}\right) \end{aligned} \quad (16\text{-}3)$$

$$\begin{aligned} &AYT_{ij}^{US,r^*} = 0 \\ &AYT_{ij}^{m,r^*} = AYT_{ij}^{m,r} \\ &AYT_{ij}^{sr^*} = AYT_{ij}^{sr} \Big/ \sum_s AYT_{ij}^{sr}\left(1 - \sum_m AYT_{ij}^{mr}\right) \end{aligned} \quad (16\text{-}4)$$

The fourth scenario called 'shared import replacement' (S4) assumes excluded imports are replaced by both domestic production and imports from RoW at the same time, which is shown as:

$$\begin{aligned} &AT_{ij}^{r,US^*} = 0 \\ &AT_{ij}^{US,US^*} = AT_{ij}^{US,US} \Big/ \left(1 - \sum_r AT_{ij}^{r,US}\right) \\ &AT_{ij}^{s,US^*} = AT_{ij}^{s,US} \Big/ \left(1 - \sum_r AT_{ij}^{r,US}\right) \end{aligned} \quad (17\text{-}1)$$

$$\begin{aligned} &AYT_{ij}^{r,US^*} = 0 \\ &AYT_{ij}^{US,US^*} = AYT_{ij}^{US,US} \Big/ \left(1 - \sum_r AYT_{ij}^{r,US}\right) \\ &AYT_{ij}^{s,US^*} = AYT_{ij}^{s,US} \Big/ \left(1 - \sum_r AYT_{ij}^{r,US}\right) \end{aligned} \quad (17\text{-}2)$$

$$\begin{aligned} &AT_{ij}^{US,r^*} = 0 \\ &AT_{ij}^{mr^*} = AT_{ij}^{mr} \Big/ \left(1 - AT_{ij}^{US,China}\right) \\ &AT_{ij}^{sr^*} = AT_{ij}^{sr} \Big/ \left(1 - AT_{ij}^{US,China}\right) \end{aligned} \quad (17\text{-}3)$$

$$\begin{aligned} &AYT_{ij}^{US,r^*} = 0 \\ &AYT_{ij}^{mr^*} = AYT_{ij}^{mr} \Big/ \left(1 - \sum_r AYT_{ij}^{US,r}\right) \\ &AYT_{ij}^{sr^*} = AYT_{ij}^{sr} \Big/ \left(1 - \sum_r AYT_{ij}^{US,r}\right) \end{aligned} \quad (17\text{-}4)$$

The equations for the last three scenarios allow exploring the difference between baseline emissions and emissions in each of the three scenarios:

$$\Delta E = (ER^* + EY^*) - (ER + EY) \quad (18)$$

In order to analyze the impact mechanism, we can estimate the new emissions in the last three scenarios as:

$$ER^* = ER^{dir} + ER^{fb} = F\,L^* AY^*\,YT + F\,L^*\,AY^*\,(YT^* - YT) \quad (19\text{-}1)$$

$$EY^* = EY^{dir} + EY^{fb} = FY\,YT + FY\,(YT^* - YT) \quad (19\text{-}2)$$

Based on Eqs. (19), the new emissions (ER^* and EY^*) can be induced by two parts, which are from the changes of technical and consumption coefficients and the changes of final demand. The emissions induced by the changes of technical and consumption coefficients with the identical final demand as the baseline can be viewed as a direct effect (*dir*) due to the substitution of new Leontief inverse matrix (L^*) and consumption matrix (AY^*). The emissions caused by the changes of final demand can be viewed as an expenditure feedback effect, because the new final demand of each country (YT^*) can be obtained from the new equilibrium by Eq. (13), which is indirectly induced by the changes of technical and consumption coefficients.

Thus, we can distinguish a total emissions impact of China-US trade war into a direct substitution effect and an expenditure feedback effect as:

$$\Delta E^{dir} = (F\,L^* AY^*\,YT - FY\,YT) - (ER + EY) \quad (20\text{-}1)$$

$$\Delta E^{fb} = F\,L^*\,AY^*\,(YT^* - YT) + FY\,(YT^* - YT) \quad (20\text{-}2)$$

Noted that in the first scenario, the total final demand of the world is different from the 2017 benchmark, and we do not reallocate the lost trade part by adjusting technological/consumption coefficients. This means that the final demand of each country cannot be reallocated. Thus, we could not identify the expenditure feedback effect that is from the adjustment of final demand. In order to simplify the description of results, we directly reflect the total impact of S1 as the direct substitution effect. However, the first scenario is still important as it considers that there is no trade between China and the USA, which should be a reference result providing references for other three scenarios. The general framework for scenario settings can be seen in the Fig. 1.

3. Results

We first provide an overview of the emissions embodied in the China-US trade from the multi-regional and multi-sectoral perspectives, which is a baseline against which scenarios are assessed. Then we develop scenario analysis for the emissions impact of China-US trade conflicts considering the reallocation of trade pattern.

3.1. Emissions embodied in the China-US trade: an overview

Emissions embodied in China's exports to the US (C—U) decreased 39.6% from 591.9 $MtCO_2eq$ in 2010 to 357.8 $MtCO_2eq$ by 2017, while the emissions embodied in the US' exports to China (U—C) increased 12.4% from 120.6 Mt. in 2010 to 135.5 Mt. in 2017 (Fig. 2.a). The imbalance of value-added increased by 3.65% (Fig. 2.b), while China's position as a net exporter of embodied emissions reduced rapidly (−53.8%) due to the reduction in the emissions intensity within China (Guan et al., 2018, details are *elaborated in SI Appendix, Section 3*). The emissions share from EU, Japan and South Korea embodied in C—U exports, grew respectively by 0.8%, 1.4% and 0.7% between 2010 and 2017 (Fig.S1). The share of DF embodied in the C—U exports (less than 60%) was lower than that of the U—C exports (more than 85%) in 2017. The gap in the share of DF was mainly from the services industry (Fig. S2). The share of DF accounted for more than 95% of the total emissions of services industry embodied in the U—C exports, while the share DF in the services for the C—U exports was less than 5%. The

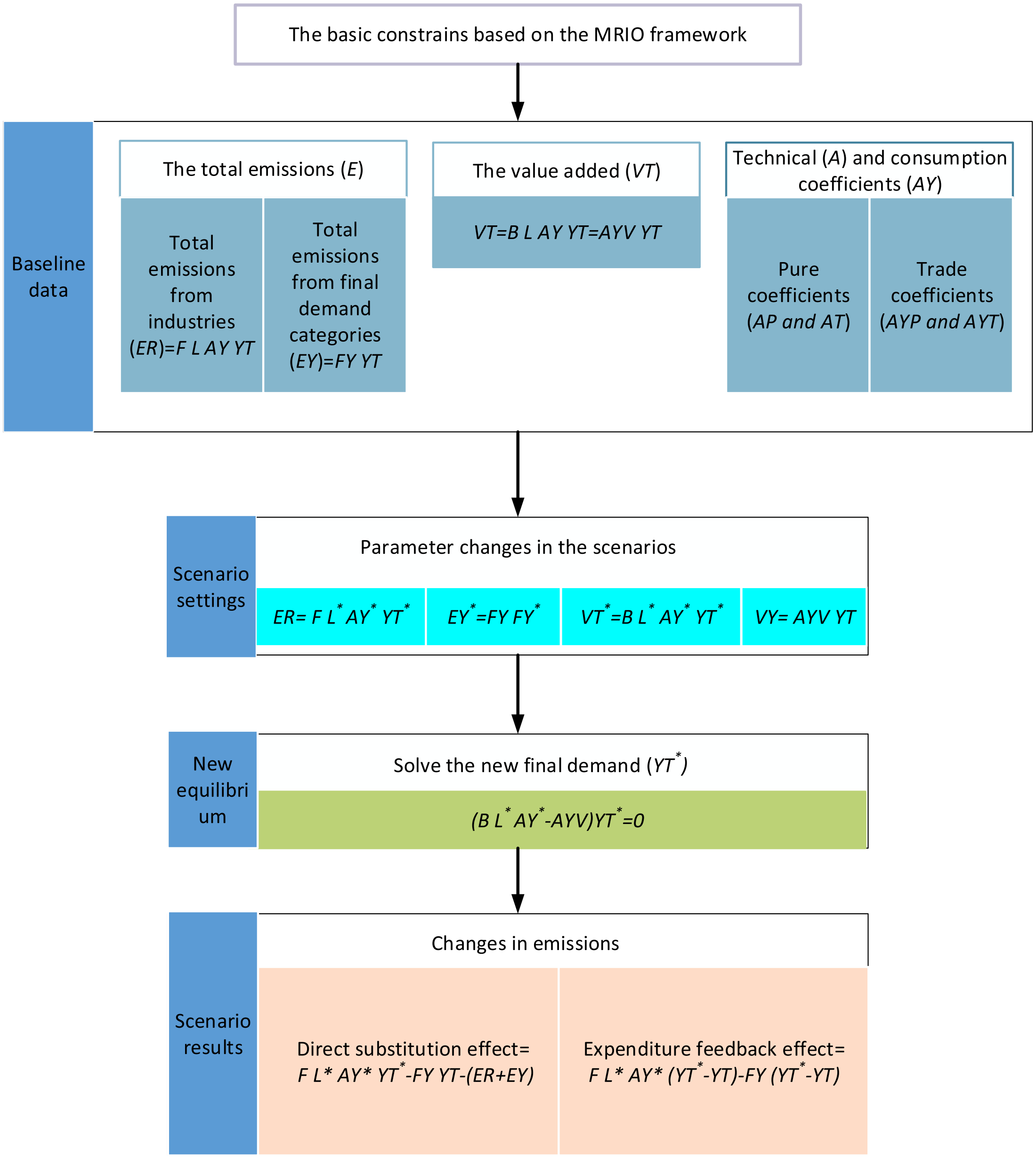

Fig. 1. The general framework for scenario settings.

emissions from C—U exports were generated mainly from affluent coastal provinces (e.g., Jiangsu, Zhejiang and Guangdong) and industrial bases (e.g., Hebei and Shanxi) (Figs2.c and e). Considering the embodied value-added, 80% and 40% of China's provinces were net exporters during 2010–2017. The top three value-added exporters were Zhejiang, Jiangsu, and Guangdong, and they totally accounted for 52.5% and 92.7% of the total net value-added in 2010 and 2017 respectively (Figs. 2.d and f).

