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Assessing the role of international trade in global CO_2 emissions: An index decomposition analysis approach

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HIGHLIGHTS

- Modelling the impact of international trade on global/national emissions using IDA.
- Decomposition of production- and consumption-based emission changes.
- Further decomposition of emission balance changes.
- Empirical analysis of global economies' emission changes during 1995–2009.

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ABSTRACT

Trade-related CO_2 emissions are an important component in global emissions. Understanding the role of international trade in emissions is of direct relevance to global and national emission reductions, particularly for major exporters and importers. In the literature, the issue has seldom been studied using index decomposition analysis (IDA), which is a popular tool in assessing growth in national-level CO_2 emissions. In this paper, based on a multi-region I-O analysis, we introduce three inter-linked IDA models to quantify the impacts of trade on the production-based emissions, the consumption-based emissions, and the emission balance of economies, respectively. A salient feature of the models, when applied together, is that they can help to assess the role of trade and the emission performance of economies from multiple perspectives. We discuss the relevant methodological issues as well as the advantages and limitations of the models. We then apply the models to evaluate the impact of international trade on changes in global CO_2 emissions from 1995 to 2009. It is found that while the growing trade volume drove up the total emissions, changes in the emission intensity and goods composition related to trade led to some degree of emission mitigation, particularly after 2005.

1. Introduction

Climate change is a global concern. Growth in energy-related CO_2 emissions has been identified as the main cause of climate change. The growing trend will persist if no substantial efforts on constraining emissions are made [1]. Global initiatives aiming at reducing emissions include the 1992 Kyoto Protocol and the 2015 Paris Climate Agreement. Actions have also been taken at regional and country levels to reduce emissions. An important issue behind climate policies is to identify pathways for emission mitigation. It is grounded largely on understanding changes in energy use and CO_2 emissions.

Index decomposition analysis (IDA) and structural decomposition analysis (SDA) are two analytical techniques that have been widely used to study changes in national-level energy and emissions. They aim at distributing a change in an aggregate to pre-defined factors. They have the same objective but differ in methodological basis and data requirements [2]. From an energy systems analysis viewpoint, the basic form of IDA yields three effects to explain a change in national energy consumption, i.e. sectoral intensity effect, economy structure effect, and total activity effect [3]. The decomposition results present useful insight into national energy and emissions dynamics, and shed lights on a country's energy and emission performances. SDA, built upon input-output (I-O) models, is inherently tied to the study of the inter-industry linkage effect and final demand effect. They can respectively be viewed as an indication of production technology and reflects the impacts of final consumption structure and total final consumption. With multi-

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region I-O tables, SDA can further discriminate the impact of trade on energy/emissions and national economic activities. A review of recent IDA and SDA literature as well as a comparison between the two techniques are given in Wang et al. [2].

Of the two techniques, IDA has been more widely used in policy development and assessment. A main reason is that the results of IDA have strong linkages with policy measures. Examples of such studies are IPCC assessment reports [4,5], Global Tracking Framework of the SE4All program initiated by the United Nations [6], European Environment Agency [7], IEA [8–10], UNIDO [11], Federal Statistical Office of Switzerland [12], Environment Canada [13] and European Union [14]. In comparison SDA has received less attention in energy and emission policy studies in practice. The focus of this study is the technique of IDA and its application to trade-related CO_2 emissions which has traditionally been studied using SDA.

Trade-related CO_2 emissions have become an increasingly important component in global/national emissions. Globalization with supply chains crossing national borders has led to growth in emissions embodied in trade (EET). Xu and Dietzenbacher [15] report that the share of EET in global emissions increased from 24% in 1995 to 33% in 2007. At the country level, the survey by Sato [16] shows that during 1995–2007 the share of EET in China's production-based emissions ranged from 4% to 38% depending on the reported source.[1] The corresponding figures for the United States and Japan were 2–27% and 3–44%, respectively. If international trade continues to grow, economies, particularly major importers and exporters such as China, United States and EU, are likely to see a growing EET. The development may lead to a trade-emission dilemma which needs to be resolved in the context of global emissions reduction. As an example, Liu et al. [17] attempt to identify opportunities to decouple emissions from trade in China.

The varying specialization of economies in the global production system has led to carbon leakage between advanced economies and emerging economies. To more fairly reflect climate responsibilities of countries, consumption-based emission inventory has been advocated as an alternative to the conventional production-based accounting system [18].[2] The consumption-based emission inventory has a number of advantages over the production-based system [19] and has increasingly been used as the baseline to develop various climate policy options, including both trade-related policies (e.g. border carbon adjustments) and domestic policies (e.g. improving production technology and adjusting economy structure) [20,21].[3] For example, Zhang [22] studies the sharing of emission responsibilities among Chinese provinces based on the production-based principle, Barrett et al. [23] study policy issues to control the consumption-based emissions in UK, Mundaca et al. [24] provide a production-based and consumption-based macroeconomic-climate assessment of Sweden's CO_2 emissions, Deloitte [25] assesses Australia's performance in consumption-based emissions and further discusses the climate target setting of the country, and Barrett et al. [26] and Fouré et al. [27] discuss the effectiveness of border carbon tax in the EU context.

Capturing the impact of international trade on global/national emissions has been a widely debated and studied issue. In the literature, the bulk of IDA studies examine the production-based energy use or emissions.[4] Using IDA to study trade-related emissions is a very recent development [2] and the number of reported studies is still very small. A main reason is that data on emissions and economic activity associated with trade is not readily available. The normal practice to gather these data is to adopt the environmentally extended I-O analysis. On the basis of EET calculated using the I-O model, IDA has only recently been applied to study the impact of trade specialization on economies' emission balance in a specific year [17,32–34], and analyze changes in the emissions embodied in bilateral trade [35,36]. Analyzing the impact of trade on the temporal changes in global/national production-based emissions using IDA, however, has not been widely reported. Besides, no IDA study on temporal changes in consumption-based emissions or emission balance has been reported.

