Applied Energy 201 (2017) 188–199

Contents lists available at ScienceDirect

Applied Energy

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

Border carbon adjustments for exports of the United States and the European Union: Taking border-crossing frequency into account

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HIGHLIGHTS

- Emissions induced by intermediate product trade accounts for a significant share.
- Multiple rebate revenue reaches 422.14 million dollars.
- Consumers of China benefit the most from border carbon adjustments for exports.
- The impact on the electrical equipment sector is more sensitive to border-crossing.
- The rebate rate should be set lower than the carbon price faced by domestic firms.

ARTICLE INFO

Article history:
Received 12 February 2017
Received in revised form 3 April 2017
Accepted 3 May 2017
Available online 22 May 2017

Keywords:
Border carbon adjustment
Carbon footprint
Border-crossing frequency
Input-output analysis

ABSTRACT

This paper proposes that not only the size and component of carbon footprints are relevant to environmental policies but the border-crossing frequency associated with carbon footprints also has important policy implications, especially given that the fragmentation of production across national boundaries has been developing quickly in recent years. Based on the World Input Output Database, this paper traces carbon transfer along cross-border supply chains and proposes both the upstream and downstream decomposition of export rebates of the United States and the European Union. The carbon transfer from the United States and the European Union to other countries or regions is mainly through international trade in intermediate products, which may cross national borders multiple times. The multiple rebate revenue reaches 422.14 million dollars, and the problem of multiple rebates is much more serious for the sectors with a greater degree of global production fragmentation, such as the electrical and optical equipment sector. In addition, export rebates are mainly targeted at the carbon emissions that are generated in the electricity generation sector and embodied in exports.

1. Introduction

To address competitiveness concerns and carbon leakage, some developed countries that adopt unilateral climate regulations are considering border carbon adjustments. For instance, the European Union emissions trading system, the American Clean Energy and Security Act of 2010 and the American Opportunity Carbon Fee Act of 2014 have drafted border carbon adjustments into legislative language [1–5]. Through careful design, border carbon adjustments can also be consistent with the World Trade Organization (WTO) rules [6]. However, this problem becomes extremely complex given that international trade has recently been significantly reshaped by global production fragmentation. For example, cross-border intermediate goods account for as much as two-thirds of the international trade. The purpose of this study is to gain a deeper understanding of border adjustments from the perspective of global production fragmentation.

The WTO rules favor border adjustments for carbon footprints of imports and exports [1]. For example, according to the World Trade Organization Agreement on Subsidies and Countervailing Measures, indirect tax rebate schemes allow for the exemption, remission or deferral of prior-stage cumulative indirect taxes levied on inputs that are consumed in the production of the exported product. However, the existing literature mainly focuses on the environmental effects of global production fragmentation from the perspective of the size and components of carbon footprints [7–15]. This present study holds the viewpoint that not only the size and component of carbon footprints are relevant to environmental policies, but also the border-crossing frequency

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http://dx.doi.org/10.1016/j.apenergy.2017.05.065
0306-2619/

associated with carbon footprints may influence the effectiveness of border carbon adjustments.

Global production fragmentation indicates that intermediate products may cross the national border multiple times and are thus repeatedly impacted by border carbon adjustments. Therefore, the spatial fragmentation of production across national boundaries may have an amplification effect on the rebate revenue. Border-crossing frequency has been gradually recognized by researchers and policy makers as an important influence factor on trade policy [16,17]. However, as far as we know, the impacts of border-crossing frequencies on the effectiveness of border carbon adjustments have not been analyzed by the existing literature. This present study attempts to fill this gap by focusing on the border adjustments of the United States and the European Union, which is also the focus of previous studies [2,18–23].

We trace regional emissions along cross-border supply chains and then discuss the effects of the border-crossing frequency on border carbon adjustments for exports of the United States and the European Union. This paper provides both upstream and downstream decomposition of export revenues and discusses whose emissions are stimulated by the export rebate and who finally benefits from the export rebates. We show that not only are the size and components of carbon footprints relevant to environmental policies but also the border-crossing frequency associated with carbon footprints has important policy implications. The remainder is organized into five sections. Section 2 reviews the relevant literature of the present paper. Section 3 describes the methodology, Section 4 presents the simulation results, and Section 5 provides the summary remarks.

2. Literature review

To mitigate global warming, a variety of countries are implementing climate regulations, such as cap and trade [24] and carbon tax [25,26]. Unilateral climate regulations may alter comparative advantages and could result in carbon leakage [27], which indicates that the carbon abatement of regions that adopt climate regulations are offset by the increase in carbon emissions of other regions. Therefore, different types of border carbon adjustments have been proposed in recent years to address carbon leakage. Even though more than 190 countries have signed the Pairs Climate Agreement, the European Commission still states that the carbon leakage provisions of the EU Emissions Trading System will continue as long as other major economies have not adopted comparable climate regulations.[1] It has realistic significance for us to discuss border carbon adjustments.

Border carbon adjustments can be divided into different types. For instance, the government could levy carbon tariffs on imports [28,29] or adopt export rebates [30] to protect the comparative advantages of domestic firms. The sum of the carbon tariffs and export rebates are called full border carbon adjustments [31,32]. In addition, border carbon adjustments can also be divided by coverage. Border adjustments may be targeted at only direct emissions or both direct and indirect emissions [21,33]. Fischer and Fox [31] provided a comparison among different border adjustments and concluded that it is difficult to rank order different types of border adjustments. The present study focuses on border carbon adjustments for exports, which is an important anti-leakage measure [34].

The existing studies mainly discuss the legality of border carbon adjustments [19,35], explore the design of border carbon adjustments [15,21,36], and evaluate the application effectiveness of border carbon adjustments [30–32,37–40]. The literature shows that different border adjustment measures face different legal hurdles and correspond to different anti-leakage effects [31]. Some studies [37,41,42] conclude that border carbon adjustments can effectively reduce carbon leakage. However, other studies find that border adjustment is not an effective approach for reducing carbon leakage [15,43–47] and report that border adjustment does not necessarily result in less leakage. The effectiveness of border adjustments depends on the design features of border adjustments and economic parameters[2] [31,32]. The inconsistent results in the literature indicate that a more in-depth analysis on border carbon adjustments is necessary. This present study attempts to enrich the literature on border adjustments by taking border crossing frequencies into account.

