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RESEARCH ARTICLE

Quantitative analysis of CO_2 embodiment in international trade: An overview of emerging literatures

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Abstract The increasing volume of CO_2 embodiment in international trade adds a layer of complexity to environmental policies and has raised arguments on the traditional production based responsibility for CO_2 emissions. In order to help understand the quantity of CO_2 embodiment in trade and its policy implications, this paper gives observations to recently emerging literatures that quantitatively discuss CO_2 embodiment in trade. The analytical approaches share the principle of using input and output modeling but vary dramatically in study boundary and estimation accuracy. The calculations can be roughly categorized into three types: direct quantification of CO_2 embodiments in multiregional trade, direct quantification of CO_2 embodiment in bilateral trade, and indirect analysis by comparing the scenarios with or without trade. The practical estimations strongly rely on trade partner selection and data availability. An obvious imbalance of net CO_2 embodiment in the commodity trade between major developed countries and developing economies as a whole was confirmed by these literatures. Carbon taxes and other possible limitations on CO_2 emissions have been addressed. The consistency across the calculations could be enhanced by systematic analyses in more detail to convince the international community to take binding commitments for the reduction of global CO_2 emissions.

Keywords CO_2 embodiment, international trade, quantitative estimation, analytical approach

1 Introduction

CO_2 embodiment refers to CO_2 emitted at all phases in a goods' manufacturing process, from the mining of raw materials through the distribution process, to the final product for the consumer. The fast growing volume of CO_2 embodiment in international trade of goods has raised discussions on some important questions for future climate change agreements. One of them is whether the emission responsibilities shall be allocated at the point of manufacturing, which is currently performed, or at the point of consumption. This question has particular implications for the developing countries like China, which is experiencing significant economic growth driven by increases in exports and energy use. There may be large economic cost associated with the participation of global climate regime for the countries which have a large share of exports in carbon intensive production [1]. If the climate regime has inadequate participation, there is a risk that production will be increasingly shifted to nonparticipating countries [2].

The embodied carbon in trade may become a negotiating issue for China and other rapidly developing countries due to the pressure to curb CO_2 emissions, while there is still a lack of good research results to academically support this kind of discussion. With increasing global production, a lot of low cost mitigation options may be located outside of the country of consumption. However, very few proposals have been assessed on whether trade underlying some of the concerns with the Kyoto Protocol. Overall, there may be three aspects for the research of carbon embodied in trade. One is the direct quantitative estimation of the amount to provide a better understanding of the environmental separation between domestic consumption and global production. The second is the analysis of carbon leakage which can reveal the extent of the shifted pollution rather than the abated. The third issue is whether the trade adjusted carbon emission inventories could eliminate carbon leakage and mitigate global CO_2 emissions.

In order to help understand the current development of quantitative analysis on carbon embodied in trade, the first aspect of researches mentioned above, this paper gives an overview of the related literature emerging in recent years. Due to the lack of data for developing economies, most of

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the studies analyzed the carbon content of the trade flows among the member countries of the Organization for Economic Cooperation and Development (OECD). Based on certain assumptions, a few other studies looked into the cases between selected developing countries and developed countries, such as China-US and China-UK cases, etc. After outlining the necessities of these quantitative analyses, the calculation methodologies adopted were classified and described. The preconditions for the use of these categorized methods, including available data sources and study assumptions, were discussed to assist the proper understanding and correct applications of these approaches. The main findings of these reviewed literatures were summarized to enlighten more discussions and further similar studies.

