Energy Economics 73 (2018) 274–285

Contents lists available at ScienceDirect

Energy Economics

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

Technology-adjusted national carbon accounting for a greener trade pattern

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ARTICLE INFO

Article history:
Received 1 August 2017
Received in revised form 7 May 2018
Accepted 17 May 2018
Available online 19 May 2018

JEL classification:
C670
F180
O330
Q540
Q560
Q580

Keywords:
Carbon accounting
Intermediate input structure
Technology adjustment
Trade pattern
Input-output model

ABSTRACT

Crediting green trade patterns is essential for effective national carbon accounting. Neither production- nor consumption-based accounting satisfies this condition. Thus, Kander et al. [Kander, A., Jiborn, M., Moran, D.D., Wiedmann, T.O., 2015. National greenhouse-gas accounting for effective climate policy on international trade. Nature Climate Chang. 5(5):431–435.] proposed a technology-adjusted consumption-based carbon accounting method that focuses on interregional differences in sectoral carbon intensity. The intermediate input structure is also closely related to the production technology level. Therefore, this study recommends a new technology-adjusted consumption-based carbon accounting framework that distinguishes between direct and cumulative exports, forward and backward industrial linkages, and different trade patterns. Based on the consideration that production-based accounting will remain the core indicator for regional emissions in the near future, this study proposes a technology-adjusted production-based accounting framework. The empirical study is based on the World Input-Output Database, and the results indicate that technology-adjusted carbon accounting will redraw the global emissions map if the intermediate input linkage is considered. The technology-adjusted carbon accounting method satisfies the conditions of additivity, sensitivity, monotonicity, and scale invariance, through proper selection of the world average emissions multipliers.

1. Introduction

A large proportion of global emissions is generated by international trade (Davis et al., 2011; Davis and Caldeira, 2010; Hertwich and Peters, 2009; Jakob and Marschinski, 2012; Peters et al., 2011; Peters and Hertwich, 2008a). However, neither production-based accounting (PBA) nor consumption-based accounting (CBA) schemes satisfy the requirement that the carbon accounting system should encourage trade patterns that generate global carbon savings (Grasso and Roberts, 2014; Jakob and Marschinski, 2012; Kander et al., 2015). PBA faces the problem of carbon leakage, and CBA fails to encourage countries to clean up the production of export products. To address this issue, Kander et al. (2015) proposed a technology-adjusted consumption-based accounting (TCBA) method based on a Leontief demand-pull model. However, because it could not decompose intermediate product flows (Wang et al., 2015), the original Leontief insight in the inter-country input-output model is not sufficient to quantify the emissions induced by export flows at the bilateral level. Intermediate product trade has become the main form of international carbon transfer (Zhang et al., 2017a). This study designs a new technology-adjusted carbon accounting scheme based on another gross trade accounting framework recently developed by Wang et al. (2015).

TCBA is the equivalent of PBA to which imported embodied emissions are added and from which the potential world average emissions generated to produce the exported products are subtracted. Under TCBA, a country should be responsible not only for the emissions embodied in its imports but also for the portion of export-embodied emissions that surpasses the world average level. A country's exports will be credited if its production is cleaner than the world average level; alternatively, the country will be penalized. Technology differences among export sectors should not only consider sectoral direct CO_2 emissions but also the emissions embodied in intermediate inputs. For instance, a large amount of CO_2 emissions from China's electricity generation sector is generated to support the production of exports by other sectors. However, the amount of directly exported electricity is negligible (Meng et al., 2018). The TCBA framework developed by Kander et al. (2015) focuses primarily on the interregional differences in sectoral carbon intensity and tends to credit the exports of a country with higher electricity generation efficiency rather than those of a country with

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https://doi.org/10.1016/j.eneco.2018.05.025
0140-9883/

higher electricity use efficiency. This paper attempts to address this gap by tracing a region's direct and indirect emissions produced by exports through the intermediate input linkage.

TCBA can be viewed as an improvement of CBA (Domingos et al., 2016) that encounters practical difficulties due to uncertainty and system boundaries (Peters, 2008). Steininger et al. (2016) note that PBA will remain the core indicator for regional emissions in the near future. Therefore, this paper directly modifies PBA and proposes technology-adjusted production-based accounting (TPBA). TPBA is the equivalent of CBA to which export-embodied emissions are added and from which the potential world average emissions generated to produce imported products are subtracted. TPBA not only considers the direct emissions produced within a country's territory but also what alternative production this country's imports replace. Thus, TPBA could alleviate the carbon leakage problem faced by PBA. In addition, the TPBA framework distinguishes between domestic and global Leontief inverse matrices and could solve a weakness of CBA, i.e., its failure to encourage countries specializing in production stages that they have a comparative advantage.

The main contributions of the paper are summarized as follows. First, the paper proposes a new technology-adjusted carbon accounting framework that takes the intermediate input structure into account. TPBA can be viewed as an improvement of PBA, which will remain the core indicator for regional emissions in the near future. Second, this study applies the proposed method to the World Input-Output Database (WIOD) (Timmer et al., 2015) and compares global emissions maps under four different accounting methods. The global emissions map can be redrawn if technology-adjusted carbon accounting considers the intermediate input structure. Third, this paper demonstrates that the technology-adjusted carbon accounting method satisfies the conditions of additivity, sensitivity, monotonicity, and scale invariance, through proper selection of different average emissions multipliers.

The remainder of the paper is organized as follows. Section 2 reviews the relevant literature. Section 3 describes the technology-adjusted carbon accounting method. Section 4 presents the theoretical analysis. Section 5 provides empirical analysis results, and Section 6 summarizes the conclusions.

2. Literature review

Climate change negotiations may adopt top-down or bottom-up approaches. The former allocates responsibility for carbon emissions among nations based on certain principles, e.g., production-based accounting in the Kyoto Protocol, whereas the latter allows nation to set their own emission reduction target and timetable, e.g., the Paris Agreement. In recent years, the top-down approach for climate negotiation has all but stalled because of its several shortcomings (Leal-Arcas, 2011; Rayner, 2010). Considering the domestic incentive to reduce carbon emissions (Parry et al., 2015), researchers proposed a bottom-up approach for climate negotiation (Leal-Arcas, 2011). In 2015, the Conference of the Parties to the UN Framework Convention on Climate Change represented a gradual victory of the bottom-up approach (Rose et al., 2017). However, an effective global climate architecture calls for a balance between top-down and bottom-up approaches for climate negotiations (Green et al., 2014).

Climate change negotiation is shifting from top-down and state-centric to bottom-up and polycentric (Andresen, 2015; Jordan et al., 2015). The related studies can also be divided into two lines. The first one analyzes carbon responsibility from the perspective of nation-states, and the second one understands it from the perspective of corporate entities. Analysis of nation-states' responsibility focuses mainly on the allocation of trade-related carbon emissions between carbon emitting regions and final consuming regions (Davis et al., 2011; Davis and Caldeira, 2010; Lenzen et al., 2007; Peters, 2008; Peters et al., 2011). An analysis of carbon responsibility in terms of corporate entities indicated that 63% of cumulative carbon emissions can be traced to 90 producers of fossil fuels and cement (Ekwurzel et al., 2017; Heede, 2014; Heede and Oreskes, 2016).

Both of these two types of assessment have important but different policy implications. The nation-state approach fits the framework of international law (Heede, 2014) because treaties and conventions are based on agreements between nation-states. The second type of analysis from the perspective of corporate entities has important implications for identifying the key countries that need to join the international climate negotiation (Heede and Oreskes, 2016). It is found that state-owned oil, natural gas, and coal companies hold the majority of fuel resources. A critical factor that determines that success of curbing climate change is whether the nations that own these entities are involved in climate agreements (Heede and Oreskes, 2016).

This study contributes to the top-down approach by proposing a new technology-adjusted carbon accounting framework that takes the intermediate input structure into account. There is growing literature that traces CO_2 emissions along global supply chains and analyzes the environmental effects of global production fragmentation (Davis et al., 2011; Dietzenbacher et al., 2012; Du et al., 2011; Jakob and Marschinski, 2012; Meng et al., 2018; Zhang et al., 2017a, 2017b). Meng et al. (2018) note that it is crucial to distinguish between forward and backward industrial linkages when measuring embodied emissions in trade at a disaggregated level. This paper is based on the view that technology-adjusted carbon accounting should focus on regional differences in domestic emissions generated to support the production of a sector's gross exports from the perspective of backward industrial linkages. In addition, the literature reveals significant differences among the environmental effects of different trade patterns (Dietzenbacher et al., 2012; Jiang et al., 2015; Zhang et al., 2017a). For instance, Zhang et al. (2017a) note that final product trade became increasingly less environmentally effective over the 1995–2009 period and that international trade in intermediate products generated global emissions savings. Intermediate products trade accounts for approximately two-thirds of the world's gross trade (Johnson and Noguera, 2012). Therefore, the technology-adjusted carbon accounting scheme introduced in this paper distinguishes between final and intermediate goods trade.

