

Allocating carbon responsibility: The role of spatial production fragmentation

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ABSTRACT

A number of studies have compared national carbon abatement responsibility under different carbon accounting schemes. However, the difficulty of the shift among different national carbon accounting schemes has rarely been quantitatively evaluated in the literature. Spatial production fragmentation over the recent decades has led to geographical separation among the primary inputs supplying regions, carbon emitting regions, and final consuming regions. The purpose of this paper is to reveal the effects of spatial production fragmentation on the shift from production-based to consumption-based and income-based national carbon accounting. Based on both demand- and supply-driven input-output analytical frameworks, this paper analyses the allocation of carbon responsibility for embodied and enabled emissions along production chains over the period 1995–2009. It was found that as much as 25% of embodied emissions and 20% of enabled emissions crossed national borders more than once in 2009. The shift among different carbon accounting schemes is not only related to the magnitude of trade related emissions but also related to border-crossing frequency associated with emissions embodied in or enabled by international trade. The increasingly fragmented production networks complicate the shift from production-based to consumption-based or income-based accounting and weaken the effectiveness of consumption-based or income-based accounting.

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1. Introduction

Production-based accounting (PBA) is a metric adopted by most climate policies (Marques et al., 2012; Zhang 2012a and 2012b). To reflect suppliers' and consumers' responsibility, the literature further proposes consumption-based accounting (CBA), which measures emissions driven by regional final consumption (Afionis et al., 2017; Davis and Caldeira, 2010; Druckman and Jackson, 2009; Feng et al., 2013; Guo et al., 2012; Hertwich and Peters, 2009; Liu, 2014; Peters, 2008; Peters et al., 2011; Su and Ang, 2011; Weber et al., 2008) and income-based accounting (IBA), which measures emissions enabled by regional primary inputs (Gallego and Lenzen, 2005a, 2005b; Lenzen and Murray, 2010; Liang et al., 2017, 2016; Marques et al., 2012). The key steps of shifting from PBA to CBA and IBA lie in relocating carbon responsibility along global supply chains. However, production processes have been increasingly fragmented across national borders over recent decades, and spatial production fragmentation leads to geographical separation among the primary input suppliers, carbon emitters, and final consumers. This means that it may become increasingly challenging to shift among different carbon accounting schemes because of regional jurisdiction (Turner et al., 2011). Therefore, the purpose of this paper is to reveal the effects of spatial production fragmentation on the allocation of carbon abatement responsibility¹ along global production networks.

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¹ PBA, CBA, and IBA are respectively corresponding to territory, downstream, and upstream responsibility (Lenzen and Murray, 2010; Marques et al., 2012).

What matters for the relocation of carbon responsibility along global value chains? We illustrate this issue with a simple example. The ability to throw a stone across a river is determined not only by the weight of the stone but also by the width of the river. Two sides of the river can be viewed as the source and destination regions of carbon transfer, and the stone represents the reallocated carbon responsibility. The volume of trade-related emissions may be so huge that the USA refuse to bear the carbon reduction responsibility for emissions emitted in China to meet with the demand in the USA. With the rise of South–South trade (Meng et al., 2018), China's exports may be first processed in the other countries, such as Southeast Asian countries, and then reexported to the USA. Due to spatial production fragmentation, the supplier, producer, and consumer regions may be far away from each other in global supply chains, and it is difficult for China to reallocate carbon responsibility to the USA. To the best of our knowledge, the existing literature focuses primarily on the magnitude of trade-related emissions (Davis et al., 2011; Davis and Caldeira, 2010; Hertwich and Peters, 2009; Jakob and Marschinski, 2012; Peters et al., 2011; Weber and Matthews, 2007; Zhang et al., 2014). However, less attention has been paid to the economic length of global supply chain. Thus, this paper attempts to enrich the existing literature by analyzing the shift from PBA to CBA and IBA from the perspective of spatial production fragmentation.

In this paper, the width of the river represents the economic distance between two countries in global supply chains. A variety of studies (Antràs et al., 2012; Dietzenbacher et al., 2005; Dietzenbacher and Romero, 2007; Fally, 2012; Ni et al., 2016; Wang et al., 2014) evaluate a country's relative position in global value chains by the Average Production Length (APL) proposed by Dietzenbacher et al. (2005). APL measures the average number of steps that a sector takes to influence the production of another sector (Dietzenbacher et al., 2005). However, Oosterhaven and Bouwmeester (2013) warn that the APL is only suitable for pure industry linkage and cannot be used to compare different economies. In addition, this present paper focuses mainly on the regional jurisdiction that can be reflected by the number of countries that are involved in the global production chains. The APL cannot be directly used in this paper to evaluate the economic distance between pairs of countries. To address this problem, this paper makes a decomposition of the APL and uses the average number of border-crossing frequency (BCF) associated with trade-related emissions to evaluate the economic length between different agents.

BCF is defined as the number of borders a traded product crosses in a supply chain (Zhang et al., 2017a, 2017b). A greater BCF associated with trade-related emissions means that the reallocated carbon responsibility has to be transferred between different countries or regions multiple times. The data quality and availability of the trading partners cannot be assured as an increasing number of countries are involved in the production of traded products (Afionis et al., 2017). This would result in a great uncertainty and hinder the shift from PBA to CBA or IBA (Peters, 2008; Peters and Hertwich, 2008a). In addition, some countries are not relatively active in responding to the climate change. The longer the carbon transfer path is, the greater is the possibility that the reallocation of carbon responsibility is hindered because of some countries' non-cooperation. In other words, a greater BCF means that the supplier, producer, and consumer regions are farther away from each other in global supply chains and that it is more difficult to shift national carbon accounting. The literature has noticed the geographical separation among supplier, producer, and consumer regions (Marques et al., 2013). Against the globalization background, a full picture of carbon emissions embodied in global supply chains becomes more and more important for policy makers to determine regional carbon responsibility. A policy implication of this study lies in providing a new insight (e.g., border-crossing frequency associated with trade-related emissions) for understanding carbon responsibility allocation along global supply chains.

The measure of BCF associated with traded products is first analyzed in the research area of global value chains (Muradov, 2016; Wang et al., 2017). Zhang et al. (2017a, 2017b) propose another calculation method and first defined the BCF associated with embodied emissions based on the demand-pull input-output model. Tracing embodied and enabled emissions along the global supply chain is a primary condition for shifting from PBA to CBA and IBA. This paper extends Zhang et al.'s study (Zhang et al., 2017a, b)(2017a; 2017b) to supply-push input-output model and proposes the BCF associated with enabled emissions. More specifically, this study calculates BCFs associated with embodied and enabled emissions by dividing the Leontief and Ghosh inverse matrix. In addition, the study introduces the structural path analysis (SPA) (Kanemoto et al., 2014; Lenzen et al., 2012a, 2012b; Meng et al., 2015; Peters and Hertwich, 2007; Skelton et al., 2011) to map emissions enabled by cross-border value chains and emissions embodied in cross-border trade flows.

This paper builds on previous studies that analyze the relationship and divergence among different national carbon accounting schemes. Based on who (i.e., producer, consumer, extractor or income beneficiary) is responsible for the trade-related emissions, there are four types of accounting schemes: PBA, CBA, IBA and EBA (extraction-based accounting) (Steininger et al., 2016). CBA is equal to PBA plus foreign upstream emissions embodied in imports minus domestic upstream emissions embodied in exports (Afionis et al., 2017; Arce et al., 2016; Davis et al., 2011; Peters and Hertwich, 2008b; Su and Ang, 2014). IBA is equal to PBA plus foreign downstream emissions enabled by exports minus domestic downstream emissions enabled by imports (Liang et al., 2016, 2017; Marques et al., 2012). EBA is different from PBA in how to allocate emissions related to traded fuels (Steininger et al., 2016). However, the fuel production process is relatively less fragmented spatially. Therefore, this study focuses mainly on the transfer from PBA to CBA and IBA. In addition, we believe that this study may help better understand the difficulty of sharing carbon responsibility along global supply chains (Lenzen et al., 2012a, 2012b; Lenzen et al., 2007).

This paper is organized into five sections. Section 2 describes the methodology. Section 3 presents the simulation results. Conclusions are presented in Section 4.

2. Methodology

This paper adopts a global multiregional input-output model (GMRIO) to trace trade-related emissions along global supply chains. The GMRIO framework is presented in Table 1.

The world is composed of M countries, with each country separated into N sectors. The final output of country s is represented by x^s , x is the diagonal matrix of x^s , and $s = 1, \dots, M$. A^{sr} is the input-output coefficient matrix, and $r = 1, \dots, M$. The intermediate input matrix from country s to country r is denoted by $A^{sr}X^s$. y^{sr} represents the final product exports from country s to country r . The value added of country s is represented by v^s . The emissions of country s are represented by e^s . We define F as a $MN \times MN$ diagonal matrix with sectoral carbon

Table 1
Global multiregional input-output framework.

		Outputs	Inputs	Intermediate demand			Final demand		Output	
		Country1	...	Country M	Country1	...	Country M			
		Sector1...Sector N			Sector1...Sector N					
Intermediate inputs	Country1	Sector 1	∴ Sector N	$\hat{A}^{11}x^1$	...	$A^{1M}x^1$	y^{11}	...	y^{1M}	x^1
				\vdots		\vdots	\vdots		\vdots	\vdots
	Country G	Sector 1	∴ Sector N	$A^{M1}x^M$	...	$A^{MM}x^M$	y^{M1}	...	y^{MM}	x^M
		Value added				v^M				
	Output			$(x^1)'$		$(x^M)'$				
	Emissions			e^1		e^M				

intensity in each country as its elements. Based on the Leontief and Ghosh models, we obtain the emissions (\bar{E}) that are induced by the final demand of different countries and the emissions (\tilde{E}) that are enabled by value added of different countries, respectively.

$$\bar{E} = F(I - A)^{-1}Y \tag{1a}$$

$$\tilde{E} = F(I - H')^{-1}V \tag{1b}$$

where $A = \begin{bmatrix} A^{11} & A^{12} & \dots & A^{1M} \\ A^{21} & A^{22} & \dots & A^{2M} \\ \vdots & \vdots & \ddots & \vdots \\ A^{M1} & A^{M2} & \dots & A^{MM} \end{bmatrix}$ is the $MN \times MN$ input-output coefficient matrix, $H = \begin{bmatrix} H^{11} & H^{12} & \dots & H^{1M} \\ H^{21} & H^{22} & \dots & H^{2M} \\ \vdots & \vdots & \ddots & \vdots \\ H^{M1} & H^{M2} & \dots & H^{MM} \end{bmatrix}$ is the $MN \times MN$ direct

distribution coefficient matrix (the elements satisfy $h_{ij} = z_{ij}/x_i$), $\hat{Y} = \begin{bmatrix} \hat{y}^{11} & \hat{y}^{12} & \dots & \hat{y}^{1M} \\ \hat{y}^{21} & \hat{y}^{22} & \dots & \hat{y}^{2M} \\ \vdots & \vdots & \ddots & \vdots \\ \hat{y}^{M1} & \hat{y}^{M2} & \dots & \hat{y}^{MM} \end{bmatrix}$, $\hat{V} = \begin{bmatrix} \hat{v}^1 & 0 & \dots & 0 \\ 0 & \hat{v}^2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \hat{v}^M \end{bmatrix}$ is a $MN \times MN$ diag-

onal matrix with the sectoral value added in each country as its elements. From the horizontal perspective of \bar{E} , we could obtain a certain country's production-based emissions induced by the final demands of other countries. From the vertical perspective of \bar{E} , we could obtain the emissions induced by the final demand of a certain country, which corresponds to consumption-based accounting. From the horizontal perspective of \tilde{E} , we could obtain a certain country's production-based emissions enabled by value added from each country. From the vertical perspective of \tilde{E} , we could obtain the emissions enabled by value added of a certain country, which corresponds to the income-based accounting.