There is rapidly growing literature on the environmental effects of cross-border economic activity, such as emissions embodied in trade flows [48–52] and the pollution haven effect associated with foreign direct investment (FDI) flows [53–55]. Cross-border activities not only play significant roles in shaping the pattern of global emissions but may also influence the stringency and effectiveness of climate regulations. For instance, Cole and Fredriksson [56] find that cross-border FDI flows may have a positive or negative influence on the stringency of the environmental policy, and the impact is determined by the number of legislative units. Global production fragmentation makes cross-border activities more complicated, and intermediate products may cross borders multiples times. Therefore, this paper mainly focuses on the border-crossing frequencies of traded products.

Hummels et al. [17] were perhaps the first to note that intermediate product trade may incur trade costs multiple times. In addition, a growing amount of literature on the numerical estimates of cumulated trade costs have emerged [57–61]. Border adjustment is a trade measure that corresponds to extra trade costs. Bueb et al. [16] noted that border carbon adjustments may also face the problem of double regulation. However, as far as we know, the effects of border-crossing frequencies on the effectiveness of border carbon adjustments for exports have not been quantitatively evaluated by previous studies. This study attempts to fill this gap by tracing carbon emissions along border-crossing supply chains and discusses the effects of the border-crossing frequency on border carbon adjustments for exports.

This paper is also closely related to the literature that characterizes the functional and spatial fragmentation of production systems. For instance, Dietzenbacher et al. [62] proposed a method to calculate the number of production stages, which was used to indicate the relative positions in the global value chains [63–66]. Some literature focuses on spatial fragmentation and analyzes the number of transnational production stages that involve border-crossing. Wang et al. [66] calculated the number of border crossing frequency of value added. Muradov [60] proposed a method to calculate the number of border crossing of exports. This study attempts to apply the concept of border crossing frequency into the discussion on carbon footprint and provides a bridge to understand the relationship between carbon transfer and global value chains. Specifically, we focus on border crossing frequencies associated with carbon footprints.

The numerical simulation of this study is based on the input-output model [67], which can be further divided into the

[1] Sources: http://carbonmarketwatch.org/wp-content/uploads/2015/12/The-impact-of-the-Paris-agreement-on-the-EU-climate-policies_FINAL.pdf.

[2] First, the effectiveness of border carbon adjustments depends on their design features. Zhang [32] point out that the coverage of regulations, the source of emissions, the scope of adjustments, and the carbon intensity criterion would influence the effectiveness of climate regulations. Second, the effectiveness of border carbon adjustments is determined by the economic parameters. Fischer and Fox [31] conclude that the effectiveness of climate regulations is determined by the relative carbon intensities, substitution elasticities, and consumption volumes.

single-region and the multi-region model. This present study adopts the multi-regional input-output analysis, which endogenously determines trade in intermediate consumption. Methodologically, the literature calculates border crossing frequencies mainly through decomposing the intermediate input coefficient matrix [60,66]. However, the calculation of carbon footprints is directly related to the Leontief inverse matrix. Therefore, this present study proposes another method to calculate border crossing frequencies based on decomposing the Leontief inverse matrix. The proposed method also allows us to implement upstream and downstream decompositions of export revenues and discuss whose emissions are stimulated by the export rebate and who finally benefits from the export rebates.

3. Methodology

3.1. Tracing carbon emissions along cross-border supply chains

There are G countries and N sectors in each country. We split the output of country s (X_s) into intermediate goods and final goods, which satisfy the demands of different countries. The mathematical expression is presented below

$$X_s = \sum_r^G A_{sr} X_r + \sum_r^G Y_{sr} \tag{1}$$

where A_{sr} is the input-output coefficient matrix, the element of which represents the intermediate use of country r supplied by country s; Y_{sr} is the final demand vector that gives the final use of country r supplied by country s. The summary of notation is presented in the Appendix. Through rearranging, we obtain the classical Leontief equation,

$$X_s = \sum_t^G \sum_r^G B_{st} Y_{tr} \tag{2}$$

where B_{st} is the global Leontief inverse matrix, which satisfies $\begin{bmatrix} B_{11} & B_{12} & \cdots & B_{1G} \\ B_{21} & B_{22} & \cdots & B_{2G} \\ \vdots & \vdots & \ddots & \vdots \\ B_{G1} & B_{G2} & \cdots & B_{GG} \end{bmatrix} = \begin{bmatrix} I - A_{11} & -A_{12} & \cdots & -A_{1G} \\ -A_{21} & I - A_{22} & \cdots & -A_{2G} \\ \vdots & \vdots & \ddots & \vdots \\ -A_{G1} & -A_{G2} & \cdots & I - A_{GG} \end{bmatrix}^{-1}$. Eq. (2) provides the output of country s directly or indirectly induced by the final demand of country r. We define $F_s = \begin{bmatrix} f_{s,1} & 0 & \cdots & 0 \\ 0 & f_{s,2} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & f_{s,N} \end{bmatrix}$, where $f_{s,i}$ represents the carbon intensity of the sector i of country s. The emissions of country s induced by the final consumption of country r is

$$E_{sr} = \sum_t^G F_s B_{st} Y_{tr} \tag{3}$$

According to Wang et al.'s study [68], we can prove that $B_{ss} = L_{ss} + L_{ss} \sum_{r \neq s}^G A_{sr} B_{rs}$ and $B_{sr} = L_{ss} \sum_{t \neq s}^G A_{st} B_{tr}$, where $L_{ss} = (I - A_{ss})^{-1}$ represents the local Leontief inverse matrix. Inserting these two equations into Eq. (3) in an infinite process, we have

$$E = \underbrace{FL^D Y^D}_{NT} + \underbrace{FL^D Y^E}_{T\_f} + \underbrace{FL^D (Z + Z^2 + \ldots) Y}_{T\_i} \tag{4}$$