This study is an attempt to assess the role of international trade in global/national emissions using IDA. Specifically, based on the multi-region I-O model, we first estimate the production (consumption) by destination (source) as well as emissions embodied in product flows of global economies. The impact of exports on economies' production-based emissions and that of imports on consumption-based emissions are investigated. In addition to the entire national emission inventories, emission balance changes are issues of interest to policymakers since they help to characterize countries' role in international climate negotiation. Quantifying the drivers behind changes in countries' emission balance offers insights on the causes of the trade-emission dilemma [17]. We therefore further study changes in countries' emission balance over time. Three inter-linked IDA models to respectively study changes in production-based emissions, consumption-based emissions, and emission balance with a focus on trade are proposed. For illustration purposes, we apply these models and use the World Input-Output Database to examine global economies' emission changes from 1995 to 2009.

The rest of the paper is organized as follows. Section 2 describes the multi-region I-O approach. Section 3 introduces the three IDA models. Section 4 presents the case study. Section 5 concludes.

2. Basics of multi-region I-O models

The most commonly used technique to estimate consumption-based emissions and EET is the environmentally extended multi-region I-O model. Peters [18] classifies the multi-region I-O methodology into two approaches, namely the emissions embodied in bilateral trade (EEBT) approach and multi-region I-O (MRIO) approach. The difference between them lies in the production technology assumption for trade partners [37]. MRIO approach adopts the domestic production technology for all economies, rendering it superior in EET accounting [38]. Examples using the MRIO approach to compute consumption-based emission inventory and EET include Nansai et al. [39], Wiedmann et al. [40], and Gasim [34]. In the sections that follow we apply the MRIO approach to compute the emission inventories and economic activities of countries.[5]

Assume N economies, each of which is disaggregated into M (i, $j = 1,\ldots,M$) economic sectors, are under consideration. The structure of the MRIO table for the N economies is given in Table 1. The integrated matrix of intermediates $\mathbf{Z}$ is expressed as:

$$\mathbf{Z} = \begin{bmatrix} \mathbf{Z}^{11},\mathbf{Z}^{12},\ldots,\mathbf{Z}^{1N} \\ \mathbf{Z}^{21},\mathbf{Z}^{22},\ldots,\mathbf{Z}^{2N} \\ \cdots \\ \mathbf{Z}^{N1},\mathbf{Z}^{N2},\ldots,\mathbf{Z}^{NN} \end{bmatrix}$$

where $\mathbf{Z}^{rs}$ is a $M \times M$ matrix denoting the intermediates exported from country r to country s. Define the total output $\mathbf{X} = (\mathbf{X}^{1'},\mathbf{X}^{2'},\ldots,\mathbf{X}^{N'})'$ where $\mathbf{X}^{r'}$ is a $1 \times M$ vector for the total output of country r, and the final demand $\mathbf{Y} = (\mathbf{Y}^{1'},\mathbf{Y}^{2'},\ldots,\mathbf{Y}^{N'})'$ where $\mathbf{Y}^{r'} = \sum_s \mathbf{Y}^{rs'}$ and $\mathbf{Y}^{rs'}$ is a $1 \times M$

[1] Production-based emissions refer to the amount of CO_2 emitted from production activities occurred within a country's territory.

[2] Consumption-based inventory accounts for all the emissions induced by the final demand of a country, regardless of emitters.

[3] Despite its growing popularity in academic research and policy studies, the consumption-based accounting system faces a number of practical challenges in design and implementation. These challenges include the uncertainty in allocating emissions according to consumption activities and the difficulty in implementing consumption-based policy measures in foreign countries. Details about these problems and challenges have been widely reported in the literature. Interested readers can refer to Peters [18].

[4] Examples of decomposition analysis dealing with production-based emissions include Mundaca and Markandya [28], Mundaca et al. [29], Ang et al. [30] and Goh et al. [31].

[5] Although the I-O technique has been widely applied, it should be noted that a number of limitations, including linear modelling of complex economic systems, exist in the approach [41].

Table 1
Structure of the MRIO table.

	Intermediate transactions	Final demand	Total outputs
Intermediate inputs	$\mathbf{Z}^{11},\mathbf{Z}^{12},...,\mathbf{Z}^{1N}$	$\mathbf{Y}^{11},\mathbf{Y}^{12},...,\mathbf{Y}^{1N}$	$\mathbf{X}^{1}$
	$\mathbf{Z}^{21},\mathbf{Z}^{22},...,\mathbf{Z}^{2N}$	$\mathbf{Y}^{21},\mathbf{Y}^{22},...,\mathbf{Y}^{2N}$	$\mathbf{X}^{2}$
	...	...	...
	$\mathbf{Z}^{N1},\mathbf{Z}^{N2},...,\mathbf{Z}^{NN}$	$\mathbf{Y}^{N1},\mathbf{Y}^{N2},...,\mathbf{Y}^{NN}$	$\mathbf{X}^{N}$
Value added	$\mathbf{V}^{1'},\mathbf{V}^{2'},...,\mathbf{V}^{N'}$		
Total inputs	$\mathbf{X}^{1'},\mathbf{X}^{2'},...,\mathbf{X}^{N'}$		

vector for the traded final demand from country r to country s. Since the total output of an economy equals to the intermediate use by economic sectors plus the final demand by consumers, the economic production of the N economies can then be formulated as follows:

$$\mathbf{X} = \mathbf{Z1} + \mathbf{Y} \tag{1}$$

where $\mathbf{1}$ is a summation vector with proper length. Define an integrated matrix of direct inputs coefficients $\mathbf{A}$ as follows:

$$\mathbf{A} = \begin{bmatrix} \mathbf{A}^{11},\mathbf{A}^{12},...,\mathbf{A}^{1N} \\ \mathbf{A}^{21},\mathbf{A}^{22},...,\mathbf{A}^{2N} \\ ... \\ \mathbf{A}^{N1},\mathbf{A}^{N2},...,\mathbf{A}^{NN} \end{bmatrix}$$

where $\mathbf{A}^{rs}$ is a $M \times M$ matrix denoting the direct input coefficients exported from country r to country s with elements $A_{ij}^{rs} = Z_{ij}^{rs}/X_j^s$. Eq. (1) can then be rewritten as an I-O model:

$$\mathbf{X} = (\mathbf{I}-\mathbf{A})^{-1}\mathbf{Y} = \mathbf{LY} \tag{2}$$

where $\mathbf{I}$ is the identity matrix and $\mathbf{L} = (\mathbf{I}-\mathbf{A})^{-1}$ is the Leontief inverse matrix.

