Energy Economics 65 (2017) 105–114

Contents lists available at ScienceDirect

Energy Economics

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

The effects of border-crossing frequencies associated with carbon footprints on border carbon adjustments

Zengkai Zhang [a,*], Kunfu Zhu [b], Geoffrey J.D. Hewings [c]

[a] College of Management and Economics, Tianjin University, Tianjin 300072, China
[b] University of International Business and Economics, Beijing 100029, China
[c] Regional Economics Applications Laboratory, University of Illinois at Urbana-Champaign, Urbana, 61801-3671, USA

ARTICLE INFO

Article history:
Received 11 November 2016
Received in revised form 23 February 2017
Accepted 21 April 2017
Available online 27 April 2017

JEL classification:
F12
F18
H23
Q56
Q58
R15

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

ABSTRACT

The fragmentation of production across national boundaries has become an important feature of the world economy. This present paper adopts the viewpoint that not only the size and composition of carbon footprints are relevant but also the border-crossing frequency associated with these carbon footprints, which is defined as the number of borders a product crosses in a supply chain; this process will affect the spatial accounting of the carbon emissions produced to support the economic activity. The calculation of border-crossing frequencies of carbon footprint is accomplished by decomposing the Leontief inverse matrix derived from the world input–output database. We find that the aggregated average border crossing frequencies of carbon footprints show an increasing tendency, which is influenced by the economic crisis obviously. The policy application focuses on the United States, which we assume to levy carbon tariffs on foreign emissions embodied in imports. We find that the indirect carbon tariff on emissions embodied in international trade take a significant share. The border carbon adjustments are mainly targeted at emissions generated in China, which also pays the greatest share of the tariff burden. The implication of carbon tariffs faces the problem of multiple taxation.

1. Introduction

Carbon footprint is defined as the gross carbon emissions produced to directly and indirectly support an economic activity (Hertwich and Peters, 2009). In the last three decades, production systems have become increasingly fragmented both spatially and functionally; this paper focuses on the impacts of spatial fragmentation (the location of different stages of the production chain in different countries).[1] The number of borders crossed by a production chain will affect the carbon emissions embodied in the final product; each border-crossing will then accumulate embodied emissions and the carbon footprint accounting needs to allocate these appropriately. The paper explores the changing trends of border-crossing frequencies of carbon footprints over the period 1995–2009 and considers the policy implication of border-crossing frequencies. This is the primary research focus of the present study. Specifically, the practical application of this present paper studies the impacts of spatial fragmentation on border carbon adjustments, which are usually proposed by developed countries to address comparative concerns and carbon leakage.

Border carbon adjustments may be targeted at importers (e.g., carbon tariffs on imports) or exporters (e.g., rebates to exporters). In this present paper, border carbon adjustments refer in particular to levying carbon tariffs on foreign emissions directly and indirectly generated to support the production of imported products. Policy makers are interested in the following questions: whose emissions are regulated and how much tariffs are targeted at their emissions? Who pay carbon tariffs and how much do they pay? All these questions are closely related to the concept of border crossing frequencies because the country that adopts border carbon adjustments could levy carbon tariffs on foreign emissions embodied in imported products each time the traded products cross the national boundary of this country. For instance, greater border crossing frequencies may result in a greater proportion of indirect tariffs and serious multiple taxation problems (see Schenker et al., 2012).

The significance of this present study is that we highlight the spatial fragmentation of production across national boundaries may have important implications for climate policies. This is, as far as we know, the first study that discusses carbon footprints from the perspective of

* Corresponding author.
E-mail address: zengkaizhang@tju.edu.cn (Z. Zhang).

[1] Functional specialization is defined and addressed in Romero et al. (2009).

http://dx.doi.org/10.1016/j.eneco.2017.04.017

border-crossing frequencies. The policy makers of border carbon adjustments should consider not only the size and composition of carbon footprints, but also the border crossing frequencies of carbon footprints, especially under the condition more than one county are adopting the border carbon adjustments. The paper is organized into five sections. Section 2 reviews the relevant literature and summarizes the contributions of the present paper. Section 3 describes the methodology, while Section 4 presents the simulation results. Section 5 focuses on the multiple taxation problem, and Section 6 provides some summary remarks.

2. Literature review

A considerable body of literature has emerged that explores carbon footprints of different economic activities, such as household consumption (e.g., Weber and Matthews, 2008; Druckman and Jackson, 2009), production activity (e.g., Messagie et al., 2014; Ji and Chen, 2016), and international trade (e.g., Lin and Sun, 2010; Xu and Dietzenbacher, 2014). With the development of global production fragmentation, there exists a growing literature that traces carbon emissions along global value chains (e.g., Dietzenbacher et al., 2012; Su et al., 2013; Liu et al., 2015; Meng et al., 2015). To identity the carbon reduction responsibility, the existing literature mainly focuses on the size or composition of carbon footprints. This present paper extends the literature by adopting the viewpoint that not only the size and composition of carbon footprints is relevant but also the border crossing frequencies associated with these carbon footprints. The analytical tool of this present study is the multi-country input–output analysis framework, which has been widely adopted in the literature (e.g., Brizga et al., 2017; Weber and Matthews, 2008; Zhang et al., 2014; Zhang and Tang, 2015).

This present paper is also closely related to the literature that characterize the global production network through measuring the number of production stages (e.g., Dietzenbacher et al., 2005; Dietzenbacher and Romero, 2007; Chen, 2014; Fally, 2012; Antràs et al., 2012; Antràs and Chor, 2013; Wang et al., 2014). Rather than counting each production stage, this present paper focuses especially on the number of transnational production stages that involves border-crossing.[2] Wang et al. (2014) introduced a method to calculate border-crossing frequencies of value added by decomposing the direct requirement matrix. Muradov (2016) proposed a measure of the weighted average number of border crossings in global value chain; the proposed measure also focuses on the direct requirement matrix. However, the inputoutput analysis framework of carbon footprints usually multiplies carbon coefficient by the total requirement matrix (Leontief inverse matrix) to obtain the carbon footprints. Thus, this present paper attempts to propose an alternative method of calculating border-crossing frequencies by decomposing the Leontief inverse matrix.

Böhringer et al. (2012) note that the existing literature on carbon tariffs vary with respect to the coverage of regulated emissions, such as only direct emissions (Böhringer et al., 2012; Monjon and Quirion, 2011), direct emissions plus indirect emissions from electricity use (Winchester, 2012; Tang et al., 2015), and full carbon footprints (Schenker et al., 2012; McAusland and Najjar, 2015; Böhringer et al., 2011). The policy application of this present paper discusses carbon tariffs levied on foreign emissions generated to support the production of imported products in order to avoid double regulation of emissions from the country that adopts unilateral climate regulations (Böhringer et al., 2012). To provide a comprehensive analysis of the effects of border-crossing frequencies associated with carbon footprints on carbon tariffs, this present paper makes both forward and backward international-linkage-based decompositions on the carbon tariffs, which are divided into direct, indirect, and multiple tariffs according to the border-crossing frequencies. The contributions of this present study are summarized below.

1) This present paper extends the literature on carbon footprints by focusing on border crossing frequencies of carbon footprints. With the fragmentation of production across national boundaries being an increasingly important feature of the world economy, the viewpoint adopted is that not only the size and composition of carbon footprints is relevant but also the border-crossing frequencies of carbon footprints, defined as the number of borders a product crosses in a supply chain. 2) The paper also enriches the literature by proposing another calculation approach of border-crossing frequencies based on a decomposition of the Leontief inverse matrix derived from a multi-country input–output model. The proposed approach is applied to the World Input–Output Database (WIOD, Timmer et al., 2015). The results show that, over the period 1995–2009, the aggregated average border-crossing frequencies of carbon footprints increase. 3) This present study increases the understanding of border carbon adjustments by considering the border crossing frequencies of carbon footprints. The results show that the indirect carbon tariff on emissions embodied in international trade take a significant share. The problem of multiple taxation could become increasingly serious as the number of countries that adopt carbon tariff increases. The carbon tariff of the United States is mainly targeted at emissions generated in China, which also pays the greatest share of the tariff burden.