Being in line with the logic of our previous study (Zhang et al., 2017a), this paper deconstructs national emissions into two parts. The first one is induced by pure domestic economic activity, and the second represents emissions embodied in international trade flows.

$$\hat{E} = FL^D\hat{Y} + \underbrace{FL^D\hat{Y} + FL^D\hat{A}^E\hat{B}\hat{Y}}_{Embodied Emissions(EEX)} \tag{2a}$$

$$\hat{\tilde{E}} = FG^D\hat{V} + \underbrace{FG^D\hat{H}^E\hat{G}\hat{V}}_{Enabled Emissions(EEI)} \tag{2b}$$

where $L^D = \begin{bmatrix} L^{11} & 0 & \dots & 0 \\ 0 & L^{22} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & L^{MM} \end{bmatrix}$, $L^{ss} = (I - A^{ss})^{-1}$ represents the local Leontief inverse matrix of region s , $\hat{Y} =$

$\begin{bmatrix} \hat{y}^{11} & 0 & \dots & 0 \\ 0 & \hat{y}^{22} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \hat{y}^{MM} \end{bmatrix}$ represents the final outputs that are used to satisfy domestic final demand, $\hat{Y} = \hat{Y} - \hat{Y} =$

$$\begin{bmatrix} 0 & \hat{A}^{12} & \dots & \hat{A}^{1M} \\ \hat{A}^{21} & \mathbf{y} & \dots & \hat{A}^{2M} \\ \mathbf{y} & 0 & \dots & \mathbf{y} \\ \vdots & \vdots & \ddots & \vdots \\ \hat{A}^{M1} & \hat{A}^{M2} & \dots & 0 \\ \mathbf{y} & \mathbf{y} & \dots & 0 \end{bmatrix}$$
 represents the final products exports, $\mathbf{B}=(\mathbf{I}-\mathbf{A})^{-1}$ represent the Leontief inverse matrix, and $\mathbf{A}^E \hat{\mathbf{B}} \mathbf{Y}$ represents the intermediate products exports. International trade is represented by $\mathbf{T}_{ex} = \mathbf{Y}^E + \mathbf{A}^E \hat{\mathbf{B}} \mathbf{Y}$. According to Wang et al. (2015), the relation between \mathbf{B} and \mathbf{L}^D satisfies $\mathbf{B} = \mathbf{L}^D + \mathbf{L}^D \mathbf{A}^E \mathbf{B}$, where $\mathbf{A}^E = \begin{bmatrix} 0 & \hat{\mathbf{A}}^{12} & \dots & \hat{\mathbf{A}}^{1M} \\ \hat{\mathbf{A}}^{21} & 0 & \dots & \hat{\mathbf{A}}^{2M} \\ \vdots & \vdots & \ddots & \vdots \\ \hat{\mathbf{A}}^{M1} & \hat{\mathbf{A}}^{M2} & \dots & 0 \end{bmatrix}$. The second and third parts of Eq. (2a) represent regional emissions embodied in international trade flows (EEX), respectively. $\mathbf{G}=(\mathbf{I}-\mathbf{H})^{-1}$ represents the change in sectoral outputs due to unit change in value added. We define $\mathbf{G}^{ss}=(\mathbf{I}-\mathbf{H}^{ss})^{-1}$ and $\mathbf{G}^D = \begin{bmatrix} \mathbf{G}^{11} & 0 & \dots & 0 \\ 0 & \mathbf{G}^{22} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \mathbf{G}^{MM} \end{bmatrix}$. The relation between \mathbf{G} and \mathbf{G}^D is represented by the equation $\mathbf{G} = \mathbf{G}^D + \mathbf{G}^D \mathbf{H}^E \mathbf{G}$, where $\mathbf{H}^E = \begin{bmatrix} 0 & \mathbf{H}^{12} & \dots & \mathbf{H}^{1M} \\ \mathbf{H}^{21} & 0 & \dots & \mathbf{H}^{2M} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{H}^{M1} & \mathbf{H}^{M2} & \dots & 0 \end{bmatrix}$. Additionally, $\mathbf{T}_{im} = \mathbf{H}^E \hat{\mathbf{G}} \mathbf{V}$ represents the intermediate products exports. The second part of Eq. (2b) represents a country's emissions enabled by international imports. Intermediate products may cross national borders multiple times. This paper further deconstructs national emissions based on border crossing frequency associated with trade flows.

$$\bar{\mathbf{E}} = \underbrace{\mathbf{F}\hat{\mathbf{L}}^D\mathbf{Y}}_{BCF=0} + \underbrace{\mathbf{F}\hat{\mathbf{L}}^D\mathbf{Z}\mathbf{Y}}_{BCF=1} + \underbrace{\mathbf{F}\hat{\mathbf{L}}^D\mathbf{Y}}_{BCF=1} + \underbrace{\mathbf{F}\hat{\mathbf{L}}^D\mathbf{Z}^2\mathbf{Y}}_{BCF=2} + \underbrace{\mathbf{F}\hat{\mathbf{L}}^D\mathbf{Z}\mathbf{Y}}_{BCF=2} + \underbrace{\mathbf{F}\hat{\mathbf{L}}^D\mathbf{Z}^3\mathbf{Y}}_{BCF=3} + \underbrace{\mathbf{F}\hat{\mathbf{L}}^D\mathbf{Z}^2\mathbf{Y}}_{BCF=3} + \dots \tag{3a}$$

$$\tilde{\mathbf{E}} = \underbrace{\mathbf{F}\hat{\mathbf{G}}^D\mathbf{V}}_{BCF=0} + \underbrace{\mathbf{F}\hat{\mathbf{G}}^D\mathbf{W}\mathbf{V}}_{BCF=1} + \underbrace{\mathbf{F}\hat{\mathbf{G}}^D\mathbf{W}^2\mathbf{V}}_{BCF=2} + \underbrace{\mathbf{F}\hat{\mathbf{G}}^D\mathbf{W}^3\mathbf{V}}_{BCF=3} + \dots \tag{3b}$$

where $\mathbf{Z}=\mathbf{A}^E\mathbf{L}^D$, and it satisfies $\mathbf{B}=\mathbf{L}^D(\mathbf{I}-\mathbf{Z})^{-1}$ ². $\mathbf{F}\hat{\mathbf{L}}^D\mathbf{Y}^E$ represents the carbon emissions embodied in final product trade, which cross borders once. $\mathbf{F}\hat{\mathbf{L}}^D(\mathbf{Z})^t\mathbf{Y}^D$ represents the carbon emissions embodied in intermediate product trade flows. The intermediate products cross borders t times and the final products are absorbed by the country that produces them. $\mathbf{F}\hat{\mathbf{L}}^D(\mathbf{Z})^t\mathbf{Y}^E$ represents the carbon transfer that is related to both intermediate and final products trade. The intermediate products cross regional borders t times and the final product cross regional borders once. $\mathbf{W}=\mathbf{H}^E\mathbf{G}^D$, and it satisfies $\mathbf{G}=\mathbf{G}^D(\mathbf{I}-\mathbf{W})^{-1}$ ³. $\mathbf{F}\hat{\mathbf{G}}^D\mathbf{W}^t\mathbf{V}$ represents carbon emissions enabled by international imports which cross national borders t times.

There exist different cross-border trade flows. Which one plays the most important role in the bilateral carbon transfer? This paper seeks to answer this question based on structural path analysis from a spatial perspective. Taking the Leontief input-output model as

an example, we suppose $\mathbf{L}_s^D = \begin{bmatrix} \mathbf{p}^1\mathbf{L}^{11} & 0 & \dots & 0 \\ 0 & \mathbf{p}^2\mathbf{L}^{22} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \mathbf{p}^M\mathbf{L}^{MM} \end{bmatrix}$, $\mathbf{Y}_s^D = \begin{bmatrix} \mathbf{p}^1\mathbf{y} & 0 & \dots & 0 \\ 0 & \mathbf{p}^2\mathbf{y} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \mathbf{p}^M\mathbf{y} \end{bmatrix}$, ($\mathbf{p}^m = \mathbf{I}$ if $m = s$, otherwise, $\mathbf{p}^m = 0$),

² According to $\mathbf{B}=\mathbf{L}^D+\mathbf{L}^D\mathbf{A}^E\mathbf{B}$, we obtain

$$\begin{aligned} \mathbf{B} &= \mathbf{L}^D + \mathbf{L}^D \mathbf{A}^E \mathbf{B} \\ &= \mathbf{L}^D + \mathbf{L}^D \mathbf{A}^E (\mathbf{L}^D + \mathbf{L}^D \mathbf{A}^E \mathbf{B}) \\ &= \mathbf{L}^D + \mathbf{L}^D \mathbf{A}^E \mathbf{L}^D + \mathbf{L}^D \mathbf{A}^E \mathbf{L}^D \mathbf{A}^E \mathbf{L}^D + \mathbf{L}^D \mathbf{A}^E \mathbf{L}^D \mathbf{A}^E \mathbf{L}^D \mathbf{A}^E \mathbf{L}^D + \dots \\ &= \mathbf{L}^D + \mathbf{L}^D \mathbf{Z} + \mathbf{L}^D \mathbf{Z}^2 + \mathbf{L}^D \mathbf{Z}^3 + \dots \\ &= \mathbf{L}^D (\mathbf{I} - \mathbf{Z})^{-1} \end{aligned}$$