Combined with emission intensity, Eq. (2) can be used to estimate emissions embodied in various output categories. Define countries' emission intensity as $\mathbf{f}' = (\mathbf{f}^{1'},\mathbf{f}^{2'},...,\mathbf{f}^{N'})$, where $\mathbf{f}^{r'}$ is a $1 \times M$ vector with entries $f_i^r = C_i^r/V_i^r$, where C denotes emissions and V denotes value added.[6] Aggregate emissions can be modelled as follows:

$$C = \mathbf{f}'\mathbf{V} = \mathbf{f}'\hat{\mathbf{K}}\hat{\mathbf{X}} = \mathbf{f}'\hat{\mathbf{K}}\hat{\mathbf{L}}\mathbf{Y} = \mathbf{f}'\mathbf{HY} \tag{3}$$

where $\mathbf{H} = \hat{\mathbf{K}}\mathbf{L}$, $\mathbf{V} = (\mathbf{V}^{1'},\mathbf{V}^{2'},...,\mathbf{V}^{N'})'$ is a $MN \times 1$ vector, $\mathbf{V}^r$ is a $M \times 1$ vector for the sectoral value added of country r, $\hat{\mathbf{K}}$ is a $MN \times MN$ diagonal matrix with entries $K_i^r = V_i^r/X_i^r$ representing the ratio between value added and total output. According to the usual emission accounting principles, country r's production-based emission inventory consists of two parts, the emissions caused by the goods/services produced and finally consumed in country r (C^{rr}) and the emissions emitted in country r but embodied in exports to other countries ($EEE^r = \sum_{k\neq r} C^{rk}$). Its consumption-based emissions cover the emissions emitted in and embodied in goods consumed by country r (C^{rr}) and the emissions emitted in other countries but embodied in the imports absorbed by country r ($EEI^r = \sum_{k\neq r} C^{kr}$). Following Boitier [43] and Wiebe and Yamano [44], these components can be calculated as $C^{rr} = \sum_s \mathbf{f}^{r'}\mathbf{H}^{rs}\mathbf{Y}^{sr}$, $EEE^r = \sum_{k\neq r,s} \mathbf{f}^{r'}\mathbf{H}^{rs}\mathbf{Y}^{sk}$, and $EEI^r = \sum_{k\neq r,s} \mathbf{f}^{k'}\mathbf{H}^{ks}\mathbf{Y}^{sr}$, where k denotes country. As such, country r's production-based emission inventory is $C^{r,prd} = \sum_{ks} \mathbf{f}^{r'}\mathbf{H}^{rs}\mathbf{Y}^{sk}$, while its consumption-based emissions is $C^{r,con} = \sum_{ks} \mathbf{f}^{k'}\mathbf{H}^{ks}\mathbf{Y}^{sr}$. Further, the difference between the production-based and consumption-based emissions is usually defined as the emission balance (EB) of an economy, i.e. $EB^r = C^{r,prd}-C^{r,con} = EEE^r-EEI^r$. It indicates the net effect of trade, including both imports and exports, on countries' emissions. A positive (negative) EB indicates the country is a net exporter (importer) of emissions.

Countries' economic activity can be measured in the same way as the emission accounting. Instead of gross output/trade that has conventionally used in I-O analysis, we use value added to measure the economic activity and trade of countries.[7] An advantage of the value added measurement is to avoid the 'double counting' problem [47]. From the production perspective, the value added of all the goods/serviced produced in country r is $GDP^r = \sum_k V^{rk} = \sum_k \sum_s \mathbf{1}'\mathbf{H}^{rs}\mathbf{Y}^{sk}$, where V^{rk} is the value added of goods produced in country r and finally consumed in country k. The value added in export for country r is given by $VAE^r = \sum_{k\neq r} V^{rk}$. From a consumption viewpoint, on the other hand, the value added of all the goods finally consumed in country r can be defined as absorbed value added, i.e. $AVA^r = \sum_k V^{kr} = \sum_k \sum_s \mathbf{1}'\mathbf{H}^{ks}\mathbf{Y}^{sr}$, and the value added in imports is $VAI^r = \sum_{k\neq r} V^{kr}$. For an individual country, GDP^r usually does not equal to AVA^r. For all economies as a whole, however, the aggregate value added $AGDP = \sum_r GDP^r = \sum_r AVA^r$.

3. IDA models

The preceding shows that production-based emissions and consumption-based emissions of countries have fairly different formulations. Trade plays different roles in the two emission accounting systems. We study them separately and further examine the emission balance of countries.

3.1. Production-based IDA

From Section 2, country r's production-based emissions can be modelled as follows:

$$C^{r,prd} = \sum_{k,i} \frac{C_i^{rk}}{V_i^{rk}}\frac{V_i^{rk}}{V^{rk}}\frac{V^{rk}}{GDP^r}GDP^r = \sum_{k,i} f_i^r S_i^{rk} U^{rk} GDP^r \tag{4}$$

where $S_i^{rk} = V_i^{rk}/V^{rk}$ is the composition of exports from country r to country k, and $U^{rk} = V^{rk}/GDP^r$ is the value added share of the exports to country k in country r's overall output. For domestically consumed goods, i.e. when $k = r$ in Eq. (4), S_i^{rr} denotes the products composition and U^{rr} is the share of country r's products remained in the country. On the other hand, as to exports, i.e. when $k \neq r$ in Eq. (4), $\sum_{k\neq r,i} S_i^{rk}$ captures the exported goods composition, and $\sum_{k\neq r} U^{rk}$ is the export share in country r's total GDP.

Suppose data for year 0 and T are available. The arithmetic change in country r's production-based emissions is decomposed as:[8]

$$C^{r,prd,T}-C^{r,prd,0} = \Delta C_{int}^{r,prd} + \Delta C_{com}^{r,prd} + \Delta C_{vshare}^{r,prd} + \Delta C_{GDP}^{r,prd} \tag{5}$$

where Δ denotes the additive decomposition effect, *int* the sectoral intensity effect, *com* the production composition effect, *vshare* the effect of value added share by destination and *GDP* the total production output effect. The four effects in Eq. (5) together explain the arithmetic change in the total production-based emissions. To compute these effects, a specific decomposition method is needed. Following the guidelines in Ang [3], we use LMDI-I to calculate the four effects as follows:[9]

[6] Following Wang et al. [42], we define emission intensity as emissions per unit of value added. The reason is that the definition is consistent with the widely used emission per GDP indicator. Changes can be easily made to accommodate alternative emission intensity definitions, e.g. emission per unit of output.