3. Methodology

3.1. Border-crossing frequencies associated with carbon footprints

Assume a world with G countries, with each country producing tradable products in N differentiated sectors. Products are used to satisfy intermediate or final demand of both domestic and foreign countries. The input–output analysis clarifies the flow of products as follows:

$$X_s = \sum_{r}^{G} A_{sr} X_r + \sum_{r}^{G} Y_{sr}\,(s, r = 1, 2, \ldots, G) \tag{1}$$

where A_{sr} is the $N \times N$ input–output coefficient matrix that reveals the intermediate use of country r supplied by country s. X_s is the $N \times 1$ gross output vector of country s, Y_{sr} is the $N \times 1$ final demand vector that gives final use of country r supplied by country s. Rearranging,

$$X_s = \sum_{r}^{G} \sum_{t}^{G} B_{st} Y_{tr} (t = 1, 2, \ldots, G) \tag{2}$$

where B_{st} is the $N \times N$ global Leontief inverse matrix that provides the gross output of country s required for a one-unit increase in the final production of country t. The relationship between the input–output coefficient matrix and the Leontief inverse matrix satisfies

$$B = \begin{bmatrix} B_{11} & B_{12} & \cdots & B_{1G} \\ B_{21} & B_{22} & \cdots & B_{2G} \\ \vdots & \vdots & \ddots & \vdots \\ B_{G1} & B_{G2} & \cdots & B_{GG} \end{bmatrix} = \begin{bmatrix} I - A_{11} & -A_{12} & \cdots & -A_{1G} \\ -A_{21} & I - A_{22} & \cdots & -A_{2G} \\ \vdots & \vdots & \ddots & \vdots \\ -A_{G1} & -A_{G2} & \cdots & I - A_{GG} \end{bmatrix}^{-1},$$

where I demotes a $N \times N$ identity matrix. The carbon intensity of the sector i of country s is defined as $f_{s,i} = e_{s,i}/x_{s,i}$, where $e_{s,i}$ represents the carbon emissions of the sector i of country s, $x_{s,i}$ represents the output of the sector i of country s. F_s is a $N \times N$diagonal matrix with a typical

[2] The difference between border crossing frequencies of this study and the related concepts are summarized below. 1) The average production lengths (APL) (Dietzenbacher et al., 2005) and the upstreamness (Antràs et al., 2012) measure the economic distance between two sectors. The border crossing frequencies measure the economic distance between two regions. 2) The traditional measure of APL or upstreamness is based on the value added accounting framework, while this study adopts the gross exports accounting framework (Muradov, 2015).

element $f_{s,i}$. The emissions of country s induced by final demand of different countries are

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

where $E_{sr} = F_s B_{st} Y_{tr}$ represents the emissions of country s induced by the final demand of country r. Emissions of country s may be induced by the final products exported to country r or by exports of intermediate products that are finally absorbed by country r. The final products cross national border once. However, the intermediate products may cross national border multiple times. Therefore, Eq. (3) if further decomposed to obtain more detailed information on different types of carbon footprints. According to Wang et al.'s study (2015), proof can be shown 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 $L_{ss} = (I - A_{ss})^{-1}$ is the domestic Leontief inverse matrix of country s. Inserting these two equations into Eq. (3) in an infinite process:[3]

$$E = FL^D Y^D + FL^D T \tag{4}$$

where $E = \begin{bmatrix} E_{11} & E_{12} & \cdots & E_{1G} \\ E_{21} & E_{22} & \cdots & E_{2G} \\ \vdots & \vdots & \ddots & \vdots \\ E_{G1} & E_{G2} & \cdots & E_{GG} \end{bmatrix}$, $F = \begin{bmatrix} F_1 & 0 & \cdots & 0 \\ 0 & F_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & F_G \end{bmatrix}$, $L^D = \begin{bmatrix} L_{11} & 0 & \cdots & 0 \\ 0 & L_{22} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & L_{GG} \end{bmatrix}$, $Y^D = \begin{bmatrix} Y_{11} & 0 & \cdots & 0 \\ 0 & Y_{22} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & Y_{GG} \end{bmatrix}$,

$T = Y^E + (Z + Z^2 + \ldots)Y$, $Y^E = \begin{bmatrix} 0 & Y_{12} & \cdots & Y_{1G} \\ Y_{21} & 0 & \cdots & Y_{2G} \\ \vdots & \vdots & \ddots & \vdots \\ Y_{G1} & Y_{G2} & \cdots & 0 \end{bmatrix}$, $Y = Y^D + Y^E = \begin{bmatrix} Y_{11} & Y_{12} & \cdots & Y_{1G} \\ Y_{21} & Y_{22} & \cdots & Y_{2G} \\ \vdots & \vdots & \ddots & \vdots \\ Y_{G1} & Y_{G2} & \cdots & Y_{GG} \end{bmatrix}$, $Z = \begin{bmatrix} 0 & A_{12}L_{22} & \cdots & A_{1G}L_{GG} \\ A_{21}L_{11} & 0 & \cdots & A_{2G}L_{GG} \\ \vdots & \vdots & \ddots & \vdots \\ A_{31}L_{11} & A_{32}L_{22} & \cdots & 0 \end{bmatrix}$. The first term ($FL^DY^D$) represents the emissions that are induced by domestic demand through domestic economic linkages, with no relation with international trade. The second term (FL^DT) represents emissions generated to support international trade (represented by T). The traded final products (represented by Y^E) only cross the border once. The trade intermediate products (represented by $(Z + Z^2 + \ldots)Y$) are processed in at least two countries before they are finally absorbed by the domestic or a foreign country, and the process may cross national borders multiple times. For instance, FL^DZY^D represents the carbon footprints that cross borders once, FL^DZY^E and $FL^DZ^2Y^D$ represents the carbon footprints that cross borders twice. Then the aggregated average border-crossing frequencies of carbon footprints related to international trade can be represented as follows:

$$BCF = \frac{FL^D\left(1Z + 2Z^2 + \ldots\right)Y^D + FL^D\left(I + 2Z + 3Z^2 + \ldots\right)Y^E}{FL^DT}. \tag{5}$$

The division symbol in this present paper denotes elements-wide divisions. From Eq. (5), the border-crossing frequencies can be obtained for different types of carbon footprints. Adding up all elements in the matrix, it is possible to obtain the aggregated average global border-crossing frequencies of carbon footprints. Summing up the row of matrix, an emitter's total emissions can be traced along the forward industrial linkage until the associated outputs are finally absorbed. For each column, all the emissions generated in the upstream production stages to satisfy a specific country's final demand along the global value chains can be obtained. In other words, it is possible to obtain national border-crossing frequencies of carbon footprints under both a forward and backward perspective. In addition, similar frequencies can be calculated for each sector.

While Eq. (5) is intuitive, it cannot be used to calculate the border-crossing frequencies of carbon footprints directly because there is infinite number of terms. According to the characteristic of inverse matrix, we obtain $I + Z + Z^2 + \ldots = (I - Z)^{-1}$, $I + 2Z + 3Z^2 + \ldots = ((I - Z)^{-1})^2$, and $B = L^D(I - Z)^{-1}$. Then the closed-form solution of aggregated average border-crossing frequencies of carbon footprints is:

$$BCF = \frac{FBT}{FL^DT}. \tag{6}$$

3.2. Border carbon adjustments

This section discusses the policy applications of border crossing frequencies of carbon footprints to border carbon adjustments. Assume that a group of countries V ($V \subset (1, 2, \ldots, G)$) levy carbon tariffs on other countries' U ($U \subset (1, 2, \ldots, G)$)carbon emissions that are generated to support the production of imported products. Based on border-crossing frequencies of carbon footprints, the carbon tariff is decomposed into direct, indirect, and multiple tariffs from both forward and backward perspectives. The forward international-based decomposition focuses on whose emissions are regulated and how much tariffs are targeted on their emissions? The backward international-based decomposition answers the question about who pays carbon tariffs and how much they pay.