Other carbon accounting approaches exist, such as extraction-based accounting (Steininger et al., 2016) and income-based accounting (Marques et al., 2013, 2012; Steininger et al., 2016). Liang et al. (2017) provide a detailed comparison of these two accounting approaches. A country's factor endowment is relatively less flexible than its production and consumption structure. Therefore, this study primarily focuses on technology-adjusted production- and consumption-based accounting. However, the rational of technology-adjusted carbon accounting also applies to the two other carbon accounting schemes. For instance, extraction-based accounting fails to encourage a fossil fuel importer to adopt greener production technology. However, technology-adjusted extraction-based accounting could solve this problem by taking an importer's use efficiency of imported fossil fuels relative to the world average into account. In addition, technology-adjusted carbon accounting could also be viewed as a special case of shared producer and consumer responsibility (Andrew and Forgie, 2008; Cadarso et al., 2012; Gallego and Lenzen, 2005; Lenzen, 2007; Lenzen et al., 2007; Lenzen and Murray, 2010), and the responsibility share is determined by the relative technology level.

The potential contributions of this present paper to the bottom-up approach lie in three perspectives. First, the bottom-up approach may solve some political problems that have plagued climate negotiations in the short term. However, this approach would eventually encounter the problems faced by the top-down approach in the long term. The method proposed in this study could be adopted to solve these potential problems of the bottom-up approach. For instance, the bottom-up approach lets nations set their own unilateral climate policies, which would eventually be linked (Green et al., 2014), such as the link between California's and Quebec's cap-and-trade programs. Green et al. (2014) note that an agreement on targets among different nations is necessary for linking climate policies. Otherwise, the linked jurisdiction would try to raise their cap. In addition, the five-year review cycles included in the Paris Agreement will bring climate burden distributional issues back to the forefront of the climate negotiations (Rose et al., 2017). This study contributes to the determination of targets and the distribution of the climate burden.

Second, the bottom-up approach does not need to divide the global carbon reduction target among different nations, but a country's committed carbon reduction target may still need to be divided among subregions. For instance, the provinces in China should determine their carbon reduction target based on the national carbon reduction target and timetable. There are significant differences in production technology among the provinces, which are connected to each other through interprovincial trade. An important branch of the literature analyzes the carbon flow within China (Feng et al., 2013; Guo et al., 2012; Mi et al., 2017; Zhang et al., 2014; Zhang and Lin, 2018). The logic of this study is suitable for determining provincial carbon reduction responsibility in China.

Third, this paper contributes to Heede (2014) by highlighting that policy makers should focus on both carbon producers (e.g., crude oil and natural gas producers, coal extractors, and cement producers) and carbon emitters (e.g., thermal power plants). A fossil fuel producer uses only a small share of its own fuels, which are mainly used as intermediate inputs in the production of other commodities (Heede, 2014). For instance, the power industry generates approximately 40% of global energy-related carbon emissions (Tong et al., 2018). To curb climate change, we should not only limit the use of the fossil fuel reserve owned by these major carbon producers but also encourage technology innovation among carbon emitters. Future studies could provide a more detailed discussion on this problem based on other bottom-up models, such as the TIMES (The Integrated MARKAL-EFOM System) model (Loulou et al., 2005), which is out of the scope of the present study.

3. Basic model

The method used in this study is based on the multi-region input-output model (Leontief, 1936). This section explains the methodology using a hypothetical world of G countries and N sectors. The countries are connected through the interregional trade of intermediate and final products, and each country's outputs are used to satisfy intermediate or final consumption.

$$\begin{bmatrix} X^1 \\ X^2 \\ \vdots \\ X^g \end{bmatrix} = \begin{bmatrix} A^{11} & A^{12} & \cdots & A^{1g} \\ A^{21} & A^{22} & \cdots & A^{2g} \\ \vdots & \vdots & \ddots & \vdots \\ A^{g1} & A^{g2} & \cdots & A^{gg} \end{bmatrix} \begin{bmatrix} X^1 \\ X^2 \\ \vdots \\ X^g \end{bmatrix} + \begin{bmatrix} \sum_r^G Y^{1r} \\ \sum_r^G Y^{2r} \\ \vdots \\ \sum_r^G Y^{gr} \end{bmatrix} \tag{1}$$

where X^s represents the final output of country s $(s = 1, \cdots, g)$, Y^{sr} represents the final demand of country r $(r = 1, \cdots, g)$ for products from country s, and A^{sr} is the intermediate input coefficient matrix that represents the intermediate use in country r of goods produced in country s. The elements of the input coefficient matrix satisfy $a_{ij}^{sr} = z_{ijsr}/x_j^r$, where z_{ij}^{sr} $(i = j = 1, \cdots, n)$ represents the transfer from sector i of country s to sector j of country r. The intermediate input matrix from country s to country r is represented by $Z^{sr} = A^{sr}X^r$. Eq. (1) can be rearranged as follows:

$$\begin{bmatrix} X^1 \\ X^2 \\ \vdots \\ X^g \end{bmatrix} = \begin{bmatrix} I-A^{11} & -A^{12} & \cdots & -A^{1g} \\ -A^{21} & I-A^{22} & \cdots & -A^{2g} \\ \vdots & \vdots & \ddots & \vdots \\ -A^{g1} & -A^{g2} & \cdots & I-A^{gg} \end{bmatrix}^{-1} \begin{bmatrix} \sum_r^G Y^{1r} \\ \sum_r^G Y^{2r} \\ \vdots \\ \sum_r^G Y^{gr} \end{bmatrix}$$
$$= \begin{bmatrix} B^{11} & B^{12} & \cdots & B^{1g} \\ B^{21} & B^{22} & \cdots & B^{2g} \\ \vdots & \vdots & \ddots & \vdots \\ B^{g1} & B^{g2} & \cdots & B^{gg} \end{bmatrix} \begin{bmatrix} \sum_r^G Y^{1r} \\ \sum_r^G Y^{2r} \\ \vdots \\ \sum_r^G Y^{gr} \end{bmatrix} \tag{2}$$

where B^{sr} represents the quantity of the gross output of country s for a one-unit increase in the final demand of country r. From Eq. (2), the final output of country r is as follows:

$$X^r = \sum_t^G B^{rt} \sum_u^G Y^{tu} \tag{3}$$

The intermediate input of country r from country s is $Z^{sr} = A^{sr}X^r$. Here, gross output is converted from an endogenous to an exogenous variable. Then, the bilateral exports from country s to country r can be divided into two types: direct and cumulative exports (i.e., exports embodied in exports) (Muradov, 2015). The direct exports represent the direct trade linkage between two countries, and the traded products are not necessarily absorbed by the trade partner. The cumulative exports represent the direct and indirect delivery of exported products between two regions, and the traded products are absorbed by the other region.

$$T_{bil}^{sr} = \underbrace{Y^{sr}}_{T_{bil,f}^{sr}} + \underbrace{A^{sr} \sum_t^G B^{rt} Y^{ts}}_{R_{bil,i}^{sr}} + \underbrace{A^{sr} \sum_t^G B^{rt} \sum_{u \neq s}^G Y^{tu}}_{T_{bil,i}^{sr}} \tag{4a}$$

$$T_{cum}^{sr} = \underbrace{Y^{sr}}_{T_{cum,f}^{sr}} + \underbrace{\sum_{u \neq s}^G A^{su} \sum_t^G B^{ut} Y^{tr}}_{T_{cum,i}^{sr}} \tag{4b}$$

where $T_{bil,\,f}^{sr}$ and $T_{cum,\,f}^{sr}$ represent the direct and cumulative exports, respectively, of final goods $(T_{bil,\,f}^{sr} = T_{cum,\,f}^{sr})$, $R_{bil,\,i}^{sr}$ represents the direct exports of intermediate goods that would be returned and absorbed by country s, $T_{bil,\,i}^{sr}$ represents the direct exports of intermediate goods that would be absorbed by other countries, and $T_{cum,\,i}^{sr}$ represents the cumulative exports of intermediate goods that would be finally absorbed by country r. The intermediate goods trade can be further divided by the international production stage (Arce González et al., 2012; López et al., 2013). Appendix A presents the method used to categorize international trade into three patterns: the final goods trade, trade in intermediate goods for the last stage of production and trade in intermediate goods for the remaining stages of international production. The calculation results reveal that there is no significant influence on the regional carbon responsibility to further categorize the intermediate goods trade. Therefore, this study only divides trade into final and intermediate goods trade.