We further divide 30 provinces into 5 regions based on the GDP per capita level in 2017 (see Table S4) and observe the virtual flows of emissions embodied in the China-US trade between 2010 and 2017 (Fig. 3). The total emissions from the highest, middle-high, and middle regions accounted for more than 50% of the total C—U exports emissions between 2010 and 2017. A large part of them was sold to satisfy the final demand of US's knowledge-intensive manufacturing industry, which accounted for more than 35% of the total C—U exports emissions in 2010 and 2017. The final demand of China's rich coastal provinces (e.g., Guangdong, Zhejiang, and Jiangsu) brought large emissions generating in the US, accounting for 27.5% and 31.4% of the total emissions in the embodied U—C exports in 2010 and 2017 respectively. The final demand of China's highest, middle-high, and middle regions mainly caused the emissions in the services industry of the US, which accounted for more than 35% of the total U—C exports emissions in 2010 and 2017.

Moreover, we analyze the economic and environmental benefits for 30 provinces by comparing net emissions and net value-added (Fig. 4). In 2010, all provinces were net exporters of embodied emissions, but in 2017 Beijing switched to being a net importer of embodied emissions. In 2017, Beijing obtained net gains of 2.36 billion US dollars and outsourced 1.11 Mt. emissions, which indicates it realized economic development and emissions mitigation simultaneously. In 2010, 80% of provinces owned the double-loss patterns with net outflows of emissions and value-added, while 60% of provinces showed double-loss patterns in 2017. 20% and 57% of provinces showed Economic-Win (Ec-W) pattern in 2010 and 2017 respectively, which means that they obtained economic benefits on the sacrifice of environment. This is because these provinces exchanged high emission-intensity manufacturing products

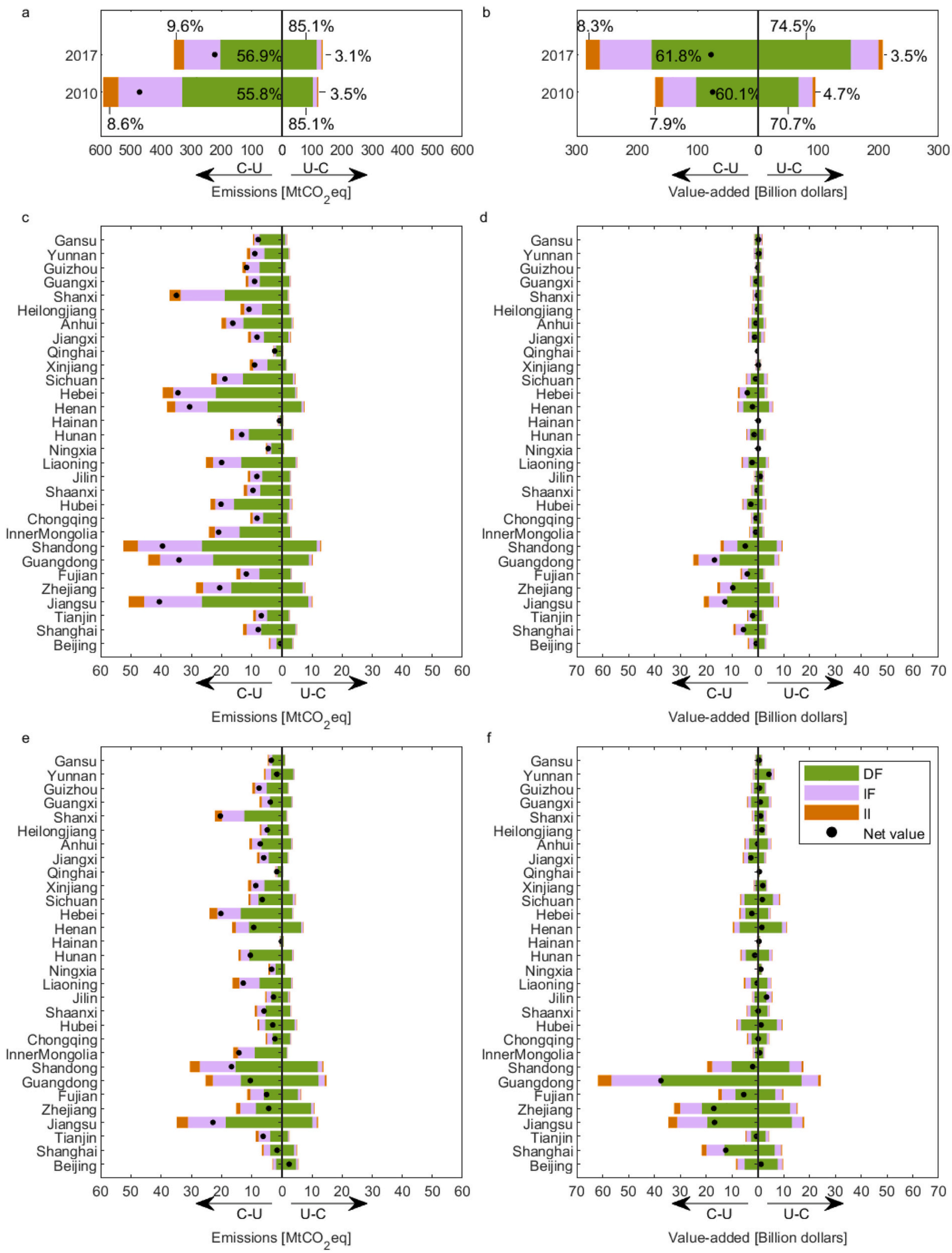

Fig. 2. a. The GHG emissions embodied in China-US trade between 2010 and 2017, b. The value-added embodied in China-US trade between 2010 and 2017, c. The GHG emissions embodied in China-US trade for 30 provinces in 2010, d. The value-added embodied in China-US trade for 30 provinces in 2010, e. The GHG emissions embodied in China-US trade for 30 provinces in 2017, f. The value-added embodied in China-US trade for 30 provinces in 2017. Note: C—U reflects China's exports to US, and U—C reflects US's exports to China. The black dot shows the net embodied emissions/value-added. The 30 provinces are aligned on the y-axis following an ascending order by GDP per capita in 2017. *DF* is the embodied emissions in China's final exports to US; *IF* is the embodied emissions in China's intermediate exports to US; *II* is the embodied emissions in intermediate products of China's indirect exports to US. Percentage numbers in Figures a and b show the emission share of DF, IF and II.