3.2.1. Forward international-based decomposition

From the perspective of forward international linkages, it is possible to trace the emitter's exports along the global production networks and obtain the scale of carbon tariffs targeted on each country's carbon emissions. This present study assumes the carbon tariff is exogenous, and thus has no impact on structure of the input–output coefficient matrix. The carbon tariffs levied on carbon emissions of a certain country t is equal to the multiplication of carbon tariff rate, the scale of carbon emissions of country t embodied in imports of countries V, and the frequencies of crossing the borders of the group of countries V through imports. The mathematical expression is presented as follows:

$$CT_{t\_}f = R^{tV}FL^D\left(I - MZ^{UV}\right)^{-1}T^{UV} \tag{7}$$

where $R^{tV} = \begin{bmatrix} k_{11}R & \cdots & 0 & \cdots & 0 \\ 0 & \cdots & k_{22}R & \cdots & 0 \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & \cdots & k_{GG}R \end{bmatrix}$ ($k_{ss} = 1$ if $s = t$; otherwise, $k_{ss} = 0$) and R is a $N \times N$ diagonal matrix made up of the rate of carbon tariff rate, $Z^{UV} = \begin{bmatrix} 0 & h_{12}A_{12}L_{22} & \cdots & h_{1G}A_{1G}L_{GG} \\ h_{21}A_{21}L_{11} & 0 & \cdots & h_{2G}A_{2G}L_{GG} \\ \vdots & \vdots & \ddots & \vdots \\ h_{31}A_{31}L_{11} & h_{32}A_{32}L_{22} & \cdots & 0 \end{bmatrix}$ ($h_{sr} = 1$ if $s \in U$ and $r \in V$, otherwise, $h_{sr} = 0$), and $M = (I - Z + Z^{UV})^{-1}$, T^{UV} represents the exports from the group of country U to the group of country V. Please refer the Appendix A for the mathematical proof of Eq. (7).

Using a forward international-linkage-based decomposition, the gross carbon tariffs targeted at each country are divided into direct, indirect and multiple carbon tariffs, according to the border-crossing frequencies of carbon footprints. The direct carbon tariff (DCT_f) is targeted at emissions generated in the exporting country to support the production of products that are directly exported to the group of countries V, and the traded production only cross the border from the group of country U to the group of country V once. The mathematical expression of direct emissions is $T^{tV}FL^DY^{UV} + T^{tV}FL^DZ^{UV}(I + (Z - Z^{UV}) + (Z - Z^{UV})^2 + \ldots)(Y - Y^{UV})$. According to the characteristic of inverse matrix, the closed form expressions of

[3] Su and Ang (2011) propose the stepwise distribution of emissions embodied in trade (SWD-EET) method to trace the infinite distribution of embodied emissions in trade. Equation (4) is aligning with the Equation (18) in Su and Ang's (2011) study .

direct carbon tariffs can be obtained from the forward international linkage.

$$DCT_t\_f = R^{tV} FL^D D\_T^{UV} \tag{8}$$

where D_T^{UV} represents the products of country U that are exported to the group of country V directly and only cross the border from the group of country U to the group of country V once. The indirect carbon tariff (ICT_f) is targeted at emissions generated to support the production of imports of the group of country U, and the imported products would be processed and exported to the group of country V. The traded products cross the border from the group of country U to the group of country V once. The mathematical expression of the indirect carbon tariff is

$$ICT_t\_f = R^{tV} FL^D I\_T^{UV} \tag{9}$$

where I_T^{UV} represents the intermediate products of other countries that are first exported to the group of country U and then exported to the group of country V. The traded products only cross the border from the group of country U to the group of country V once. Since intermediate goods trade between the group of countries U and Voften results in movement in both directions, border carbon adjustments may levy carbon tariffs on carbon emissions embodied in intermediate products multiple times, generating what may be termed multiple carbon tariffs (MCT_f) in this present paper. The mathematical expression is

$$MCT_t\_f = R^{tV} FL^D M\_T^{UV} \tag{10}$$

where M_T^{UV} represents the accumulation of the traded products that cross the border from the group of country U to the group of country V multiple times. The first two parts ($DCT_f$and ICT_f) are determined by the tariff rate and the size of carbon footprints; however, the last one (MCT_f) is also determined by the border-crossing frequencies of carbon footprints. The carbon tariff revenue will be underestimated if we ignore the impact of border-crossing frequencies.

3.2.2. Backward international-based decomposition

From the perspective of backward international linkage, it is possible to trace all the emissions generated in the upstream production stages to support the production of a country's exports to a country such as the United States. The carbon tariffs paid by a country t is equal to the multiplication of the carbon tariff rate, the scale of emissions embodied in exports of country t to the group of countries V, and the frequency of crossing the borders of the group of countries V through imports from country t.

$$CT_t\_b = R^{UV} FL^D \left(I - NZ^{tV}\right)^{-1} T^{tV} \tag{11}$$

where R^{UV} is a $NG \times NG$ diagonal matrix made up of the rate of carbon tariff rate, $Z^{tV} = \begin{bmatrix} 0 & h_{12}A_{12}L_{22} & \cdots & h_{1G}A_{1G}L_{GG} \\ h_{21}A_{21}L_{11} & 0 & \cdots & h_{2G}A_{2G}L_{GG} \\ \vdots & \vdots & \ddots & \vdots \\ h_{31}A_{31}L_{11} & h_{32}A_{32}L_{22} & \cdots & 0 \end{bmatrix}$, ($h_{sr} = 1$ if $s = t$ and $r \in V$, otherwise, $h_{sr} = 0$), and $N = (I - Z + Z^{tV})^{-1}$. T^{tV} represents the traded products that cross the national borders from country t to the group of country V. Please refer the Appendix B for the mathematical proof of Eq. (11).

Using backward international-linkage-based decomposition, we further divide the gross carbon tariffs paid by each country into direct, indirect and multiple carbon tariffs, according to the border-crossing frequencies of carbon footprints. The direct carbon tariffs (DCT_b) are targeted at domestic emissions generated to support the production of traded products that are exported to the group of countries V. The border-crossing frequency of carbon footprints of exports of country t to the group of countries is V one. The direct carbon tariff on domestic emissions can be measured as $TFL^D Y^{tV} + TFL^D Z^{tV}(I + (Z - Z^{tV}) + (Z - Z^{tV})^2 + \ldots)(Y - Y^{tV})$. Rearranging,

$$DCT_t\_b = R^{UV} FL^D D\_T^{tV} \tag{12}$$

where D_T^{tV} represents the products of country t that are exported to the group of country V directly and only cross the border from country t to the group of country V once. The emitter and taxpayer may be two different countries. The indirect carbon tariffs (ICT_b) are targeted at foreign emissions embodied in exports of country t to the group of countries V. The border crossing frequency of carbon footprints of exports of country is at least twice, but it crosses the boundary of the group of countries V through imports only once. The mathematical expression is

$$ICT_t\_b = R^{UV} FL^D I\_T^{tV} \tag{13}$$

where I_T^{tV} represents the intermediate products of other countries that are fist exported to country t and then exported to the group of country V. The traded products only cross the border from country t to the group of country V once. Both domestic and foreign intermediate products may cross the border from country t to the group of countries V multiple times, and then country t has to pay carbon tariffs for emissions embodied in intermediate products multiple times (multiple carbon tariff, MCT_b).

$$MCT_t\_b = R^{UV} FL^D M\_T^{tV} \tag{14}$$

where M_T^{UV} represents the accumulation of the traded products that cross the border from country t to the group of country V multiple times. Based on border-crossing frequencies of carbon footprints, this present paper divides the gross carbon tariff paid by a certain country into direct, indirect, and multiple carbon tariffs from the perspective of backward international linkages. The multiple tariff is the result of the double counting of emissions embodied in exports from country t to the group of countries V due to global production fragmentation.

4. Results

The proposed approach was applied to the WIOD database, which provides Inter-Country Input–Output database covering 40 countries and 35 industries (see the Appendix C and D for details) over the period 1995–2011 and national carbon emissions by sector and energy commodity over the period 1995–2009. We calculate border-crossing frequencies of carbon footprints over the period 1995–2009 by the WIOD in constant 1995 prices. The discussion on the effects of border-crossing frequencies associated with carbon footprints on border carbon adjustments is based on the WIOD in 2009 at current prices.