Based on the balance of gross output $X^s = A^{ss}X^s + Y^{ss} + \sum_{s \neq r}^M T_{bil}^{sr}$, this paper obtains the gross output of country s as $X^s = L^{ss}Y^{ss} + L^{ss} \sum_{s \neq r}^G T_{bil}^{sr}$, where $L^{rr} = (I - A^{rr})^{-1}$ is the domestic Leontief inverse matrix of country r. This study defines the carbon intensity of sector i of country s as $f_i^s = e_i^s / x_i^s$, where e_i^s represents the CO_2 emissions of sector i of country s. F^s is a diagonal matrix that consists of f_i^s. The production-based emissions of country s are as follows:

$$E_{pro}^s = F^s L^{ss} \# \tilde{Y}^{ss} + F^s L^{ss} \# \sum_{s \neq r}^G \tilde{R}_{bil,i}^{sr} + F^s L^{ss} \# \sum_{s \neq r}^G \tilde{T}_{bil,f}^{sr} + F^s L^{ss} \# \sum_{s \neq r}^G \tilde{T}_{bil,i}^{sr} \tag{5}$$

where # indicates element-wise matrix multiplication, and $\tilde{T}_{bil,f}^{sr} = \begin{bmatrix} (T_{bil,f}^{sr})_T \\ (T_{bil,f}^{sr})_T \\ \vdots \\ (T_{bil,f}^{sr})_T \end{bmatrix}$. The consumption-based emissions of country s are as follows:

$$E_{con}^s = E_{pro}^s - F^s L^{ss} \# \sum_h \sum_{r \neq s}^G \tilde{T}_{bil,h}^{sr} + \sum_h \sum_{r \neq s}^G F^r L^{rr} \# \tilde{T}_{cum,h}^{rs} \tag{6}$$

where $h = f, i$. CBA is the equivalent of PBA to which emissions embodied in cumulative exports from other regions to this region are added and from which emissions embodied in bilateral exports from this region to other regions are subtracted, and the bilateral exported products are finally absorbed by other regions. This paper defines the average emissions multiplier of different trade patterns as follows:

$$N_{bil,h} = \frac{\sum_{s}^{G}\sum_{r\neq s}^{G} F^s L^{ss} \# \tilde{T}_{bil,h}^{sr}}{\sum_{s}^{G}\sum_{r\neq s}^{G} \tilde{T}_{bil,h}^{sr}} \tag{7a}$$

$$N_{cum,h} = \frac{\sum_{s}^{G}\sum_{r\neq s}^{G} F^s L^{ss} \# \tilde{T}_{cum,h}^{sr}}{\sum_{s}^{G}\sum_{r\neq s}^{G} \tilde{T}_{cum,h}^{sr}} \tag{7b}$$

Since $\sum_{r}^{G} \tilde{T}_{bil,h}^{sr} = \sum_{r}^{G} \tilde{T}_{cum,h}^{sr}$, in this paper, $N_{bil,\ h} = N_{cum,\ h}$. Then, the technology-adjusted consumption-based accounting takes the following form:

$$TCBA^s = E_{pro}^s - \sum_{h} N_{bil,h} \# \sum_{r\neq s}^{G} \tilde{T}_{bil,h}^{sr} + \sum_{h}\sum_{r\neq s}^{G} F^r L^{rr} \# \tilde{T}_{cum,h}^{rs} \tag{8}$$

Eq. (8) has a similar formula as Eq. (6) except that the emissions embodied in bilateral exports are calculated based on the world average production technology. The TCBA approach not only considers the emissions produced by a country's final consumption but also the alternative production that is replaced by this country's exports. The exports of a region are credited if greener technology than the global average level is adopted by the region to produce exported products. In addition, TCBA encourages countries to import products from regions with a greener production technology level.

A mathematical expression of technology-adjusted production-based accounting was derived in this study:

$$TPBA^s = E_{con}^s - \sum_{h}\sum_{r\neq s}^{G} N_{cum,h} \# \tilde{T}_{cum,h}^{rs} + F^s L^{ss} \# \sum_{h}\sum_{r\neq s}^{G} \tilde{T}_{bil,h}^{sr} \tag{9}$$

TPBA considers not only the direct emissions in a country's territory but also the impact of this country's imports on global emissions. First, TPBA alleviates the carbon leakage problem faced by PBA. Second, TPBA encourages countries to clean up their export industries. Finally, Kander et al. (2015) note that national carbon accounting should encourage production specialization that generates global emissions savings. Vertical specialization is closely related to intermediate input linkage, which is represented by the domestic Leontief inverse matrix in the proposed technology-adjusted national carbon accounting approach. For instance, TPBA encourages exporters to reduce domestic sectoral carbon intensity and outsource the production stages that are relatively less environmentally effective. Therefore, the proposed technology-adjusted national carbon accounting scheme credits production specialization that generates global emissions savings.

4. Theoretical analysis

This section analyzes some conditions that a useful indicator for national carbon emissions responsibility should satisfy and compares the proposed analytical framework with the literature based on a simple example.

4.1. Four conditions of national carbon accounting schemes

Technology-adjusted national carbon accounting is mainly inspired by a condition of indicator of carbon responsibility that it should credit green trade patterns. To facilitate climate negotiations, an effective indicator of regional environmental responsibility should also satisfy several other conditions (Rodrigues et al., 2006).The previous literature (Domingos et al., 2016; Kander et al., 2015) paid special attention to four important conditions: 1) additivity, implying that the sum of national emissions for all countries should equal total global emissions; 2) sensitivity, implying that the accounting method should be responsive to factors that countries could influence; 3) monotonicity, implying that countries cannot reduce domestic emissions in ways that increase global emissions; and 4) the scale invariance condition, which means that the carbon responsibility of a union of countries should equal the sum of the carbon responsibilities of each county. This present paper also focuses on these four conditions.

To reach global climate targets, the indicator of regional environmental responsibility should decompose responsibility for global emissions and then assign them to different countries. National responsibility would be overestimated if the sum of their responsibility exceeded the global emissions. Besides, the global climate target cannot be guaranteed if no countries were responsible for a certain part of global emissions. Technology-adjusted national carbon accounting focuses mainly on carbon emissions generated to support international trade. The definition of the world average emissions multiplier of different trade patterns guarantees that the gross volume of embodied emissions in international trade remains consistent. Therefore, the technology-adjusted accounting method satisfies the additivity condition. The empirical analysis (Section 5) further shows that the volume of global emissions is not influenced by the adoption of technology-adjusted national carbon accounting schemes.

A country cannot reduce its carbon emissions at the cost of increasing global emissions. The effects of a country's behavior on global emissions should be reflected by the indicator of carbon responsibility. In other words, national carbon accounting should satisfy sensitivity and monotonicity conditions. Kander et al. (2015) note that technology-adjusted consumption-based carbon accounting does not fully satisfy the monotonicity condition and introduce additional assumptions to solve this problem. The present paper focuses primarily on technology-adjusted production-based carbon accounting and proposes a modified TPBA approach that satisfies the sensitivity and monotonicity conditions by redefining the world average emissions multiplier of different trade patterns (please see Appendix B). The modified TPBA approach subtracts embodied emissions in cumulative exports from other countries to the country being assessed based on the world average technology for exports, which does not include the corresponding exporter country. The modified TPBA approach provides an alternative choice for policy makers when they believe the monotonicity condition is more important than the additivity condition. Kander et al. (2015) note that it may be impossible to construct a measure that satisfies both monotonicity and additivity conditions.

Domingos et al. (2016) note that technology-adjusted accounting should satisfy the scale invariance condition. This condition is especially important because of the existence of country unions. For instance, the sum of all EU countries' carbon responsibility should be equal to the carbon responsibility of the EU. To address this problem, this paper distinguishes between domestic trade within the union and international trade. The bilateral and cumulative exports between two countries within the union of countries should be replaced by the average production technology of the union; alternatively, the replaced exports would be provided by the world average production technology. When we define a group of regions as a union, we tacitly admit that this group of regions differs from the other groups, as does the corresponding trade. For instance, trade between provinces within China is termed domestic trade, whereas trade between provinces and other countries is termed

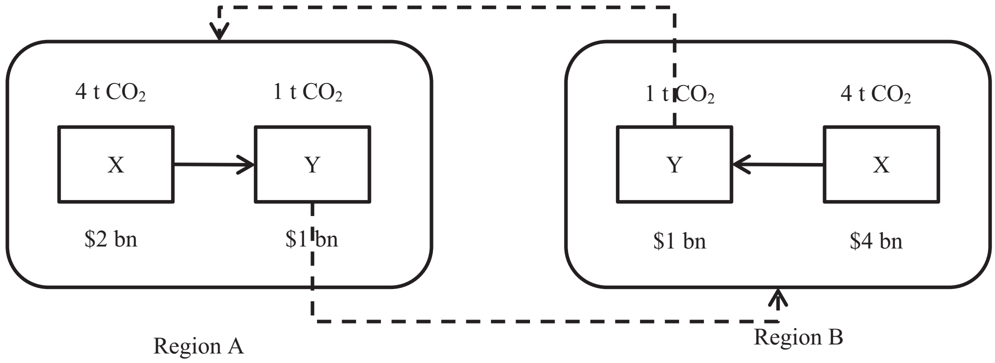

Fig. 1. Sectoral output, emissions and economic linkage for Regions A and B.

international trade. The replaced exports between provinces would be produced by the average production technology of these provinces; alternatively, the replaced exports would be provided by the world average production technology. As shown in Appendix C, the carbon responsibility that is determined by the average of the TPBA and TCBA accounting schemes, which is similar to the share-responsibility scheme (Lenzen et al., 2007), satisfies the scale invariance condition.