2 Rationales of quantitative estimation of CO_2 embodiment in trade

The international framework to tackle climate change problem beyond 2012, the post-Kyoto regime, has been intensively discussed. The current negotiation process summarized that the framework should address the actual benefits both globally and individually for each country. The importance of comprehensive strategies for reducing the intensities of energy consumption and CO_2 emissions at country and industrial sector levels should be addressed. The widely adopted principle for accounting CO_2 emissions are production based [3]. The Intergovernmental Panel on Climate Change (IPCC) authorized methodology presents that a country only takes the responsibility for CO_2 emissions derived from the internal combustion of fossil fuels. Almost all the discussions so far are based on this measurement approach for national CO_2 inventory. However, it has been recently argued whether the production based measurement standard of CO_2 emissions could effectively encourage the emissions reduction efforts [1]. For instance, Helm et al. [4] found that UK's CO_2 emissions have fallen by 15% since 1990 based on IPCC measurement, whereas they have risen by 19% in the same period if using consumption-based measurement.

The difference between the two measurements can be traced back to the principle of CO_2 emission responsibilities. The consumption-based measurement corresponds to 'beneficiary pays principle' while the production based measurement follows 'polluter pays principle'. The differences in the accounting principles have substantial impacts on the cooperation in implementing coherent reduction policies across countries. Theoretically, the consumption based measurements have more attractive features than production based quantification [5]. It is said that the consumption based measurements are important for allocating the reduction of CO_2 emissions from the viewpoint of equity. They have the advantages of avoiding carbon leakage, increasing the options for mitigation, encouraging environmental comparative advantage, addressing competitiveness concerns, and inevitably speeding up technology diffusion [1].

The consumption-based measurement calculates CO_2 emissions generated for producing the goods consumed inside a region regardless of the place of production. Naturally, international trade, the imports and exports of goods, is taken into account as the most important factor for this approach. However, a detailed and systematic global analysis by consumption-based principle is still lacking. There is little information on consumption-based CO_2 emissions available across the regions and industrial sectors. The comparative advantage of the principle of consumption-based responsibility and the absence of relevant academic data generate the basic rationale for quantitatively estimating the CO_2 embodiment in international trade. This quantification can help the countries to be aware of their actual contributions to global CO_2 emissions by commodities consumption. The analysis of energy intensities at sector level and trade balance among the trade partners can identify the opportunities for reducing total CO_2 emissions, and thus have great implications for CO_2 mitigation policies in the changing and obviously integrating world economies. Due to the difference of CO_2 emission intensities and self-sufficiency ratio, the disaggregated regions and sectors need to be considered in the measurement.

3 Analytical approaches for quantification of CO_2 embodiment in trade

A number of tools and methodologies have been developed to calculate the embodied CO_2 emissions in products, among which life cycle assessment (LCA) is a production based analytical tool. LCA has been empirically applied to specific stages of the full life cycle, usually not covering emissions during the use and final disposal stages. As a bottom-up method, LCA calculations examine the production processes of specific product and need a large amount of preliminary data. The level of detailed data and technological information required are not available in nearly all the developing countries due to insufficient data collection and weak statistics institutions.

The top-down methods, using input-output (IO) analysis, have often been applied to estimate embodied energy, CO_2 emissions, pollutants, and land appropriation from international trade activities [6–10]. IO analysis was originated by Leontief [11], and then was extended to interregional and international trade applications in early contributions by Isard [12], Chenery [13], and Moses [14]. This method can analyze the embodied CO_2 emissions in imports and exports of a country as a whole, whereas has some difficulties in details at the sector level [15]. IO tables are usually expressed in the value added by sector, and each sector spans a number of different products with different CO_2 emission coefficients. The sector carbon coefficients are usually averaged by the ratios for all the products in each sector. This kind of quantitative estimation inevitably generates particular uncertainties.

Even for the implemented researches using certain forms of IO modeling, the available IO tables greatly determine the level of detail and accuracy of these studies. For the ideal case, a worldwide multiregional IO (MRIO) model is required to relate different countries' exports and imports and assign CO_2 emission factors based on their net consumption of goods and services. This would distinguish the CO_2 emission intensities among different trading partners, as well as among different goods. The approach using MRIO model to do a full analysis is a data intensive and time consuming process, which makes it infeasible in most cases. A few other methods, applying the principle of IO analysis, have been practically adopted to simplify the estimation based on the available data sources and certain assumptions. The quantification methodologies used in these practical studies for estimating CO_2 embodiment in trade can be classified into three types from the emerging literatures as described below.