³ According to $\mathbf{G}=\mathbf{G}^D+\mathbf{G}^D\mathbf{H}^E\mathbf{G}$, we obtain

$$\begin{aligned} \mathbf{G} &= \mathbf{G}^D + \mathbf{G}^D \mathbf{H}^E \mathbf{G} \\ &= \mathbf{G}^D + \mathbf{G}^D \mathbf{H}^E (\mathbf{G}^D + \mathbf{G}^D \mathbf{H}^E \mathbf{G}) \\ &= \mathbf{G}^D + \mathbf{G}^D \mathbf{H}^E \mathbf{G}^D + \mathbf{G}^D \mathbf{H}^E \mathbf{G}^D \mathbf{H}^E \mathbf{G}^D + \mathbf{G}^D \mathbf{H}^E \mathbf{G}^D \mathbf{H}^E \mathbf{G}^D \mathbf{H}^E \mathbf{G}^D + \dots \\ &= \mathbf{G}^D + \mathbf{G}^D \mathbf{W} + \mathbf{G}^D \mathbf{W}^2 + \mathbf{G}^D \mathbf{W}^3 + \dots \\ &= \mathbf{G}^D (\mathbf{I} - \mathbf{W})^{-1} \end{aligned}$$

$$\text{and } \mathbf{Z}_{sr} = \begin{bmatrix} 0 & \mathbf{h}^{12} \mathbf{A}^{12} \mathbf{L}^{22} & \dots & \mathbf{h}^{1M} \mathbf{A}^{1M} \mathbf{L}^{MM} \\ \mathbf{h}^{21} \mathbf{A}^{21} \mathbf{L}^{11} & 0 & \dots & \mathbf{h}^{2M} \mathbf{A}^{2M} \mathbf{L}^{MM} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{h}^{M1} \mathbf{A}^{M1} \mathbf{L}^{11} & \mathbf{h}^{M2} \mathbf{A}^{M2} \mathbf{L}^{22} & \dots & 0 \end{bmatrix} \text{ and } \mathbf{Y}_{sr}^E = \begin{bmatrix} 0 & \mathbf{h}^{12} \hat{\mathbf{y}}^{12} & \dots & \mathbf{h}^{1M} \hat{\mathbf{y}}^{1M} \\ \mathbf{h}^{21} \hat{\mathbf{y}}^{21} & 0 & \dots & \mathbf{h}^{2M} \hat{\mathbf{y}}^{2M} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{h}^{M1} \hat{\mathbf{y}}^{M1} & \mathbf{h}^{M2} \hat{\mathbf{y}}^{M2} & \dots & 0 \end{bmatrix} \quad (\mathbf{h}^{mn} = \mathbf{I} \text{ if } m=s \text{ and } n=r, \text{ other-}$$

wise, $\mathbf{h}^{mn} = 0$). The direct carbon transfer from country s to country r is represented by $\mathbf{FL}_s^D \mathbf{Z}_{sr} \mathbf{Y}_r^D + \mathbf{FL}_s^D \mathbf{Y}_{sr}^E$. The exported products of country s may be first processed in country t before they are finally absorbed by country r . The corresponding carbon transfer path is $\mathbf{FL}_s^D \mathbf{Z}_{st} \mathbf{Z}_{tr} \mathbf{Y}_r^D + \mathbf{FL}_s^D \mathbf{Z}_{st} \mathbf{Y}_{tr}^E$. Similarly, we could obtain other carbon transfer paths from country s to country r . Although there are an infinite number of structural paths, the magnitude of embodied emissions would decrease as the carbon transfer length becomes longer. Therefore, it is possible to find the most important carbon transfer paths. Summing of the embodied emissions of all structural paths yields the total carbon transfer from country s to country r . Based on Ghosh input-output model, we could implement structural path analysis from a spatial perspective to clarify the cross-border value chains that correspond to different BCF and different magnitude of enabled emissions. The average length of carbon transfer is^{4,5}

$$AL.L = \frac{\mathbf{FBT}_{ex}}{\mathbf{FL}^D \mathbf{T}_{ex}} \tag{4a}$$

$$AL.G = \frac{\mathbf{FGT}_{im}}{\mathbf{FG}^D \mathbf{T}_{im}} \tag{4b}$$

The final consumer's (raw material supplier's) influential power on the carbon emitter may decrease exponentially with the BCF associated with embodied (enabled) emissions because of international differences in politics, economy, and culture. In other words, spatial production fragmentation hinders the environmental effectiveness of CBA and IBA. This paper assumes that the final consumer's and primary input supplier's influential power on the embodied and enabled emissions are α^{BCF} and β^{BCF} , respectively. $0 < \alpha < 1$, and $0 < \beta < 1$. If $\alpha = 1$ and $\beta = 1$, we obtain the traditional CBA and IBA. Otherwise, the influential power of the final consumer region and the raw material supplier region on the carbon emitter can be calculated by

$$\hat{E}.bcf = \mathbf{FL}^D \hat{\mathbf{Y}}^D + \mathbf{FL}^D \alpha \mathbf{Z} (\mathbf{I} - \alpha \mathbf{Z})^{-1} \hat{\mathbf{Y}}^D + \mathbf{FL}^D \alpha (\mathbf{I} - \alpha \mathbf{Z})^{-1} \hat{\mathbf{Y}}^E \tag{5a}$$

$$\hat{E}.bcf = \mathbf{FG}^D \hat{\mathbf{V}} + \mathbf{FG}^D \beta \mathbf{W} (\mathbf{I} - \beta \mathbf{W})^{-1} \hat{\mathbf{V}} \tag{5b}$$

There are a number of different sources of inter-country input-output tables, such as the World Input-Output Database (WIOD) (Timmer et al., 2015), the multi-region input-output table based on the Global Trade Analysis Project Database (Andrew and Peters, 2013), and the Eora multi-region input-output table database (Lenzen et al., 2012a, 2012b). The quantitative calculation of this study is based on the WIOD, which adopted the recommended residence principle for emissions allocation (Zhang et al., 2017b). The WIOD divides the world into 41

$$\begin{aligned} AL.L &= \frac{\mathbf{FL}^D (\mathbf{Z} + 2\mathbf{Z}^2 + \dots) \mathbf{Y}^D + \mathbf{FL}^D (\mathbf{I} + 2\mathbf{Z} + 3\mathbf{Z}^2 + \dots) \mathbf{Y}^E}{\mathbf{FL}^D \mathbf{T}_{ex}} \\ &= \frac{\mathbf{FL}^D ((\mathbf{I} - \mathbf{Z})^{-1})^2 \mathbf{Y} - \mathbf{FL}^D (\mathbf{I} - \mathbf{Z})^{-1} \mathbf{Y}^D}{\mathbf{FL}^D \mathbf{T}_{ex}} \\ &= \frac{\mathbf{FB} ((\mathbf{I} - \mathbf{Z})^{-1} \mathbf{Y} - \mathbf{Y}^D)}{\mathbf{FL}^D \mathbf{T}_{ex}} \\ &= \frac{\mathbf{FB} (\mathbf{Y}^E + (\mathbf{Z} + \mathbf{Z}^2 + \dots) \mathbf{Y})}{\mathbf{FL}^D \mathbf{T}_{ex}} \\ &= \frac{\mathbf{FB} (\mathbf{Y}^E + \mathbf{A}^E \mathbf{B} \mathbf{Y})}{\mathbf{FL}^D \mathbf{T}_{ex}} \\ &= \frac{\mathbf{FBT}_{ex}}{\mathbf{FL}^D \mathbf{T}_{ex}} \\ AL.G &= \frac{\mathbf{FG}^D (\mathbf{W} + 2\mathbf{W}^2 + \dots) \hat{\mathbf{V}}}{\mathbf{FG}^D \mathbf{T}_{im}} \\ &= \frac{\mathbf{FG}^D ((\mathbf{I} - \mathbf{W})^{-1})^2 \hat{\mathbf{V}} - \mathbf{FG}^D (\mathbf{I} - \mathbf{W})^{-1} \hat{\mathbf{V}}}{\mathbf{FG}^D \mathbf{T}_{im}} \\ &= \frac{\mathbf{FG} ((\mathbf{I} - \mathbf{W})^{-1} \hat{\mathbf{V}} - \hat{\mathbf{V}})}{\mathbf{FG}^D \mathbf{T}_{im}} \\ &= \frac{\mathbf{FG} (\mathbf{W} + \mathbf{W}^2 + \dots) \hat{\mathbf{V}}}{\mathbf{FG}^D \mathbf{T}_{im}} \\ &= \frac{\mathbf{FGH}^E \mathbf{G} \mathbf{V}}{\mathbf{FG}^D \mathbf{T}_{im}} \\ &= \frac{\mathbf{FGT}_{im}}{\mathbf{FG}^D \mathbf{T}_{im}} \\ &= \frac{\mathbf{FBT}_{ex}}{\mathbf{FL}^D \mathbf{T}_{ex}} \end{aligned}$$

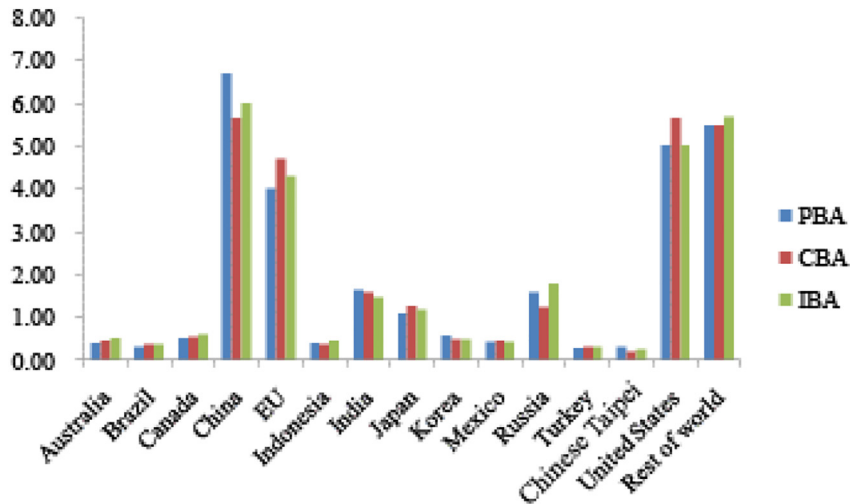


Fig. 1. National carbon emissions under PBA, CBA and IBA in 2009 (billion tons).

countries/regions, and each country has 35 sectors (the abbreviations are presented in Appendixes A and B). The WIOD only provides national carbon emissions by sector over the period 1995–2009. Therefore, this paper focuses primarily on the effect of spatial production fragmentation on the allocation of carbon responsibility along global supply chains over the period 1995–2009. The robustness analysis of this study is based on the Eora multi-region input-output table database, which covers as much as 190 countries or regions (Appendix G).

3. Results

This section first compares regional carbon inventories under the three different carbon accounting schemes. The shift from PBA to CBA and IBA means reallocating regional carbon responsibility, which is explained by both the volume of carbon transfer and the BCF associated with trade-related emissions. This study shows that spatial production fragmentation makes the shift of carbon responsibility increasingly challenging over the period 1995–2009, suggesting that spatial production fragmentation decreases the effectiveness of CBA and IBA.