where $E = \begin{bmatrix} E_{11} & E_{12} & \cdots & E_{1G} \\ E_{21} & E_{22} & \cdots & E_{2G} \\ \vdots & \vdots & \ddots & \vdots \\ E_{G1} & E_{G2} & \cdots & E_{GG} \end{bmatrix}$ represents the carbon transfer among different countries, $F = \begin{bmatrix} F_1 & 0 & \cdots & 0 \\ 0 & F_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & F_G \end{bmatrix}$ represents the carbon intensities for different countries, $L^D = \begin{bmatrix} L_{11} & 0 & \cdots & 0 \\ 0 & L_{22} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & L_{GG} \end{bmatrix}$ represents the local Leontief inverse matrix for different countries, $Y^D = \begin{bmatrix} \widehat{Y}_{11} & 0 & \cdots & 0 \\ 0 & \widehat{Y}_{22} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \widehat{Y}_{GG} \end{bmatrix}$ represents the output to satisfy domestic final demand, $Y^E = \begin{bmatrix} 0 & \widehat{Y}_{12} & \cdots & \widehat{Y}_{1G} \\ \widehat{Y}_{21} & 0 & \cdots & \widehat{Y}_{2G} \\ \vdots & \vdots & \ddots & \vdots \\ \widehat{Y}_{G1} & \widehat{Y}_{G2} & \cdots & 0 \end{bmatrix}$ represent the output to satisfy foreign final demand ($\widehat{Y}_{sr}$denotes a diagonal matrix with the elements of Y_{sr} in its diagonal), and $Y = Y^D + Y^E = \begin{bmatrix} \widehat{Y}_{11} & \widehat{Y}_{12} & \cdots & \widehat{Y}_{1G} \\ \widehat{Y}_{21} & \widehat{Y}_{22} & \cdots & \widehat{Y}_{2G} \\ \vdots & \vdots & \ddots & \vdots \\ \widehat{Y}_{G1} & \widehat{Y}_{G2} & \cdots & \widehat{Y}_{GG} \end{bmatrix}$. $Z = \begin{bmatrix} 0 & A_{12}L_{22} & \cdots & A_{1G}L_{GG} \\ A_{21}L_{11} & 0 & \cdots & A_{2G}L_{GG} \\ \vdots & \vdots & \ddots & \vdots \\ A_{31}L_{11} & A_{32}L_{22} & \cdots & 0 \end{bmatrix}$ represents the rise in imports of intermediate products in each sector due to the unit increase in the output.

The first term of Eq. (4) represents the emissions that are induced by domestic demand through domestic economic linkage, which has no relationship with international trade. The second term represents emissions generated to support final product trade, and the traded products only cross the border one time. The third term represents emissions that are induced by intermediate product trade, and the traded products are processed in at least two countries before they are finally absorbed by a domestic or foreign country. Therefore, we further classify the carbon footprints of international trade by the number of border crossing in global value chains. The results are presented below.

$$EEX = \underbrace{FL^D(Y^E + ZY^D)}_{1} + \underbrace{FL^D(ZY^E + Z^2Y^D)}_{2} + \underbrace{FL^D(Z^2Y^E + Z^3Y^D)}_{3} + \ldots \tag{5}$$

where EEX represents the emissions embodied in exports. The first term of the right part of Eq. (5) represents the emissions embodied in goods that are imported and absorbed by another country. The traded products may be final or intermediate goods. The number of border crossing times of carbon footprints of the foreign consumption is one. The other terms represent the carbon footprints that cross border multiple times. We can use Eq. (5) to trace emissions embodied in exported products that will cross borders multiple times and emissions embodied in imported products that have crossed borders multiple times.

3.2. Border carbon adjustments for exports

We assume a group of countries U adopt the border carbon adjustment for products that are exported to the other countries V ($U \cap V = \varnothing$). The carbon rebate is targeted at domestic emissions embodied in exports $EEX = FL^D Y^E + FL^D(Z + Z^2 + \ldots)Y$. Exporters receive rebates from the government each time the products cross the border between the group of countries U and V. Similar to Section 3.1, we classify the carbon footprints by the number of border crossings between the group of countries U and V. We define

$$Z^{UV} = \begin{bmatrix} 0 & H_{12}A_{12}L_{22} & \cdots & H_{1G}A_{1G}L_{GG} \\ H_{21}A_{21}L_{11} & 0 & \cdots & H_{2G}A_{2G}L_{GG} \\ \vdots & \vdots & \ddots & \vdots \\ H_{31}A_{31}L_{11} & H_{32}A_{32}L_{22} & \cdots & 0 \end{bmatrix},$$

$$Y^{UV} = \begin{bmatrix} 0 & H_{12}\widehat{Y}_{12} & \cdots & H_{1G}\widehat{Y}_{1G} \\ H_{21}\widehat{Y}_{21} & 0 & \cdots & H_{2G}\widehat{Y}_{2G} \\ \vdots & \vdots & \ddots & \vdots \\ H_{G1}\widehat{Y}_{G1} & H_{G2}\widehat{Y}_{G2} & \cdots & 0 \end{bmatrix}$$

(H_{sr} is an $N \times N$ identity matrix if $s \in U$ and $r \in V$; otherwise, H_{sr} is a zero matrix). According to $Y^E = Y^{UV} + (Y^E - Y^{UV})$, $Y = Y^{UV} + (Y - Y^{UV})$, and $Z = Z^{UV} + (Z - Z^{UV})$, we obtain

$$EEX = \underbrace{FL^D(Y^E - Y^{UV})}_{0} + \underbrace{FL^D(M - I)(Y - Y^{UV})}_{0} + \underbrace{FL^D M(Y^{UV} + Z^{UV}M(Y - Y^{UV}))}_{1} + \underbrace{FL^D MZ^{UV}M(Y^{UV} + Z^{UV}M(Y - Y^{UV}))}_{2} + \underbrace{FL^D MZ^{UV}MZ^{UV}M(Y^{UV} + Z^{UV}M(Y - Y^{UV}))}_{3} + \ldots \quad (6)$$

where $M = I + (Z - Z^{UV}) + (Z - Z^{UV})^2 + \ldots = (I - Z + Z^{UV})^{-1}$ represents the economic activity that does not cross the borders between the two country groups U and V. The first term represents the emissions generated to support the production of the traded final products, which does not cross the borders between the two country groups U and V. The second term represents the emissions embodied in exports of intermediate products, which also does not cross the borders between the two country groups U and V. The third term represents the emissions that are induced by intermediate product trade, and the traded products cross the border between the two country groups U and V once before they are finally absorbed by a domestic or foreign country. The other terms represent the carbon footprints that cross borders multiple times between the two country groups U and V.Considering the impact of border-crossing frequencies on the border carbon adjustments, the rebate revenue is equal to the multiplication of the carbon rebate rate $\left(T = \begin{bmatrix} T_1 & 0 & \cdots & 0 \\ 0 & T_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & T_G \end{bmatrix} \right)$, the emissions of the group of countries U embodied in exports and the number of border crossing between the group of countries U and V. The mathematical expression is

$$R = \underbrace{TFL^D MY^{UV} + TFL^D MZ^{UV}M(Y - Y^{UV})}_{7.a} + \underbrace{TFL^D M[((I - Z^{UV}M)^{-1})^2 - I]Y^{UV} + TFL^D MZ^{UV}M[((I - Z^{UV}M)^{-1})^2 - I](Y - Y^{UV})}_{7.b} \quad (7)$$

where R is a $GN \times GN$ matrix, which represents the rebate revenue associated with emissions generated in a country/sector to support the final consumption. Summing up the rows of the matrix, we obtain the size of the rebate that is targeted at a country's or sector's emissions that is embodied in the exports of the group of countries U. By adding up all of the elements in each column, we could trace the rebate that is targeted at all of the emissions of the group of countries U generated in the upstream production stages to satisfy a specific country's final consumption. The policy maker is also concerned with who receives the rebate from the government. We assume H_{sr} is an $N \times N$ identity matrix if $s = t$, $t \in U$ and $r \in V$; otherwise, H_{sr} is a zero matrix. Then according to Eq. (7), we could obtain the rebate received by country t. Similarly, we could obtain the rebate received by other countries. Term (7.a) represents the rebate target emissions embodied in traded products that cross the border once between the two country groups U and V. Term (7.b) represents multiple rebates on emissions embodied in trade flow from the country groups U to V.