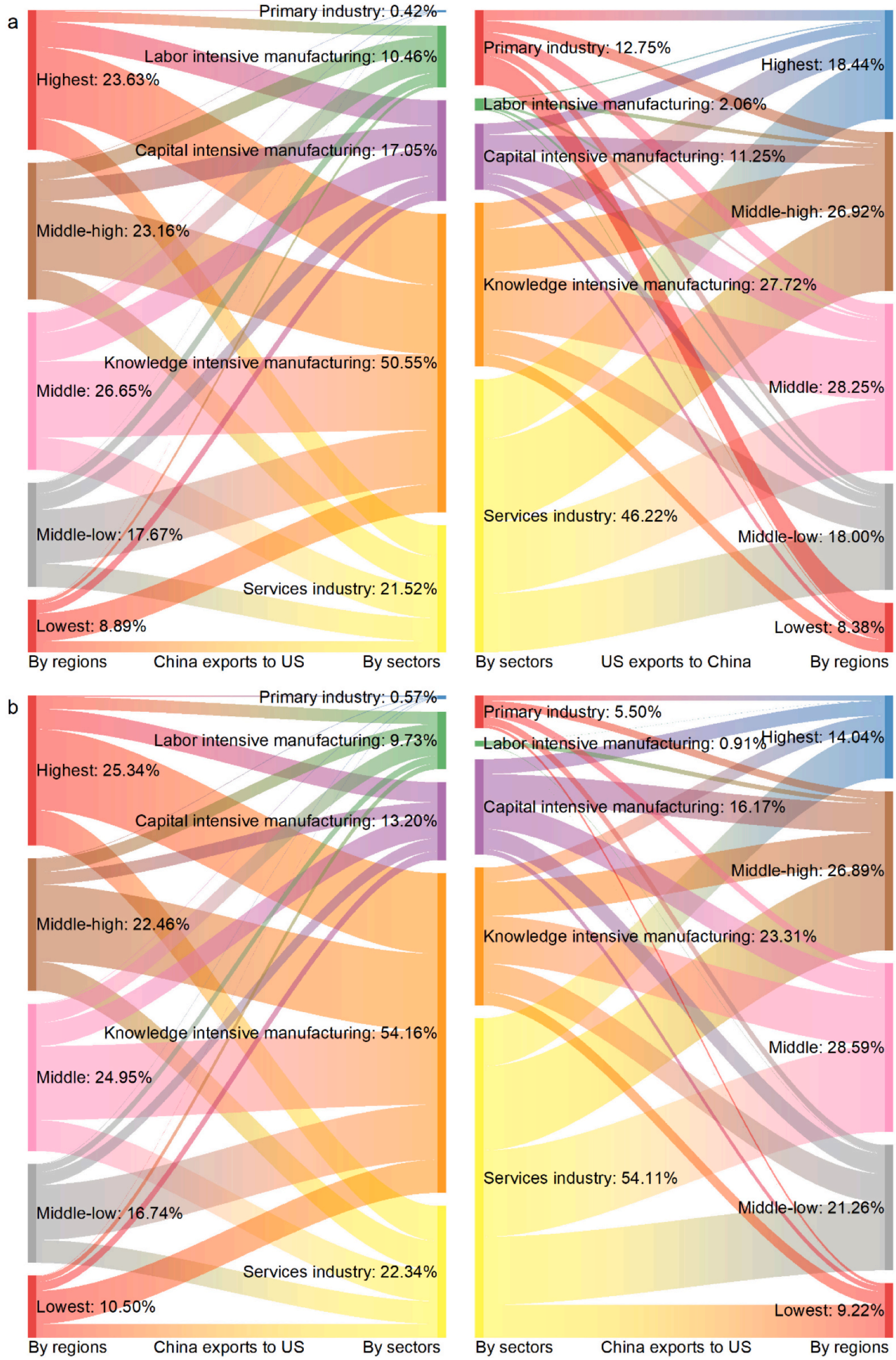

Fig. 3. a. Virtual flows of emissions embodied in the China-US trade in 2010. b. Virtual flows of emissions embodied in the China-US trade in 2017. Note: 30 provinces are aggregated into 5 regions in terms of GDP level in 2017, which can be found in Table S4. Region breakdown is shown by left and right bars, sector breakdown is shown by bars in the middle, and combined region-sector breakdown is shown by shadow curves. Sector classification is identified in the Table S3.

for low-emission-intensity service products in the trade. For example, since 77.2% of the emissions embodied in the Shanxi-US exports was from manufacturing industry (Fig. S3), Shaanxi obtained 0.94 billion US dollars from the US while it was outsourced 20.4 Mt. emissions.

3.2. Effects of bilateral China-US trade interruptions on global emissions

In S1 which sees a complete cessation of bilateral trade we find a 1.2% reduction in global emissions based on 2017 levels (Fig. 5). In S2, the import substitution of domestic production leads to a 0.3% emissions increase. The expenditure feedback effect, the change in emissions in a

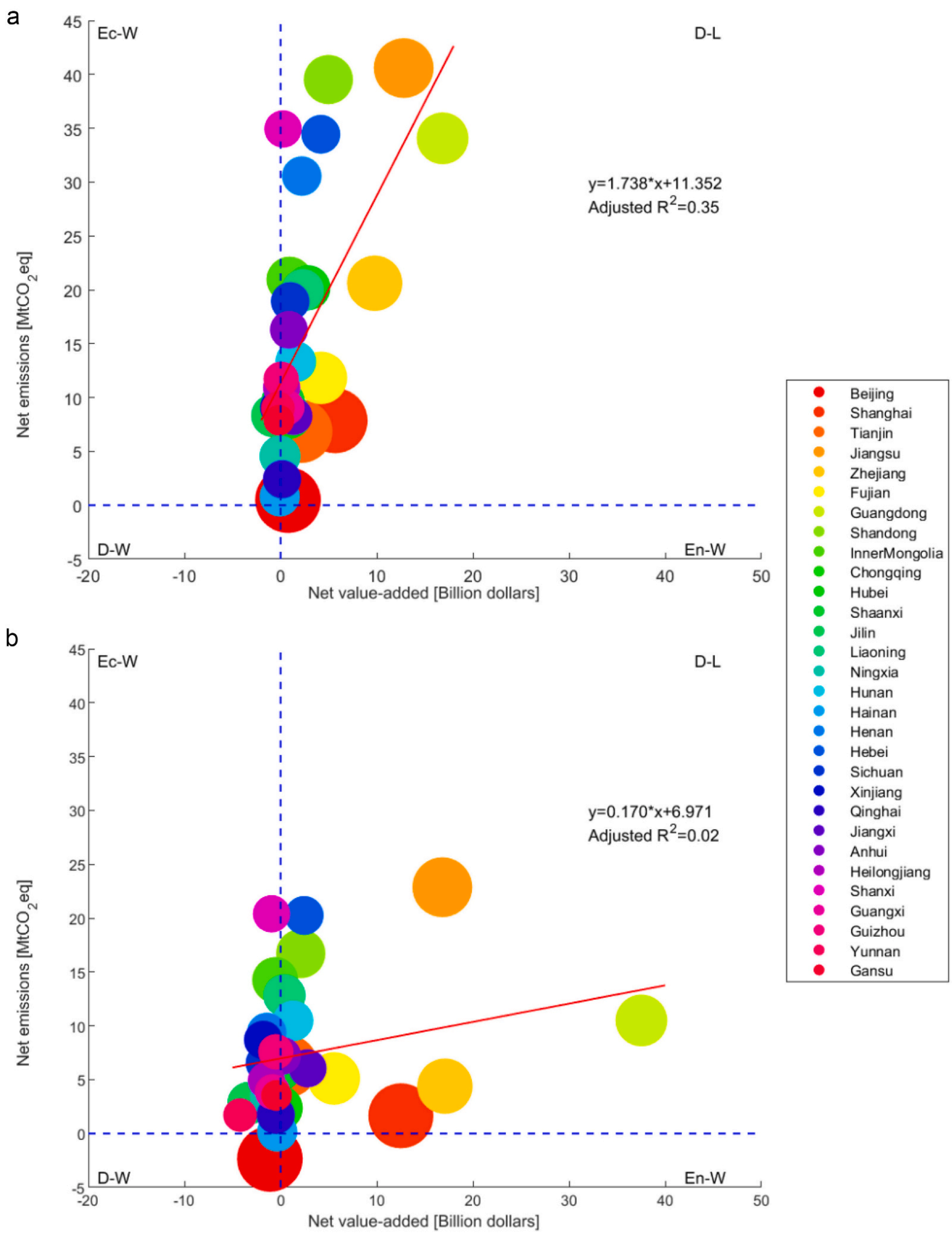

Fig. 4. Classification of 30 provinces based on the net emissions and value-added embodied in the China-US trade. a. in 2010. b. in 2017. D-L, located in the upper-right-hand quadrant, shows double-loss provinces with net outflows of both emissions and value-added, which outsource emissions and value-added to the US through the consumption of US's final products. Ec-W, located in the upper-left-hand quadrant, shows economic-win provinces with net outflows of emissions and net inflows of value-added (or, in other words, they outsource a larger share of emissions and retain relatively more value-added than other provinces). D—W, located in the lower-left-hand quadrant, shows that double-win provinces have relatively more emissions but also more value-added than other provinces. En-W, located in the lower-right-hand quadrant, which shows environmental-win provinces with more emissions and less value-added through providing products for the US and, at the same time, receiving a higher share of emissions from the US. The circle size shows the GDP per capita level of each province. Red line shows the fitted curve reflecting the linear relationship between net emissions and net value-added. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

given region as a response to expenditure change in other regions caused by input changes, contributes 0.61% of the emissions increase. The direct substitution effect which is directly caused by trade allocation decreases global emissions by 0.35%. In S3, where excluded products are replaced with inputs from the RoW, we see the RoW import substitution increasing emissions by 1.8%, owning to a significant expenditure feedback (+922 $MtCO_2eq$). In S4, where the removed trade is supplied by both other global trade and domestic production, global emissions increase by 1.1%. Compared to 2017, emissions increase by 1.36% due to the expenditure feedback effect, while the direct substitution effect drives a reduction in emissions of 0.26%.