3.1. Comparisons of carbon accounting schemes

This study calculates regional carbon responsibility under PBA, CBA and IBA according to Eqs. (1a) and (1b). The results are presented in Fig. 1.

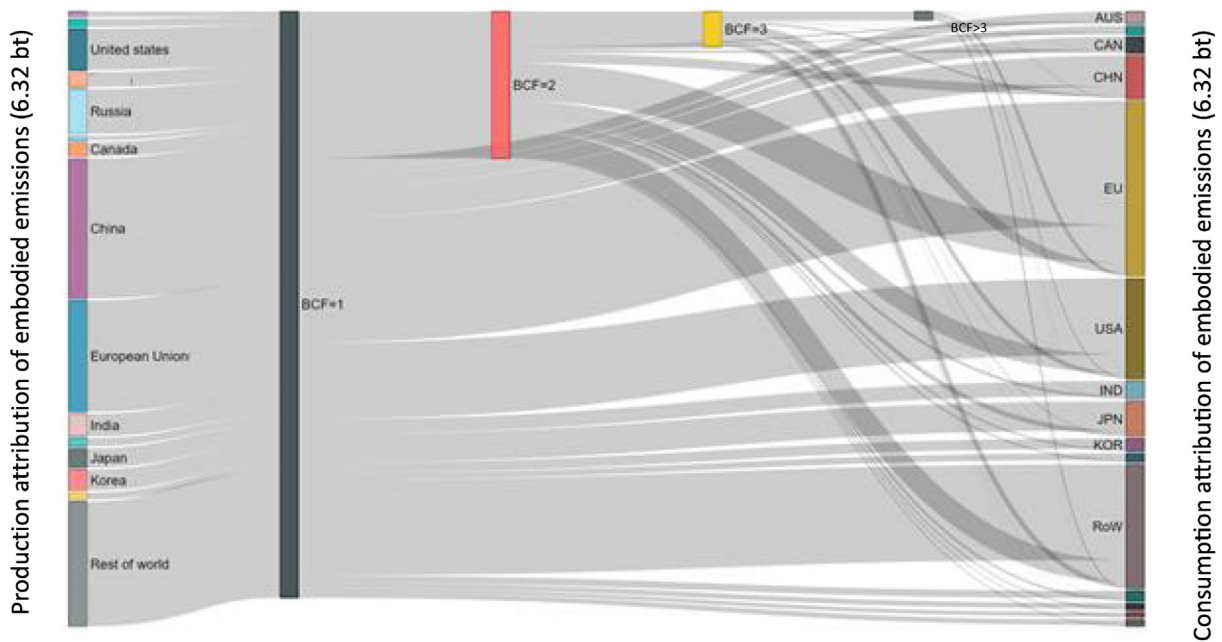
As shows in Fig. 1, China is the largest carbon emitter and faces the greatest carbon responsibility under PBA, followed by the USA and EU. However, a large share of China's emissions are generated to produce products for the final consumption of the developed countries. Therefore, CBA frameworks tend to place more carbon responsibility upon the developed countries, such as the USA, EU, and Japan. Meanwhile, CBA would lower the carbon responsibility of the developing countries, such as China, India, and Russia. The difference between PBA and CBA lies in the allocation of carbon responsibility for emissions embodied in international trade. The developing countries and countries with economies in transition, such as China, Russia, and India, tend to be net carbon exporters (the magnitude of embodied emissions in exports is greater than the magnitude of embodied emissions in imports). Therefore, carbon responsibility of the developing countries under CBA is lower than that under PBA. By comparison, developed countries, such as the USA and EU tend to be net carbon importers and face greater carbon responsibility under CBA.

The difference between PBA and IBA lies in the allocation of carbon responsibility for emissions enabled by international trade. The results show that the resource exporting countries tend to face a greater scale of emissions enabled by exports rather than that enabled by imports. For instance, Russia, Canada and Australia are important suppliers of raw materials that are exported to other countries and used as essential inputs to industrial production. Therefore, these three countries would bear greater carbon responsibility under IBA than PBA. China not only imports a large number of raw materials but also imports a large amount of intermediate products from developed countries, such as Japan and EU. Therefore, IBA would place greater carbon responsibility upon Japan and EU than that under PBA. In addition, China would face a noticed decrease in carbon responsibility when the national carbon accounting shifts from PBA to IBA. There is no marked change in the carbon responsibility of the United States under PBA and IBA.

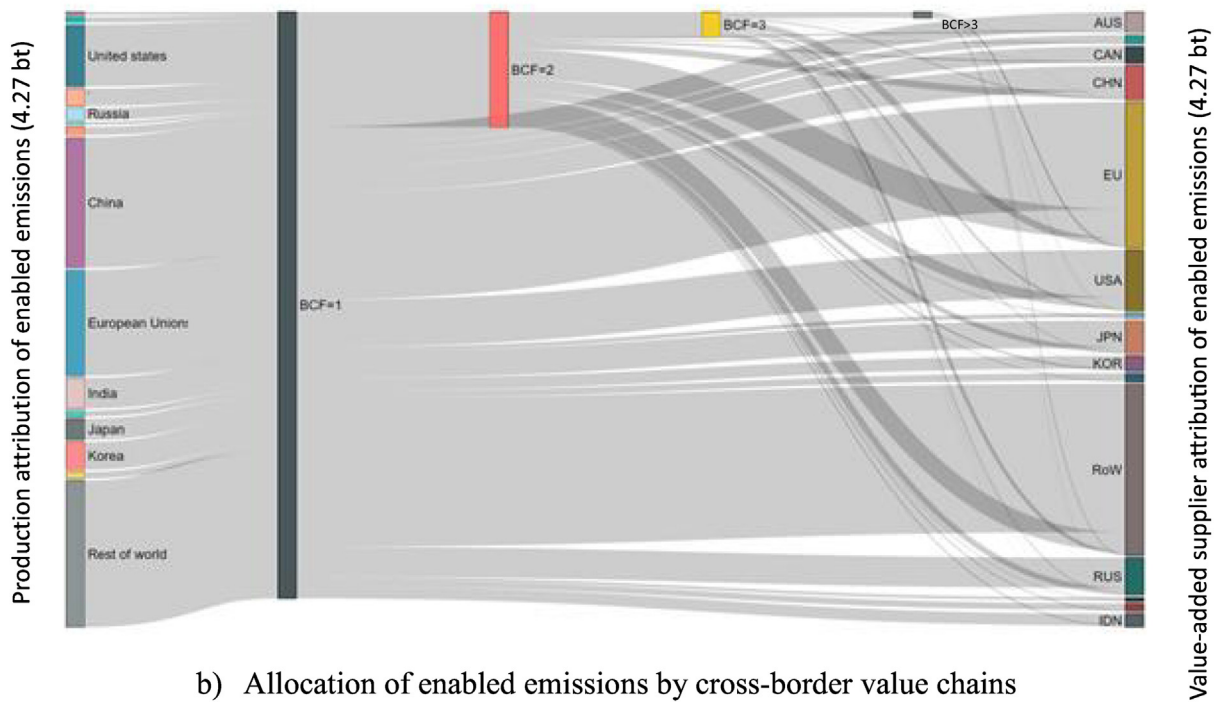
The key distinction among different carbon accounting schemes lies in the allocation of carbon responsibility on trade-related emissions. According to Eqs. (2a) and (2b), we calculate the volume of each region's trade-related emissions under different carbon accounting schemes. The results are presented in Appendix C. However, the allocation of regional carbon responsibility is not only related to the volume of trade-related emissions but is also related to border-crossing frequency associated with traded emissions. From these two perspectives, this paper further examines the allocation of embodied and enabled emissions when the regional carbon accounting scheme shifts from PBA to CBA and IBA.

3.2. Allocations of regional carbon responsibility

According to Eqs. (3a) and (3b), we deconstruct trade-related emissions by the border-crossing frequency. When the carbon accounting scheme is shifted from PBA to CBA or IBA, the regional reallocation of trade-related emissions is presented in Fig. 2.



a) Allocation of embodied emissions in cross-border trade flows



b) Allocation of enabled emissions by cross-border value chains

Fig. 2. Sankey diagram of the world embodied and enabled emissions in 2009.

a) Allocation of embodied emissions in cross-border trade flows

b) Allocation of enabled emissions by cross-border value chains

Fig. 2a presents the national attribution of embodied emissions under PBA and CBA. The left-hand side of the map shows the magnitude of national emissions induced by international trade. The right-hand side of the map presents the embodied emissions that are generated for the final consumption of each country. The gross magnitude of emissions embodied in cross-border trade flows was 6.32 billion tons in 2009. China is the largest carbon exporter (1.51 billion tons), which is mainly driven by the final demand of developed countries. The final consumption of the USA, EU, and Japan play the dominant role in driving carbon emissions embodied in international trade. Therefore, these countries would bear greater carbon responsibility under CBA than that under PBA (more detailed information is provided in Appendix D). We further classify different types of carbon transfer by the BCF associated with embodied emissions. The results show that 74.98% of interregional carbon transfer cross national borders once, 18.99% of interregional carbon transfer cross national borders twice, 4.58% of

the interregional carbon transfer cross national borders three times, and 1.45% of the interregional carbon transfer cross national borders four times or more.

Fig. 2.b presents the national attribution of enabled emissions under PBA and IBA. The left-hand side of the map shows the magnitude of national emissions enabled by cross-border value chains. The right-hand side of the map presents the magnitude of emissions enabled by a country's value-added. The gross magnitude of emissions enabled by cross-border value chains is 4.27 billion tons, which is less than the scale of embodied emissions (6.32 billion tons). Emissions embodied in exported products are not necessarily enabled by foreign value added. Therefore, the scale of embodied emissions is not equal to enabled emissions. China corresponds to the largest volume (0.95 billion tons) of carbon emissions that are enabled by value added of other regions, such as the USA and European Union. The primary inputs supplier and the carbon emitter may not be directly connected in global supply chains. The results show that 80.40% of enabled emissions are pushed by value-added that crosses national borders once, 15.33% of enabled emissions are pushed by value-added that crosses national borders twice, 3.29% of enabled emissions are pushed by value-added that crosses national border three times, and 0.98% of the enabled emissions are pushed by value-added that crosses national borders four times or more.