[7] Value added has recently been adopted by several international agencies to quantify international trade to accurately characterize global economy. See, for example, the joint OECD-WTO Trade in Value-Added (TiVA) initiative [45] and the Global Value Chains (GVCs) analysis conducted jointly by OECD, WTO and World Bank [46].

[8] As an alternative, the ratio change in emissions can be similarly studied using the multiplicative decomposition. In this study we only present the additive decomposition for illustration purposes.

[9] The main advantages of LMDI-I over other decomposition methods include perfect decomposition at both the aggregate and sub-aggregate levels and consistency in aggregation [48,49]. These two features help to eliminate residual terms in decomposition and avoid inconsistent decomposition results when multilevel data are used.

$$\Delta C_{int}^{r,prd} = \sum_{k,i} w_{ki}\ln\frac{f_i^{r,T}}{f_i^{r,0}} \tag{6a}$$

$$\Delta C_{com}^{r,prd} = \sum_{k,i} w_{ki}\ln\frac{S_i^{rk,T}}{S_i^{rk,0}} \tag{6b}$$

$$\Delta C_{vshare}^{r,prd} = \sum_{k,i} w_{ki}\ln\frac{U^{rk,T}}{U^{rk,0}} \tag{6c}$$

$$\Delta C_{GDP}^{r,prd} = \sum_{k,i} w_{ki}\ln\frac{GDP^{r,T}}{GDP^{r,0}} \tag{6d}$$

where $w_{ki} = L(C_i^{rk,T},C_i^{rk,0})$ is the weight function and $L(\cdot,\cdot)$ is the logarithmic mean function. A positive effect implies that the change in that factor drives up the overall production-based emissions, and vice versa. The production composition effect, i.e. $\Delta C_{com}^{r,prd}$ in Eq. (6b), can be divided into two parts, namely the domestic goods composition effect $\left(\Delta C_{dcom}^{r,prd} = \sum_i w_{ri}\ln\frac{S_i^{rr,T}}{S_i^{rr,0}}\right)$ and export goods composition effect $\left(\Delta C_{excom}^{r,prd} = \sum_{k\neq r,i} w_{ki}\ln\frac{S_i^{rk,T}}{S_i^{rk,0}}\right)$. Similarly, the value-added share effect ($\Delta C_{vshare}^{r,prd}$) in Eq. (6c) can be split into the domestic share effect $\left(\Delta C_{dshare}^{r,prd} = \sum_i w_{ri}\ln\frac{U^{rr,T}}{U^{rr,0}}\right)$ and the export share effect $\left(\Delta C_{exshare}^{r,prd} = \sum_{k\neq r,i} w_{ki}\ln\frac{U^{rk,T}}{U^{rk,0}}\right)$. The two terms, $\Delta C_{excom}^{r,prd}$ and $\Delta C_{exshare}^{r,prd}$, quantify the impact of export on country *r*'s production-based emissions. The former if larger (smaller) than zero indicates the exported goods become more (less) emission intensive during year 0 and *T*, while the latter if larger (smaller) than zero means the export share in country *r*'s total production rises (decreases) and hence contributes to increases (reductions) in emissions. Eventually Eq. (5) can be rewritten as:

$$C^{r,prd,T}-C^{r,prd,0} = \Delta C_{int}^{r,prd} + \Delta C_{dcom}^{r,prd} + \Delta C_{excom}^{r,prd} + \Delta C_{dshare}^{r,prd} + \Delta C_{exshare}^{r,prd} + \Delta C_{GDP}^{r,prd} \tag{7}$$

Eq. (7) will be referred to as the production-based IDA (hereafter P-IDA) model.

The above country-level analysis in the P-IDA model can be extended to study a change in aggregate production-based emissions (i.e. $C = \sum_r C^{r,prd}$), which is formulated as follows:

$$C^T-C^0 = \sum_r C^{r,prd,T} - \sum_r C^{r,prd,0} = \sum_r (\Delta C_{int}^{r,prd} + \Delta C_{dcom}^{r,prd} + \Delta C_{dshare}^{r,prd} + \Delta C_{excom}^{r,prd} + \Delta C_{exshare}^{r,prd} + \Delta C_{GDPshare}^{r,prd}) + \Delta C_{AGDP} \tag{8}$$

where *GDPshare* is defined as $GDP^r/AGDP$ that denotes the share of country *r* in the aggregate GDP.

3.2. Consumption-based IDA

From Section 2, country *r*'s consumption-based emissions can be modelled as follows:

$$C^{r,con} = \sum_{k,i} \frac{C_i^{kr}}{V_i^{kr}}\frac{V_i^{kr}}{V^{kr}}\frac{V^{kr}}{AVA^r}AVA^r = \sum_{k,i} f_i^k Q_i^{kr} P^{kr} AVA^r \tag{9}$$

where $Q_i^{kr} = V_i^{kr}/V^{kr}$ denotes the domestic/imported goods composition, $P^{kr} = V^{kr}/AVA^r$ is the share of value added from country *k* to country *r* in the country's overall absorbed value added. The change in country *r*'s consumption-based emissions from year 0 to *T* can be decomposed as:

$$C^{r,con,T}-C^{r,con,0} = \Delta C_{int}^{r,con} + \Delta C_{com}^{r,con} + \Delta C_{vshare}^{r,con} + \Delta C_{AVA}^{r,con} \tag{10}$$

where *AVA* denotes the total absorbed value added effect. Eq. (9) shows that the intensity effect ($\Delta C_{int}^{r,con}$), the goods composition effect ($\Delta C_{com}^{r,con}$) and the value share effect ($\Delta C_{vshare}^{r,con}$) are impacted by both domestic goods and imports. Similar to the P-IDA model and by differentiating the source of goods, Eq. (10) can be rewritten as:

$$C^{r,con,T}-C^{r,con,0} = \Delta C_{dint}^{r,con} + \Delta C_{imint}^{r,con} + \Delta C_{dcom}^{r,con} + \Delta C_{imcom}^{r,con} + \Delta C_{dshare}^{r,con} + \Delta C_{imshare}^{r,con} + \Delta C_{AVA}^{r,con} \tag{11}$$

where *dint* denotes the emission intensity of domestic goods, *imint* is the emission intensity of imported goods, *imcom* is the imported goods composition and *imshare* is the share of imported goods in country *r*'s overall absorbed value added. Eq. (11) will be referred to as the consumption-based IDA (hereafter C-IDA) model.