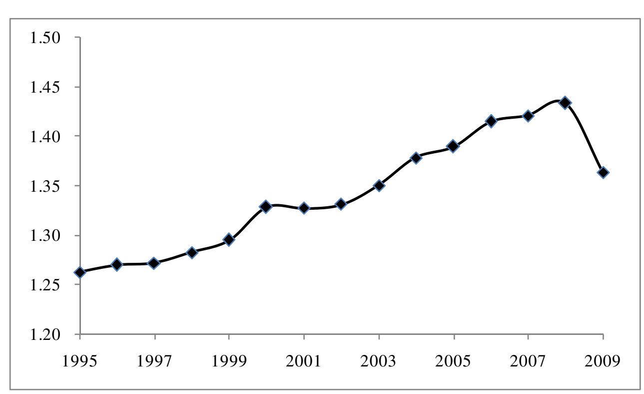

Fig. 1. The aggregated average border-crossing frequencies of carbon footprints related to international trade over the period 1995–2009.

Table 1
The aggregated average border-crossing frequencies of carbon transfer matrix.

	AUS	BRA	CAN	CHN	EU	IDN	IND	JPN	KOR	MEX	RUS	TUR	TWN	USA	RoW	Sum
AUS	2.25	1.83	1.39	1.20	1.66	1.20	1.19	1.15	1.19	2.00	1.85	2.16	1.21	1.52	1.29	1.35
BRA	1.87	2.26	1.40	1.22	1.52	1.51	1.62	1.47	1.43	1.36	1.50	1.67	1.51	1.41	1.19	1.36
CAN	1.42	1.26	2.14	1.37	1.50	1.57	1.40	1.33	1.46	1.42	1.88	1.92	1.51	1.07	1.43	1.26
CHN	1.14	1.26	1.24	2.23	1.37	1.17	1.22	1.12	1.13	1.28	1.25	1.30	1.21	1.22	1.22	1.26
EU	1.39	1.42	1.46	1.59	1.31	1.65	1.65	1.62	1.56	1.54	1.36	1.30	1.57	1.50	1.26	1.34
IDN	1.26	1.57	1.60	1.41	1.59	2.22	1.34	1.15	1.19	1.77	1.60	1.25	1.18	1.48	1.26	1.37
IND	1.23	1.35	1.14	1.35	1.35	1.14	2.22	1.36	1.40	1.54	1.36	1.16	1.30	1.24	1.16	1.26
JPN	1.40	1.61	1.52	1.25	1.71	1.24	1.74	2.23	1.13	1.47	1.52	1.88	1.11	1.47	1.17	1.34
KOR	1.41	1.46	1.54	1.17	1.61	1.24	1.49	1.26	2.22	1.38	1.39	1.39	1.27	1.50	1.16	1.32
MEX	1.71	1.30	1.28	1.68	1.56	2.05	1.83	1.58	1.75	2.10	2.04	1.89	2.01	1.05	1.42	1.22
RUS	2.18	1.75	2.03	1.52	1.55	1.98	1.80	1.66	1.66	2.11	2.37	1.43	1.77	1.85	1.36	1.56
TUR	1.68	1.67	1.53	1.87	1.27	1.70	1.66	1.98	1.86	1.92	1.22	2.23	1.89	1.59	1.15	1.30
TWN	1.50	1.56	1.59	1.19	1.69	1.42	1.75	1.13	1.45	1.54	1.97	1.82	2.24	1.45	1.46	1.41
USA	1.28	1.24	1.06	1.32	1.42	1.48	1.42	1.23	1.24	1.06	1.64	1.64	1.21	2.17	1.18	1.31
RoW	1.21	1.20	1.44	1.24	1.37	1.17	1.08	1.17	1.19	1.49	1.31	1.25	1.22	1.28	2.24	1.33
Sum	1.27	1.32	1.29	1.38	1.39	1.27	1.24	1.22	1.25	1.33	1.39	1.33	1.28	1.32	1.30	

4.1. Border-crossing frequencies of carbon footprints

4.1.1. Global perspective

Using Eq. (6), the aggregated average border-crossing frequencies of carbon footprints related to international trade over the period 1995–2009 are presented in Fig. 1.

Fig. 1 presents the changing trend of the aggregated average border-crossing frequencies of carbon footprints related to international trade over the period 1995–2009. The figure reveals an increasing tendency in the border-crossing frequencies of carbon footprints. It first increased from 1.26 in 1995 to 1.33 in the year 2000 and then experienced a small decrease as a result of the global economic recession in 2001 that had a negative impact on international trade. After 2002, the frequencies increased again and peaked in 2008 at 1.43. The financial crisis in 2008–2009 shocked the global production fragmentation significantly, and the frequencies declined sharply in 2009. The results show that border-crossing frequencies of carbon footprints are influenced by the economic crisis with the global recession that began in 2008–2009 having a much greater impact on the global production fragmentation than the economic recession in 2001.

The increasing tendency of the border-crossing frequencies of carbon footprints suggests that the global production fragmentation is becoming increasingly complex. The literature shows that the scale of carbon emission transfer through international trade has increased obviously (e.g., Xu and Dietzenbacher, 2014). This present study enriches the previous studies by showing that the international carbon transfer is crossing an increasingly number of national borders. This present paper further discusses the border-crossing frequencies of carbon footprints from the national perspective.

4.1.2. National perspective

Carbon transfer via international trade has great significance for the determination of carbon reduction responsibility. The existing studies mainly focus on the size and channels of carbon transfer. This present paper extends the literature by focusing on the border-crossing frequencies of carbon transfer. The calculation results are presented in Table 1.

Table 1 presents the border-crossing frequencies of carbon transfer between different countries in 2009. We can trace a carbon emitter's exported products along the forward international linkage until they are finally absorbed. From the horizontal perspective, the aggregated average border-crossing frequency reflects the distance from an emitter to the final consumers if we assume the distance between any two different countries is 1. Countries that export huge quantity of row materials tends to have greater border-crossing frequencies from the forward international perspective. For instance, oil and natural gas accounts for a significant share in Russia's exports[4]; therefore, Russia has the highest border crossing frequency (1.56) from the forward international perspective. Mexico is located in the downstream production chain (Chen, 2014) and has the lowest border-crossing frequencies (1.22) from the forward international perspective. Processing trade accounts for a significant share in China's exports (Dietzenbacher et al., 2012); thus, China exports large number of final products to other countries and has a low aggregated average border-crossing frequency (1.26) from a forward approach. In a word, the border-crossing frequencies depend on mixed factors, such as country's position in global production network, industrial structure and carbon intensity.

We can also traces all the emissions generated in the upstream production stages to satisfy a specific country's final demand along the global value chains. From the vertical perspective, the aggregated average border-crossing frequency reflects the average number of transnational production stages it takes an exogenous change in a country's final demand to affect the consumption-based emissions. A country will have greater border crossing frequency of carbon footprints under the backward approach if the imported products are processed in several different countries; for instance, the European Union (1.39). In contrast, Japan (1.22) imports large volumes of raw materials, the production stage of which is relatively simple. Therefore, Japan has the lowest border-crossing frequency from the perspective of backward international linkages.

Based on the aggregated average border-crossing frequency in 2009, these countries can be classified into four types. The first type countries, such as European Union and Russia, have higher border-crossing frequency from both forward and backward international linkages. This means the imported and exported products of the first type countries are processed in several different countries. The problem of carbon emission transfer faced by these countries is more complex. For the second type, such as Australia, Brazil, Indonesia, Japan, and Taiwan, the border-crossing frequency is greater from forward international linkages and lower from backward international linkages. Measured by the border crossing frequencies, these countries are closer to the supplier but have a longer distance from the consumer. The third type counties, such as China and Turkey, have lower border-crossing frequency from forward international linkages and higher border-crossing frequency from backward international linkages. The exported products of these countries are absorbed by consumers quickly. However, the imported products are processed in several different countries before they are imported. For the fourth type, such as the Unite State, Canada, Mexico, and Korea, they have lower border-crossing frequency

[4] Data sources: http://www.eia.gov/todayinenergy/detail.php?id=17231.

from both forward and backward international linkages. The traded products of these countries are processed in relatively fewer countries, and the problem of carbon emission transfer faced by these countries is relatively simple from the perspective of border-crossing frequency.