Next, we analyze the emissions changes in various regions in the four scenarios. In the S1, the negative effect on the China (−3.3%) is greater than the negative effect on the US (−1.3%) (Fig. 6a). Moreover, other regions all receive negative effects due to the remove of China-US trade, however, their negative impacts are all smaller than −1%. In the S2, we find that the increased emissions are mainly due to the reduction of transportation cost by domestic production, resulting in lower prices, which stimulates an increase in domestic consumption and leads to emissions increase in China (8.4%) and the US (+3.8%) (Fig. 6b). However, except for Canada (+1.8%), the import substitution of domestic production causes the emissions decline in other regions with the largest in EU (−6.3%) due to its significant reduction of final demand. In the S3, the large emissions increase is predominately due to increases in China's final demand with the reallocation of trade, resulting in emissions increase of 5% (Fig. 6c). Additionally, as major trade partners of China and US (see Fig.S1), the final demands of Korea, Japan, and Mexico increase, which leads to increases in emissions of more than 5%. Several Asian developing nations with a large amount of labor-intensive manufacturing have a large relocation share. However, their energy mixes are generally inefficient, so there is significant increase in emissions (+3.8%). In contrast, the emissions in the US decrease by 10.1%

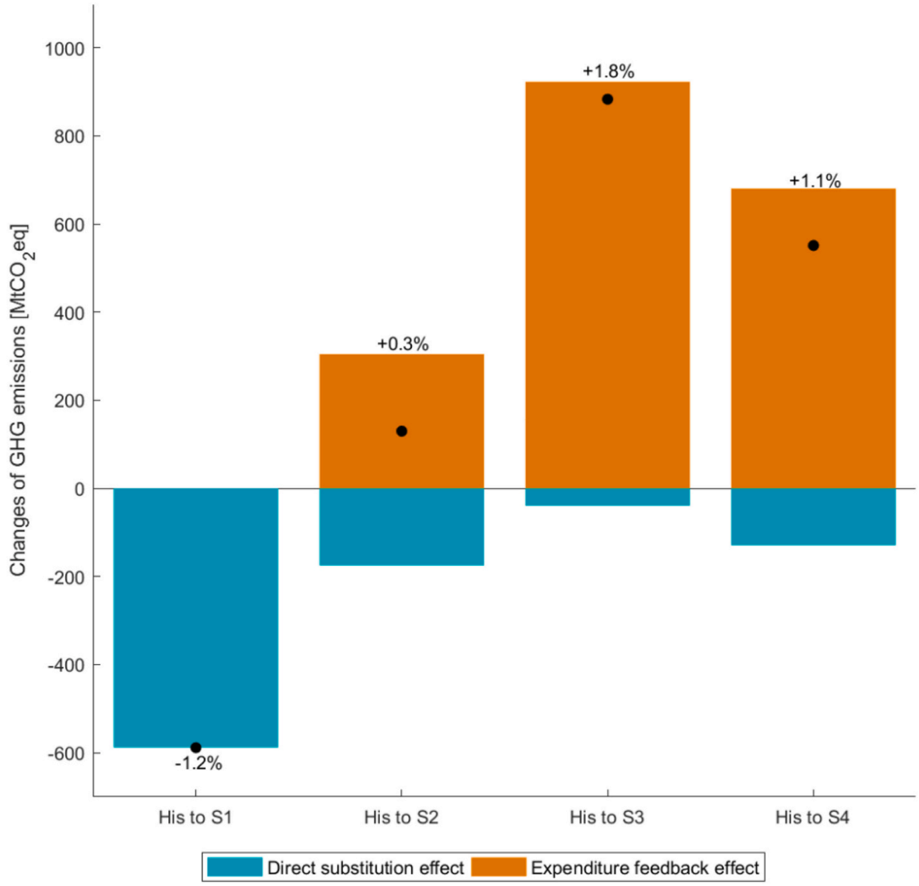

Fig. 5. Emissions changes between 2017 and scenarios. Note: black dots show the total change in the emissions. Numbers show the change rate between 2017 historical data and scenarios, which can be estimated as $\frac{\Delta}{E_{2017}}$.Δ is the change of emissions change between 2017 and scenarios.

due to the decrease in final demand as higher import fees exists when China's relatively cheap inputs are substituted by other trading partners (e.g., Canada and Australia). In the S4, China sees the largest emission increases (+8.7%), mainly driven by increasing final demand (Fig. 6d). The emissions in the US decrease only by 2.5%, lower than those in S3 as a given share of imports from China would be replaced with US's domestic production and its emission intensity is relatively low. The emissions changes in the S4 for the RoW are heterogeneous. EU, RoW Europe, and Turkey are the regions with the largest negative impacts (all more than −3%), because China's final exports to the US cause large intermediate production in these regions (Fig. S1). For example, China is the second largest trading partner of the EU. As an energy hub, the China-Pakistan-Iran-Turkey energy corridor caters to most of China's gas import needs. The absent trade will reduce intermediate production in Turkey and RoW Europe, and the final demand declines caused by which contributes to their emissions decrease.

We further analyze the emissions changes from the sectoral perspective (Fig. 7) and find that the loss of China-US trade in the S1 mainly causes emissions reduction in the labor-intensive and knowledge-intensive manufacturing industries (both are −1.9%), as the China-US trade relationship mainly focuses on the two industries. In the S2, the emissions increase is primarily driven by labor-intensive manufacturing industry (+5.7% compared to 2017 levels). This is because that the expansion of domestic production in the China's labor-intensive manufacturing industry may provide more work opportunities for labor, which increases household income, driving consumption and emissions increases. However, the import substitution of domestic production results in emissions reduction from the knowledge-intensive manufacturing industry (−1.5%) due to relatively lower emissions intensity of US with more advanced technologies. In the S3, when the China-US trade is allocated among other regions, the large emissions increase is from knowledge-intensive manufacturing industry (+2.9%). This is because that China may have to develop trade relations with other developing countries those have higher emissions intensities in the knowledge-intensive manufacturing industry considering economic benefits. In the S4, the capital-intensive manufacturing industry receives the largest impact, resulting a 2.3% increase in the emissions.

Finally, we investigate the emissions changes in the four scenarios from the provincial perspective (Fig. 8) and find that in the S1, the emissions reduction is mainly from coastal developed provinces, including Shanghai, Jiangsu, Zhejiang, Fujian, and Guangdong (larger than −4.5%). This is because the coastal regions of China actively join trade activities due to advantageous geographical location and a significant quantity of emissions are induced to meet foreign demands. Thus, the loss of trade relations would reduce their emissions. In the S2, the expansion of domestic production mainly causes the emissions growth in the developing provinces, including Hubei (+47.8%), Sichuan (26.8%), and Hunan (+12.1%), as these provinces export large quantities of capital-intensive products such as plastics, ships, and steel every year. In the S3, the reallocation of trade among other regions still results in the emissions increase in the developing provinces with the largest in Hubei (+44.1%), and Sichuan (+22.6%). However, the impacts are smaller than those in the S2. Moreover, in the S3, the emissions in the developed regions decline, for example Fujian (−3.6%), Guangdong (−2.9%), Zhejiang (−1.4%) and Tianjin (−1.2%). In the S4, China's emission increases are generally focus on developing provinces (e.g., Hubei, Sichuan, and Anhui), as they provide a large proportion of manufacturing. This means that rapid reductions in emission intensities across developing provinces are needed to offset negative environmental impacts of extreme trade conflicts.