The formulae for calculating the effects in Eq. (11) are given in Appendix A. Of the seven effects, the imports emission intensity effect ($\Delta C_{imint}^{r,con}$), the imports composition effect ($\Delta C_{imcom}^{r,con}$) and the imports share effect ($\Delta C_{imshare}^{r,con}$) together capture the impact of imports on country *r*'s consumption-based emissions. Similar to Eq. (8) and the P-IDA model, the country-level analysis in the C-IDA model can be extended to study the change in the aggregate consumption-based emissions as follows:

$$C^{con,T}-C^{con,0} = \sum_r C^{r,con,T} - \sum_r C^{r,con,0} = \sum_r (\Delta C_{dint}^{r,con} + \Delta C_{imint}^{r,con} + \Delta C_{dcom}^{r,con} + \Delta C_{imcom}^{r,con} + \Delta C_{dshare}^{r,con} + \Delta C_{imshare}^{r,con} + \Delta C_{AVAshare}^{r,con}) + \Delta C_{AGDP} \tag{12}$$

where *AVAshare* denotes country *r*'s absorbed value added share in the aggregate economy, i.e. $AVA^r/AGDP$.

3.3. Decomposition of emission balance

The emission balance of country *r* is given by $EB^r = C^{r,prd}-C^{r,con} = EEE^r-EEI^r$. The emissions embodied in export can be modelled as:

$$EEE^r = \sum_{k\neq r,i} \frac{C_i^{rk}}{V_i^{rk}}\frac{V_i^{rk}}{VAE^r}VAE^r \tag{13}$$

and the emissions embodied in imports is:

$$EEI^r = \sum_{k\neq r,i} \frac{C_i^{kr}}{V_i^{kr}}\frac{V_i^{kr}}{VAI^r}VAI^r \tag{14}$$

The arithmetic change in country *r*'s emission balance during year 0 and *T* can then be formulated as:

$$\begin{aligned}\Delta EB^r = EB^{r,T}-EB^{r,0} &= (EEE^{r,T}-EEE^{r,0})-(EEI^{r,T}-EEI^{r,0})\\ &= (\Delta EEE_{int}^r + \Delta EEE_{exstr}^r + \Delta EEE_{exv}^r)-(\Delta EEI_{int}^r + \Delta EEI_{imstr}^r + \Delta EEI_{imv}^r) = \Delta EB_{int}^r + \Delta EB_{str}^r + \Delta EB_{tb}^r\end{aligned} \tag{15}$$

where *str* denotes the impact of structure of traded goods and *tb* denotes the trade balance effect. Eq. (15) will be referred to as the emission balance (hereafter EB-IDA) model.

Three effects are specified to explain the temporal change in country *r*'s emission balance. The intensity effect (ΔEB_{int}^r) is the impact of all trade partners' emission intensity on country *r*'s emission balance. The trade composition effect (ΔEB_{str}^r) is a measure of changes in the traded goods/services structure, while the trade balance effect (ΔEB_{tb}^r) is the impact of trade balance on the emission balance. The decomposition effects in the EB-IDA model can be calculated by applying a specific decomposition method. Alternatively, these effects can also be computed as the difference between the decomposition results of the P-IDA model and those of the C-IDA model, as shown in Appendix B. This linkage provides a straightforward way to analyze changes in emission balance given the decomposition results of the P-IDA and C-IDA models.

3.4. Further discussions

Unlike the conventional IDA models, the three proposed models have been formulated to analyze aggregate emissions by distinguishing the destination/source of goods, and therefore the embodied emissions, produced/consumed in a country. This is done by using the embodied emissions and economic activity estimated from I-O analysis. As a result, trade related factors (e.g. traded goods composition and trade share in total production/consumption) are specifically modelled. The export (import) related impacts on production-based (consumption-based) emissions are captured by the P-IDA (C-IDA) model. The difference between the P-IDA and C-IDA model yields the EB-IDA model, which is used to analyze changes in the emission balance of countries. The impacts of both exports and imports on the emission balance are quantified.

The proposed models are extensions of the conventional IDA models with domestic goods and traded goods in relevant factors distinguished. Among them, the P-IDA model is closer to the conventional IDA models since the latter usually deals with the production-based emissions. Appendix C shows that the sum of the four effects other than the intensity effect and total economic activity effect in the P-IDA model, i.e. $\Delta C^{r,prd}_{dcom} + \Delta C^{r,prd}_{dshare} + \Delta C^{r,prd}_{excom} + \Delta C^{r,prd}_{exshare}$, capture the overall economy structure effect of country *r*. The sum of the four effects other than intensity effect and total consumption effect in the C-IDA model, i.e. $\Delta C^{r,con}_{dcom} + \Delta C^{r,con}_{dshare} + \Delta C^{r,con}_{imcom} + \Delta C^{r,con}_{imshare}$, capture the overall consumption structure effect of country *r*. This implies that while being consistent with the simplest three-factor IDA model,[10] the P-IDA (C-IDA) model isolates export (import) related effects.

The preceding analysis deals with changes in total emissions, which is based on a quantity indicator. Intensity indicators (e.g. emission intensity defined as total emissions divided by GDP) have also been widely used in policy studies, e.g. climate target setting of some countries such as China and India. The proposed models can be easily modified to study intensity indicators in a similar way.[11] The results obtained can inform policymakers of the impact of international trade on national emission intensity changes. In addition to the international trade, domestic trade can also be studied if relevant I-O tables are available. The proposed models can therefore be generally applied to assess the role of trade in progressing toward the climate target of countries.

With the same dataset and instead of the proposed IDA models, SDA can be implemented to explain the change in emissions and reveal the impact of trade.[12] A brief description of SDA is given in Appendix D. The results given by SDA and those by the proposed models are different and have different meanings. The impact of trade is captured differently. Specifically, trade is further differentiated between intermediate use and final demand in SDA, but not in IDA. This is due to the difference between the two techniques in methodology foundation [2]. As discussed in Wang et al. [55], the main difference between IDA and SDA in terms of modelling is on the economy structure, i.e. the Leontief structure and final demand structure specified in SDA versus the value added share used in IDA. This is shown in Appendix D in which the conceptual linkage between IDA modelling and SDA modelling is established.[13] The main strength of SDA is to scrutinize the inter-industry linkage in an economy, while the proposed IDA models provide comprehensive information on emission changes and the impact of trade. As discussed earlier, the proposed IDA models are simpler, and the results show stronger linkages with policy measures and are easier to implement and understand. This advantage may facilitate the application of the proposed IDA models in some specific areas in energy and environment policy development and assessment.