Table 1 also presents the border-crossing frequency of carbon transfer between different countries. The border-crossing frequency associated with carbon transfer between two different countries is at least once. However, the traded products need to cross borders at least twice before return to domestic country; therefore, the diagonal elements of Table 1 is greater than 2 except EU because there is international trade between European countries. Smaller border-cross frequency means the carbon transfer between these two countries mainly happen through the direct international trade, such as the carbon transfer from Mexico to the United States, the frequency is only 1.05. Greater border-crossing frequency means the indirect trade plays an important role in the international carbon transfer. For example, the frequency of carbon transfer from Russia to Australia reaches as much as 2.18. In addition, the exported products of a country may return to this country again; therefore, the diagonal elements are positive. The traded products cross the border of this county at least twice; therefore the frequency is greater than 2 except the European Union because there is bilateral trade between countries within the European Union.

4.1.3. Sectoral perspective

Sectoral emissions are generated to support the production of exported products, which cross borders multiple times until they are finally absorbed until they are absorbed by final consumers. The aggregated average border-crossing frequencies of carbon footprints from the sectoral perspective are presented in Fig. 2.

The 35 sectors are listed in descending order of border-crossing frequencies in Fig. 2. Based on the the aggregated average border-crossing frequency in 2009, these sectors can be classified into two types. The border-crossing frequency of the first type is greater than the average level (1.33) in 2009. For instance, the sector C12 (Basic Metals and Fabricated Metal, 1.42) has the largest number of border-crossings, followed by the sector C2 (Mining and Quarrying, 1.41) and C26 (Other Supporting and Auxiliary Transport Activities, 1.40). The products associated with these sectors are widely used in the industrial production or provide supportive services to international trade. For the second type sectors, the border crossing frequency is lower than the average level in 2009. The second type sectors are mainly made up of that belong to the primary, tertiary industries, and light industry. An explanation is that the production of these sectors is less fragmented than the heavy industrial production. For instance, the border-crossing frequency of the sector C35 (Private Households with Employed Persons) is only 1.05, which means the emissions of these sector are less influenced by the carbon transfer through international trade. This present paper further provides a more comprehensive analysis on border-crossing frequencies of the sector C12, which corresponds to the greatest border-crossing frequency. The results are presented in Fig. 3.

Fig. 3 presents the emissions of the sector C12 that are induced by exports of each country, which are listed in increasing order of border-crossing frequency. The results show that the emissions of sector C12 induced by exports vary along a U-shaped curve with the border-crossing frequency. The sector C12 of China has the greatest size of emissions (192.57 Mt) induced by exports, followed by that of the European Union (127.06 Mt) and Russia (85.23 Mt). However, there exist significant differences on border-crossing frequencies of carbon footprints. The sector C12 of China has the lowest border-crossing frequency (1.29); while the sector C12 of Russia (1.60) corresponds to the highest border-crossing frequency, followed by the European Union (1.53). In other words, the final demand crosses fewer borders to affect the carbon emissions of the sector C12 of China than that of Russia and the European union. There also exist significant differences on border-crossing frequencies of the sector C12 for other countries; however, the size of emissions induced by exports is relatively small.

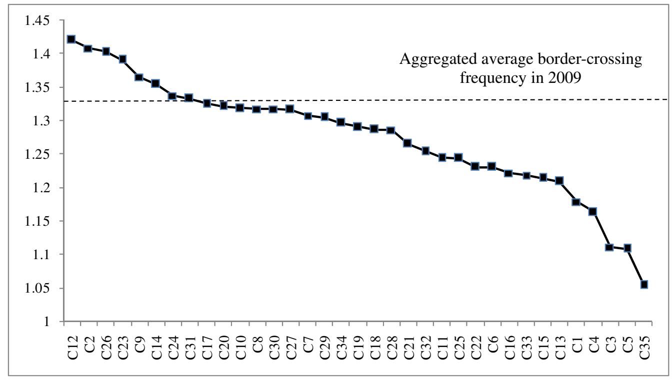

Fig. 2. Sectoral border-crossing frequencies of carbon footprints in 2009.

In the next section, the focus is on one country, the United States, to illuminate the new insights offered by the perspective proposed in this paper.

To test the robustness of the calculation results to spatial and sectoral aggregation levels, this study calculates the border crossing frequencies associated with carbon footprints based on 3-sector level WIOD (the three sectors are agriculture, industry, and service) and 4-regionl level WIOD (the US, the EU, China and Rest of world). We compare the simulation results from regional, bilateral and sectoral perspectives (the calculation results are present in Appendix E). The calculation results show that border-crossing frequencies would decrease with spatial and sectoral aggregation. However, the regional and sectoral rankings of border-crossing frequencies keep relatively consistent. This means that there exists high comparability across sectors and regions in border-crossing frequencies associated with carbon footprints.

4.2. Border carbon adjustments of the United States

This section simulates the scenario that the United States implements border carbon adjustments and levies carbon tariffs on foreign emissions embodied in imports based on the inter-country input–output table developed for 2009. It is assumed that the carbon tariff rate is 20 dollar per ton of carbon emissions, which is the lowest level of regulations in Tang et al.'s study (2015). The calculation results are explained in detail from both forward and backward international linkages.

4.2.1. At whose emissions is the American carbon tariff targeted?

From Eq. (7), the scale of carbon tariffs targeted at carbon emissions of different countries can be obtained; the results are shown in Fig. 4.

Fig. 4 divides the carbon tariff revenues of the USA by the source of targeted emissions. The results show that the border carbon

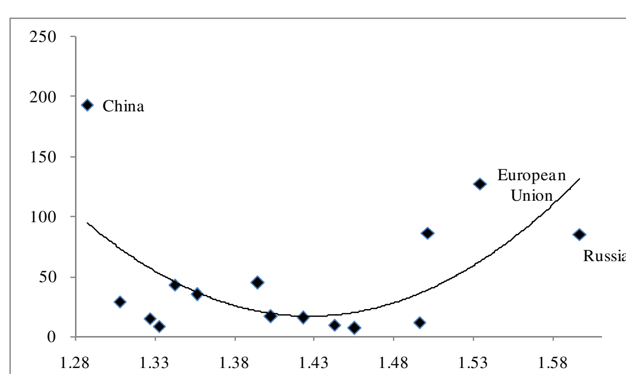

Fig. 3. The relation between emissions of the sector C12 (Basic Metals and Fabricated Metal) that are embodied in exports (Mt) and border-crossing frequency.

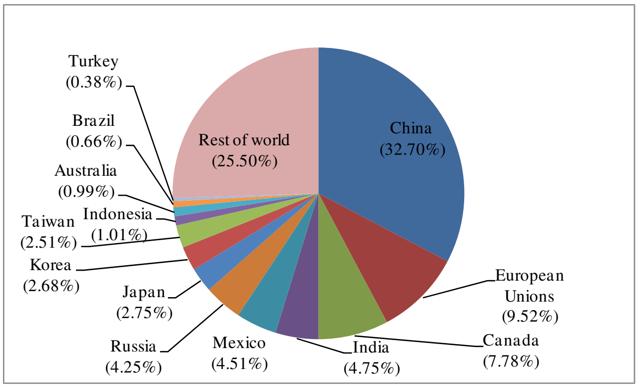

Fig. 4. The United States levy carbon tariffs on whose emissions.

adjustments of the United States are mainly targeted at emissions generated in China (32.70%), followed by the European Union (9.52%). China is the largest trade partner of the United States and has relatively greater carbon intensity. Therefore, border carbon adjustments of the United States mainly regulate the carbon emissions generated in China. This is consistent with the literature that the largest carbon emission transfer through international trade is from the United States to China (Davis and Caldeira, 2010). The United States also levies large carbon tariffs on emissions generated in Russia, although the scale of direct trade between USA and Russia is not large. A reasonable explanation is that Russia is a major exporter of raw materials, which are further processed in other countries and finally exported to the USA. This highlights that the United States does not only levy direct carbon tariffs on emissions of each country; the indirect carbon tariffs also account for a significant share in the carbon tariff revenue of the United States. Using forward international-linkage-decomposition, the carbon tariff on emissions of each country are divided into the direct, indirect and multiple tariff contributions.