The above shows that the technology-adjusted carbon accounting method satisfies the additivity, sensitivity, monotonicity, and scale invariance conditions, through proper selection of the world average emissions multipliers. This highlights that technology-adjusted national carbon accounting has potential applications for determining regional carbon responsibility.

4.2. Comparisons with the literature using a simple example

This section compares this study's analysis framework with that proposed by Kander et al.'s study (2015) based on a two-region (region A and region B) model. Each region contains two vertically linked sectors (sector X and sector Y). The economic linkage is presented in Fig. 1.

All products of upstream sector X are used to satisfy the domestic intermediate demand of downstream sector Y, and the gross output of sector Y is exported to satisfy foreign demand. The outputs of sectors X and Y in region A are \$2 billion (bn) and \$1 bn, respectively. The outputs of sectors X and Y in region B are \$4 bn and \$1 bn, respectively. It is assumed that the two regions have the same price level. The sectoral CO_2 emissions of region A are 2 ton (t) for sector X and 1 t for sector Y. The sectoral CO_2 emissions of region B are 1 t for both sectors X and Y. Based on the method proposed by Kander et al. (2015) and that proposed in this paper, the carbon responsibility of the two regions under different carbon accounting frameworks is presented in Table 1.

Under PBA and CBA, the direct emissions within the territory of these two regions are both 5 t. The method proposed by Kander et al. (2015) focuses primarily on the difference in sectoral carbon intensity. For sector Y, regions A and B have the same carbon intensity (1 t/bn). However, region A has greater carbon intensity for sector X (2 t/bn) compared with region B (1 t/bn). Therefore, region A bears greater carbon responsibility than region B under the TCBA approach proposed by Kander et al.'s study (2015).[1] However, when the intermediate input structure is considered, the exports of regions A and B contribute equally to global emissions. The production of exports of region A requires a smaller scale of intermediate inputs than does that of region B. However, the production of intermediate inputs of region A corresponds to greater carbon intensity than that of region B. From a comprehensive perspective, there is no difference between the CO_2 emissions produced by the exports of the two regions. Thus, regional emissions under the four different accounting systems are equal under the TPBA and TCBA approaches proposed in this study.

Significant differences exist between backward tracing the gross emissions induced by the exports of a particular sector and forward integrating a particular sector's CO_2 emissions induced by a region's gross exports. Kander et al. (2015) adopt the forward industrial linkage perspective. However, this study argues that technology-adjusted carbon accounting should focus on regional differences in domestic emissions generated to support the production of a sector's gross exports (i.e., backward industrial linkage) rather than a sector's emissions generated to support exports of different sectors (i.e., forward industrial linkage). This is because the production of replaced exports not only promotes direct CO_2 emissions from the corresponding sectors but also stimulates the indirect emissions of other sectors through intermediate input linkages. This phenomenon is the primary cause of the different results under these two analytical frameworks.

5. Empirical analysis

This section applies the proposed analytical framework to intercountry input-output tables. There are different global multi-region input-output databases that are suitable for this study, such as the WIOD (Timmer et al., 2015) and the Eora multi-region input-output table database (Lenzen et al., 2012). This study adopts the WIOD to facilitate the comparison of its calculation results with those presented by Kander et al. (2015). The production-based emissions are obtained directly from the “Environmental Accounts” of the WIOD 2013 release, which provides CO_2 emissions of 27 EU countries and 13 other major countries for the period 1995–2009. In line with previous literature (Kander et al., 2015; Peters, 2008; Peters et al., 2011), the consumption-based emissions are calculated based on the traditional

Table 1
Regional carbon responsibility according to different accounting approaches.

		PBA	CBA	TPBA	TCBA
Kander et al. (2015)	Region A	5 t	5 t	–	19/3 t
	Region B	5 t	5 t	–	11/3 t
This paper	Region A	5 t	5 t	5 t	5 t
	Region B	5 t	5 t	5 t	5 t

[1] The average carbon intensity of sector X is (4 t + 4 t) ÷ (2bn + 4bn) = 4 / 3 t/bn. The average carbon intensity of sector Y is (1 t + 1 t) ÷ (1bn + 1bn) = 1 t / bn. Under the analytical framework presented by Kander et al. (2015), the average emissions generated to produce region A's exports are 2bn × 4/3 t/bn + 1bn × 1 t / bn = 11 / 3 t, and the average emissions generated to produce region B's exports are 4bn × 4 / 3 t/bn + 1bn × 1 t/bn = 19 / 3 t. The embodied emissions in both regions A and B are 5 t. Then, region A's carbon responsibility under TCBA approach is 5 t – 11 / 3 t + 5 t = 19/3 t, and region B's carbon responsibility under TCBA is 5 t – 19 / 3 t + 5 t = 11/3 t.

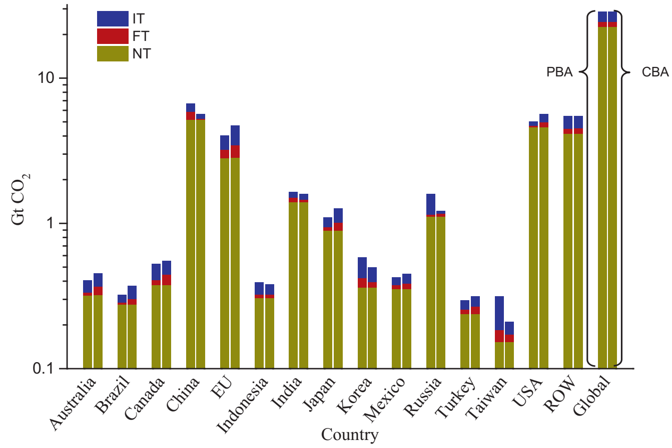

Fig. 2. National production- and consumption-based emissions related to different economic activities in 2009. Notes: NT: domestic economic activity that has no relationship with trade; FT: final goods trade; IT: intermediate goods trade.

Leontief demand-pull model. The inter-country input-output tables are also obtained from the WIOD 2013 release. The inter-country input-output tables document international trade flows from 1995 to 2009. According to Eqs. (4a) and (4b), international trade flows are divided into final and intermediate goods trade, and the latter is further divided based on the destination of final products. Carbon emissions embodied in different types of trade flows are calculated as the product of the emissions multiplier and the trade volume. Based on the world average emissions multiplier, calculated by Eqs. (7a) and (7b), this study obtains the potential world average emissions generated to produce the traded products. Based on Eqs. (8) and (9), this study obtains the regional emissions under TPBA and TCBA. The calculation results are presented below.

5.1. CO_2 emissions embodied in direct and cumulative exports

Given that production has become increasingly fragmented across national boundaries, how to distribute CO_2 emissions induced by global production activity along the supply chain is a key difference among the various carbon accounting methods (Davis et al., 2011; Davis and Caldeira, 2010; Lenzen et al., 2007; Peters and Hertwich, 2008b). For instance, domestic emissions induced by pure domestic economic activity are covered by PBA and CBA. However, PBA calculates domestic emissions induced by domestic consumption and direct exports of final and intermediate goods in a certain region, whereas CBA measures emissions embodied in domestic consumption and cumulative exports from other regions to this region. The decomposition of regional and global CO_2 emissions under PBA and CBA is presented in Fig. 2.

For each region, the left bar represents the regional emissions under PBA, which are further divided into three parts. The first part consists of emissions solely induced by domestic economic activity. The second part represents the emissions induced by direct exports of final goods, and the third part is the emissions induced by direct exports of intermediate goods. The right bar represents the regional emissions under CBA, which are also divided into three parts. The first part represents emissions induced solely by domestic economic activity. The second part consists of the emissions induced by cumulative exports of final goods from other regions to a particular region. The third part represents the emissions induced by the cumulative exports of intermediate goods from other regions to a particular region. The total cumulative exports to all destinations are equal to the total direct gross exports (Muradov, 2015). Therefore, from the global perspective, PBA and CBA are consistent.