Fig. 2 presents the allocation of regional carbon responsibility by a simple sankey diagram. However, Fig. 2 fails to reveal the destinations of final demand that drives a country's emissions or the sources of primary inputs that enable a country's emissions. To reveal the carbon transfer between country pairs, a chord chart on bilateral carbon transfer in 2009 is presented in Appendix D. The results show that the largest carbon transfer of embodied emissions is from China to the USA. In addition, a large volume of China's emissions are enabled by the value added of other countries because China is located at the downstream of global value chains. A country's territory emissions can be further classified at a sectoral level (Appendix E). Although the scale of direct international electricity transfer is small, electricity is an important primary input to support the production of internationally traded industrial products. Therefore, the electricity generation sector corresponds to the largest scale of emissions that are embodied in other sectors' exports or enabled by other sectors' imports. The products of mining and heavy industry sectors are not only directly exported to other countries but are also widely used as intermediate inputs to support the production of traded products. Therefore, these countries also correspond to large scale of trade-related emissions. Finally, the transportation sectors provide transportation services to support the international trade. Therefore, the scales of embodied and enabled emissions of these three sectors are also great. The products of agriculture and service industries are mainly used to satisfy domestic final demand. Therefore, the scale of trade-related emissions are small for agricultural and service sectors (more detailed information is presented in Appendix E).

3.3. Average length of carbon transfer

The changing trends of average length of global carbon transfer over the period 1995–2009 are presented in Fig. 3, as well as the changing trends of average length of selected countries' and sectors' carbon transfer. These regions and sectors all correspond to top five and top ten large scale of trade-related emissions. A greater number of average length of a region or sector's carbon transfer means that it is more difficult to replace the corresponding carbon responsibility.

The results show that the ALL associated with the world's embodied emissions is greater than the ALG associated with the world's enabled emissions. This is consistent with the above finding that a smaller share of enabled emissions correspond to BCF that is greater than one. Carbon-intensive industries, such as electricity generation sector, tend to be located in the upstream of production chains. In other words, carbon emitters are closer to the raw material supplier than the final consumer. Therefore, ALL tend to be greater than the ALG . With the development of global production fragmentation, the average length of carbon transfer shows a generally increasing trend over the period 1995–2008. For instance, the world ALG associated with enabled emissions increased from 1.19 in 1995 to 1.30 in 2008 (robustness analysis of the average length of carbon transfer in 2008 are presented in Appendix G). Ignoring the impact of the financial crisis, we could conclude that spatial production fragmentation means that it becomes increasingly more challenging to shift from PBA to CBA or IBA. The world ALG associated with enabled emissions decreased to 1.25 in 2009 due to the financial crisis in 2008. The ALL associated with embodied emissions also decreased obviously in 2009. The volume of world trade of all products in 2009 decreased by 21.74% compared with the trade volume in 2008. The world trade of intermediate goods and raw materials decreased by 24.28% and 30.94%.⁶ The global financial crisis has a greater impact on the international trade of intermediate products, which may cross national borders multiple times. Therefore, the financial crisis in 2008 also had a significant negative impact on the world average border-crossing frequency associated with trade-related emissions.

Fig. 3a and b list the changing trends of average length of carbon transfer at regional level. Russia is a raw materials supplying country whose raw materials may be processed by different countries before being finally absorbed by consumers. Therefore, Russia has a great average ALL associated with embodied emissions. China is located in the downstream of global production chains and directly exports a large scale of products to meet the final demand of other countries. Therefore, the ALL associated with China's embodied emissions is small. A large scale of carbon emissions in the USA is enabled by raw materials from Mexico and Canada. The close economic linkage between these three countries determines that the USA corresponds to a smaller ALG associated its enabled emissions. Similarly, Japan's emissions are also mainly enabled by raw materials imports. Russia and China's emissions are mainly enabled by imports of intermediate inputs from the developed countries. Therefore, these two countries correspond to a large ALG associated with their enabled emissions. The ALG associated with the European Union's enabled emissions are similar to the world average. It should be noted that the average length of carbon transfer can also be illuminated from the bilateral perspective (Appendix F).

Fig. 3c and d show that there exist marked differences in average length of carbon transfer at sectoral level. Sector C12 (Basic Metals and Fabricated Metal) corresponds to the largest average ALL associated with embodied emissions. This is because metal products are widely used as intermediate inputs to support the production of traded industrial products. The production process is relatively simple for sectors C25 (Air Transport) and C11 (Other Non-Metallic Mineral). Therefore, these sectors are corresponding to smaller average ALL associated with embodied emissions. Sector C8 (Coke, Refined Petroleum and Nuclear Fuel) has the smallest average BCF associated with

⁶ Data sources: <https://wits.worldbank.org/CountryProfile/en/Country/WLD/StartYear/2006/EndYear/2017/TradeFlow/Export/Indicator/XPRT-TRD-VL/Partner/WLD/Product/all-groups>

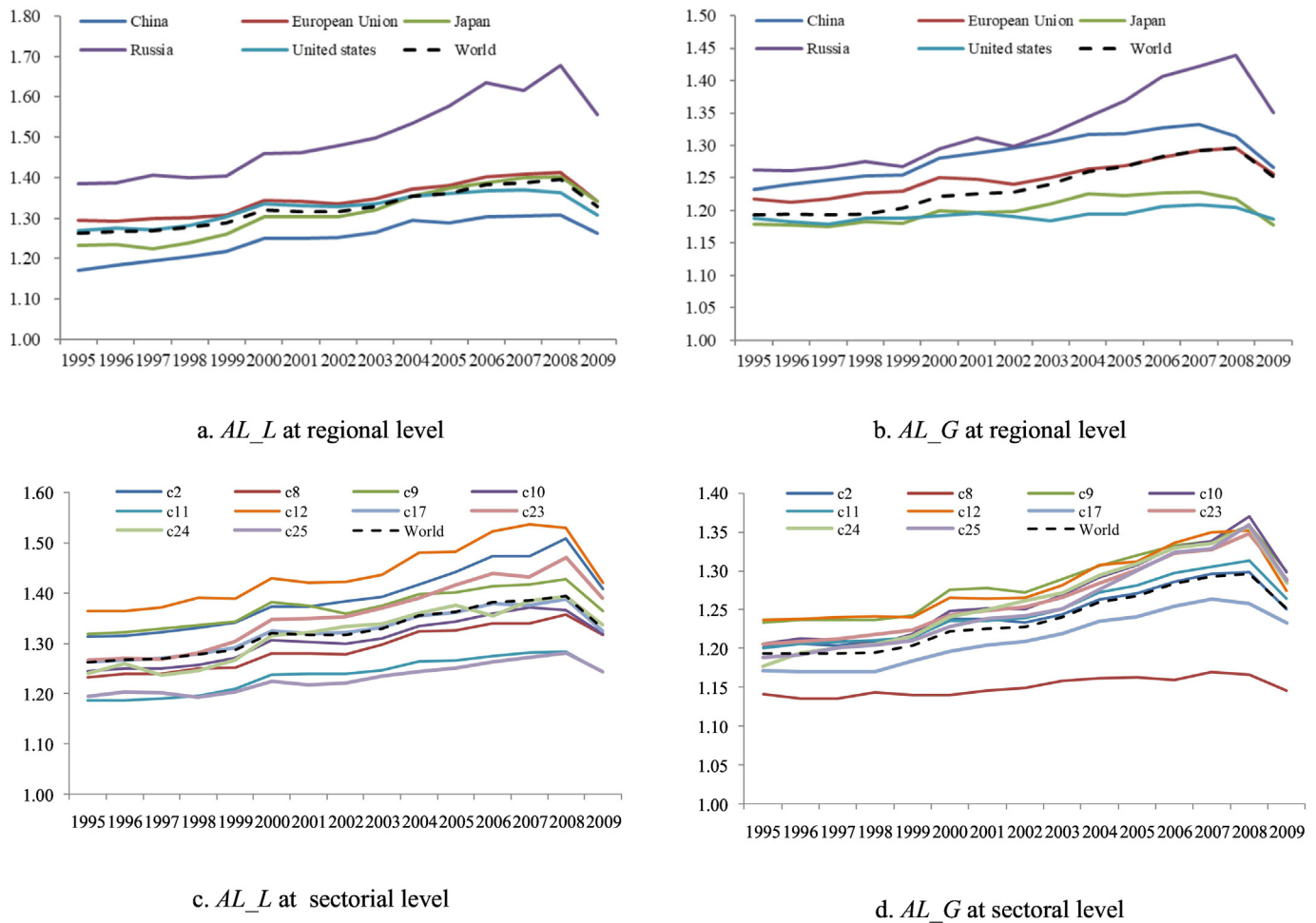


Fig. 3. Changing trend of world average length of carbon transfer.

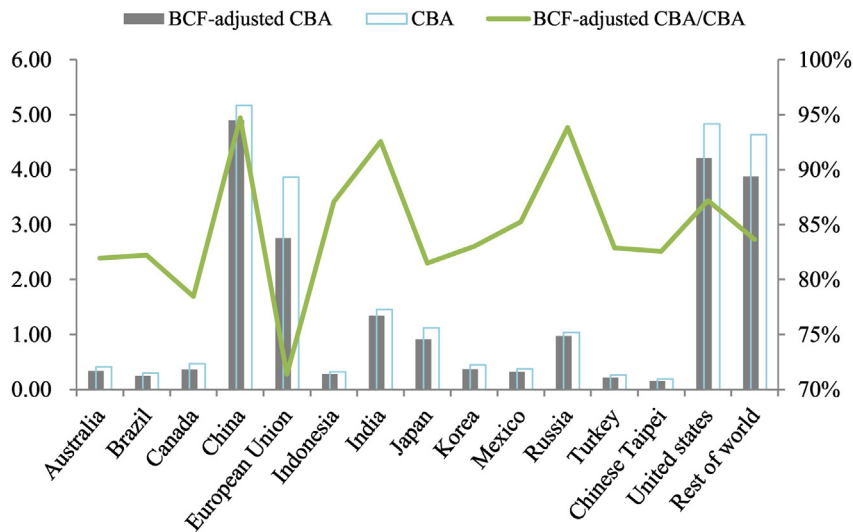
enabled emissions. This is because coal and crude oil account for a significant share in the production of sector C8. The production location of the coal and crude oil are strongly related to the regional resource endowment, and the production process is less spatial fragmented. Therefore, sector C8 corresponds to the lowest average AL_G associated with enabled emissions. Similarly, sector C17 (Electricity, Gas and Water Supply) also has lower average AL_G in Fig. 3d. The sectors with a greater average length of carbon transfer would face a greater challenge to shift from PBA to CBA or IBA. In addition, there is an increasing trend for the average length of carbon transfer for most sectors over the period 1995–2008.⁷ This phenomenon reflects that the production stages of products are fragmented among different regions. It becomes more and more challenging to shift carbon responsibility along global supply chains.