Table 2 presents the forward international-linkage-based decomposition of US carbon tariffs on foreign emissions embodied in imports. The carbon emitter pays the direct carbon tariff directly. The indirect tariff targeted at a country's emissions that are embodied in another country's exports to the United States, and the exporter pays the carbon tariffs, rather than the emitter. Both the direct and indirect tariffs are paid once; however, the multiple tariffs are paid at least twice by the carbon emitter or other countries. The results show that the share of direct carbon tariff takes a relatively greater share for most countries, such as Canada (94.40%) and Mexico (95.52%). According to Section 4.1, Mexico and Canada have lower border-crossing frequencies under the forward approach, implying that most of the exported products of these two countries are absorbed by the trade partner directly. Therefore, the United States levies greater direct tariffs on carbon emissions of Mexico and Canada. Russia has the greatest border-crossing frequencies under the forward approach. Thus, the United States mainly levies a greater share (58.70%) of indirect carbon tariffs on emissions generated in Russia to support the production of American imports. In other words, more than half of carbon tariffs targeted at emissions of Russia are paid by other countries. As shown in Fig. 4, the multiple tariffs involve more than 1 % of all countries. The previous studies that overlook the impacts of border-crossing frequencies would underestimate the carbon tariff revenue. Section 5 provides a more detailed discussion on the multiple taxation problem of carbon tariffs.

4.2.2. Who pay carbon tariffs to the United States?

Using Eq. (11), the scale of carbon tariffs paid by each country can be obtained; the results are presented in Fig. 5.

Fig. 5 divides the carbon tariff revenue of the United States by the share of each country's tax burdens. The results show that 30.32% of the carbon tariff revenue of the United States is paid by China. This means that the border carbon adjustments of the United States have the most significant impact on China, followed by the European Union, Canada and Mexico. These countries pay more than half of the carbon tariff revenue earned by the United States. Comparisons between Figs. 4 and 5 show that the carbon tariffs paid by China is a little smaller than the carbon tariffs targeted at Chinese emissions generated to support the production of American imports. However, the share of carbon tariffs of the European Union, Canada and Mexico from the backward international linkage is significantly greater than that from the forward international linkage. An explanation is that these two countries not only pay direct tariffs targeted at domestic emissions but also pay a large amount of indirect carbon tariffs targeted at foreign emissions. To address this issue, the carbon tariff burdens of different countries are decomposed into the direct tariff, the indirect tariff, and the multiple tariff using backward international-linkage-based decomposition. The calculation results are presented in Table 3.

Each country pays direct carbon tariffs for domestic emissions embodied in products exported to the United States. At the same time, each country needs to pay indirect carbon tariffs for foreign emissions embodied in products exported to the United States. The multiple intermediate products cross the border from a country to the United States several times, and the country has to pay carbon tariffs for the associated emissions multiple times. However, the multiple carbon tariffs under the forward international linkage reflect the carbon tariffs paid multiple times by a country or different countries. Therefore, the multiple tariffs under the backward international linkage is smaller than that under the forward international linkage. At the aggregated level, two

Table 2
Forward international-linkage-based decomposition of carbon tariffs targeted at emissions of each country.

	DCT_f		*ICT_f*		*MCT_f*		Sum
Australia	138.01	(59.22%)	91.48	(39.25%)	3.57	(1.53%)	233.07
Brazil	107.13	(68.78%)	45.54	(29.24%)	3.09	(1.98%)	155.76
Canada	1722.27	(94.40%)	67.78	(3.72%)	34.43	(1.89%)	1824.48
China	6343.96	(82.71%)	1225.35	(15.98%)	100.77	(1.31%)	7670.08
European Union	1419.24	(63.56%)	781.01	(34.98%)	32.54	(1.46%)	2232.78
Indonesia	150.11	(63.23%)	84.53	(35.60%)	2.78	(1.17%)	237.41
India	886.26	(79.49%)	215.29	(19.31%)	13.38	(1.20%)	1114.93
Japan	413.89	(64.12%)	220.98	(34.24%)	10.58	(1.64%)	645.44
Korea	379.28	(60.28%)	239.24	(38.02%)	10.66	(1.69%)	629.18
Mexico	1010.41	(95.52%)	28.26	(2.67%)	19.11	(1.81%)	1057.77
Russia	391.40	(39.25%)	585.38	(58.70%)	20.39	(2.04%)	997.17
Turkey	50.67	(56.92%)	36.83	(41.38%)	1.52	(1.71%)	89.02
Taiwan	383.94	(65.27%)	195.10	(33.17%)	9.21	(1.57%)	588.24
United States	0.00	–	0.00	–	0.00	–	0.00
Rest of world	4711.57	(78.78%)	1180.75	(19.74%)	88.10	(1.47%)	5980.42
Sum	18,108.13	(77.20%)	4997.52	(21.31%)	350.13	(1.49%)	23,455.77

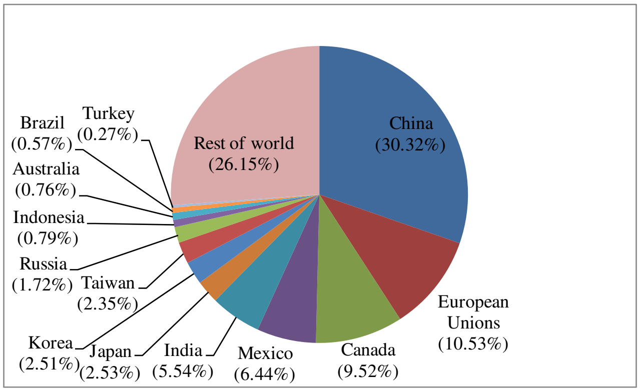

Fig. 5. Who pays carbon tariffs to the United States.

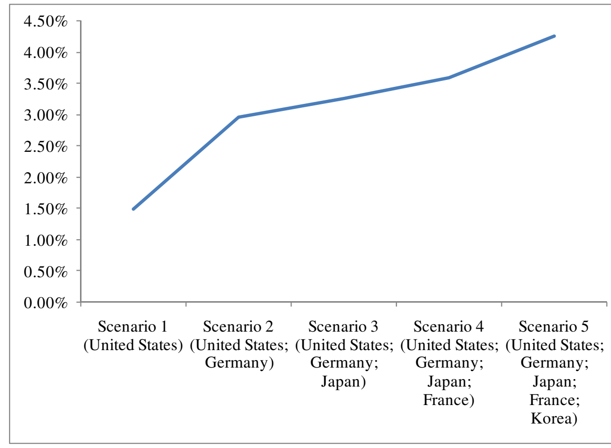

Fig. 6. The share of multiple carbon tariffs under different scenarios.

decomposition methods produce the same gross tariffs, which is 23.456 billion dollars.

Table 3 shows that there exist significant differences in the share of direct and indirect carbon tariffs for different countries. For instance, the share of direct carbon tariffs reaches as much as 89.10% for China, while 46.70% of the carbon tariffs paid by Germany are targeted at emissions generated in the pre-final production stage. Border carbon adjustments of the United States would promote foreign countries to reduce domestic emissions through the direct carbon tariff and encourage foreign countries to import less energy-intensive intermediate products through the indirect carbon tariffs. In other words, the border carbon adjustments of the United States mainly influence the production structure of China and have a significant impact on the import structure of Germany. The results show that indirect carbon tariffs take a significant share for most countries, which implies that the border carbon adjustments only targeted at direct emissions cannot reduce carbon emission of other countries effectively because they could reduce carbon emissions by importing products from other countries. The United States does not levy carbon tariffs on itself; therefore, three types of carbon tariffs of the United States are all zero.

5. Discussions

Section 4 simulates the scenario that the United States adopts border carbon adjustments for imports based on embodied emissions. The results show that the carbon tariff revenue will be underestimated if the border crossing frequencies of carbon footprints are ignored because a country may levy carbon tariffs on imports multiple times. In the real world, another reason for the problem of multiple taxation is that different countries levy tariffs on imports at the same time. Therefore, this section further discusses the scenarios that a group of countries levy carbon tariffs on the other countries' emissions generated to support the production of imported products.

The countries that adopt border carbon adjustments in five different scenarios are presented in Fig. 6. As noted earlier, the backward international-linkage-based decomposition would underestimate the multiple carbon tariffs because it excludes carbon tariffs paid multiple times by different countries. Thus, this section only discusses the multiple taxation problem of carbon tariffs from the perspective of forward international linkage. The global average share of multiple carbon tariffs of five different scenarios are presented in Fig. 6.