The regional emissions that are related solely to domestic economic activity are equal under PBA and CBA. However, there are significant differences among the regional emissions that are related to international trade. For example, China's emissions embodied in direct exports to other regions are greater than the emissions that are induced by cumulative exports from other regions to China. This fact means that China is a net carbon exporter, which corresponds to lower CO_2 emissions under

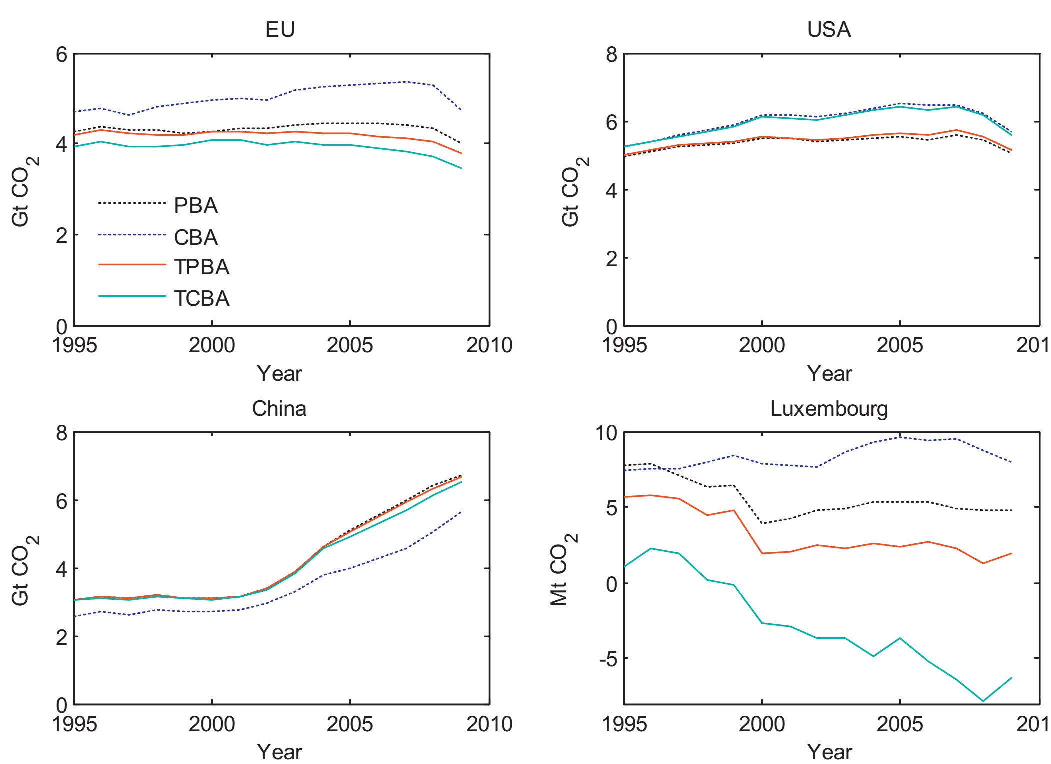

Fig. 3. Changing trends of emissions of the EU, the USA, China and Luxembourg according to four accounting systems (1995 to 2009).

CBA. The other net carbon exporters are Russia, Taiwan, and Korea. These countries generate large-scale CO_2 emissions to support consumption in developed regions, such as the USA and the EU, which are net carbon importers.

This paper further divides international trade into final and intermediate goods trades. Fig. 2 shows that the intermediate goods trade plays a significant role in international carbon transfer that is critical to the determination of regional carbon responsibility. The downstream region of production chains tends to be located in China. Therefore, the magnitude of emissions that are related to the final goods trade is greater under PBA than under CBA. The different trade patterns of the final and intermediate goods trade mean that there would be significant differences in the world average carbon intensity of different trade patterns, which is critical to estimating regional emissions under technology-adjusted carbon accounting. This study further discusses regional emissions under four different accounting methods.

5.2. Changing trends of regional emissions over the 1995–2009 period

Regional carbon responsibility under PBA and CBA is interconvertible. A region's emissions under CBA are equal to emissions under PBA after adding emissions embodied in cumulative exports to this region and subtracting emissions induced by direct exports of this region. TCBA applies a formula similar to CBA, but subtracts exported emissions based on the world average intensity. Similarly, a region's emissions under TPBA are equal to regional emissions under CBA after adding emissions embodied in bilateral exports of this region and subtracting emissions generated to produce cumulative exports to this region by the world average production technology. The changing trends of CO_2 emissions of the EU, the USA, China and Luxembourg according to four accounting methods are presented in Fig. 3.

For the EU, emissions under TCBA are significantly lower than those calculated under CBA, and emissions under TPBA are lower than those calculated under PBA. This fact implies that the EU has lower carbon intensity than the world average and imports products from regions with a carbon intensity relatively lower than the world average. The EU contributes to global carbon savings through trade with other countries. This is consistent with the literature. Zhang et al. (2017a, 2017b) estimated the effects of international trade on regional and domestic emissions and found that most EU countries correspond to a negative balance of embodied emissions and a negative balance of avoided emissions. Thus, the EU bears lower carbon responsibility under technology-adjusted carbon accounting.

For the USA, CO_2 emissions under CBA are greater than those calculated under PBA. There is no significant decrease in national carbon responsibility when CBA shifts to TCBA. This outcome implies that the carbon efficiency of the USA remained consistent with the world average during the study period. The USA's CO_2 emissions under TPBA are slightly higher than those calculated under PBA, indicating that the imports of the USA have a positive impact on global emissions. Zhang et al. (2017a, 2017b) reported that the USA reduced domestic emissions by 469.23 million tons through international trade, but this resulted in greater global emissions by 70.13 million tons. This means that other developing countries, such as China, emit more CO_2 to produce the products exported to the USA.

For China, the CO_2 emissions under PBA, TPBA and TCBA are nearly the same or greater than those calculated under CBA. First, China is the world's largest net carbon exporter(Liu et al., 2015). Thus, CO_2 emissions under CBA are obviously lower than those calculated under PBA. Second, China has a carbon intensity that is higher than the world average. Therefore, CO_2 emissions under TCBA are obviously greater than those calculated under CBA. Third, the carbon intensity of China's imported products is similar to the world average. Thus, there is no significant change in national carbon responsibility when the carbon accounting system shifts from PBA to TPBA.

Luxembourg is an EU country. The ranking of Luxembourg's CO_2 emissions under the four different accounting schemes is consistent with that of the EU (CBA > PBA > TPBA > TCBA). However, the carbon responsibility under TCBA is negative because the carbon intensity of Luxembourg's exports is significantly lower than the world average. Under TPBA, the carbon responsibility of Luxembourg is also small but positive. The sign of the carbon responsibility under TCBA is determined by the relative size of the domestic carbon intensity and the world average carbon intensity, while the sign of a country's carbon responsibility under TPBA depends on the relative size of the carbon intensities of the countries that export products to that country and the world average carbon intensity. In other words, the sign of TCBA is determined only by domestic carbon intensity, while the sign of TPBA is determined by all direct and indirect trade partners. Therefore, regional carbon responsibility under TPBA is less likely to be negative than that under TCBA because of trade diversification.

5.3. Mapping global emissions in 2009

A country has different carbon reduction responsibilities, under different carbon accounting schemes. This section presents the regional carbon responsibility under four different accounting schemes from the perspective of total and per capita emissions. National CO_2 emissions in 2009 under the four accounting methods are presented in Table 2.

Table 2
National CO_2 emissions in 2009 under the four accounting methods (billion tons).