There exist different multi-regional input-output databases that are suitable for this study, such as the World Input-Output Database (WIOD) [69] and the Eora multi-region input-output table database [70]. This study adopts the WIOD database (release 2013), which mainly focuses on the European Union and covers 27 EU countries and 13 other major countries in the world. In addition, the WIOD provides carbon emissions of 35 sectors (please refer to Appendix C) over the period 1995–2009. The numerical study of this paper is based on the input-output table and environmental accounts in 2009.

4. Results

4.1. Carbon transfer from the European Union and the United States to other regions

Using Eq. (4), we divided the territory-based carbon emissions of 27 European Union countries and the United States into the part induced by domestic economic activities and the part that is generated to support the production of exported products. The decomposition results are presented below.

Table 1 shows that the global emissions generated in the production process reached 7348.17 million tons in 2009, and about approximately a quarter of the global emissions were induced by international trade. The United States has a greater share of emissions induced by domestic economic activities than the 27 European Union countries. As shown in Table 1, 89.43% of the direct

Table 1
Decomposition of the direct emissions of 27 European Union countries and the United States in 2009 (million tons).

	Domestic economic activity		Final product trade		Intermediate product trade		Sum
Austria	22.46	(46.90%)	6.22	(13.00%)	19.21	(40.11%)	47.90
Belgium	33.22	(36.51%)	16.38	(18.01%)	41.39	(45.49%)	90.99
Bulgaria	21.67	(52.02%)	6.49	(15.58%)	13.50	(32.40%)	41.66
Cyprus	5.52	(82.30%)	0.54	(8.09%)	0.65	(9.61%)	6.71
Czech Republic	53.26	(55.06%)	12.86	(13.30%)	30.62	(31.65%)	96.75
Germany	383.50	(60.29%)	82.93	(13.04%)	169.64	(26.67%)	636.06
Denmark	22.12	(28.29%)	14.34	(18.35%)	41.72	(53.36%)	78.17
Spain	162.89	(70.61%)	25.86	(11.21%)	41.93	(18.18%)	230.68
Estonia	7.47	(52.50%)	2.26	(15.85%)	4.51	(31.65%)	14.24
Finland	32.81	(59.49%)	5.20	(9.43%)	17.15	(31.08%)	55.16
France	175.69	(67.50%)	32.42	(12.45%)	52.19	(20.05%)	260.30
United Kingdom	283.59	(67.17%)	42.76	(10.13%)	95.83	(22.70%)	422.18
Greece	78.45	(83.67%)	4.97	(5.30%)	10.34	(11.03%)	93.76
Hungary	22.34	(53.73%)	6.09	(14.66%)	13.15	(31.62%)	41.59
Ireland	15.95	(57.88%)	4.22	(15.30%)	7.39	(26.82%)	27.56
Italy	237.92	(72.26%)	38.20	(11.60%)	53.15	(16.14%)	329.27
Lithuania	5.91	(51.28%)	1.52	(13.22%)	4.09	(35.50%)	11.52
Luxembourg	1.20	(39.41%)	0.31	(10.36%)	1.53	(50.23%)	3.04
Latvia	4.40	(61.28%)	0.70	(9.78%)	2.08	(28.94%)	7.18
Malta	1.53	(61.01%)	0.30	(11.96%)	0.68	(27.02%)	2.51
Netherlands	70.05	(42.17%)	32.91	(19.81%)	63.15	(38.02%)	166.11
Poland	187.44	(68.17%)	32.30	(11.75%)	55.21	(20.08%)	274.95
Portugal	36.03	(69.06%)	5.38	(10.32%)	10.76	(20.62%)	52.17
Romania	56.02	(72.96%)	5.93	(7.72%)	14.83	(19.32%)	76.78
Slovak Republic	14.60	(44.03%)	4.96	(14.97%)	13.59	(41.00%)	33.15
Slovenia	6.83	(52.36%)	2.03	(15.54%)	4.19	(32.10%)	13.04
Sweden	21.88	(46.24%)	5.95	(12.57%)	19.50	(41.20%)	47.33
United states	3744.65	(89.43%)	134.10	(3.20%)	308.66	(7.37%)	4187.41
World	5709.42	(74.59%)	528.15	(7.86%)	1110.60	(17.55%)	7348.17

Notes: This table does not cover the emissions generated in the final consumption process.