3.1 Type 1: Direct quantification of CO_2 embodiment in multiregional trade

The first approach is popularly used for the case of multiregional analysis [5]. It directly determines the domestic CO_2 emissions in each country during production of goods for the trade with other countries. This explicit modeling of the embodied CO_2 emissions requires a decomposition of the standard IO analysis framework into domestic and traded components. The total production based CO_2 emissions occurring in a country r can be expressed as equation (1).

$$\mathrm{Em}_r = \mathrm{EF}_r(I-A_{rr})^{-1}\left(y_{rr}+\sum_s e_{rs}\right), \tag{1}$$

EF_r: a row vector with each element representing the CO_2 emissions per unit industry output

A_{rr}: the inter-industry requirements of domestically produced products demanded by domestic industries

y_{rr}: the products produced and consumed domestically

e_{rs}: the bilateral exports from country r to country s

I: the identity matrix

The linearity assumption of IO analysis allows Eq. (1) to be decomposed into components for domestic demand on domestic production and the embodied emissions from country r to country s, as indicated in Eq. (2). The total emissions embodied in exports from country r to all other countries could be summarized as Eq. (3). Similarly, the total emissions embodied in imports are obtained by reversing the summation as Eq. (4). Another quantity often discussed is the balance of emissions embodied in trade (BEET), which represents a country's trade balance for CO_2 emissions. BEET can be derived from Eq. (5).

$$\mathrm{Em}_{rs} = \mathrm{EF}_r(I-A_{rr})^{-1}e_{rs}, \tag{2}$$

$$\mathrm{Em}_r^e = \sum_s \mathrm{Em}_{rs}, \tag{3}$$

$$\mathrm{Em}_r^m = \sum_s \mathrm{Em}_{sr}, \tag{4}$$

$$\mathrm{Em}_r^{\mathrm{BEET}} = \mathrm{Em}_r^e - \mathrm{Em}_r^m. \tag{5}$$

This method is transparent and can sum up the total emissions embodied in the imports and exports of a defined country with all other countries. Therefore, it can be used to monitor the CO_2 emission balance of a country's trade as a whole. However, it does not assess the imports required to produce the goods for trade. In the simplest cases, some studies used the total trade balance data for an entire economy; however, they did not give due consideration to the differences in CO_2 intensities at sector level [4,16–20]. In these cases, the quantification results inevitably indicate high uncertainties.

3.2 Type 2: Direct quantification of CO_2 embodiment in bilateral trade

This method is used for the bilateral trade cases [9,21]. The CO_2 embodiment in exports/imports is directly quantified by multiplying the monetary value of each exported/imported product by the corresponding CO_2 emission coefficient for the same kind of product produced in exporting (importing) country. Considering two countries, named A and B respectively, the CO_2 embodiment in A's exports to B can be calculated by Eq. (6). The induced CO_2 emission intensities of A's products (EF_i) shall be used as CO_2 emission factors in the equation. This means that both the direct and indirect CO_2 emissions for manufacturing the products shall be considered. The induced CO_2 emission coefficients can be obtained from the environmental IO-LCA industrial benchmark model, which is normally based on a country's IO data for a certain prior year of t_0. The CPI (consumption price index) of the year of t for calculation shall be used to normalize trade data to the baseline year of t_0. We should also be aware that the same value of B's product and A's export in the same or similar category may represent different quantities of goods produced in each country. Therefore, the relative purchasing power parity (RPPP) is used to translate the values documented by B's Census Bureau to the actual quantity of A's exports using emission factors derived from environmental IO-LCA of country A.