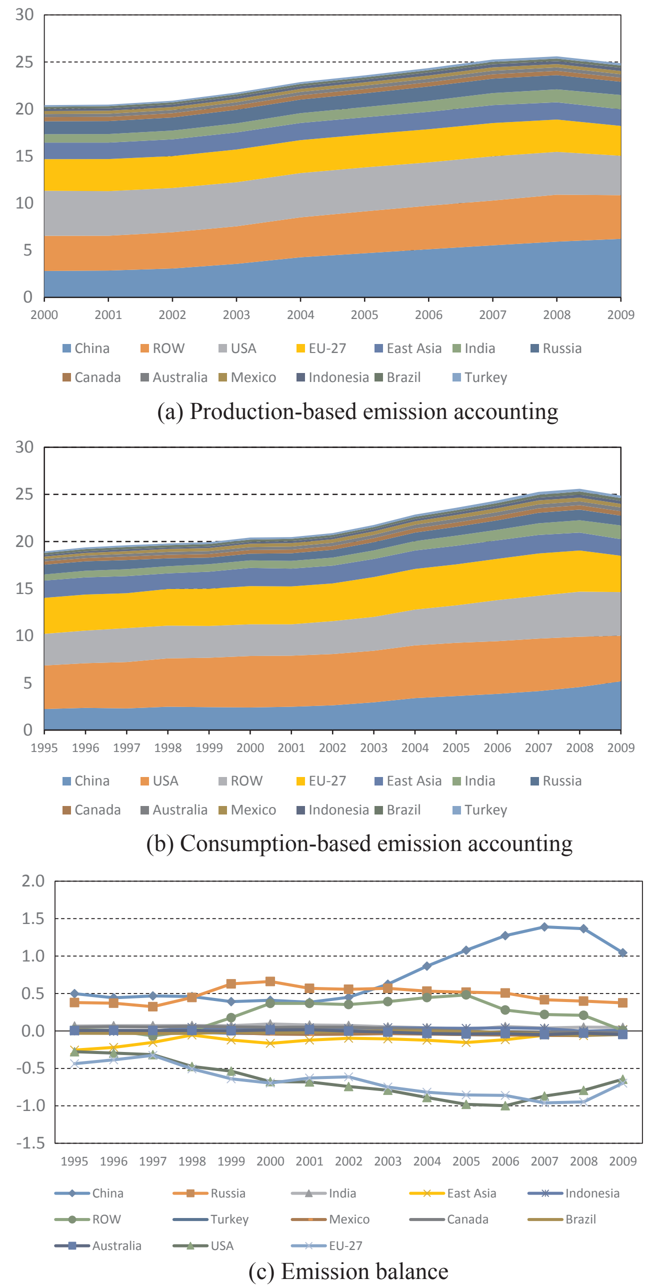

Fig. 1. Global economies' CO_2 emissions, 1995–2009 (unit: billion tons of CO_2). Note: East Asia includes Taiwan, Japan and Korea. EU-27 covers Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Poland, Portugal, Romania, Slovak Republic, Slovenia, Spain, Sweden and the United Kingdom.

4. Case study

4.1. Data

We apply the proposed IDA models to study the impact of international trade on global CO_2 emissions. We use the global multi-region I-O

[10] Refer to Eqs. (C1), (C2) in Appendix C.

[11] See Ang [3] for the generalized IDA formulation of intensity indicators. Examples of IDA studies dealing with intensity indicators include Fernández González [50], Tan et al. [51] and Timma et al. [52].

[12] Examples of SDA studies dealing with global energy consumption and emissions include Jiang and Guan [53] and Lan et al. [54].

[13] It should be noted that here the conceptual linkage is for IDA and SDA dealing with quantity indicator, while the linkage between the two techniques when studying intensity indicator is given in Wang et al. [55]. The two linkages are different due to the fact that quantity indicator and intensity indicator are modelled fairly different in SDA.

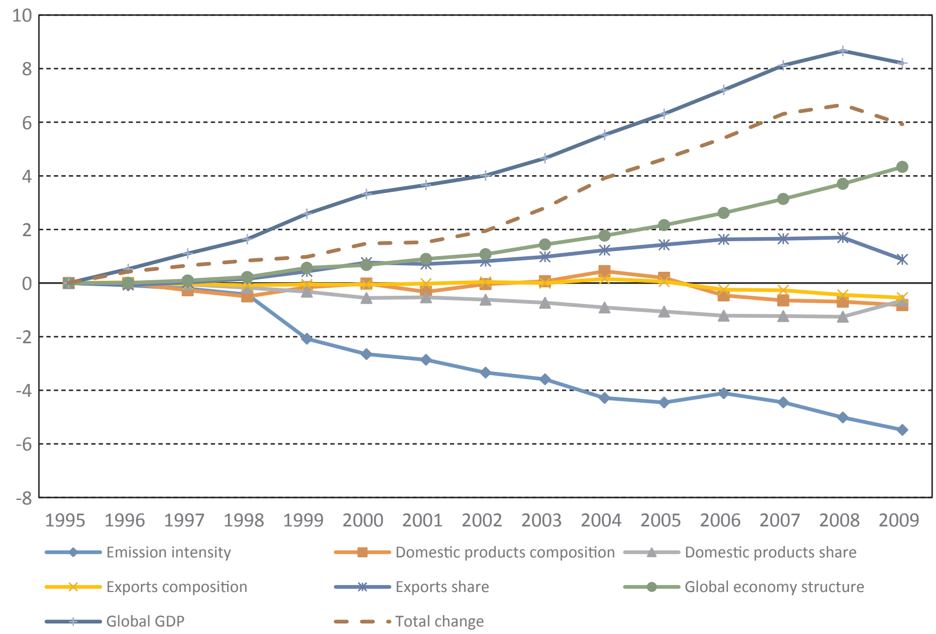

Fig. 2. Cumulative production-based decomposition results of global emissions, 1995–2009 (unit: billion tons of CO_2).