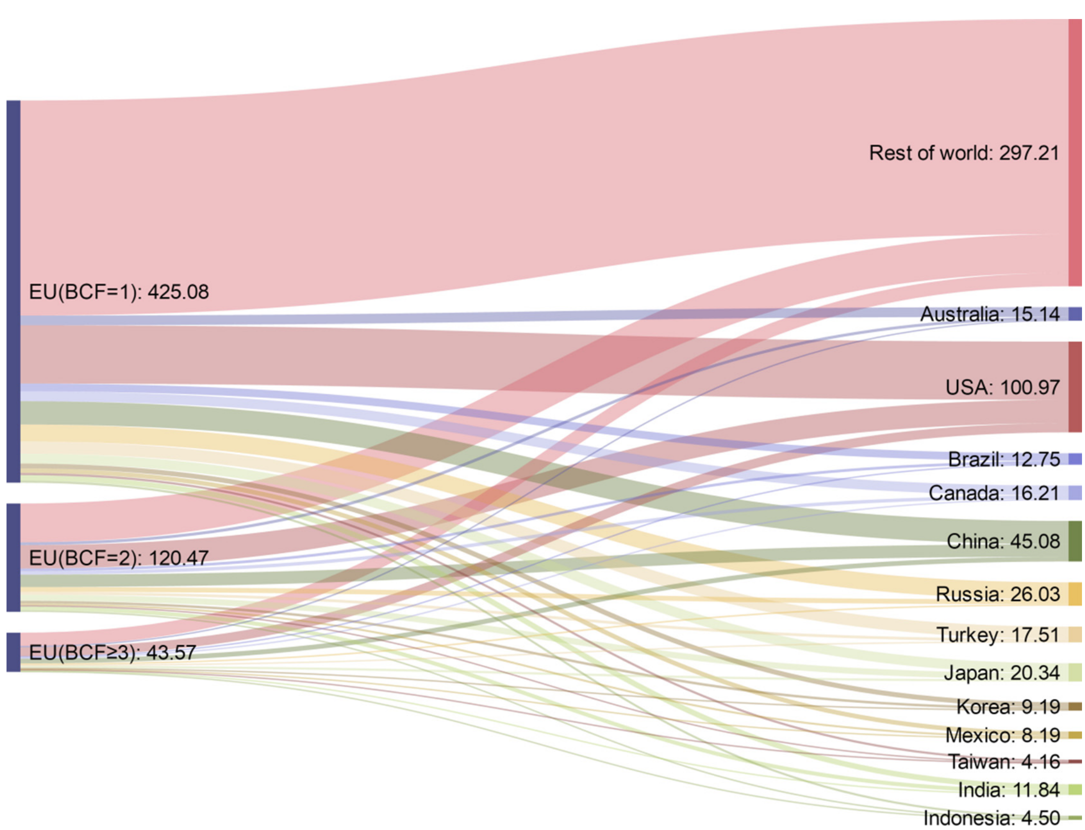

Fig. 1. Carbon transfer from the European Union and the United States to other regions in 2009 (million tons).

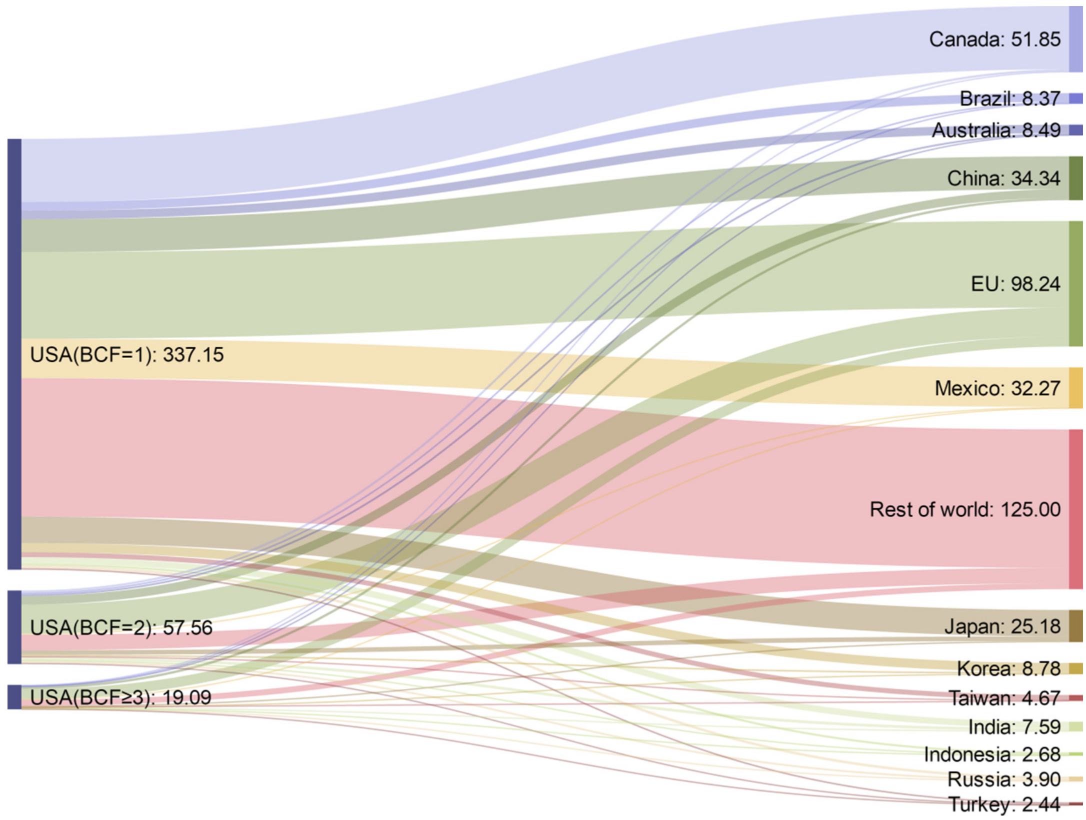

Fig. 1 (*continued*)

American emissions had no relation with international trade and were induced by pure domestic economic activities in 2009. The consumption-oriented economy structure of the United States determines that the direct emissions are mainly induced by domestic economic activity. For the 27 European Union countries, the share of emissions induced by international trade was greater than the global average level. Exports play an important role in the economy of these countries; therefore, a greater share of the emissions of these countries was generated to support the production of exported products. For instance, more than two thirds (71.71%) of the carbon emissions of Denmark were induced by exports.

Table 1 further divides international trade into final and intermediate product trade flows. The results show that the share of emissions embodied in intermediate product trade was significantly greater than that of final product trade. With the development of global production fragmentation, different production stages are distributed in different countries and the trade in intermediate products has become the leading form of international trade in recent years. The trade flow in final products travel across national borders only once. However, the intermediate products may cross national borders multiple times. This paper further traces the carbon transfer from the European Union and the United States to the other regions and takes border-crossing frequency into account. The calculation results are presented in Fig. 1.

Fig. 1 presents the carbon emissions embodied in international trade from the European Union and the United States to other countries or regions in 2009. Fig. 1a shows that 589.11 million tons of carbon emissions in the European Union were generated to support the final consumption of other countries or regions. The final consumption of the United States corresponded to the largest scale of the European Union's carbon emissions (100.97 million tons) followed by China (45.08 million tons). The United States and China are the top two largest trading partners of the European Union. The pattern of carbon transfer is consistent with that of trade flows. Fig. 1b shows that 413.78 million tons of carbon emissions in the United States were generated to support the final consumption of other countries or regions. The greatest carbon transfer is from the United States to the European Union (98.24 million tons), followed by Canada (51.85 million tons) and China (34.34 million tons). It should be noted that the exported products of the European Union and the United States may finally return to the domestic country. This type of carbon transfer is not presented in Fig. 1 because we mainly focus on carbon transfer between different regions. This present paper further provides an in-depth analysis on carbon transfer by taking border-crossing frequencies into account.