$$\sum_i \mathrm{ExCO}_{2_{i,t}} = \sum_i \left(X_{i,t} \times \mathrm{RPPP}_t \times \frac{\mathrm{CPI}_{i,t_0}}{\mathrm{CPI}_{i,t}} \times \mathrm{EF}_i\right), \tag{6}$$

$ExCO_{2_{i,t}}$: the embodied CO_2 emissions in A's export i to B in the year of t

$X_{i,t}$: A's export i with the trade value in the year of t

EF_i: the induced CO_2 emission factor of A's export i

The necessary trade data can be obtained from the Census Bureaus of the targeted pair of countries. For several major economies, the environmental IO tables (EIOT) have been available and played an important role in economic policy analysis [22]. For example, Green Design Initiative at Carnegie Mellon University developed the economic IO-LCA software for assessing the environmental impacts of the products in the US. Japan National Institute for Environmental Studies (NIES) constructed embodied energy and emission intensity data (3EID) for Japan using national IO tables at a rate of every five years during 1975 to 2000 [23]. UK adopted the European Union's guidelines for providing an integrated set of economic and environmental accounts [24,25]. In UK's EIO table of 1993, there are direct and indirect CO_2 emission factors for 91 industrial production sectors which can be linked with economic data.

In many cases, the CO_2 emission factors based on environmental IO-LCA estimation are not currently available in developing countries like China. For analyzing the CO_2 embodiment in the trade between a developing country (e.g., country A) and a developed economy (e.g., country B), a CO_2 emission ratio based on the fuels used in industrial sectors of both countries can be used to estimate the CO_2 emission coefficients associated with A's industrial processes. The ratio may be defined by equation (7). Since the fuel mix, which determines the relative CO_2 emission rates, changes with time, it is necessary to update the CO_2 emission coefficients in the baseline year's EIO tables using a coefficient defined by Eq. (8).

$$F_t = \frac{\sum(\text{AIndFuel}_{m,t} \times \text{ACE}_m)}{\sum(\text{BIndFuel}_{n,t} \times \text{BCE}_{n,t})}, \tag{7}$$

$\text{AIndFuel}_{m,t}$: CO_2 emissions in A's industrial sector by fuel type m in the year of t

ACE_m: CO_2 coefficient by A's fuel type m

$\text{BIndFuel}_{n,t}$: CO_2 emissions in B's industrial sector by fuel type n in the year of t

BCE_n: CO_2 coefficient by B's fuel type n

$$F_y = \frac{\sum(F_{i,t} \times C_i)}{\sum(F_{i,t_0} \times C_i)}, \tag{8}$$

F_y : the ratio of carbon content intensity in the fuel mix of the industrial sector in the year of t compared to that in the year of t_0

F_i: the CO_2 emissions from the industrial sector i by fuel type

C_i: the carbon coefficient associated with each fuel type

The major barrier for this calculation is the availability of environmental IO tables of the targeted trade partner. Even for the above mentioned countries in which EIO tables have been developed, the induced CO_2 emission coefficients at sector level are only available for several specific years. The assumptions as defined by Eqs. (7) and (8) will definitely give uncertainties in this kind of quantification.

3.3 Type 3: Indirect analysis by comparing CO_2 emission in scenarios with and without trade

This approach is adopted to analyze the CO_2 emission impact of a bilateral trade and global trade with the selected pair of countries [26]. Considering two countries 1 and 2, with X as the output vector, A as the input coefficient matrix, and F as the final demand vector, the familiar one region IO model can be extended as Eq. (9). The solution can be expressed as Eq. (10). The model's estimations of output can be multiplied by the carbon coefficients to obtain CO_2 emissions from each sector. It provides the 'base case' for the analysis, showing actual conditions in the selected years. A natural way to measure the effects of the bilateral trade is to set matrix blocks A_{12} and A_{21}, which represent one country's inputs into another country's production processes, to be zero. Then recalculate the output that would be required to satisfy the same final demand under this assumption.