3.4. BCF-adjusted consumption- and income-based accounting

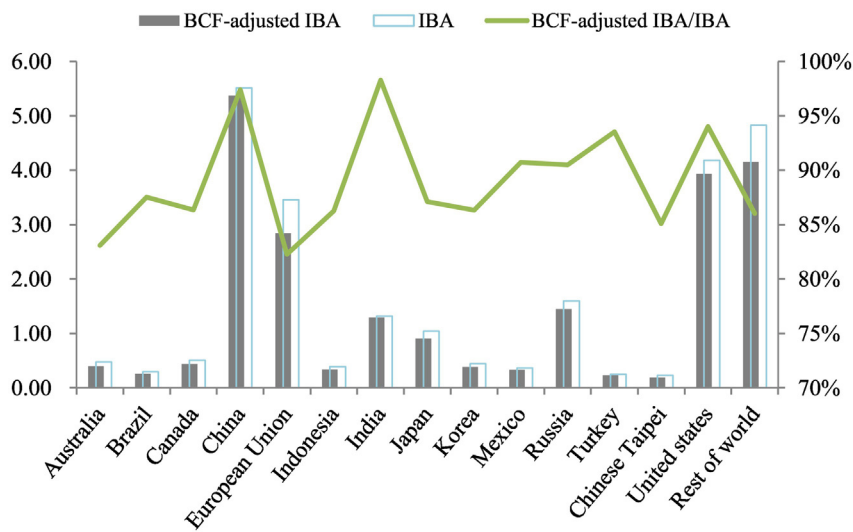
CBA and IBA focus on the influence of final demand and primary input supplier on the carbon emissions. However, the final consumer's (raw material supplier's) influential power on the carbon emitter may decrease exponentially with the BCF associated with embodied (enabled) emissions because of international differences in politics, economy, and culture across countries. In other words, spatial production fragmentation hinders the environmental effectiveness of CBA and IBA. This paper quantifies consumption-based and income-based national carbon emissions according to the influence-criterion, assuming $\alpha = 0.5$ and $\beta = 0.5$.

Under PBA, the territory emissions of a region would decrease proportionally if the region decreases the volume of output. However, the decrease of a country's final demand has a disproportionate influence on the emissions induced by this region's final demand. An explanation is the international trade substitution, which means that the carbon emitter may increase the outputs that are generated to meet other region's final demand. Similarly, the influential power of the raw material supplier on the enabled emissions would also decrease with increasing BCF associated with global value chains. This is closely related to the boundary of political power. A country only has direct control over emissions generated in its administered territory and has an indirect influence on emissions generated in other regions. Fig. 4 shows that the traditional CBA and IBA tend to overestimate the influential power of final demand and raw material supplier on the carbon emitter. Spatial production fragmentation hinders the environmental effectiveness of these two carbon accounting schemes because of inconsistency with political and environmental boundaries. This problem is extremely serious for the developed countries,

⁷ The changing trends in the average BCF associated with trade-related emissions for the sector with large scale of embodied or enabled emissions are presented in Appendix F.



a) Consumption-based regional carbon inventories



b) Income-based regional carbon inventories

Fig. 4. Consumption-based and income-based regional carbon inventories taking BCF associated with trade-related emission into account (billion tons).
 a) Consumption-based regional carbon inventories
 b) Income-based regional carbon inventories

such as the EU. CBA can be observed as another type of border adjustment (Peters, 2008). This provides support for the assertion that trade-related climate regulations should also take border-crossing frequency associated with trade-related emissions into account (Zhang et al., 2017a; Zhang and Zhu, 2017).

The largest carbon transfer through international trade is from China to the USA (Davis and Caldeira, 2010). How do the consumption-based regulations in the USA influence the carbon emissions in China? The results show that the traditional intermediate and final product trade, with a BCF of 1, corresponds to the largest share (83.34%) of carbon transfer from China to the USA. The traded products cross national borders twice. 12.81% of carbon transfer from China to the USA is through the international trade whose associated BCF is 2. Trade flows that cross national borders three or more times account for 3.85% of gross carbon transfer from China to the USA. With the increase of BCF, the influential power of the USA's consumption-based climate regulations on embodied emissions would decrease. The top 20 carbon transfer paths are presented in Table 2.

The results show that many countries are involved in the carbon transfer from China to the USA. The influential power of the USA's climate regulations would decrease with the increase with BCF of a carbon transfer path. For instance, the 3rd carbon transfer path shows that the traded products are first processed by Mexico and then exported to the USA. The traded products cross national borders twice. The USA's consumption-based climate regulations first influence the production activity of upstream enterprises in Mexico and then influence the economic activities in China. The 12th carbon transfer path corresponds to smaller volume of embodied emissions than the 11th carbon transfer path. However, the BCF associated with the 12th carbon transfer path is smaller than that of the 11th carbon transfer path. This means the USA's consumption-based climate regulations may have a greater impact on embodied emissions through the 12th carbon

Table 2
Structural path lists for carbon transfer from China to the USA.

Rank	Path description	BCF	Volume (Mt CO ₂)	Coverage of path in total	Cumulative coverage
1	CHN → USA	1	293.39	83.34%	83.34%
2	CHN → RoW → USA	2	13.86	3.94%	87.28%
3	CHN → MEX → USA	2	8.72	2.48%	89.75%
4	CHN → IND → USA	2	4.62	1.31%	91.07%
5	CHN → CAN → USA	2	4.58	1.30%	92.37%
6	CHN → KOR → USA	2	2.87	0.81%	93.18%
7	CHN → JPN → USA	2	2.29	0.65%	93.83%
8	CHN → TWN → USA	2	1.74	0.50%	94.33%
9	CHN → DEU → USA	2	1.54	0.44%	94.76%
10	CHN → RoW → IND → USA	3	0.98	0.28%	95.04%
11	CHN → RoW → CHN → USA	3	0.80	0.23%	95.27%
12	CHN → GBR → USA	2	0.79	0.23%	95.49%
13	CHN → TWN → CHN → USA	3	0.64	0.18%	95.68%
14	CHN → IDN → USA	2	0.60	0.17%	95.85%
15	CHN → KOR → CHN → USA	3	0.57	0.16%	96.01%
16	CHN → AUS → USA	2	0.55	0.16%	96.16%
17	CHN → USA → CAN → USA	3	0.53	0.15%	96.31%
18	CHN → USA → MEX → USA	3	0.48	0.14%	96.45%
19	CHN → KOR → RoW → USA	3	0.47	0.13%	96.58%
20	CHN → FRA → USA	2	0.46	0.13%	96.72%

transfer path than the 11th carbon transfer path. It should be noted that the traded products may cross national border between China and the USA twice or more before they are finally consumed. For instance, the 18th carbon transfer path means that the traded products are first exported from China to the USA and the traded products are first processed by Mexico before they are absorbed by the USA. The results show that global production fragmentation complicates the carbon transfer through international trade. A full picture of carbon transfer along global supply chains is necessary for the shifting between different accounting schemes. In the end, the proposed method could also be used to analyze carbon transfer between any two countries and the emissions enabled by different cross-border value chains paths. Due to space limitation, this paper will not individually discuss carbon transfer paths.

4. Conclusions

Regional carbon accounting is an important debate in international climate change negotiations. Consumption-based and income-based accounting schemes are often advocated as alternatives of traditional production-based accounting to reallocate carbon responsibility from a carbon emitting region to a final consuming region and raw material supplying region. However, CBA and IBA have the limitation of a wide system boundary (Peters, 2008). The development of spatial production fragmentation in recent years may further complicate the shift of national carbon accounting. This paper adopts border-crossing frequency associated with trade-related emissions to evaluate the effect of spatial production fragmentation on the shift of national carbon accounting. The main results of this study are summarized below.

First, the differences among different national carbon accounting lie in the allocation of carbon responsibility on trade-related emissions. The raw material supplying country, the carbon emitting country, and the final consuming country are not necessarily connected to one another in the cross-border supply chains. With the magnitude of embodied and enabled emissions being 6.32 billion tons and 4.27 billion tons in 2009, as much as 25.02% of embodied emissions and 19.60% of enabled emissions crossed national borders more than once in 2009. This means that the shift among different carbon accounting schemes is not only related to the magnitude of trade related emissions but also related to border-crossing frequency associated with emissions embodied in or enabled by international trade.

Second, spatial production fragmentation makes the shift of carbon responsibility increasingly challenging. It is found that there is an increasing trend of geographical separation among the primary input supplier, carbon emitter, and final consumer over the recent decades. This trend is obviously influenced by the financial crisis of 2008. The increasing trend of BCF associated with trade-related emissions means that extra steps are required for the shifting from PBA to CBA and IBA, and uncertainty inevitably increases. This may impact the implementation of CBA and IBA, although they may have some advantages over PBA. In addition, there exist obvious differences between BCF associated with trade-related emissions at the regional and sectoral levels.

Third, spatial production fragmentation reduces the effectiveness of CBA and IBA. Assuming that the final consumer's (raw material supplier's) influential power on the carbon emitter decreases exponentially with the BCF associated with embodied (enabled) emissions, we find that BCF-adjusted CBA and IBA are smaller than the traditional CBA and IBA, especially for the developed countries. This means that the traditional CBA and IBA tend to overestimate the influential power of final demand and raw material suppliers on the carbon emitter. It is suggested to increase the data quality and availability among direct and indirect trading partners. This increase in data quality and availability is extremely important for the developing countries, which are playing an increasingly important role in global supply chains. Finally, this study proposes that structural path analysis could be adopted to clarify the main carbon transfer path, with the carbon transfer from China to the USA as an example. In addition, we discuss the effect of the spatial aggregation level on the robustness of the final results.

Acknowledgements

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from two anonymous referees. That said, views expressed here are those of the authors and do not necessarily reflect the views of the grant providers. The authors bear sole responsibility for any errors and omissions that may remain.