Fig. 6 shows that the aggregated average share of multiple carbon tariff increases obviously as the number of countries that adopt border carbon adjustments increase. The share of multiple carbon tariff is only 1.49% for the Scenario 1 that only the United States adopt border carbon adjustments. For Scenario 5, the share of multiple carbon tariff reaches 4.24% when the United States, Germany, Japan, France, and Korea levy carbon tariffs on other countries' emissions embodied in imports. Greater share of multiple carbon tariffs means a more serious problem of multiple taxation. Border carbon adjustments not only protect domestic enterprises in the international market, but also put foreign countries under a comparative disadvantage because their emissions embodied in international trade may be levied carbon tariffs multiple times. This problem is even more serious when the downstream are sensitive to the production cost. They would face a greater increase in the production cost if they use products of the countries that do not adopt border carbon adjustments as intermediate inputs. This present paper further discusses the forward international-

Table 3
Backward international-linkage-based decomposition of carbon tariffs paid by each country.

	DCT_b		*ICT_b*		*MCT_b*		Sum
Australia	138.97	(78.46%)	38.16	(21.54%)	0.01	(0.00%)	177.13
Brazil	108.29	(81.44%)	24.66	(18.55%)	0.01	(0.01%)	132.96
Canada	1733.66	(77.65%)	485.74	(21.76%)	13.29	(0.60%)	2232.69
China	6381.85	(89.73%)	721.67	(10.15%)	8.65	(0.12%)	7112.17
European Union	1429.44	(57.89%)	1039.47	(42.10%)	0.43	(0.02%)	2469.33
Indonesia	150.84	(81.29%)	34.72	(18.71%)	0.00	(0.00%)	185.56
India	890.94	(68.59%)	406.99	(31.33%)	1.09	(0.08%)	1299.02
Japan	417.40	(70.35%)	175.74	(29.62%)	0.18	(0.03%)	593.32
Korea	382.76	(65.09%)	205.12	(34.88%)	0.18	(0.03%)	588.06
Mexico	1017.23	(67.30%)	486.73	(32.20%)	7.48	(0.49%)	1511.43
Russia	396.99	(98.31%)	6.83	(1.69%)	0.00	(0.00%)	403.83
Turkey	51.13	(79.46%)	13.22	(20.54%)	0.00	(0.00%)	64.35
Taiwan	387.10	(70.17%)	164.41	(29.80%)	0.17	(0.03%)	551.68
United States	0.00	–	0.00	–	0.00	–	0.00
Rest of world	4739.70	(77.27%)	1375.98	(22.43%)	18.56	(0.30%)	6134.25
Sum	18,226.31	(77.71%)	5179.42	(22.08%)	50.04	(0.21%)	23,455.77

Table 4
Downstream decomposition of carbon tariffs on emissions of each country (United States, Germany, Japan, France, and Korea adopt border carbon adjustments).

	DCT_f		*ICT_f*		*MCT_f*		Sum
Australia	522.62	(74.40%)	145.56	(20.72%)	34.22	(4.87%)	702.41
Brazil	229.28	(69.31%)	84.85	(25.65%)	16.67	(5.04%)	330.80
Canada	1999.35	(90.91%)	123.13	(5.60%)	76.71	(3.49%)	2199.20
China	13,028.74	(84.71%)	1811.57	(11.78%)	540.95	(3.52%)	15,381.26
European Union	4666.34	(74.45%)	1292.27	(20.62%)	309.54	(4.94%)	6268.15
Indonesia	588.34	(76.58%)	143.11	(18.63%)	36.77	(4.79%)	768.23
India	1453.71	(77.16%)	370.82	(19.68%)	59.41	(3.15%)	1883.94
Japan	0.00	–	0.00	–	0.00	–	0.00
Korea	0.00	–	0.00	–	0.00	–	0.00
Mexico	1090.79	(93.00%)	47.15	(4.02%)	34.90	(2.98%)	1172.84
Russia	1812.06	(53.02%)	1394.43	(40.80%)	211.50	(6.19%)	3417.98
Turkey	242.24	(70.76%)	85.38	(24.94%)	14.71	(4.30%)	342.33
Taiwan	1289.61	(76.81%)	298.75	(17.79%)	90.58	(5.39%)	1678.93
United States	0.00	–	0.00	–	0.00	–	0.00
Rest of world	10,925.69	(81.00%)	1968.71	(14.59%)	594.77	(4.41%)	13,489.17
Sum	37,848.79	(79.46%)	7765.72	(16.30%)	2020.72	(4.24%)	47,635.23

linkage-based decomposition results of carbon tariffs from the national perspectives, with the Scenario 5 as an example. The results are presented in Table 4.

Notes, the carbon tariffs targeted at emission of five countries in the Scenario 5 are all zero; therefore, Table 4 only presents the sum of carbon tariffs that are targeted at emissions of other European countries, other than Germany and France.

In order to avoid double regulation of emissions from the country that adopts unilateral climate regulations, these five countries only levy carbon tariffs on emissions of the other countries that generated to support the production of imported products. Therefore, the carbon tariffs targeted at emissions of these five countries are zero. The size of carbon tariffs in Table 4 is greater than that in Table 2 because of the greater coverage of border carbon adjustments. At the same time, the share of the multiple carbon tariff increases obviously; for instance, the multiple carbon tariffs takes as much as 6.19% of the gross carbon tariffs targeted at emissions generated in Russia. Against the background that global production fragmentation is developing quickly and an increasing number of developed countries are considering border carbon adjustments, the multiple taxation problem of carbon tariffs would be increasingly serious. The multiple taxation problem would make the international debate on border carbon adjustments more intense. Therefore, the concept of border-crossing frequencies of carbon footprints has great policy implication for the international cooperation to reduce carbon emissions.

It should be noted that the scale of emissions covered by carbon tariffs is not only determined by the number of countries that adopt carbon tariffs, but also related to the number of countries that have not internalized the carbon costs in production. In an extreme case that all regions join an effective global climate agreement, the carbon tariffs faced by each country is zero. Therefore, the scale of emissions covered by carbon tariffs experiences two stages as the number of countries that adopt carbon tariffs increase. In the first stage, the scale of emissions covered by carbon tariffs would increase with the number of countries that adopt climate regulations increase. In the second stage, the scale of emissions covered by carbon tariffs would decrease with the number of countries that have not adopted climate regulations decrease. And meanwhile, the share of multiple carbon tariffs would first increase with the number of countries that adopt carbon tariffs and may experience some decrease latter, which is determined by the order of countries that adopt carbon tariffs.

6. Conclusions

In recent years, the fragmentation of production across national boundaries has been an important feature of the world economy. This present study adopts the viewpoint that not only the size and composition of carbon footprints are relevant but also the border-crossing frequencies. First, border-crossing frequencies of carbon footprints are defined as the number of borders crossed by the associated supply chain. Secondly, an approach is proposed to calculate border-crossing frequencies of carbon footprints by decomposing the Leontief inverse matrix of a multi-country input–output framework. Finally, we discuss the policy implication of border-crossing frequencies of carbon footprints on border carbon adjustments for imports based on embodied emissions. The main results of the paper are summarized below.

(1) Using the WIOD database for the period 1995–2009, we find that the aggregated average border crossing frequencies of carbon footprints show an increasing tendency, which is influenced by the economic crisis obviously. There are significant differences on border-crossing frequencies of carbon transfer between different countries and sectors, which are determined by different factors, such as a country's position in global production network, the industrial structure and the carbon intensity. Russia and Mexico corresponds to the highest and lowest border-crossing frequency of carbon footprints under the forward international perspective. The EU and Japan have highest and lowest border-crossing frequencies of carbon footprints from the backward international perspective. The emissions of sector C12 (Basic Metals and Fabricated Metal) induced by exports of different countries vary along a U-shaped curve with the border-crossing frequency.
(2) The simulation scenario assumes that the United States adopts border carbon adjustments on foreign emissions generated to support the production of imported products. The simulation results show that 32.70% of carbon tariffs are levied on Chinese emissions generated to support the production of American imports; 30.32% of carbon tariff revenues earned by the United States are paid by China. Global production fragmentation means that the country that emits carbon emissions may be different from the one that pays carbon tariffs. At the aggregated level, the gross carbon tariffs remain consistent from both forward and backward international linkage perspectives. The indirect carbon tariff on emissions embodied in international trade accounts for a significant share.
(3) The implication of carbon tariffs faces the problem of multiple taxation. We find that the multiple taxation problem of carbon tariffs would become increasingly serous with an increase in number of countries adopting border carbon adjustments because carbon emissions embodied in intermediate traded products may be targeted by border carbon adjustments of different countries. The share of multiple carbon tariffs increases to as much as 4.24% if the United States, Germany, Japan, France, and

Korea all adopt border carbon adjustments on other countries' emissions that generated to support the production of imported products. The multiple taxation problem of carbon tariffs would make the international debate about border carbon adjustments more intense. The results of this paper enrich the literature by highlighting the policy implication of the concept of border-crossing frequencies of carbon footprints.