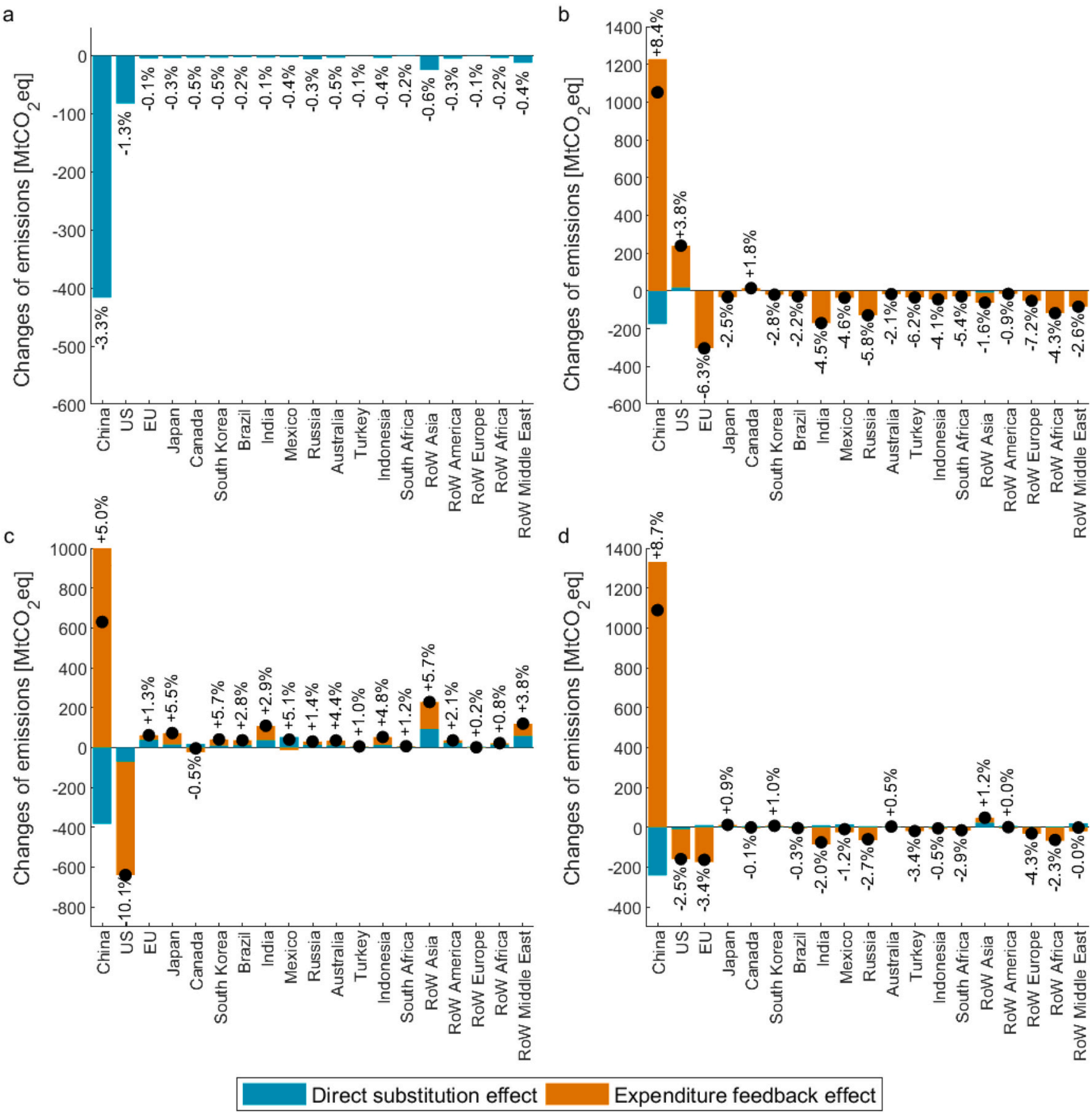

Fig. 6. a. Emissions changes between historical data in 2017 and scenario 1 by region. b. Emissions changes between historical data in 2017 and scenario 2 by region. c. Emissions changes between historical data in 2017 and scenario 3 by region. d. Emissions changes between historical data in 2017 and scenario 4 by region. Note: black dots in Figs.6 b-d show the total change in the emissions from two effects. Numbers show the change rate between historical data in 2017 and scenarios, which can be estimated referring to Fig. 5.

4. Discussion

4.1. Comparison with other studies

The result we find in S1, where bilateral trade ends, is similar to those of other studies (Wu et al., 2021). However, previous studies do not include the reallocation of absent imports to other countries in the global supply chain. Based on S1, we developed three substitution scenarios, and show that the China-US trade frictions would lead to more GHG emissions on net (+0.3% to +1.8%). It is reasonable to state, as does Yao et al. (2021), that China-US trade wars will leads to larger environmental stresses as shifting trade patterns increases the production across other regions with higher environmental intensities. This is slightly contradicted by Lin and Xu (2019) and Liu et al. (2020) that used CGE to show how trade frictions decrease emissions. Our conclusion differs as directly built scenarios to evaluate the emissions impact of “trade substitution”, without considering the effects of technological development, production structure change, consumption structure change and price floatation, within a static MRIO model. However, our analysis provides a conceptual framework to explore how emissions is translated through the redistribution of trade pattern, and model extreme results which might occur with the conflicts update.

4.2. Uncertainty analysis from the impacts of COVID-19 crisis

Since the COVID-19 crisis represents a turning point to rethink industrial policy spaces and countries’ productive autonomy, the international production system is experiencing a perfect storm from the growing protectionist tendencies (Dweck et al., 2022). Under such background, China and the US may increase their domestic production of manufactured goods. Moreover, the rapid spread of the coronavirus increases the conflicts between China and western countries. For example, China and Australia is within a downturn of trade relations. Thus, in recent years, there is a great change in the trade basket. With those in mind, we build a new COVID-19 scenario (*elaborated in SI Appendix, Section 4*) and find that due to the spread of COVID-19, the

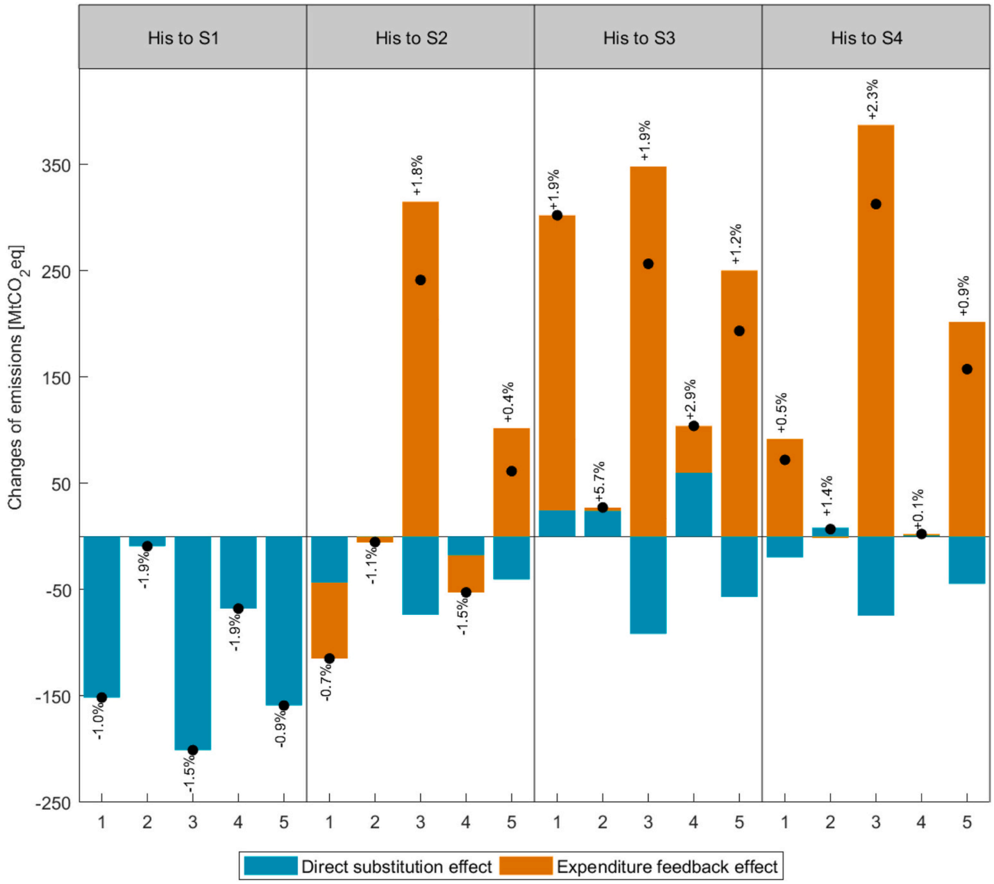

Fig. 7. Emissions changes between historical data in 2017 and scenarios by sector. Note: black dots show the total change in the emissions from two effects. Numbers show the change rate between historical data in 2017 and scenarios, which can be estimated referring to Fig. 5. Sector numbering 1, Primary industry; 2, Labor intensive manufacturing; 3, Capital intensive manufacturing; 4, Knowledge intensive manufacturing; 5, Services industry. Sector classification is identified in the Table S3.

increase in the emissions is significantly higher than previous three substitution scenarios (+3.06%) (Fig. 9). The expenditure feedback effect is a main driver, which contributes to emissions increase by 3.02%. An additional 1% allocation of inputs in the domestic production would have the largest impact on the China's capital-intensive manufacturing (+5.4%) and services of the US (+2.5%), which is significantly higher than four scenarios those we have mentioned before. This means that it is important for emission mitigation to avoid the growing sentiment for trade protectionism in the manufacturing industry during the COVID-19 pandemic period. The emissions changes for other regions are different from previous scenarios, as the new scenario considers the change of exports basket between 2017 and 2020. We find that the emissions in the Brazil (+12.7%), Mexico (+7.5%), Australia (+10.8%), South Africa (+8.7%) and RoW Europe (13.8%) increase significantly, as the escalating trade war between China and the US is opening up opportunities for emerging regions. Especially in the context of COVID-19, they seek to benefits from the trade war. For example, China will shift its large number of imports, including beef and soy, away from the US to Brazil, which may lead to a significant surge in Brazilian production and related emissions. Moreover, the importance of Australia and Mexico to the US as a supplier of raw materials increases. For example, the US was the second-largest two-way trading partner of Australia in 2020. Meanwhile, we find that the impact of Russia shifts from negative in the S4 (−2.7%), as Russian-Chinese relations are reaching a new level of development with the trade conflicts and COVID-19 spread, and the number of joint economic projects increases. Tian et al. (2022) indicated that non-negligible increases in emissions caused by the regional trade agreements (RTAs). Here we further argue that policy makers should pay attention to the negative impacts of possible RTAs that stimulated by COVID-19 global pandemic and China-US trade conflicts.