Appendix A. The abbreviations of 41 countries or regions in the database and country group classification

Nations	Abbreviation	European Union	Nations	Abbreviation	European Union	Nations	Abbreviation	European Union
Australia	AUS		France	FRA	✓	Malta	MLT	✓
Austria	AUT	✓	United Kingdom	GBR	✓	Netherlands	NLD	✓
Belgium	BEL	✓	Greece	GRC	✓	Poland	POL	✓
Bulgaria	BGR	✓	Hungary	HUN	✓	Portugal	PRT	✓
Brazil	BRA		Indonesia	IDN		Romania	ROM	✓
Canada	CAN		India	IND		Russia	RUS	
China	CHN		Ireland	IRL	✓	Slovak Republic	SVK	✓
Cyprus	CYP	✓	Italy	ITA	✓	Slovenia	SVN	✓
Czech Republic	CZE	✓	Japan	JPN		Sweden	SWE	✓
Germany	DEU	✓	Korea	KOR		Turkey	TUR	
Denmark	DNK	✓	Lithuania	LTU	✓	Chinese Taipei	TWN	
Spain	ESP	✓	Luxembourg	LUX	✓	United states	USA	
Estonia	EST	✓	Latvia	LVA	✓	Rest of world	RoW	
Finland	FIN	✓	Mexico	MEX				

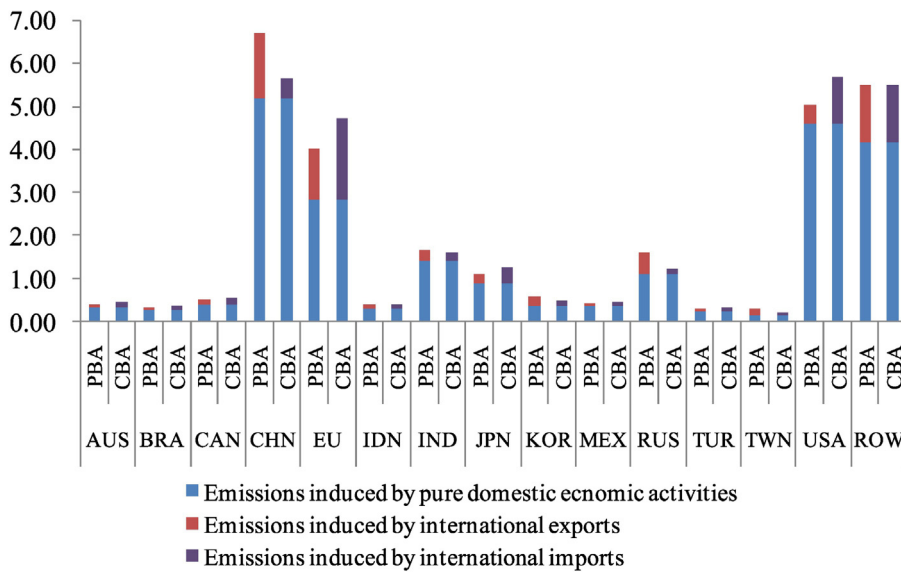
Appendix B. The 35 sectors in the inter-country input-output table

Index	Sectors
c1	Agriculture, Hunting, Forestry and Fishing
c2	Mining and Quarrying
c3	Food, Beverages and Tobacco
c4	Textiles and Textile Products
c5	Leather, Leather and Footwear
c6	Wood and Products of Wood and Cork
c7	Pulp, Paper, Paper, Printing and Publishing
c8	Coke, Refined Petroleum and Nuclear Fuel
c9	Chemicals and Chemical Products
c10	Rubber and Plastics
c11	Other Non-Metallic Mineral
c12	Basic Metals and Fabricated Metal
c13	Machinery, Nec
c14	Electrical and Optical Equipment
c15	Transport Equipment
c16	Manufacturing, Nec; Recycling
c17	Electricity, Gas and Water Supply
c18	Construction
c19	Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel
c20	Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles
c21	Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods
c22	Hotels and Restaurants
c23	Inland Transport
c24	Water Transport
c25	Air Transport
c26	Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies
c27	Post and Telecommunications
c28	Financial Intermediation
c29	Real Estate Activities
c30	Renting of M&Eq and Other Business Activities
c31	Public Admin and Defence; Compulsory Social Security
c32	Education
c33	Health and Social Work
c34	Other Community, Social and Personal Services
c35	Private Households with Employed Persons

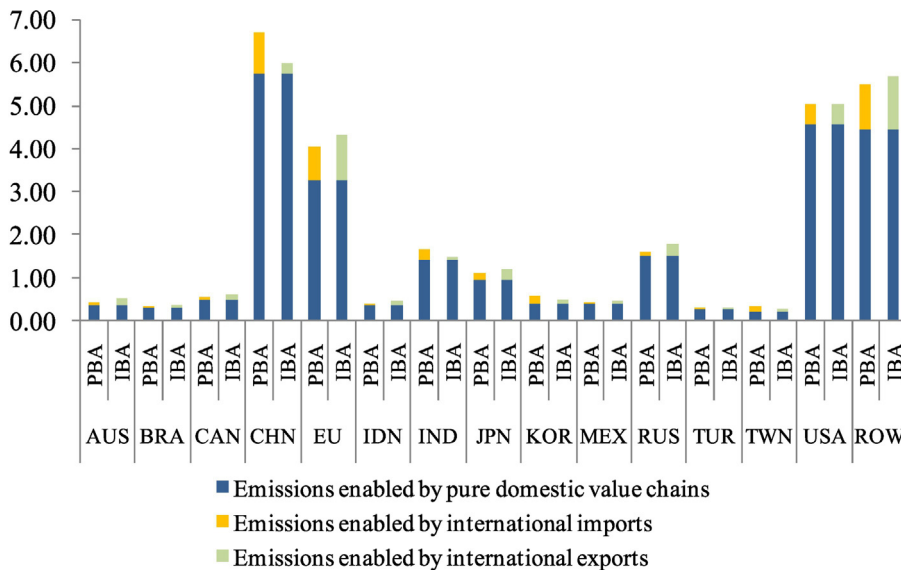
Appendix C. Decomposition of national carbon inventories under PBA, CBA and IBA

According to Eqs. (2a) and (2b), the regional carbon emissions are divided into two parts by whether the emissions are induced by or enabled by international trade. The calculation results are presented in Fig. C.1.

Fig. C.1 National emission from production-based to consumption-based and income-based accounting in 2009.



a) National emissions from production-based to consumption-based accounting



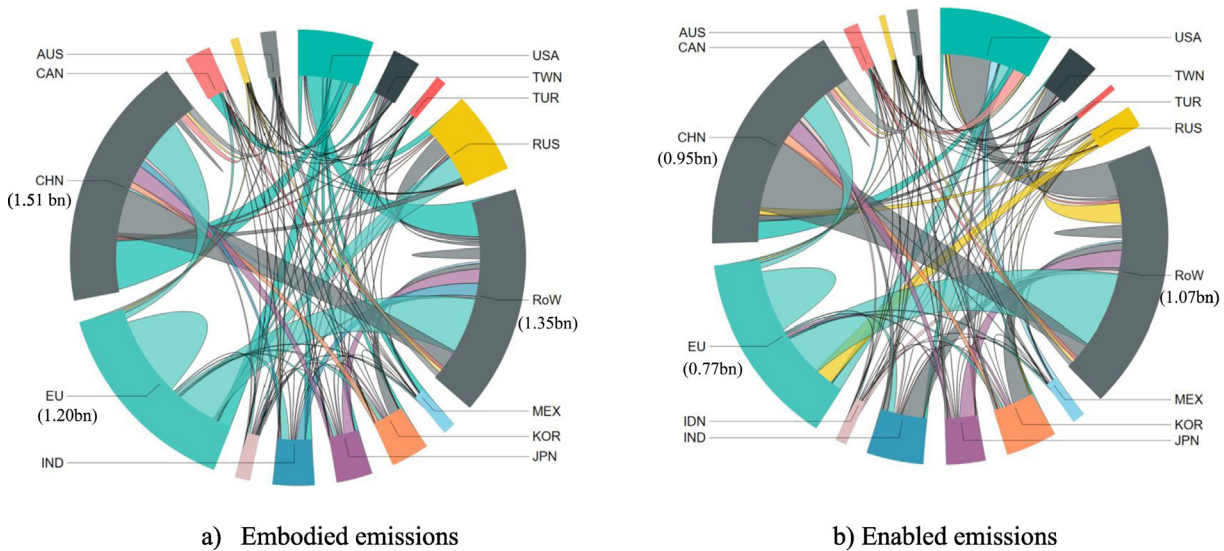
b) National emissions from production-based to income-based accounting

Fig. C.1.a divides regional emissions under production-based accounting into the part that is induced by pure domestic economic activities and the part that are induced by international exports. Only the first part is also covered by the regional emissions under CBA, which also covers emissions induced by international imports. The results show that developing countries tend to be net carbon exporters and CBA will reduce the carbon responsibility of the developing countries. By comparison, the developed countries tend to be net carbon importers, which would face greater carbon responsibility under CBA than the condition under PBA. Being in line with the literature, the net carbon transfer direction is from the developing countries to the developed countries. Fig. C.1.b shows that regional emissions that are enabled by pure domestic value chains are both covered by PBA and CBA, simultaneously. Emissions enabled by international imports and exports are covered by PBA and IBA, respectively. It should be noted that emissions that are enabled by pure domestic value chains are different from the emissions that are induced by pure domestic economic activities. For instance, the former includes emissions embodied in exported final exports, but not the latter.

Appendix D. The sources and destinations of carbon transfer

From the upstream perspective, we could find the sources of primary inputs (or value added) that enable a country's emissions. This upstream decomposition process reflects the shifting from PBA to IBA. The downstream decomposition illuminates the destination of final demand that drives a country's emissions. This process reflects the shifting from PBA to CBA. The sources and destinations of trade-related emissions are presented in Fig. D.1.

Fig. D.1 Sources and destinations of trade-related emissions.