According to border-crossing frequencies, the present paper divides carbon transfers into three types. For the first type, the exported products travel across national borders once and are absorbed by consumers of the importing country. The calculation results show that the first type of carbon transfer accounts for the greatest share. For instance, 337.15 million tons of the United States' emissions were induced by the production of traded products that cross national borders only once. The traded produces may be re-exported again by the trade partner. The first type of trade in this present paper is named the traditional trade in final and intermediate products in Wang et al.'s study [66]. The border crossing frequency of the second type of carbon transfer is twice. The United States is connected with Canada and Mexico mainly through direct trade flows; therefore, shares of the second type of carbon transfer from the United States to Canada (3.18%) and Mexico (2.95%) were significantly lower than other countries or regions. The third type of carbon transfer corresponds to border-crossing frequencies of three or more times. The last two types of trade in this present paper are defined as global value chain related

Table 2
The size of carbon rebates targeted at the carbon emissions of different countries (in millions of dollars).

	Total rebates	Multiple rebates			Total rebates	Multiple rebates	
		Scale	Share			Scale	Share
United States	7264.49	185.39	2.55%	Greece (EU)	172.24	4.22	2.45%
Germany (EU)	2350.01	53.96	2.30%	Bulgaria (EU)	163.59	3.81	2.33%
United Kingdom (EU)	1445.12	31.20	2.16%	Hungary (EU)	137.85	2.54	1.84%
Italy (EU)	908.48	16.70	1.84%	Portugal (EU)	115.91	2.36	2.04%
Denmark (EU)	881.56	20.29	2.30%	Slovak Republic (EU)	112.16	2.53	2.25%
France (EU)	802.26	16.09	2.01%	Ireland (EU)	85.05	1.86	2.18%
Netherlands (EU)	721.95	14.40	1.99%	Lithuania (EU)	57.45	1.61	2.80%
Poland (EU)	616.80	12.70	2.06%	Slovenia (EU)	55.05	1.04	1.90%
Spain (EU)	560.13	11.96	2.13%	Estonia (EU)	42.83	0.88	2.06%
Belgium (EU)	394.22	8.71	2.21%	Latvia (EU)	35.40	0.84	2.37%
Sweden (EU)	317.69	8.15	2.57%	Luxembourg (EU)	14.37	0.31	2.13%
Czech Republic (EU)	251.91	5.48	2.18%	Cyprus (EU)	11.38	0.20	1.77%
Finland (EU)	218.36	5.09	2.33%	Malta (EU)	7.69	0.19	2.45%
Austria (EU)	208.96	4.82	2.31%	Sum	18145.58	422.14	2.33%
Romania (EU)	192.68	4.84	2.51%				

trade in Wang et al.'s study [66]. If the government adopts border carbon adjustments for exports, exporters may receive an extra rebate from the government because the exported products may return to the country before being re-exported again.

4.2. Border carbon adjustments for exports

Both the United States and the European Union have considered border carbon adjustments, such as the Waxman-Markey bill. To illuminate the policy implications of border-crossing frequencies associated with carbon footprints, the present paper assumes that the United States and the European Union will adopt border carbon adjustments for exports at the same rebate rate. The emissions charges (20 dollars per ton) paid by regulated firms are rebated for exports to non-regulating countries. The present paper particularly focuses on two questions: (1) whose emissions do the export rebates stimulate and (2) who finally benefits from the export rebate?

4.2.1. Whose emissions do the export rebates stimulate?

Border carbon adjustments not only protect the comparative advantage of exporters but also stimulate emissions generated to support the production of exported products. We traced emissions generated in the upstream production stages to satisfy each sector's exports along the industrial linkage and make the upstream decomposition of export rebates. The calculation results are presented below.

Table 2 presents the export rebates targeted at the emissions of the United States and 27 European Union countries. The calculation results show that the rebate revenue of the United States is greater than that of the European countries. First, the scale of carbon emissions induced by exports of the United States is greater than that of the European countries. Second, carbon adjustments do not cover the emissions embodied in international trade among European Union countries. Therefore, the border carbon adjustments have a more significant impact on the United States. From the perspective of the European Union, border carbon adjustments for exports not only promote carbon emissions of the major economies and carbon emitters, such as Germany, the United Kingdom, Italy and France, but also have an obvious impact on the carbon emissions of Denmark. A possible explanation is that nearly half of Denmark's emissions are generated in the water transport sector, the products and services of which are mainly supplied to foreign countries. The calculation results show that as much as 71.71% of Denmark's emissions are induced by exports; therefore, border carbon adjustments for exports play an important role in promoting Denmark's emissions.

Global production fragmentation indicates that intermediate products may cross national borders from regulated to unregulated countries multiple times, which would result in the problem of multiple rebates. The calculation results show that the United States faces a more serious problem of multiple rebates. The multiple rebate revenues account for 2.55% of the total rebates targeted at emissions of the United States, which is greater than the average level of the European Union (2.17%). This is not consistent with the conclusion that carbon transfer that crosses the national border multiple times accounts for a greater share of the European Union (shown in Fig. 1), because bilateral trade flows between the European Union countries are not regulated by border adjustments. The multiple rebate problem would make the international debate on border carbon adjustments more intense. The border crossing frequency associated with carbon footprints should attract enough attention from policy makers, especially given the consideration that the fragmentation of production across national boundaries has become an important feature of the world economy. This paper further discusses the influence of border carbon adjustments on sectoral emissions. The calculation results are presented in Table 3.

Table 3 presents the scale of rebates targeted at a specific sector's carbon emissions embodied in all downstream sectors' exports. The results show that sector C17 (Electricity, Gas and Water Supply) corresponds to the largest scale of export rebate revenues followed by the sector C12 (Basic Metals and Fabricated Metal) and sector C24 (Water Transport). The international transfer of electricity is not common. However, electricity is an important factor and is used to produce exported goods. In the third phase of the EU ETS (2013–2012), the electricity generation sector cannot receive free allocation anymore[3]; therefore, border carbon adjustments should be targeted at both direct and indirect emissions embodied in the exports. Metal products and water transportation are all closely related to international trade. For instance, international trade is mainly dependent on water transportation. Thus, border carbon adjustments have an obvious impact on the emissions of the basic metals and fabricated metal sector and the water transport sector.