4.3. Policy implications

There are several policy implications that arise from our study. First, the results under the last three trade scenarios reflect that China-US trade contributes to increase global GHG emissions, which emphasize the importance of trade liberalization for global GHG reduction. In fact, the trade liberalization can play an important role for GHG mitigation by promoting technological spillover and efficient resources allocation. Thus, it is necessary to avoid the growing sentiment for trade protectionism and the escalation of trade conflicts.

Moreover, the China-US trade conflicts may promote the increase of the emissions in the major trade partners of China and US (e.g., Korea, Mexico, EU and RoW Asian), as their major trade partners would undertake more production responsibilities for intermediates due to the feedback expenditure effect. Thus, in the face of possible increase in the final demand during China-US trade war, it is of great importance for global GHG mitigation to ensure that these trade partners could create a strong technological cooperation tie for GHG reductions, such as improving the accessibility to renewable energy innovations.

Finally, during the China-US trade war period, considerable emissions can be produced from the manufacturing sectors in China's less developed provinces. As the reduction of emission intensity had a significant inhibitory impact on the emissions embodied in the China-US trade, large emissions mitigation can be realized by reducing the emissions intensities of manufacturing sectors in China's less developed provinces. Thus, the investment in research and development for achieving technological innovation should be undertaken in manufacturing sectors, which can enable China to control the emissions increase to a large extent. Moreover, China should not specialize in the production and export of emissions-intensive commodities. China can reduce its embodied GHG emissions by the structure transformation towards environmental-friendly products.

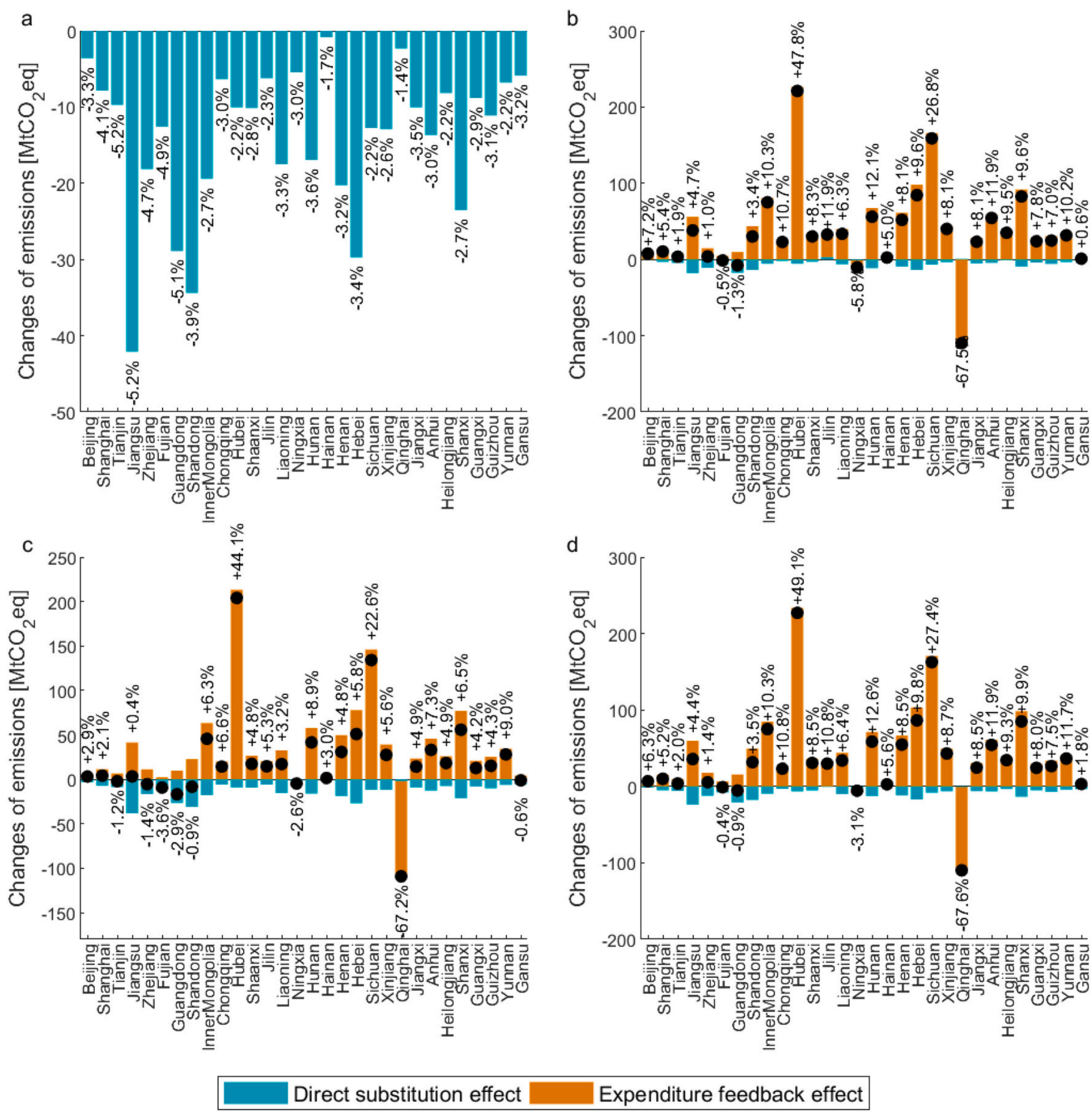

Fig. 8. a. Emissions changes between historical data in 2017 and scenario 1 in China by province. b. Emissions changes between historical data in 2017 and scenario 2 in China by province. c. Emissions changes between historical data in 2017 and scenario 3 in China by province. d. Emissions changes between historical data in 2017 and scenario 4 in China by province. Note: black dots in Figs.8 b-d show the total change in the emissions from two effects. Numbers show the change rate between historical data in 2017 and scenarios, which are estimated referring to Fig. 5. The 30 provinces are aligned on the y-axis following an ascending order by GDP per capita in 2017.

4.4. Limitations and future studies

The results point to an increase in global GHG emissions if excluded China-US trade are reallocated among regions. This happens from a modelling exercise not a projection, as we assume that the total final demand of the world and emission intensities keep unchanged with the year of 2017. We only consider the adjustment of China-US trade allocation pattern and do not consider the impact of price shock on production and consumption structure (Doğan et al., 2022), as we only want to know what will happen for GHG emission if excluded trade are reallocated with all other conditions unchanged, considering that previous studies have analyzed the impact of tariffs adjustment on global emissions. Moreover, we highlight that our analysis focuses on the short-term emission impact (that is a specific static impact in a time point with the counterfactual scenarios) by holding the final demand constant. Because in the short-term, global total final demand cannot easily change due to the consumption inertia (Xia and Li, 2010). However, as reality may be complex, further improvements could be undertaken, e.g., integrating a dynamic economic model, in order to reduce the uncertainty associated with results. In addition, our analysis reallocated imports from the sanctioned country, and thus we only consider the changes occurring in the origin region of direct inputs. This means that any contents of sanctioned country positioned in the upstream supply chain are not directly banned, although this situation may happen during the extreme conflicts (e.g., the US sanction all companies that deal with Huawei). However, it should be noted that in our scenarios, the supply chain of the China/US may be indirectly affected. For example, when the US replace imports from China with imports from the EU, the China-EU-US supply chain will change. Finally, since China's MRIO table is only up to 2017, we could not provide real GHG footprint after 2017 for a comparison. With the update of MRIO table, a comparison analysis is required for future analysis. But, noted that we are not interested in analyzing the historical impact of trade war on global GHG footprints. The aim of designing scenarios is to analyze the extreme