	PBA	CBA	TPBA	TCBA
China	6695.76	5651.32	6643.26	6503.84
United States	5025.43	5669.82	5143.92	5583.98
India	1642.72	1594.93	1685.40	1732.80
Russia	1598.29	1223.72	1590.05	1540.32
Japan	1101.93	1270.45	1173.36	1177.45
Germany	816.63	958.06	786.66	625.25
Korea	584.06	498.72	600.34	526.15
United Kingdom	558.63	658.82	526.19	580.71
Canada	528.89	554.69	541.18	528.31
Mexico	426.68	450.54	428.33	428.10
Italy	424.77	544.61	404.73	423.99
Australia	405.47	453.55	427.77	427.74
Indonesia	392.85	380.48	407.46	400.96
France	385.68	547.44	349.90	375.01
Brazil	322.73	370.46	327.37	338.03
Poland	316.88	291.50	309.33	301.05
Taiwan	313.74	210.86	317.28	258.55
Spain	299.99	370.75	271.78	303.06
Turkey	296.44	315.32	294.17	309.34
Netherlands	204.70	210.10	194.43	109.58
Belgium	120.63	145.59	102.74	51.63
Greece	110.03	139.07	107.16	117.23
Czech Republic	108.59	97.34	103.20	82.06
Romania	91.44	96.08	86.49	95.07
Denmark	86.56	63.84	79.57	36.00
Austria	64.20	94.62	52.42	39.81
Finland	61.80	69.97	60.38	53.25
Portugal	61.32	71.03	49.38	56.89
Sweden	57.85	81.47	47.55	31.50
Hungary	52.99	57.61	49.06	39.80
Bulgaria	46.52	37.60	46.56	44.04
Ireland	42.56	58.93	37.46	2.69
Slovak Republic	36.03	37.08	35.75	30.48
Slovenia	17.67	20.52	16.09	14.12
Estonia	15.58	12.35	15.51	14.21
Lithuania	14.83	19.39	16.81	16.16
Latvia	8.35	10.89	8.62	9.37
Cyprus	8.33	11.29	8.02	10.39
Luxembourg	4.81	7.97	1.98	−6.25
Malta	2.84	3.56	2.40	2.37
Rest of world	5494.18	5487.00	5499.29	5634.27
Total	28,849.33	28,849.33	28,849.33	28,849.33

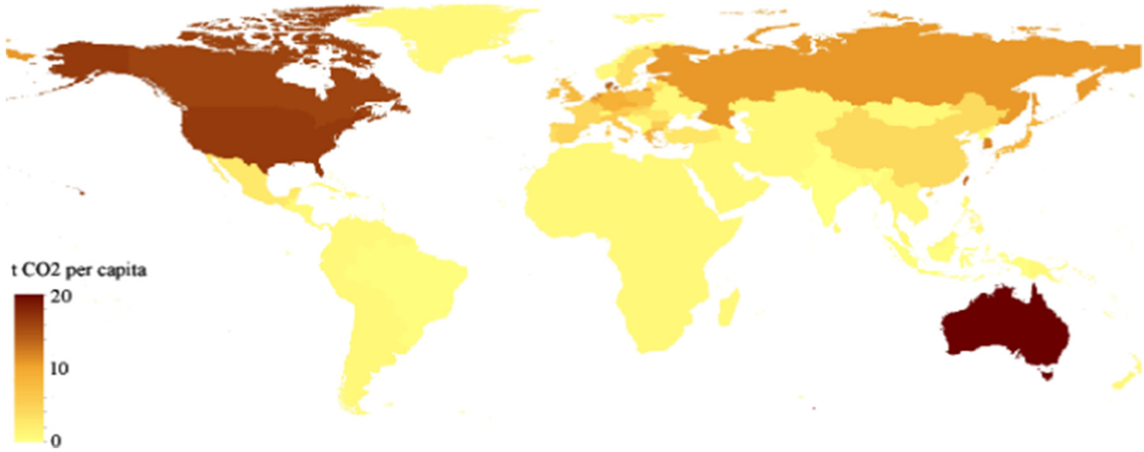

Fig. 4. Regional per-capita emissions under TPBA in 2009.

The global emissions are equal for the four different accounting schemes. China, the USA and India are always the top three countries with the largest carbon responsibility under the four carbon accounting systems. Under PBA, TPBA, and TCBA, Russia is the fourth greatest carbon emitter, followed by Japan and Germany. However, under CBA, Japan is responsible for more CO_2 emissions than Russia. Except Russia, the other developing countries with relatively high carbon intensity, such as China and India, tend to have lower carbon responsibility under CBA than under the three other accounting systems. The opposite tends to be true for developed regions, such as the USA, Japan and Germany. The TCBA scheme significantly reduces the carbon responsibility of EU countries. For instance, the carbon responsibility of Ireland decreases from 42.56 million tons under PBA and 58.93 million tons under CBA to 2.69 million tons under TCBA. The other EU countries may also face this problem. For instance, Luxembourg faces negative carbon responsibility. However, regional CO_2 emissions under TPBA are all positive. The carbon responsibility of several countries, such as China, India, Japan, Canada, Mexico and Australia, is similar under TPBA and TCBA.

A suitable carbon accounting method exists for all theoretical situations, but it may not be the best method for a given real situation. Each accounting scheme has limitations. For instance, production and consumption are simultaneously influenced by producers and consumers. However, PBA and TPBA allocate all responsibility for production to producers. By contrast, CBA and TCBA allocate all responsibility for consumption to consumers. The advantage of TPBA over PBA is that it accounts for carbon leakage in carbon-intensive regions. The advantage of TCBA over CBA is that it encourages countries to clean up their exports. Given the consideration that PBA will remain a core indicator of regional responsibility in the future (Steininger et al., 2016), TPBA may be more acceptable than TCBA. This paper maps regional per-capita emissions under TPBA for 2009.

Per-capita CO_2 emissions provide a more accurate and useful picture of carbon responsibility than absolute CO_2 emissions (Wiedenhofer et al., 2016). Fig. 4 maps regional CO_2 emissions per capita under TPBA. The results show that Australia has the highest level of per-capita emissions (19.72 t CO_2 per capita), followed by the USA and Canada. India (1.39 t CO_2 per capita) has the lowest per-capita emissions, followed by Brazil and Indonesia. Significant differences exist between regional responsibility from the gross and the per-capita perspectives. China has the largest scale of absolute CO_2 emissions because of its large population. China's carbon responsibility is 4.99 t CO_2 per capita, which is greater than the world average level of 4.256 t CO_2 per capita but significantly lower than that of most regions.

5.4. Empirical comparisons with the literature

This paper is based on the study conducted by Kander et al. (2015); these authors first proposed the TCBA approach and drew a global emissions map for the period 1995–2009. Since the intermediate input structure is closely related to production technology, this study takes the intermediate input structure and different trade patterns into account and redraws the global emissions map for the same period. This section compares the calculation results of this study with those presented by Kander et al. (2015), using the EU and China as examples (Fig. 5).

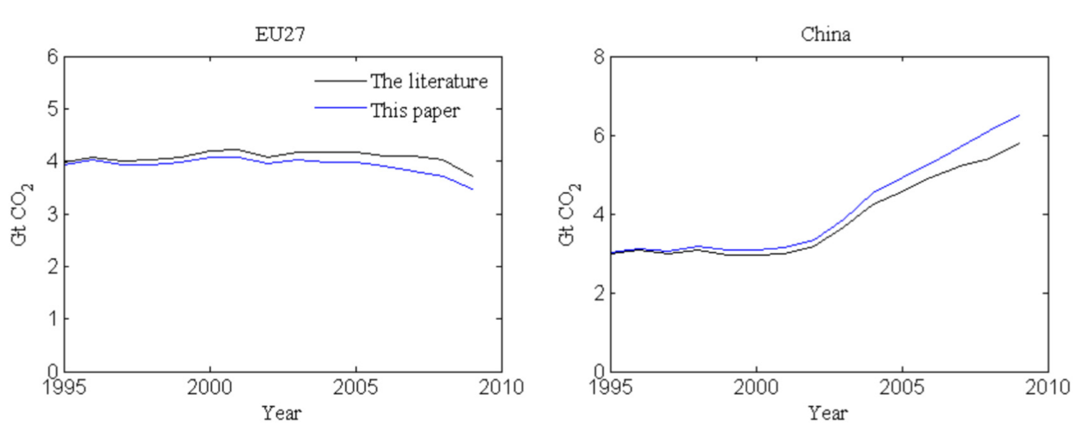

Fig. 5. Comparisons with literature results.

Fig. 5 shows that the EU is responsible for a lower volume of CO_2 emissions under the TCBA approach proposed in this paper compared with the TCBA approach proposed by Kander et al. (2015), and China bears greater carbon responsibility under the TCBA approach proposed in this present paper. The intermediate input structure of production in the EU is more environmentally effective than the world average level. Therefore, the EU bears less carbon responsibility under the TCBA approach proposed in this study. By contrast, China bears greater carbon responsibility because of its less environmentally effective intermediate input linkage. In addition, final product exports account for a greater share of China's gross exports because of China's role as the world's factory. Zhang et al. (2017a, 2017b) note that the final products trade positively contributes to global emissions over the period 1995–2009. With a distinction between different trade patterns, the method proposed in this study may also increase China's carbon responsibility. The policy implication is that national carbon accounting should not only encourage countries to decrease the carbon intensity of their export sectors but also encourage them to clean up their domestic supply chains.

6. Conclusions

Against the background that a large percentage of global emissions are generated to support international trade, Kander et al. (2015) proposed a technology-adjusted national carbon accounting scheme to encourage trade patterns that generate global carbon savings. This paper extends this scheme by taking the intermediate input structure into account, which is also closely related to the production technology of exports. In addition, this paper proposes technology-adjusted production-based accounting, given the consideration that production-based accounting will remain the core indicator for regional emissions in the near future (Steininger et al., 2016). The empirical study is based on the WIOD and calculates regional emissions under four different accounting methods. The main results of this study are presented below.