We further discuss the problem of multiple rebates from a sectoral perspective. The results show that the multiple rebate problem mainly promotes carbon emissions of the electricity generation sector (C17), followed by sector C12 (Basic Metals and Fabricated Metal) and sector C9 (Chemicals and Chemical Products). For instance, the multiple rebates of the electricity generation sector reaches 105.36 million dollars and accounts for 2.33%

[3] Sources: http://www.epa.ie/climate/emissionstradingoverview/.

Table 3
The scale of export rebates targeted at the emissions from different sectors (in millions of dollars).

	Total rebates	Multiple rebates			Total rebates	Multiple rebates	
		Scale	Share			Scale	Share
C1	395.76	3.60	0.91%	C19	35.55	0.70	1.97%
C2	486.06	15.82	3.26%	C20	176.80	3.92	2.22%
C3	264.46	1.48	0.56%	C21	69.51	1.30	1.87%
C4	125.21	1.31	1.05%	C22	31.56	0.63	2.00%
C5	7.48	0.03	0.47%	C23	1269.36	29.91	2.36%
C6	56.75	1.13	2.00%	C24	1785.79	41.94	2.35%
C7	321.24	7.89	2.46%	C25	1627.49	31.82	1.96%
C8	1162.23	27.58	2.37%	C26	264.83	6.32	2.39%
C9	1478.34	42.17	2.85%	C27	59.74	1.32	2.21%
C10	71.46	1.72	2.41%	C28	79.38	1.70	2.14%
C11	933.33	15.72	1.68%	C29	13.69	0.28	2.03%
C12	1796.48	56.32	3.14%	C30	303.88	6.97	2.29%
C13	200.73	2.98	1.49%	C31	51.74	1.35	2.60%
C14	144.35	4.00	2.77%	C32	8.83	0.15	1.75%
C15	207.36	3.22	1.55%	C33	2.17	0.03	1.50%
C16	57.06	0.88	1.54%	C34	93.17	1.81	1.94%
C17	4525.70	105.36	2.33%	C35	0.01	0.00	0.17%
C18	38.10	0.76	2.00%	Sum	18145.58	422.14	2.33%

Table 4
The size of the carbon rebate finally absorbed by consumers of different countries (in millions of dollars).

	Total rebates	Multiple rebates	
		Scale	Share
Australia	478.17	10.07	2.11%
Brazil	428.00	10.45	2.44%
Canada	1379.17	34.22	2.48%
China	1613.34	45.84	2.84%
European Union	886.82	19.41	2.19%
Indonesia	145.50	3.42	2.35%
India	394.44	10.54	2.67%
Japan	921.70	20.96	2.27%
Korea	364.38	9.13	2.51%
Mexico	819.89	20.83	2.54%
Russia	607.39	16.35	2.69%
Turkey	403.56	8.43	2.09%
Taiwan	178.90	4.53	2.53%
United states	982.31	24.16	2.46%

of the total rebates. The border adjustments raise the production cost of the exporters. However, the multiple rebate problem indicates that the exporters would receive more rebates if the rebate rate is equal to the carbon price. This would stimulate the energy intensive sectors (such as the electricity generation sector) emit more carbon emissions to support the production of exported products. An important policy implication is that the policy makers should set the rebate rate lower than the carbon price faced by domestic firms.

4.2.2. Who benefits from the rebate?

Exported products are finally either absorbed by the consumers of other countries or returned to the domestic country again. The rebates for exports reduce the price level faced by consumers who will benefit from the border carbon adjustments. This paper makes the downstream decomposition of export rebates to present how much of the rebates for the exported products are finally absorbed by consumers of different regions. The calculation results are presented below.

Border carbon rebates reduce production costs, and the consumers of the exported products benefit from the lower price level. Table 4 presents the impact of border carbon adjustments for the exports of the United States and the European Union on consumers of different countries. The calculated results show that the consumers of China (1613.34 million dollars) benefit the most from the border carbon adjustment for exports, followed by Canada (1379.17 million dollars). China imports a significant number of products from the United States and the European Union, and Canada is a major importer of products from the United States; therefore, consumers of these two countries receive the largest amount of rebate revenues. In addition, exported products may return to the exporting country and be absorbed by domestic consumers. Thus, consumers of these two countries also significantly benefit from border carbon adjustments for exports.

The impact of the border-crossing frequency on border adjustments for exports is reflected by the problem of multiple rebates. The calculation results show that the multiple rebates account for the largest share for the rebate revenue received by the consumers of China. China has close economic links with the United States and the European Union. Frequent trade flows determine that the rebate revenue received by consumers in China is more sensitive to the border-crossing frequency associated with carbon footprints. A significant difference does not exist regarding the share of multiple rebates for different regions. This paper further discusses the rebate revenue received by the consumers of products from different sectors. The calculation results are presented in Table 5.

Table 5 provides the downstream decomposition of rebate revenues and presents the amount of rebates that are finally absorbed by the consumers of products from different sectors. The results show that the consumer benefits most from the border carbon adjustments through consuming the final products of the construction sector (C18). First, the construction sector needs a large number of intermediate inputs from the energy intensive sectors. Second, the housing expenditure accounts for a greater share of the household expenditure. The consumption of transportation and foods is also an important part of the household expenditure; therefore, sectors C15 (Transport Equipment) and C3 (Food, Beverages and Tobacco) also correspond to large carbon rebate revenues. Consumers benefit less from the border carbon adjustments through consuming services because of the lower carbon intensity of the services sector.

We further discuss the impact of border-crossing frequency associated with carbon footprints on the rebate revenues received by the consumers of different sectors. The calculation results show that consumers of products from sector C14 (Electrical and Optical Equipment), which has a greater degree of global production

Table 5
The scale of rebate revenues received by consumers of products from different sectors (in millions of dollars).