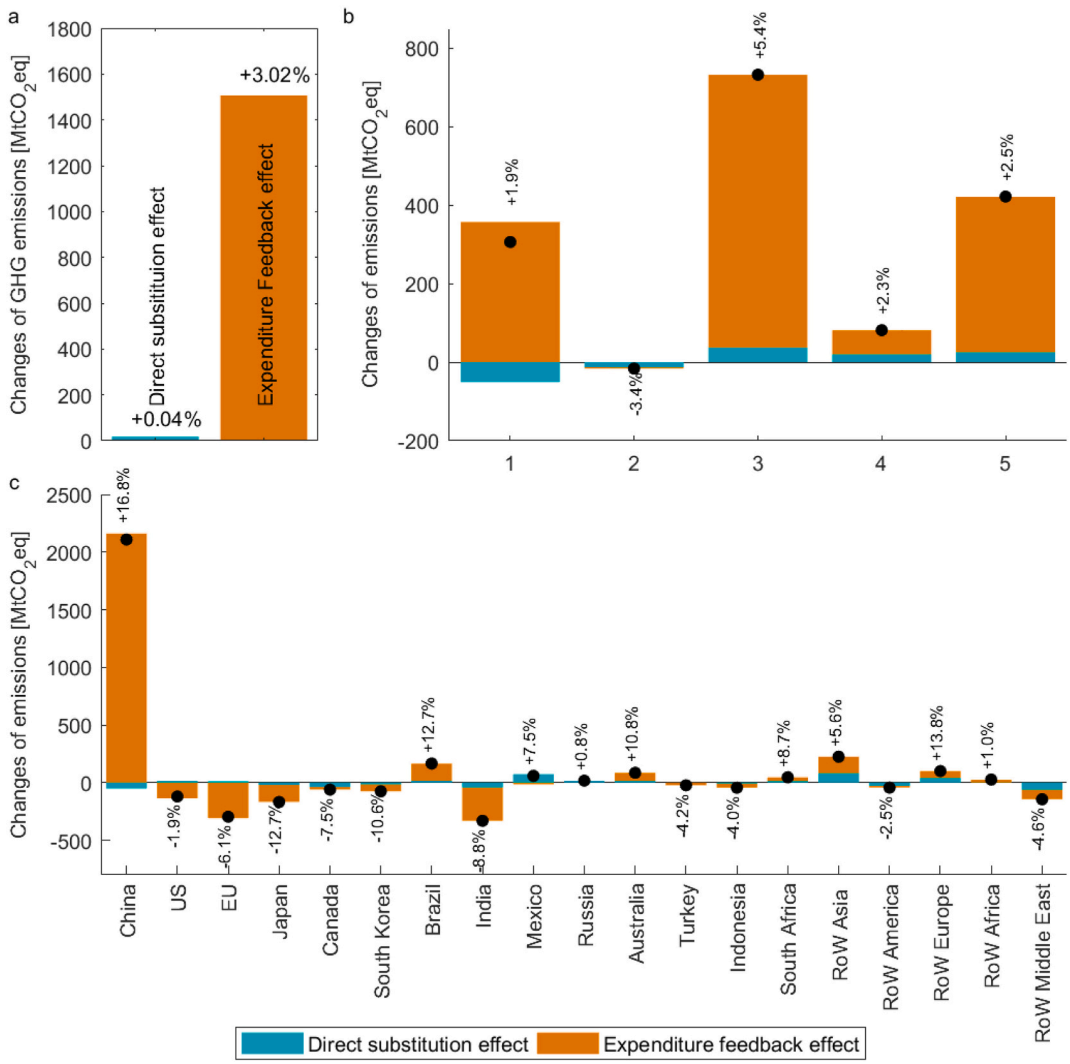

Fig. 9. a. Changes in the total emissions between 2017 and the COVID scenario. b. Emissions changes between 2017 and the COVID scenario by sector. c. Emissions changes between 2017 and the COVID scenario by region. Note: black dots show the total change in the emissions. Numbers show the change rate between 2017 historical data and scenario, which can be estimated referring to Fig. 5. Sector numbering in Fig. 9b is listed as: 1, Primary industry; 2, Labor intensive manufacturing; 3, Capital intensive manufacturing; 4, Knowledge intensive manufacturing; 5, Services industry. The sectoral classification can be seen in Table S3.

situations in which the China-US trade ties collapse and its related environmental impact. Thus, our analyze still can provide important implications for global policymakers, especially considering current growing protectionist tendencies.

5. Conclusions

In our study, we provide an overview of the embodied emissions in the China-US trade between 2010 and 2017 from multi-regional and multi-sectoral perspectives. We found that except for Beijing being the net importer in 2017, China's 29 provinces were net emissions exporters with trade of the US in 2010 and 2017. The emissions embodied in the C—U trade were mainly produced in the rich coastal provinces. We also developed scenario analysis to assess the emissions impact of reallocating trade pattern. The results under the no trade scenario (S1) indicate that global emissions reduce by 1.2%, however the reallocation of excluded trade would result in the emissions increase by 0.3–1.8% due to large expenditure feedback effect of China (+5%–8.7%). The US would increase emissions by 3.8% in the domestic scenario (S2). However, the US decreases the emissions in the distribution scenario (S3) and shared import replacement scenario (S4) by 10.1% and 2.5%, respectively, as the US needs to increase inputs from other regions with relatively higher inputs cost, leading to the reduction of final demand in the US. In the S3, the emissions in the major trade partners of China and US (e.g., Korea, Mexico and RoW Asian) increase significantly (more than 5%) due to the increase of final demand. In the S4, the Europe is the most affected after the shock of the reallocation of trade (more than −3%), as it is responsible for providing large intermediate products for the China-US trade.

CRediT authorship contribution statement

Rong Yuan: Conceptualization, Methodology, Software, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **João F.D. Rodrigues:** Conceptualization, Methodology, Formal analysis, Writing – review & editing. **Juan Wang:** Validation, Investigation, Writing – review & editing. **Paul Behrens:** Investigation, Formal analysis, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eiar.2022.106980.