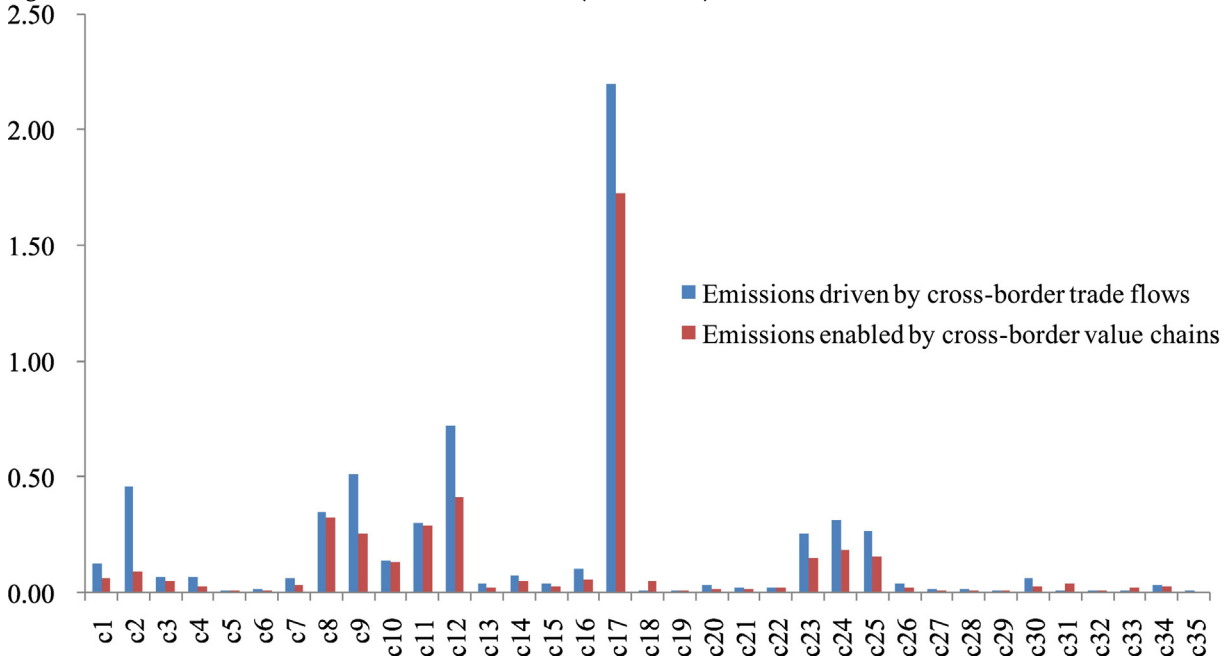


The magnitude of trade-related emissions is represented by chord charts. The area of each part of the circle represents the volume of each region's enabled (right) or embodied (left) emissions. The color of the chord indicates which country is the dominant driver of trade-related emissions. If a chord connects back to itself, it means that a country's value added drives its emissions through global supply chains (right) or that a country's final demand drives its emissions through global supply chains (left). Fig. D.1.a shows that China is the largest carbon exporter (1.51 billion tons), which are mainly driven by the final demand of developed countries. The largest net carbon transfer is from China to the USA (0.32 billion tons), followed by the carbon transfer from China to the EU (0.28 billion tons). Fig. D.1.b shows that 0.95 tons of carbon emissions in China are enabled by raw materials supplied by other countries, such as the USA and European Union. As the world factory, China mainly implements the assembling process. Research and development are usually finished in the developed countries. China is still located at the downstream of global value chains. Therefore, a large scale of China's emissions are enabled by the primary inputs of other countries. The corresponding carbon responsibility would be transferred from China to these countries when the carbon accounting scheme shift from PBA to IBA. On the contrary, Russia exports large scale of raw materials to support the production of other countries, such as China and European Union. Therefore, Russia would bear extra carbon responsibility under IBA than the condition under PBA.

Appendix E. Trade-related emissions at sectoral level

This section analyzes trade-related emissions from the sectoral perspective. It should be noted that a sector's trade-related emissions can be viewed from two angles. For instance, we could analyze a sector's emissions generated to support the production of all exports or all emissions generated to support the exports of a sector. This paper focuses on the emitting sector, rather than the exporting sector. Therefore, this section discusses a sector's both direct and indirect emissions that are related to international trade. The calculation results are presented in Fig. E.1.

Fig. E.1 Sectoral emissions related to international trade (billion tons).

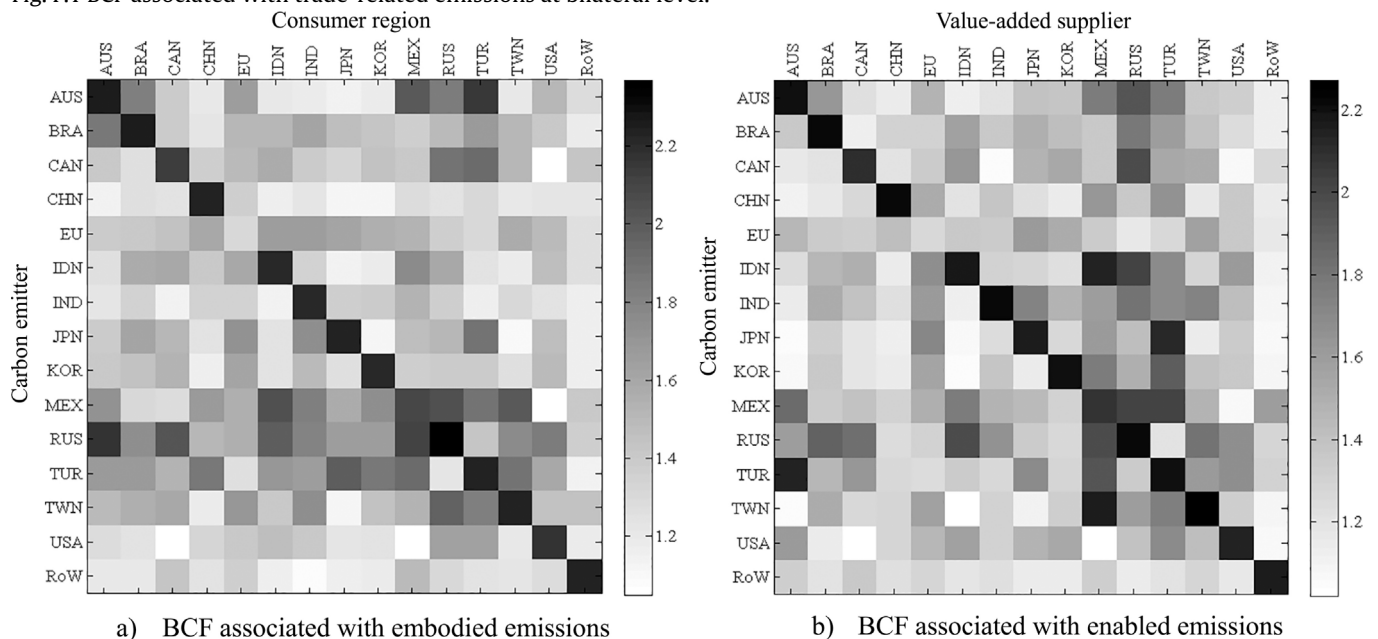


The results show that international trade mainly promotes carbon emissions of the electricity generation sector (C17). 2.20 billion tons of carbon emissions of the electricity generation sector are induced by cross-border trade flows, and 1.72 billion tons of carbon emissions of the electricity generation sector are enabled by cross-border value chains. The products of sectors c2, c8, c9, c11 and c12 are not only directly exported to other countries but also widely used as intermediate inputs to support the production of traded products. Therefore, these sectors are also corresponding to large scale of trade-related emissions. For instance, the volume of embodied and enabled emissions of the chemical sector (C9) reach 0.51 and 0.25 billion tons. The transportation sectors (c23, c24, and c25) provide transportation service to support the international trade. Therefore, the scales of embodied and enabled missions of these three sectors are also great. The products of agriculture and service industries are mainly used to satisfy domestic final demand. Therefore, the scale of trade-related emissions is small for agriculture and service sectors.

Appendix F. Trade-related emissions as bilateral level

Tracing trade-related emissions along global supply chains, we could illuminate the destination of final demand that drives a country's emissions and finds the sources of primary inputs (or value added) that enable a country's emissions. The BCF associated with trade-related emissions at the bilateral perspective are presented by heat maps in Fig. F.1.

Fig. F.1 BCF associated with trade-related emissions at bilateral level.

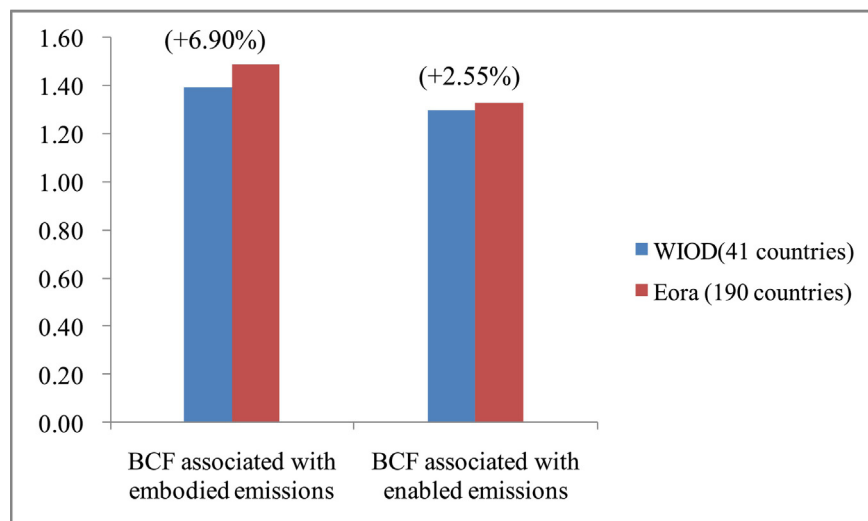


The average BCF associated with emissions embodied in bilateral trade are presented in Fig. F.1.a (left). The results show that it is practically easier for the shifting from PBA to CBA among the countries that are belong to the same trade area. For instance, the US, Canada, and Mexico are three countries that are located in North America and are closely linked through international trade. These three countries make up of the North America Free Trade Area. The BCFs associated with carbon transfer from Mexico and Canada to the USA are only 1.05 and 1.07. Similarly, the BCFs associated with carbon transfer among Asian countries or regions also tend to be small, such as embodied emissions among China, Korea, and Japan. Fig. F.1.b (right) use average BCF associated with enabled emissions to illuminate the difficulty of shifting carbon responsibility from carbon emitters to value-added suppliers. The diagonal elements are relatively greater because raw materials need to cross national borders at least twice before they return to the exporting countries. The countries that are directly linked in the global supply chain tend to have smaller BCF associated with enabled emissions. For instance, large scale of the primary inputs of Canada is directly exported to the USA and the associated BCF is only 1.03.

Appendix G. Robustness analysis of BCF associated with embodied and enabled emission in 2008

The literature shows that sectoral and spatial aggregation has obvious impacts on the measurement of trade-related emissions (Su et al., 2010; Su and Ang, 2010). The sectoral level (35 sectors) of this study is close to the sectoral level (approximately 40 sectors) suggested by Su et al. (2010). Therefore, this paper focuses primarily on the effect of spatial aggregation level on the calculation of BCF associated with trade-related emissions. An inter-country input-output table with a more detailed classification at a spatial level is more suitable for the calculation of border-crossing because the spatial aggregation will ignore the border crossing among countries that are aggregated. The Eora multi-regional input-output table (Lenzen et al., 2013) covers as much as 190 countries or regions, which is significantly greater than that (41 countries or regions) of the WIOD. Considering that international trade decreased quickly in 2009 due to the financial crisis, this paper compares the BCF associated with trade-related emissions in 2008 based on two different databases (WIOD and Eora). The calculation results are presented in Fig. G.1.

Fig. G.1 BCF associated with trade-related emissions in 2008 under WIOD and Eora.



Based on the Eora database, we not only analyze border crossing among the 40 countries or regions that are covered by the WIOD database but also the border crossing among 149 countries that are aggregated into the rest of world. Therefore, Fig. G.1 shows that the world average BCF associated with embodied and enabled emissions increases by 6.90% and 2.55%, respectively. Although the scale of countries increases by more than four times, the degree of increase in BCF is limited. This is because the 40 countries covered by WIOD play the most significant roles in international trade. For instance, these countries account for 85.80% of world's gross GDP and 80.54% of world's gross carbon emissions in 2008. If policy makers are focused mainly on border crossing among these big countries, the WIOD database may be suitable. However, policy makers should keep in mind that using this database tends to underestimate the BCF associated with trade-related emissions.

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