	Total rebates	Multiple rebates			Total rebates	Multiple rebates	
		Scale	Share			Scale	Share
C1	480.11	8.57	1.78%	C19	72.68	1.68	2.32%
C2	48.62	0.88	1.82%	C20	567.57	9.36	1.65%
C3	1652.17	29.40	1.78%	C21	307.69	5.14	1.67%
C4	502.80	10.53	2.10%	C22	296.08	5.29	1.79%
C5	92.59	2.47	2.67%	C23	497.79	8.84	1.78%
C6	17.45	0.32	1.82%	C24	500.43	3.87	0.77%
C7	165.05	2.98	1.80%	C25	406.49	2.81	0.69%
C8	526.29	13.45	2.56%	C26	94.68	1.68	1.77%
C9	885.98	19.83	2.24%	C27	181.96	3.65	2.01%
C10	144.82	3.94	2.72%	C28	249.91	4.96	1.99%
C11	72.21	0.57	0.79%	C29	273.51	4.24	1.55%
C12	326.49	7.07	2.17%	C30	321.30	6.45	2.01%
C13	1187.38	43.66	3.68%	C31	834.16	15.53	1.86%
C14	1067.45	46.92	4.40%	C32	323.07	5.66	1.75%
C15	1617.24	67.77	4.19%	C33	601.17	12.54	2.09%
C16	354.39	9.97	2.81%	C34	335.25	6.15	1.83%
C17	309.85	3.69	1.19%	C35	0.69	0.02	2.72%
C18	2830.25	52.27	1.85%	Sum	18145.58	422.14	2.33%

fragmentation, face the largest share of multiple rebates, followed by sector C15 (Transport Equipment). The multiple rebates of the electrical and optical equipment sector accounts for 4.40% of the gross rebate revenue. Comparisons between Tables 3 and 5 show that separating export rebates by forward and backward industrial linkages is crucial to analyze the environmental effects of border adjustments at the sectoral level. The policy makers should evaluate the effectiveness of border adjustment from both perspectives of forward and backward industrial linkages and especially focus on the sectors with a greater level of global production fragmentation.

5. Conclusions

Developed countries that adopted unilateral climate regulations are considering border carbon adjustments based on the emissions embodied in traded products. Based on the WIOD database, we first trace carbon emissions of the European Union and the United States along cross-border supply chains and then propose both upstream and downstream decomposition of rebate revenues by taking border-crossing frequency associated with carbon footprints into account. The main results of the present paper are presented below.

The carbon transfer from the United States and the European Union is mainly through international trade in intermediate products, which may cross national borders multiple times. The carbon transfer that crosses national borders more than once reaches 76.64 million tons and 164.04 million tons for the United States and the European Union respectively. The embodied emissions may be regulated by border carbon adjustments at multiple times. Therefore, the viewpoint of this paper is that the size and component of carbon footprints have important policy implications as well as the border crossing frequencies because of the fragmentation of production across national boundaries.

Multiple rebates account for 2.33% of the gross export rebate revenue of the United States and the European Union. The multiple rebate problem may make the international debate on border carbon adjustments more intense because it is merely induced by the duplicate counting of emissions embodied in exports. With the development of global production fragmentation, the effect of border-crossing frequency on border carbon adjustments would be more obvious. Therefore, the border-crossing frequency associated with carbon footprints should attract the attention of policy makers. An important policy implication is that the policy makers should set the rebate rate lower than the carbon price faced by domestic firms.

Obvious differences exist between upstream and downstream decompositions of export rebate revenues at the sectoral level. The export rebate is mainly targeted at the carbon emissions that are generated in the electricity generation sector and embodied in exports. The consumers of products from the construction sector, the electrical and optical equipment sector, and the transport equipment sector benefit the most from the border carbon adjustments. The policy implication is that the policy makers should evaluate the effectiveness of border adjustments from both perspectives of forward and backward industrial linkages and especially focus on the sectors with a greater level of global production fragmentation.

There are several potential extensions of this study that are worthy of pursuit. First, future studies could apply the method proposed by this present study to other multi-regional input-output databases. For instance, the Eora multi-region input–output table database [70] has a more detailed regional classification. Second, future studies are expected to discuss the impact of the border-crossing frequency on the effectiveness of other types of border adjustments such as carbon tariffs and full border adjustments. Third, the input-output model assumes the intermediate input linkage remains stable over time and is not suitable for dynamic analysis. It is suggested that future studies could discuss this topic by other simulation models such as the computable general equilibrium model.

Acknowledgements

The authors gratefully acknowledge the financial support from the National Science Foundation of China (Grant Nos. 71603179, 71473245), the National Social Sciences Fund (Grant No. 15AGL024), Tianjin Program of Philosophy and Social Science (TJGL16-007Q), Tianjin Science and Technology Development Strategy Key Project (Grant No. 14ZLZLZF00008), and Seed Foundation of Tianjin University (2017XSZ-0016). We also would like to thank the anonymous referees as well as the editors.

Appendix A. Description of notations used in this present paper

See Table A1.

Table A1
Description of notations used in this present paper.

Matrices	Description
X_s	N × 1 column vector of total output of country *s*
Y_{sr}	N × 1 column vector of final use of country *r* supplied by country *s*
$\hat{Y}_{sr}$	N × N matrix of final use of country *r* supplied by country *s*
Y^D	GN × GN matrix of final demand supplied by domestic country
Y^E	GN × GN matrix of final demand supplied by foreign country
Y	GN × GN matrix of final demand
A_{sr}	N × N matrix of input-output coefficient
I	Identity matrix
L_{ss}	N × N domestic Leontief inverse matrix of country *s*
B_{sr}	N × N global Leontief inverse matrix
L^D	GN × GN domestic Leontief inverse matrix
Z	GN × GN multiplier matrix
F_s	N × N matrix of carbon intensity of country *s*
F	GN × GN matrix of carbon intensity
E_{sr}	N × N matrix of emissions of country *s* induced by the final demand of country *r*
E	GN × GN matrix of carbon emissions
EEX	GN × GN matrix of carbon emissions embodied in international trade
T_s	N × N matrix of rebate rate of country *s*
T	GN × GN matrix of rebate rate
M	GN × GN matrix that represents the economic activity that does not cross the borders between the two country groups *U* and *V* .
R	$GN \times GN$ matrix of export rebate revenues

Table B1
The 40 countries in the database and country group classification.

	EU	Abbreviation		EU	Abbreviation		EU	Abbreviation
Australia		AUS	France	✓		Malta	✓	
Austria	✓		United Kingdom	✓		Netherlands	✓	
Belgium	✓		Greece	✓		Poland	✓	
Bulgaria	✓		Hungary	✓		Portugal	✓	
Brazil		BRA	Indonesia		IDN	Romania	✓	
Canada		CAN	India		IND	Russia		RUS
China		CHN	Ireland	✓		Slovak Republic	✓	
Cyprus	✓		Italy	✓		Slovenia	✓	
Czech Republic	✓		Japan		JPN	Sweden	✓	
Germany	✓		Korea		KOR	Turkey		TUR
Denmark	✓		Lithuania	✓		Taiwan		TWN
Spain	✓		Luxembourg	✓		United states		USA
Estonia	✓		Latvia	✓		Rest of world		RoW
Finland	✓		Mexico		MEX			

Table C1
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

(*continued on next page*)

Table C1 (*continued*)

Index	Sectors
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 B. The 40 countries in the database and country group classification

See Table B1.

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

See Table C1.

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