$$\begin{pmatrix} X_1 \\ X_2 \end{pmatrix} = \begin{pmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{pmatrix} \begin{pmatrix} X_1 \\ X_2 \end{pmatrix} + \begin{pmatrix} F_{11} \\ F_{21} \end{pmatrix} + \begin{pmatrix} F_{12} \\ F_{22} \end{pmatrix}, \tag{9}$$

$$\begin{pmatrix} X_1 \\ X_2 \end{pmatrix} = \begin{pmatrix} I-A_{11} & -A_{12} \\ -A_{21} & I-A_{22} \end{pmatrix}^{-1} \begin{pmatrix} F_{11}+F_{12} \\ F_{21}+F_{22} \end{pmatrix}. \tag{10}$$

Two scenarios can be defined to measure the CO_2 emission effects of the bilateral and global trade of the two countries. Scenario 1 is a 'no bilateral trade' scenario, where each country produces the goods at home that are now imported from another country, leaving all the trade that flows with other countries unchanged. Scenario 2 is a 'no foreign trade' scenario, where both the targeted economies eliminate all imports and exports and produce the goods at home that are now imported from all the other third world countries. In the algebraic formulation, let the subscript 1, 2, and R stand for country 1, country 2, and the rest of the world, respectively. Extended from Eq. (10) of the base case, scenario 1, assuming no bilateral trade, can be expressed as Eq. (11). With the natural extension to a three regional model, scenario 2 can be expressed as Eq. (12). The difference between emissions in the base case and scenario 1 represents the emissions attributable to bilateral trade. If the emissions are smaller in scenario 1 than in the base case, the bilateral trade would increase the global emissions. Conversely, the bilateral trade helps to reduce the emissions in total. Similarly, the difference between emissions in the base case and scenario 2 represents the emissions avoided or created by all foreign trade of the two countries.

$$\begin{pmatrix} X_1 \\ X_2 \end{pmatrix} = \begin{pmatrix} I - A_{11} - A_{21} & 0 \\ 0 & I - A_{12} - A_{22} \end{pmatrix}^{-1} \cdot \begin{pmatrix} F_{11} + F_{21} \\ F_{12} + F_{22} \end{pmatrix}, \quad (11)$$

$$\begin{pmatrix} X_1 \\ X_2 \end{pmatrix} = \begin{pmatrix} I - A_{11} - A_{21} - A_{R1} & 0 \\ 0 & I - A_{12} - A_{22} - A_{R2} \end{pmatrix}^{-1} \cdot \begin{pmatrix} F_{11} + F_{21} + F_{R1} \\ F_{12} + F_{22} + F_{R2} \end{pmatrix}. \quad (12)$$

It shall be noted that for both scenarios, this measurement excludes the foreign emissions actually created by other country's exports to these two countries. The principal drawback of this approach is the difficulty of developing the necessary and detailed data on international transactions which are irregular and increasingly dynamic. In spite of the obvious time lag problem, a few international IO tables have been prepared. For instance, the Institute of Developing Economies, Japan External Trade Organization (IDE/JETRO) constructed Japan-China IO table for the year 1985 and then developed a few bilateral IO tables for Japan and several other Asian countries for 1990. Asian International IO tables which covers 9 Asian countries and US were also constructed for the years of 1985, 1990, 1995, and 2000 accordingly [27]. Japanese government, MITI (the Ministry of International Trade and Industry, now named Ministry of Economy, Trade and Industry, METI) developed Japan-US international IO table of 175 sectors for the years of 1990, 1995, and 2000 in detail [26] The Global Trade Analysis Project (GTAP) has compiled the necessary data set which can be used for multiregional IO analysis. The GTAP provides data for the 87 countries and 57 industrial sectors in the latest version 6 for 2001 [28]. The compilation of these international IO tables took a lot of time, effort, and personnel resources, especially when the table was developed on the basis of material flow survey of the imported goods [27].