This study redraws the global CO_2 emissions map using technology-adjusted national carbon accounting. The EU bears lower carbon responsibility under TPBA and TCBA. There is no significant change in the USA's carbon responsibility when the national carbon accounting approach shifts from PBA (CBA) to TPBA (TCBA). China's carbon responsibility is nearly identical under PBA, TCBA and TPBA. Luxembourg faces negative carbon responsibility under TCBA, which is in line with Kander et al.'s study (2015). The developing countries not only correspond to greater direct carbon intensity but also have a less environmentally effective intermediate input structure. Therefore, according to this paper's accounting scheme, developing countries tend to bear greater carbon responsibility than that reported in Kander et al.'s study (2015). Finally, this paper demonstrates that the proposed technology-adjusted carbon accounting method satisfies the conditions of sensitivity, monotonicity, additivity and scale invariance, through proper selection of average emissions multipliers.

This study has several limitations. First, firms may adopt a different technology to produce products for exports and final demand. Export producers tend to have a lower carbon intensity than the national average level (Weber and Matthews, 2007), particularly foreign-invested enterprises (Dietzenbacher et al., 2012; Jiang et al., 2015; Su et al., 2013). However, this paper does not distinguish between production technology for exports and final demand because the input-output model assumes the output of each sector is homogeneous. This limitation results in an overestimation of the scale of carbon transfer for exports and influences the measurement of the national carbon inventory. Second, the technology-adjusted carbon accounting scheme assumes that the traded products are produced with the world average production technology. However, other countries may not have the corresponding technology and resources. It is suggested that future studies consider the regional differences in technology levels and resource endowment. Third, although various databases were suitable for this study, this study calculated the CO_2 emissions of different countries using only the WIOD. It is suggested that future studies apply the proposed method to other databases.

Acknowledgements

The author gratefully acknowledge the financial support from the National Natural Science Foundation of China (grant nos. 71690243 and 71603179), Tianjin Program of Philosophy and Social Science (TJGL16-007Q), and Seed Foundation of Tianjin University (2017XSZ-0016). I also would like to thank the anonymous referees and the editors.

Appendix A. Intermediate goods trade is divided by stages of processing

The intermediate goods trade can be further divided by international production stage (Arce González et al., 2012; López et al., 2013). This section provides the method for categorizing international trade into three patterns, which are final goods trade, trade in intermediate goods for the last stage of production and trade in intermediate good for the remaining stages of international production. The exports from country s to country r are $T^{sr} = Y^{sr} + A^{sr}X^{r}$. From Wang et al.'s study (2015), we can prove that $B^{rr} = L^{rr} + L^{rr}\sum_{t \neq r}^{G} A^{rt}B^{tr}$. We obtain the bilateral exports from country s to country r:

$$T_{bil}^{sr} = \underbrace{Y^{sr}}_{T_{bil,f}^{sr}} + \underbrace{A^{sr}L^{rr}Y^{rr}}_{T_{bil,i}^{sr}} + \underbrace{A^{sr}\sum_{t}^{G} B^{rt}Y^{ts}}_{R_{bil,g}^{sr}} + \underbrace{A^{sr}L^{rr}\sum_{t \neq r}^{G} A^{rt}B^{tr}Y^{rr} + A^{sr}\sum_{t \neq r}^{G} B^{rt}Y^{tr} + A^{sr}\sum_{t}^{G} B^{rt}\sum_{u \neq s,r}^{G} Y^{tu}}_{T_{bil,g}^{sr}} \quad (A1)$$

where $L^{rr} = (I - A^{rr})^{-1}$ is the domestic Leontief inverse matrix of country r. $T_{bil,f}^{sr}$ defines trade in final products. The trade partner would directly absorb the exported products, and the exporter is located in the last stage of production. $T_{bil,i}^{sr}$ is the traditional trade in intermediate products for the last stage of international production, which need to be further processed by the trade partner before finally being absorbed by the trade partner. $R_{bil,g}^{sr}$ is the narrowly defined global value chain related trade, and the traded products would finally return to country s. $T_{bil,g}^{sr}$ is the narrowly defined global value chain related trade, and the traded products would finally be absorbed by other countries.

Based on the balance of gross output $X^{s} = A^{ss}X^{s} + Y^{ss} + \sum_{s \neq r}^{M} T_{bil}^{sr}$, we obtain the gross output of country s as $X^{s} = L^{ss}Y^{ss} + L^{ss}\sum_{s \neq r}^{G} T_{bil}^{sr}$. The production-based emissions of country s are

$$E_{pro}^{s} = F^{s}X^{s} = F^{s}L^{ss}\#\tilde{Y}^{ss} + F^{s}L^{ss}\#\sum_{s \neq r}^{G} \tilde{R}_{bil,g}^{sr} + \sum_{h} F^{s}L^{ss}\#\sum_{s \neq r}^{G} \tilde{T}_{bil,h}^{sr} \quad (A2)$$

where $h = f, i, g$. The cumulative exports from country s to country r are

$$T_{cum}^{sr} = \underbrace{Y^{sr}}_{T_{cum,f}^{sr}} + \underbrace{A^{sr}L^{rr}Y^{rr}}_{T_{cum,i}^{sr}} + \underbrace{A^{sr}L^{rr}\sum_{t \neq r}^{G} A^{rt}B^{tr}Y^{rr} + A^{sr}\sum_{t \neq r}^{G} B^{rt}Y^{tr} + \sum_{u \neq s,r}^{G} A^{su}\sum_{t}^{G} B^{ut}Y^{tr}}_{T_{cum,g}^{sr}} \quad (A3)$$

The consumption-based emissions of country s are

$$E^s_{con} = E^s_{pro} - F^sL^{ss}\#\sum_h\sum_{r\neq s}^{G}\tilde{T}^{sr}_{bil,h} + \sum_h\sum_{r\neq s}^{G}F^rL^{rr}\#\tilde{T}^{rs}_{cum,h} \quad (A4)$$

The average emissions multiplier of different production stages of international production of the first type is defined as

$$\begin{cases} N_{bil,h} = \dfrac{\sum_{s,r}F^sL^{ss}\#\tilde{T}^{sr}_{bil,h}}{\sum_{s,r}\tilde{T}^{sr}_{bil,h}} \\ N_{cum,h} = \dfrac{\sum_{s,r}F^sL^{ss}\#\tilde{T}^{sr}_{cum,h}}{\sum_{s,r}\tilde{T}^{sr}_{cum,h}} \end{cases} \quad (A5)$$

Technology-adjusted production-based accounting is defined as

$$TPBA^s = E^s_{con} - \sum_h\sum_{r\neq s}^{G}N_{cum,h}\#\tilde{T}^{rs}_{cum,h} + F^sL^{ss}\#\sum_h\sum_{r\neq s}^{G}\tilde{T}^{sr}_{bil,h} \quad (A6)$$

Technology-adjusted consumption-based accounting is defined as

$$TCBA^s = E^s_{pro} - \sum_h N_{bil,h}\#\sum_{r\neq s}^{G}\tilde{T}^{sr}_{bil,h} + \sum_h\sum_{r\neq s}^{G}F^rL^{rr}\#\tilde{T}^{rs}_{cum,h} \quad (A7)$$

This study calculates the national carbon responsibility under TPBA (please refer to Appendix A1), in which the intermediate goods trade is further divided by the stage of processing. The results show that there is no significant difference in carbon responsibility for the two scenarios. Thus the paper only divides the trade into final and intermediate goods trade.

Appendix B. Modified TPBA to satisfy the monotonicity condition

Technology-adjusted carbon accounting does not fully satisfy the monotonicity condition (Kander et al., 2015). Kander et al. (2015) prove that TCBA satisfies the additivity, sensitivity and monotonicity conditions only under certain restrictive assumptions. The present paper proposes a modified TPBA approach that satisfies sensitivity and monotonicity conditions by defining the world average emissions multiplier of different trade pattern as $\dot{N}_{cum,h} = \frac{\sum_{r\neq s,t\neq s,r}F^rL^{rr}\#\triangle\tilde{T}^{rt}_{com,h}}{\sum_{r\neq s,t\neq s,r}\triangle\tilde{T}^{rt}_{com,h}}$. The proof is presented below.