References

Acquaye, A., Feng, K., Oppon, E., Salhi, S., Ibn-Mohammed, T., Genovese, A., Hubacek, K., 2017. Measuring the environmental sustainability performance of global supply chains: a multi-regional input-output analysis for carbon, sulphur oxide and water footprints. J. Environ. Manag. 187, 571–585.
Aklin, M., 2016. Re-exploring the trade and environment nexus through the diffusion of pollution. Environ. Resour. Econ. 64, 663–682.
Arce, G., López, L., Guan, D., 2016. Carbon emissions embodied in international trade: the post-China era. Appl. Energy 184, 1063–1072.
Balsalobre-Lorente, D., Driha, M.O., Halkos, G., Mishra, S., 2021. Influence of growth and urbanization on CO_2 emissions: the moderating effect of foreign direct investment on energy use in BRICS. Sustain. Dev. https://doi.org/10.1002/sd.2240.
Balsalobre-Lorente, D., Ibáñez-Luzón, L., Usman, M., Shahbaz, M., 2022. The environmental Kuznets curve, based on the economic complexity, and the pollution haven hypothesis in PIIGS countries. Renew. Energy 185, 1441–1455.
Costa, L., Moreau, V., 2019. The emission benefits of European integration. Environ. Res. Lett. 14, 084044.
Cui, C., Li, L., 2021. The effect of the US–China trade war on Chinese new firm entry. Econ. Lett. 203, 109846.
Dai, F., Yang, J., Guo, H., Sun, H., 2021. Tracing CO_2 emissions in China-US trade: a global value chain perspective. Sci. Total Environ. 775, 145701.
Davis, S.J., Caldeira, K., 2010. Consumption-based accounting of CO_2 emissions. PNAS 107, 5687–5692.
Dietzenbacher, E., Lahr, M., 2013. Expanding extractions. Econ. Syst. Res. 25, 341–360.
Doğan, B., Chu, K.L., Ghosh, S., Truong, D.H.H., Balsalobre-Lorente, D., 2022. How environmental taxes and carbon emissions are related in the G7 economies? Renew. Energy 187, 645–656.
Du, H., Guo, J., Mao, G., Smith, M.A., Wang, X., Wang, Y., 2011. CO_2 emissions embodied in China–US trade: input–output analysis based on the emergy/dollar ratio. Energy Policy 39, 5980–5987.
Dweck, E., Bassetti, M., Torracca, J., Miguex, T., 2022. COVID-19 and the Brazilian manufacturing sector: roads to reindustrialization within societal purposes. Struct. Chang. Econ. Dyn. 61, 278–293.
Guan, D., Meng, J., Reiner, D.M., Zhang, N., Shan, Y., Mi, Z., Shao, S., Liu, Z., Zhang, Q., Davis, S.J., 2018. Structural decline in China's CO_2 emissions through transitions in industry and energy systems. Nat. Geosci. 11, 551–555.
Guo, J., Huang, Q., Cui, L., 2021. The impact of the Sino-US trade conflict on global shipping carbon emissions. J. Clean. Prod. 316, 128381.
He, K., Hertwich, E.G., 2019. The flow of embodied carbon through the economies of China, the European Union, and the United States. Resour. Conserv. Recycl. 145, 190–198.
He, R.R., Zhu, D., Chen, X.W., Cao, Y., Chen, Y.Q., Wang, X.L., 2020. How the trade barrier changes environmental costs of agricultural production: an implication derived from China's demand for soybean caused by the US-China trade war. J. Clean. Prod. 227, 578–588.
Hoekstra, A.Y., Wiedmann, T.O., 2014. Humanity's unsustainable environmental footprint. Science 344, 1114–1117.
Huang, R., Chen, G., Lv, G., Malik, A., Shi, X., Xie, X., 2020. The effect of technology spillover on CO_2 emissions embodied in China-Australia trade. Energy Policy 144, 111544.
Jahanger, A., Usman, M., Murshed, M., Marhmood, H., Balsalobre-Lorente, D., 2022. The linkages between natural resources, human capital, globalization, economic growth, financial development, and ecological footprint: the moderating role of technological innovations. Res. Policy 76, 102569.
Jiang, T., Yu, Y., Jahanger, A., Balsalobre-Lorente, D., 2022. Structural emissions reduction of China's power and heating industry under the goal of "double carbon": a perspective from input-output analysis. Sustain. Product. Consump. 31, 346–356.
Kander, A., Jiborn, M., Moran, D.D., Wiedmann, T.O., 2015. National greenhouse-gas accounting for effective climate policy on international trade. Nat. Clim. Chang. 5, 431–435.
Kim, M.H., 2019. A real driver of US–China trade conflict: the Sino–US competition for global hegemony and its implications for the future. Intern. Trade, Politics Develop. 3, 30–40.
Leontief, W., 1986. Input Output Economics. Oxford Univ. Press, New York.
Li, C.D., He, C.T., Lin, C.W., 2018. Economic impacts of the possible China-US trade war. Emerg. Mark. Financ. Trade 54, 1557–1577.
Li, M.H., Balistreri, J.E., Zhang, W.D., 2020. The US-China trade war: tariff data and general equilibrium analysis. J. Asian Econ. 69, 101216.
Lin, B., Xu, M., 2019. Does China become the "pollution heaven" in south-south trade? Evidence from Sino-Russian trade. Sci. Total Environ. 666, 964–974.
Lin, J., Pan, D., Davis, S.J., Zhang, Q., He, K., Wang, C., Streets, D.G., Wuebbles, D.J., Guan, D., 2014. China's international trade and air pollution in the United States. PNAS 111.
Liu, H., Meng, Z., Lv, Z., Wang, X., Deng, F., Liu, Y., Zhang, Y., Shi, M., Zhang, Q., He, K., 2019. Emissions and health impacts from global shipping embodied in US-China bilateral trade. Nat. Sustain. 2, 1027–1033.
Liu, L., Creutzig, F., Yao, Y., Wei, Y., Liang, Q., 2020. Environmental and economic impacts of trade barriers: the example of China-US trade friction. Resour. Energy Econ. 59, 101144.
Liu, Z., Davis, S.J., Feng, K., Hubacek, K., Liang, S., Anadon, L.D., et al., 2016. Targeted opportunities to address the climate-trade dilemma in China. Nat. Clim. Chang. 6, 201–206.
Meng, B., Peters, G.P., Wang, Z., Li, M., 2018b. Tracing CO_2 emissions in global value chains. Energy Econ. 73, 24–42.
Meng, J., Mi, Z., Guan, D., Li, J., Tao, S., Li, Y., Feng, K., Liu, J., Liu, Z., Wang, X., Zhang, Q., Davis, J.S., 2018a. The rise of south-south trade and its effect on global CO_2 emissions. Nat. Commun. 9, 1871.
Mi, Z., Sun, X., 2021. Provinces with transitions in industrial structure and energy mix performed best in climate change mitigation in China. Nat. Commun. Earth Environ. 2, 182.
Miller, R.E., Blair, P.D., 2009. Input-Output Analysis: Foundations and Extensions. Cambridge University Press, Cambridge, UK, and New York.
Nemati, M., Hu, W., Reed, M., 2019. Are free trade agreements good for the environment? A Panel Data Analy. 23, 435–453.
Peters, G.P., Minx, J.C., Weber, C.L., Edenhofer, O., 2011. Growth in emission transfers via international trade from 1990 to 2008. PNAS 108, 8903–8908.
Ratchford, T.J., Blanpied, A.W., 2008. Paths to the future for science and technology in China, India and the United States. Technol. Soc. 30, 211–233.
Shi, F., Liao, X., Shen, L., Meng, C., Lai, Y., 2022. Exploring the spatiotemporal impacts of urban form on CO_2 emissions: evidence and implications from 256 Chinese cities. Environ. Impact Assess. Rev. 96, 106850.
Sinha, A., Balsalobre-Lorente, D., Zafar, W.M., Saleem, M.M., 2022. Analyzing global inequality in access to energy: developing policy framework by inequality decomposition. J. Environ. Manag. 304, 114299.
Su, B., Ang, B.W., 2010. Input–output analysis of CO_2 emissions embodied in trade: the effects of spatial aggregation. Ecol. Econ. 70, 10–18.
Su, B., Ang, B.W., 2014. Input–output analysis of CO_2 emissions embodied in trade: a multi-region model for China. Appl. Energy 114, 377–384.
Sun, C., Chen, L., Zhang, F., 2020. Exploring the trading embodied CO_2 effect and low-carbon globalization from the international division perspective. Environ. Impact Assess. Rev. 83, 106414.
Temurshoev, U., Oosterhaven, J., 2013. Analytical and Empirical Comparison of Policy-Relevant Key Sector Measures. University of Groningen, Groningen Growth and Development Centre.
Tian, K., Zhang, Y., Li, Y., Ming, X., Jiang, S., Duan, H., Yang, C., Wang, S., 2022. Regional trade agreement burdens global carbon emissions mitigation. Nat. Commun. 13, 408.
Usman, M., Balsalobre-Lorente, D., 2022. Environmental concern in the era of industrialization: can financial development, renewable energy and natural resources alleviate some load? Energy Policy 162, 112780.
Wang, H., Zhang, Y., Zhao, H., Lu, X., Zhang, Y., Zhu, W., Nielsen, P.C., Li, X., Zhang, Q., Bi, J., McElroy, B.M., 2017. Trade-driven relocation of air pollution and health impacts in China. Nat. Commun. 8, 738.
Wang, Q., Han, X., 2021. Is decoupling embodied carbon emissions from economic output in Sino-US trade possible? Technol. Forecast. Soc. Chang. 16, 120805.
Wang, W., Chen, W., Diao, Z., Ciacci, L., Pourzahedi, L., Eckelman, J.M., Yang, Y., Shi, L., 2021a. Multidimensional analyses reveal unequal resource, economic, and environmental gains and losses among the global aluminum trade leaders. Environ. Sci. Technol. 55, 7102–7112.
Wang, X., Yang, J., Zhou, Q., Liu, M., Bi, J., 2021b. Mapping the exchange between embodied economic benefits and CO2 emissions among belt and road initiative countries. Appl. Energy 25, 118206.
Weitzel, M., Ma, T., 2014. Emissions embodied in Chinese exports taking into account the special export structure of China. Energy Econ. 45, 45–52.
Wiedmann, T., Lenzen, M., 2018. Environmental and social footprints of international trade. Nat. Geosci. 11, 314–321.
WTO, 2022. https://stats.wto.org/.
Wu, Z., Yang, L., Chen, Q., Ye, Q., 2021. The impacts of international trade on global greenhouse gas emissions: a thought experiment based on a novel no-trade analysis. J. Environ. Manag. 300, 113836.
Xia, T., Li, X., 2010. Consumption inertia and asymmetric Price transmission. J. Agric. Resour. Econ. 35, 209–227.
Xie, Q., Wu, H., 2021. How does trade development affect environmental performance? New assessment from partially linear additive panel analysis. Environ. Impact Assess. Rev. 89, 106584.
Xin, Y., Kong, Y., Ji, Q., Zhang, D., 2019. Impacts of China-US trade conflicts on the energy sector. China Econ. Rev. 58, 101360.
Xiong, Y., Wu, S., 2021. Real economic benefits and environmental costs accounting of China-US trade. J. Environ. Manag. 279, 111390.

Xu, S., Gao, C., Miao, Y., Shen, W., Long, R., Chen, H., Zhao, B., Wang, S., 2019. Calculation and decomposition of China's embodied air pollutants in Sino-US trade. J. Clean. Prod. 209, 978–994.
Xu, X., Mu, M., Wang, Q., 2017. Recalculating CO2 emissions from the perspective of value-added trade: an input-output analysis of China's trade data. Energy Policy 107, 158–166.
Yan, B., Duan, Y., Wang, S., 2020. China's emissions embodied in exports: how regional and trade heterogeneity matter. Energy Econ. 87, 104479.
Yang, L., Wang, Y., Wang, R., Klemes, J.J., Bôas de Almeida, V.M.C., Jin, M., Zheng, X., Qiao, Y., 2020. Environmental-social-economic footprints of consumption and trade in the Asia-Pacific region. Nat. Commun. 11, 4490.
Yao, G., Zhang, X., Davidson, A.E., Taheripor, F., 2021. The increasing global environmental consequences of a weakening US–China crop trade relationship. Nat. Food 2, 578–586.
Yuan, R., Wang, J., 2021. Impacts of poverty alleviation on household GHG footprints in China. Energy Econ. 103, 105602.
Yuan, R., Rodrigues, J.F.D., Wang, J., Tukker, A., Behrens, P., 2022. A global overview of developments of urban and rural household GHG footprints from 2005 to 2015. Sci. Total Environ. 806, 150695.
Zhang, W., Wang, F., Hubacek, K., Liu, Y., Wang, J., Feng, K., Jiang, L., Jiang, H., Zhang, B., Bi, J., 2018. Unequal exchange of air pollution and economic benefits embodied in China's exports. Environ. Sci. Technol. 52, 3888–3898.
Zhang, Z., Xi, L., Su, B., Zhao, Y., Song, W., Ya, L., Hao, L., Zhang, Y., Ashfaq, A., Guang, S., 2019. Energy, CO_2 emissions, and value-added flows embodied in the international trade of the BRICS group: a comprehensive assessment. Renew. Sust. Energ. Rev. 116, 109432.
Zhao, Y., Wang, S., Zhang, Z., Liu, Y., Ahmad, A., 2016. Driving factors of carbon emissions embodied in China–US trade: a structural decomposition analysis. J. Clean. Prod. 131, 678–689.
Zheng, C., Deng, F., Li, C., Yang, Z., 2022. The impact of China's western development strategy on energy conservation and emission reduction. Environ. Impact Assess. Rev. 94, 106743.