4 Main findings of the quantitative estimations

Despite the significant differences between the literatures and unavoidable deficiencies in the study boundary and analytical approaches, several meaningful messages have been shared by the emerging quantitative estimations. These common findings may provide useful implications for international climate change regime, which are summarized as follows:

1) The major developed countries are net importers while developing countries as a whole are net exporters of CO_2 emissions.

A common conclusion from the literatures on trade and environment is that developed countries displace a significant amount of their environmental load onto the lower income economies. For instance, both Japan and US have displaced effectively part of the environmental burden of their consumption onto the rest of the world [29]. The literatures analyzing CO_2 embodiment in trade have given clear evidence that the major developed countries are net CO_2 importers, while developing countries as a whole and a number of developed countries with rich resources are net exporters of carbon. Wyckoff and Roop [6] showed that 13% of total carbon emissions caused by the consumption of the six largest OECD countries were due to carbon embodied in imports. Chung and Rhee [31] found that Korean exports to Japan were more carbon intensive than Japanese exports to Korea. Another analysis, focused solely on Japanese trade, showed that Japan was once a net exporter of embodied CO_2 emissions in 1975, while switched to be a net importer of CO_2 before 1990 [31].

Nevertheless, net exporters of embodied carbon include both middle income developing countries with emerging economies and a few developed countries with resource and energy intensive exports. Tolmasquim and Machado [32] indicated that Brazil had a net export of about 7% of the country's carbon emissions in the 1990s. Qi et al. [19] revealed that China was a carbon exporting nation during 1997–2006 with the net carbon export accounting for about 0.5%–2.7% of total carbon emissions during 1997–2004. The proportion increases rapidly after 2004 and reached to 10% in 2006. An OECD study estimated that in 1995 net carbon exports from China and Russia were roughly equal to net carbon imports of the OECD as a whole, which was about 5% of OECD domestic emissions [33]. Although OECD as a whole is a net carbon importer, individual countries vary widely. Ahmad and Wyckoff [33] found the net carbon exports from Australia, Canada, the Czech Republic, Denmark, Finland, Netherlands, Norway, and Poland, the balanced carbon trade in Hungary, and the net carbon imports from other countries including the US, Japan, Korea, and all the large European economies. Other studies, which analyzed individual country cases, reached similar results indicating significant net carbon exports from Australia [34], Norway [35], and Sweden [36], and approximately balanced carbon trade in Denmark [37].

2) International trade may provide opportunities for global CO_2 reduction.

In theory, environmental effects of trade can be decomposed into three kinds: composition, scale, and technique effects. The composition and technique effects encourage the optimization of resource allocation in a wider scope and the diffusion of cleaner technologies, resulting in the improvement of production efficiency. Trade also leads the countries to scale up their manufacturing capacities with comparative advantages [38]. The multi-layer effects of trade may cause positive or negative impacts on the environment [39–40]. The possibly controversial results mirrored the complexity of the topic of CO_2 embodiment in trade.

Some estimation studies provided evidence that international trade could reduce global CO_2 emissions in certain conditions. Hayami and Nakamura [41] obtained encouraging results that the bilateral trade of Japan and Canada reduced the emission in both countries. Japan exported many manufactured goods which it produced very efficiently with low carbon emissions, while Canada exported energy and resource intensive products like paper products and coal. Canada can produce these products with relatively low emissions due to its abundant natural resources which create a comparative advantage and allow more efficient production. This can also attribute to Canada's extensive use of hydroelectric power which means lower carbon emissions from electricity generation than in Japan and most other countries.

3) The importance of carbon taxes and other limitations on CO_2 emissions are most addressed.

The theory of comparative advantage suggests that each country would specialize in the production of goods for which its production costs are relatively low. Such a specialization pattern maximizes the aggregate social welfare. If every country specialized in the production of goods for which its emissions intensity is lower, the globally aggregate emissions would be minimized. However, the parallel is far from perfect in reality. There were few economic incentives for minimizing the carbon emissions in the past. The ability to emit CO_2 free might increase the comparative advantage of manufacturing. This could account for the positive correlation between comparative advantage and emissions, as occurs in US-China trade [9].