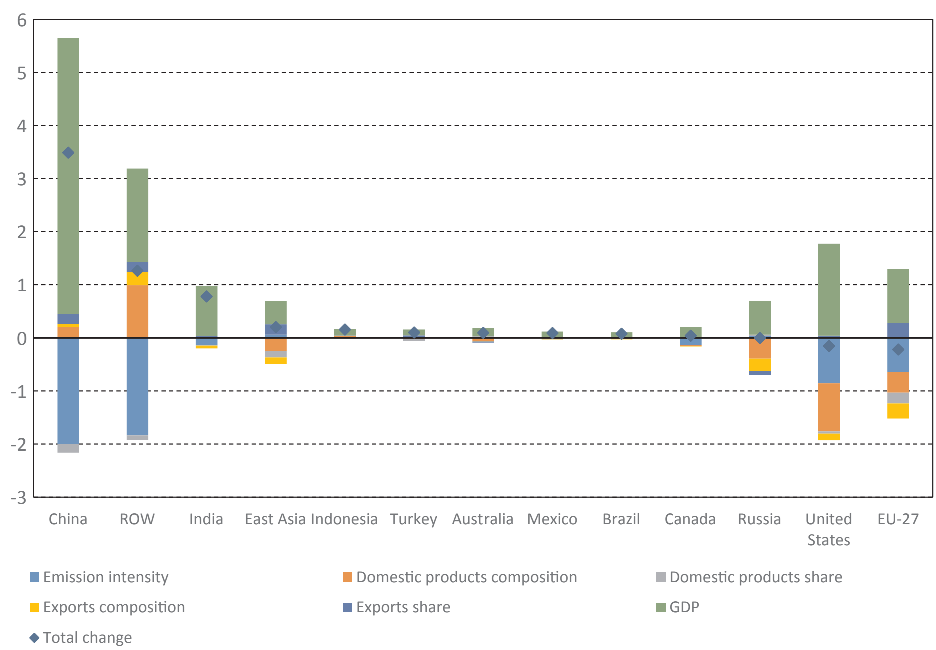

Fig. 3. Production-based emissions changes in global economies, 1995–2009 (unit: billion tons of CO_2). Note: Data are sorted by the total change in emissions.

tables and CO_2 emissions data in the World Input-Output Database (WIOD).[14] WIOD divides the global economy into 40 economies and a 'Rest of World' (ROW) region covering all the remaining countries. The data for each of the 41 economies is disaggregated into 35 economic sectors (see Appendix E). Annual data are available for the period 1995–2009. The emission and value added data in WIOD are measured on the production basis. Following Section 2 and using the WIOD data, absorbed value added and consumption-based emissions at the country-sector level can be estimated. With the data in current price and that in previous year's price, decomposition analysis between any two consecutive years can be conducted. Using additive decomposition, the results for multiple periods can be chained to explain emission changes over a longer time span.

Fig. 1(a) and (b) shows the production-based emissions and consumption-based emissions of world economies. Global emissions increased steadily from 1995 to 2008, followed by a slight decrease in 2009. The 1995 and 2009 emissions was respectively 18.95 and 24.87 billion tons of CO_2. China, the United States and the European Union were the top three emitters (excluding the ROW region) in 2009. Fig. 1(c) shows the emission balances of countries.

[14] The I-O tables are available at http://www.wiod.org/database/wiots13. The emission data are collected from the Environmental Accounts of WIOD, which can be retrieved from http://www.wiod.org/database/eas13. The quality of the WIOD data has been examined in a number of studies, e.g. Moran and Wood [56], Jiang and Guan [53] and Markandya et al. [57]. Owen et al. [58] compare WIOD and several other global MRIO databases (e.g. Eora and GTAP), and find that these databases generate consistent results. This can be viewed as a validation of the WIOD data.

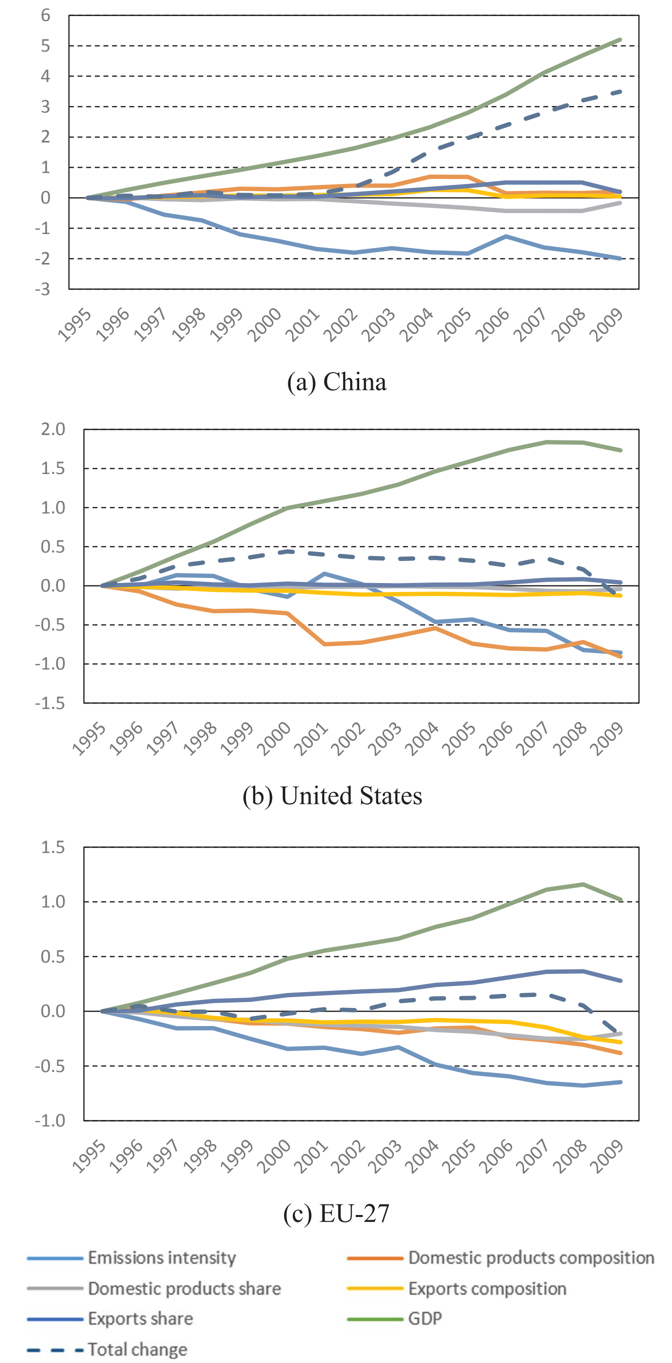

Fig. 4. Cumulative changes in production-based emissions in China, United States and EU, 1995–2009 (unit: billion tons of CO_2).