The sum of global emissions is $G = \sum_r E^r_{pro} = \sum_r E^r_{con}$. The change in global emissions is.

$$\triangle G = \triangle E^s_{con} + \sum_{r\neq s}\triangle E^r_{con} \quad (B1)$$

Under CBA, the change in emissions outside country s is $\sum_{r\neq s}\triangle E^r_{con} = \sum_h\sum_{r,t\neq s}F^rL^{rr}\#\triangle\tilde{T}^{rt}_{com,h}$. Consequently, the following is derived:

$$\triangle G = \triangle E^s_{con} + \sum_h\sum_{t\neq s}F^sL^{ss}\#\triangle\tilde{T}^{st}_{com,h} + \sum_h\sum_{r\neq s}F^sL^{ss}\#\triangle\tilde{R}^{sr}_{bil,h} + \sum_h\sum_{r\neq s,t\neq s,r}F^rL^{rr}\#\triangle\tilde{T}^{rt}_{com,h} \quad (B2)$$

This paper assumes that the cumulative exports from country r to country s are delivered to other countries, implying that $\sum_{r\neq s,t\neq s,r}\triangle\tilde{T}^{rt}_{cum,h} = -\triangle\tilde{T}^{rs}_{cum,h}$. Consequently, the following is derived:

$$\triangle G = \triangle E^s_{con} + \sum_h\sum_{s\neq t}F^sL^{ss}\#\triangle\tilde{T}^{st}_{com,h} + \sum_h\sum_{r\neq s}F^sL^{ss}\#\triangle\tilde{R}^{sr}_{bil,h} - \sum_h\sum_{r\neq s}\dot{N}_{cum,h}\#\triangle\tilde{T}^{rs}_{cum,h} \quad (B3)$$

The direct and cumulative exports of country s satisfy $\sum_{s\neq t}F^sL^{ss}\#\triangle\tilde{T}^{st}_{com,h} + \sum_{r\neq s}F^sL^{ss}\#\triangle\tilde{R}^{sr}_{bil,h} = \sum_{r\neq s}F^sL^{ss}\#\triangle\tilde{T}^{sr}_{bil,h}$. Consequently, the following is derived:

$$\triangle G = \triangle E^s_{con} + \sum_h\sum_{r\neq s}F^sL^{ss}\#\triangle\tilde{T}^{sr}_{bil,h} - \sum_h\sum_{r\neq s}\dot{N}_{cum,h}\#\triangle\tilde{T}^{rs}_{cum,h} \quad (B4)$$

According to Eq. (9), we can calculate the changes in a country's TPBA.

$$\triangle TPBA^s = \triangle E^s_{con} + \sum_h\sum_{r\neq s}F^sL^{ss}\#\triangle\tilde{T}^{sr}_{bil,h} - \sum_h\sum_{r\neq s}\dot{N}_{cum,h}\#\triangle\tilde{T}^{rs}_{cum,h} \quad (B5)$$

The equation $\triangle G = \triangle TPBA^s$ implies that it is impossible for a country to reduce its carbon emissions at the cost of increasing global emissions. In addition, the effects of a country's behavior on global emissions are reflected in the indicator of carbon responsibility. The modified

Table A1
National carbon responsibility under TPBA.

	TPBA (Intermediate goods trade is not further divided)	TPBA (Intermediate goods trade is divided by stage of processing)	Rate of change
Australia	427.33	427.77	0.10%
Austria	52.46	52.42	−0.08%
Belgium	102.52	102.74	0.22%
Bulgaria	46.58	46.56	−0.04%
Brazil	327.02	327.37	0.11%
Canada	540.70	541.18	0.09%
China	6642.25	6643.26	0.02%
Cyprus	8.01	8.02	0.07%
Czech Republic	103.19	103.20	0.02%
Germany	786.12	786.66	0.07%
Denmark	79.57	79.57	0.00%
Spain	271.66	271.78	0.05%
Estonia	15.49	15.51	0.10%
Finland	60.38	60.38	0.00%
France	349.85	349.90	0.02%
United Kingdom	526.00	526.19	0.04%
Greece	107.20	107.16	−0.03%
Hungary	49.07	49.06	−0.03%
Indonesia	407.05	407.46	0.10%
India	1685.80	1685.40	−0.02%
Ireland	37.39	37.46	0.18%
Italy	405.70	404.73	−0.24%
Japan	1174.53	1173.36	−0.10%
Korea	600.10	600.34	0.04%
Lithuania	16.84	16.81	−0.18%
Luxembourg	1.99	1.98	−0.31%
Latvia	8.59	8.62	0.24%
Mexico	427.39	428.33	0.22%
Malta	2.39	2.40	0.29%
Netherlands	194.30	194.43	0.07%
Poland	309.37	309.33	−0.01%
Portugal	49.38	49.38	0.00%
Romania	86.41	86.49	0.09%
Russis	1590.34	1590.05	−0.02%
Slovak Republic	35.80	35.75	−0.14%
Slovenia	16.05	16.09	0.26%
Sweden	47.60	47.55	−0.11%
Turkey	294.07	294.17	0.03%
Taiwan	317.17	317.28	0.04%
United States	5143.03	5143.92	0.02%
Rest of world	5502.64	5499.29	−0.06%
Sum	28,849.33	28,849.33	0.00%

TPBA satisfies both the sensitivity and monotonicity conditions. However, it should be noted that the modified TPBA no longer satisfies the additivity condition. This is consistent with the idea of Kander et al.'s study (2015), i.e., that it may be impossible to construct a measure that satisfies both monotonicity and additivity conditions.

Appendix C. Modified TPBA to satisfy the scale invariance condition

The scale invariance condition implies that the carbon responsibility of a union of countries should equal the sum of the carbon responsibilities of each county. For instance, the sum of the carbon responsibilities of provinces of China should be equal to China's carbon responsibility. This section explains a modified TPBA based on a world of G countries, which are divided into two groups V and U. The average production technology of the group of countries V is defined as.

$$N_{bil,h}^{V} = \frac{\sum_{s}^{V}\sum_{r\neq s}^{V} F^{s}L^{ss}\#\tilde{T}_{bil,h}^{sr}}{\sum_{s}^{V}\sum_{r\neq s}^{V}\tilde{T}_{bil,h}^{sr}} \quad (C1)$$

$$N_{cum,h}^{V} = \frac{\sum_{s}^{V}\sum_{r\neq s}^{V} F^{s}L^{ss}\#\tilde{T}_{cum,h}^{sr}}{\sum_{s}^{V}\sum_{r\neq s}^{V}\tilde{T}_{cum,h}^{sr}} \quad (C2)$$

where $\tilde{T}_{bil,h}^{sr}$ and $\tilde{T}_{cum,h}^{sr}$ represent the direct and cumulative exports, respectively, from country s to country r, and these two countries are all belong to the group V. We assume that the replaced exports between provinces would be produced by the average production technology of these provinces; alternatively, the replaced exports would be provided by the world average production technology. Then, the technology-adjusted accounting of country $s(s \in V)$ is.

$$TPBA^{s} = E_{con}^{s} - \sum_{h}\sum_{r\neq s}^{V} N_{cum,h}^{V}\#\tilde{T}_{cum,h}^{rs} + F^{s}L^{ss}\#\sum_{h}\sum_{r\neq s}^{V}\tilde{T}_{bil,h}^{sr} - \sum_{h}\sum_{r\neq s}^{U} N_{cum,h}\#\tilde{T}_{cum,h}^{rs} + F^{s}L^{ss}\#\sum_{h}\sum_{r\neq s}^{U}\tilde{T}_{bil,h}^{sr} \quad (C3)$$

$$TCBA^{s} = E_{pro}^{s} - \sum_{h} N_{bil,h}^{V}\#\sum_{r\neq s}^{V}\tilde{T}_{bil,h}^{sr} + \sum_{h}\sum_{r\neq s}^{V} F^{r}L^{rr}\#\tilde{T}_{cum,h}^{rs} - \sum_{h} N_{bil,h}\#\sum_{r\neq s}^{U}\tilde{T}_{bil,h}^{sr} + \sum_{h}\sum_{r\neq s}^{U} F^{r}L^{rr}\#\tilde{T}_{cum,h}^{rs} \quad (C4).$$

The assumption of average carbon intensity of the union of countries (V) determines that the emissions embodied in all exports between countries within the union of countries equal the virtual emissions induced by the production of the substitution ($\sum_{s}^{V} F^{s}L^{ss}\#\sum_{r\neq s}^{V} T_{bil,h}^{sr} = \sum_{s}^{V} N_{bil,h}^{V}\#\sum_{r\neq s}^{V} T_{bil,h}^{sr}$, $\sum_{r}^{V}\sum_{s\neq r}^{V} N_{cum,h}^{V}\#T_{cum,h}^{rs} = \sum_{r}^{V}\sum_{s\neq r}^{V} F^{r}L^{rr}\# T_{cum,h}^{rs}$). Therefore, the carbon responsibility of the group of countries V that is determined by the average of TPBA and TCBA accounting schemes ($\sum_{s}^{V}(TPBA^{s} + TCBA^{s})/2$) has no relationship with trade within the group of countries. In other words, the indicator of regional carbon responsibility that is determined by the average of TPBA and TCBA accountings schemes satisfies the scale invariance condition.

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