By indicating the noticeable change of carbon emissions embodied in international trade, most of the available literatures underlined the importance of energy and greenhouse gas policies which have been recently debated [5,26]. They suggested that assigning responsibility for pollution based on consumption, rather than production, increases the share of climate problems attributable to the richest countries. Globalization shifts but does not necessarily reduce the worldwide total amount of CO_2 emissions. From the perspective of public policy, carbon taxes and other possible limitations on CO_2 emissions should be employed. In the absence of carbon taxes or other related limitations, the developing economies, which rely on a comparative advantage in energy use and carbon intensive production, would have little incentive to shift away from the traditional model. The comparative advantage of developed countries in trade is also not necessarily concentrated in the sectors with lower emission intensities. In this circumstance, energy intensive production could be a commercially profitable strategy. National and regional policies to raise the costs of carbon emissions are required to make a lower carbon emission path worldwide. As a result, several countries in Europe have adopted carbon taxes as part of their strategies to meet Kyoto Protocol commitments, such as Denmark, Sweden, Norway, Finland, Italy, Netherlands, and UK [42]. Since their adoption, carbon taxes have proven to be largely effective. For example, Denmark's carbon tax policy, which includes using revenue from the tax to finance energy efficiency investment, resulted in the reduction of carbon dioxide emissions by 4% between 1992 and 2000. Finland's carbon tax, enacted in 1990, was credited with reducing CO_2 emissions by 7% in 1998 [43]. Because of these success, carbon taxes are likely to become increasingly common as part of national efforts to reduce CO_2 emissions.

4) Consumption based CO_2 reduction should be discussed for future global climate policy framework.

The significant imbalance of CO_2 embodiment in international trade may have a strong impact on the participation and effectiveness of global climate policies [5]. From the viewpoint of social welfare and equity, the international framework of CO_2 emissions reduction shall be based on consumption since this measurement represents the consumption magnitude domestically and is fairer than the production based approach. As an agreement achieved in COP13 (the 13th Conference of Parties) held in December of 2007, the Bali Roadmap summarized a new negotiation process for the international framework on climate change, and also addressed the real benefits not only at the global level but also at the country level. From a practical viewpoint for carbon leakage, consumption-based approach is more preferable to encourage developed countries to transfer clean technologies for improving energy efficiency and lowering carbon intensity in developing countries. Therefore, consumption-based CO_2 reduction should be also discussed for future global climate policy framework. If countries could take binding commitments as a coalition, instead of as individual countries, the impact of trade to CO_2 emissions might be substantially reduced. Adjusting emission inventories for trade can give a more consistent description of a country's environmental pressures.

5 Conclusions

The literatures aimed at quantitatively analyzing the CO_2 embodiment in international trade and to discuss its policy implications were fast emerging in the past few years. The adopted analytical methodologies shared the common principle by using IO modeling with the feasibility. Due to the shortcoming of the quantification approaches themselves and far insufficiency of necessary data, these studies indicated high diversity in boundary and estimation accuracy. Meanwhile, quite few studies were found to be concerned with the CO_2 embodiment in trade among Asian countries.

Since there are still huge gaps in the understanding of CO_2 embodiment in trade from the existing literatures, much more researches are needed to extend the coverage of countries and the classification of industrial sectors. The consistency across the future estimations has to be addressed for systematic comparison. Further quantitative estimations of CO_2 embodiment in trade are expected to assist the identification of CO_2 mitigation options in a broader sense. The assessments for carbon limitation policies are essential in identifying mitigation potential and constructing possible links with international trade. Research should also pay attention to possible impacts of the trade CO_2 embodiment on the ongoing climate change negotiation process.

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