There are several potential extensions of this study that are worthy of pursuit. First, the future studies could apply the proposed method of this study to other databases with more detailed regional and sectoral classification, such as the Eora multi-region input–output table database, and the Global Trade Analysis Project (GTAP) database. Second, rather than using the aggregated data, it is expected that future studies could calculate the border-crossing frequencies based on micro data, which could provide more detailed information on the border-crossing frequencies. Third, this study only discusses the impact of border crossing frequencies on carbon tariffs, and future studies are expected to discuss the other border carbon adjustment measures, such as export rebates.

Acknowledgements

The authors gratefully acknowledge the financial support from the National Science Foundation of China (Grant Nos. 71603179, 71473245 and 71203064), Tianjin Program of Philosophy and Social Science (TJGL16-007Q), and Seed Foundation of Tianjin University (2017XSZ-0016). We also would like to thank the anonymous referees as well as the editors.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.eneco.2017.04.017.

References

Antràs, P., Chor, D., 2013. Organizing the global value chain. Econometrica 81, 2127–2204.
Antràs, P., Chor, D., Fally, T., Hillberry, R., 2012. Measuring the upstreamness of production and trade flows three measures of upstreamness. Am. Econ. Rev. Pap. Proc. 102, 412–416.
Böhringer, C., Carbone, J.C., Rutherford, T.F., 2011. Embodied carbon tariffs. Working Paper (Sources: http://www.nber.org/papers/w17376.pdf).
Böhringer, C., Bye, B., Fæhn, T., Rosendahl, K.E., 2012. Alternative designs for tariffs on embodied carbon: a global cost-effectiveness analysis. Energy Econ. 34, 1–32.
Brizga, J., Feng, K., Hubacek, K., 2017. Household carbon footprints in the Baltic States: a global multi-regional input–output analysis from 1995 to 2011. Appl. Energy 189, 780–788.
Chen, Q., 2014. The average propagation length: an extended analysis. Paper Presented in the 22nd International Input–Output Conference, Lisbon, 2014.
Davis, S.J., Caldeira, K., 2010. Consumption-based accounting of CO_2 emissions. Proc. Natl. Acad. Sci. U. S. A. 107, 5687–5692.
Dietzenbacher, E., Romero, I., 2007. Production chains in an interregional framework: identification by means of average propagation lengths. Int. Reg. Sci. Rev. 30, 362–383.
Dietzenbacher, E., Romero Luna, I., Bosma, N.S., 2005. Using average propagation lengths to identify production chains in the Andalusian economy. Estud. Econ. Apl. 23, 405–422.
Dietzenbacher, E., Pei, J., Yang, C., 2012. Trade, production fragmentation, and China's carbon dioxide emissions. J. Environ. Econ. Manag. 64, 88–101.
Druckman, A., Jackson, T., 2009. The carbon footprint of UK households 1990–2004: a socio-economically disaggregated, quasi-multi-regional input–output model. Ecol. Econ. 68, 2066–2077.
Fally, T., 2012. On the Fragmentation of Production in the US. University of Colorado-Boulder (Sources: https://editorialexpress.com/cgi-bin/conference/download.cgi?db_name=MWITSpring2012&paper_id=99).
Hertwich, E.G., Peters, G.P., 2009. Carbon footprint of nations: a global, trade-linked analysis. Environ. Sci. Technol. 43, 6414–6420.
Ji, S., Chen, B., 2016. Carbon footprint accounting of a typical wind farm in China. Appl. Energy 180, 416–423.
Lin, B., Sun, C., 2010. Evaluating carbon dioxide emissions in international trade of China. Energy Policy 38, 613–621.
Liu, Z., Davis, S.J., Feng, K., Hubacek, K., Liang, S., Anadon, L.D., Chen, B., Liu, J., Yan, J., Guan, D., 2015. Targeted opportunities to address the climate–trade dilemma in China. Nat. Clim. Chang. 145, 143–145.
McAusland, C., Najjar, N., 2015. Carbon footprint taxes. Environ. Resour. Econ. 61, 37–70.
Meng, B., Peters, G., Wang, Z., 2015. Tracing CO_2 emissions in global value chains. IDE Discuss. Pap.
Messagie, M., Mertens, J., Oliveira, L., Rangaraju, S., Sanfelix, J., Coosemans, T., Van Mierlo, J., Macharis, C., 2014. The hourly life cycle carbon footprint of electricity generation in Belgium, bringing a temporal resolution in life cycle assessment. Appl. Energy 134, 469–476.
Monjon, S., Quirion, P., 2011. Addressing leakage in the EU ETS: border adjustment or output-based allocation? Ecol. Econ. 70, 1957–1971.
Muradov, K., 2015. Input–output calculus of international trade. Sources:. https://www.iioa.org/conferences/23rd/papers/files/2047_20150526021_MuradovIIOApaper_26.05.2015.pdf.
Muradov, K., 2016. Counting borders in global value chains. Sources:. http://ssrn.com/abstract=2808130.
Romero, I., Dietzenbacher, E., Hewings, G.J.D., 2009. Fragmentation and complexity: analyzing structural change in the Chicago regional economy. Rev. Econ. Mund. 23, 263–282.
Schenker, O., Koesler, S., Löschel, A., 2012. Taxing carbon along the value chain. Working Paper (Sources: http//www.wiod.org/conferences/groningen/Paper_Schenker_et_al.pdf).
Su, B., Ang, B.W., 2011. Multi-region input–output analysis of CO_2 emissions embodied in trade: the feedback effects. Ecol. Econ. 71, 42–53.
Su, B., Ang, B.W., Low, M., 2013. Input–output analysis of CO_2 emissions embodied in trade and the driving forces: processing and normal exports. Ecol. Econ. 88, 119–125.
Tang, L., Bao, Q., Zhang, Z.X., Wang, S., 2015. Carbon-based border tax adjustments and China's international trade: analysis based on a dynamic computable general equilibrium model. Environ. Econ. Policy Stud. 17, 329–360.
Timmer, M.P., Dietzenbacher, E., Los, B., Stehrer, R., de Vries, G.J., 2015. An illustrated user guide to the world input–output database: the case of global automotive production. Rev. Int. Econ. 23, 575–605.
Wang, Z., Wei, S.-J., Yu, X., Zhu, K., 2014. Characterizing global and regional manufacturing value chains: stable and evolving features. Working Paper.
Wang, Z., Wei, S.-J., Zhu, K., 2015. Quantifying international production sharing at the bilateral and sector levels. Working Paper (Sources: http://scholar.harvard.edu/files/jorgenson/files/zhi_wang_wwz-mar-7-2014.pdf).
Weber, C.L., Matthews, H.S., 2008. Quantifying the global and distributional aspects of American household carbon footprint. Ecol. Econ. 66, 379–391.
Winchester, N., 2012. The impact of border carbon adjustments under alternative producer responses. Am. J. Agric. Econ. 354–359.
Xu, Y., Dietzenbacher, E., 2014. A structural decomposition analysis of the emissions embodied in trade. Ecol. Econ. 101, 10–20.
Zhang, Y., Tang, Z., 2015. Driving factors of carbon embodied in China's provincial exports. Energy Econ. 51, 445–454.
Zhang, Z., Guo, J., Hewings, G.J.D., 2014. The effects of direct trade within China on regional and national CO2 emissions. Energy Econ. 46, 161–175.