4.2. Production-based decomposition results

The cumulative decomposition results at the global level are shown in Fig. 2. Unsurprisingly, economic growth was the main driver of rising emissions, while emission intensity improvement contributed the most to emission reductions. Changes in global economy structure, measured as economies' share in global GDP, are found to have increased global emissions. The results are consistent with the shift of production activities from advanced economies to emerging economies where the emission intensities are relatively higher. Although the global export became slightly less emission intensive, particularly since 2005, increases in the export share in global GDP drove up global emissions. The two effects together indicate the growing importance of international trade.

Fig. 3 displays the driving forces of production-based emissions by economy. Only the United States, the EU-27 and Russia registered decreases in emissions. China and India registered the largest growth. Emission intensity improvement occurred in most economies. All the countries experienced decarbonization of production structure except China, Indonesia and India. The production structure, both domestic and exported, of the first two became more emission intensive. India's domestic production structure became more emission intensive, while its exports became less emission intensive. The results are consistent with the difference in the exports structure of the three countries.

We further look into the top three emitters, i.e. China, the United States and the EU-27, and divided the 15 years into three sub-periods, i.e. 1995–2000 (period I), 2000–2005 (period II) and 2005–2009 (period III). Fig. 4(a) shows a dramatic rise in China's production-based emissions after 2000, driven mainly by economic growth and raising export. Emission intensity improved consistently, except in 2006 where a deterioration occurred in the electricity sector (S17) and the petroleum refinery sector (S8). Compared to the first two periods, the domestic products composition and exports composition of China in period III became greener, due mainly to the declining share of the electricity sector (S17), the non-metallic mineral (S11) and the agriculture sector (S1) in the Chinese economy. Fig. 4(b) shows that the total production-based emissions of the United States decreased gradually after 2000. The reductions in 2008 and 2009, which were likely to be caused by the global economic crisis, resulted in a net decrease for the entire period of 1995–2009. Production structure change and emission intensity improvement were the main contributors to emission reduction, and the progress made was due mainly to the electricity sector (S17), the metal sector (S12), the public admin and defense sector (S31), and the petroleum refinery sector (S8). The EU recorded a slight increase in emissions in period I, and exhibited a pattern similar to the United States in period II and period III, as shown in Fig. 4(c). However, the driving forces were different from the United States. Emission intensity improvement was the largest contributor to EU's emissions reduction, while the greening exports composition played a more important role in reducing its overall production-based emissions.

4.3. Consumption-based decomposition results

Fig. 5 shows that total consumption and global consumption structure were the main contributors to the rising global emissions. Similar to the production-based case, emission intensity improvement was the main contributor to emission reductions. Consumption structure of domestic goods and imports became slightly greener in period III. Fig. 6 shows the consumption-based emissions change by economy. Only the East Asia region registered reductions in consumption-based emissions, driven mainly by the greening consumption structure and the intensity improvement in trade partners of Japan. China and India were the largest contributors in terms of consumption-based emission growth, followed by the United States. The EU recorded a marginal increase. The driving forces in these countries were largely similar to those at the global level. Only India's imports composition became more emission intensive.

The emission changing patterns of the top three consumption-based emitters are shown in Fig. 7. Emission intensity and composition of imports contributed to reductions in China's consumption-based emissions during period II and period III. Domestic factors had a large effect on China's consumption-based emissions. On the other hand, imports had a large impact for the United States and the EU, as shown in Fig. 7(b) and (c). The imports share of the total consumption in the United States continuously drove up, while the change in imports

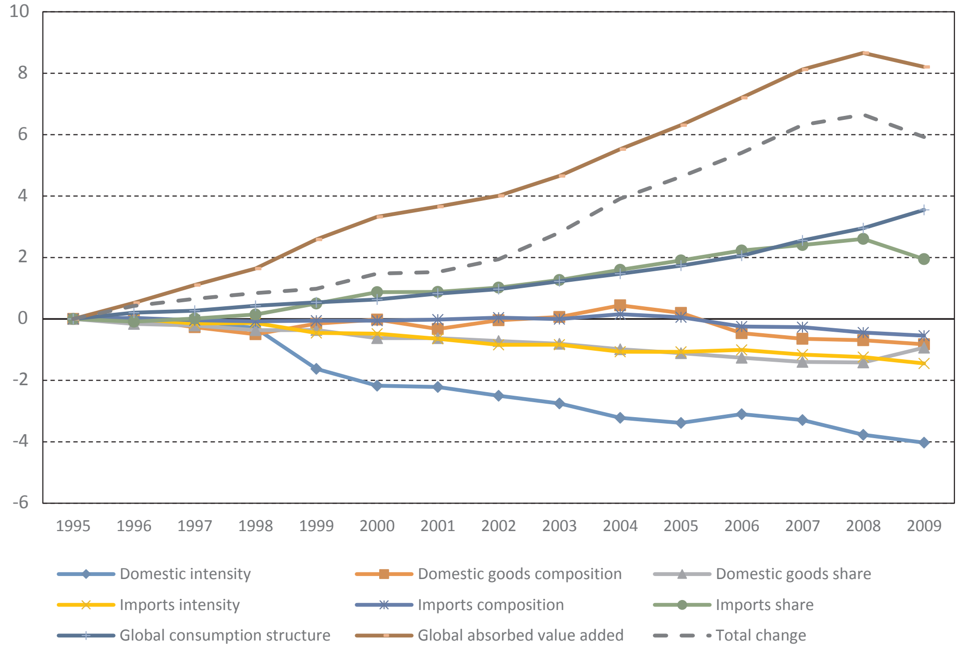

Fig. 5. Cumulative consumption-based decomposition results of global emissions, 1995–2009 (unit: billion tons of CO_2).

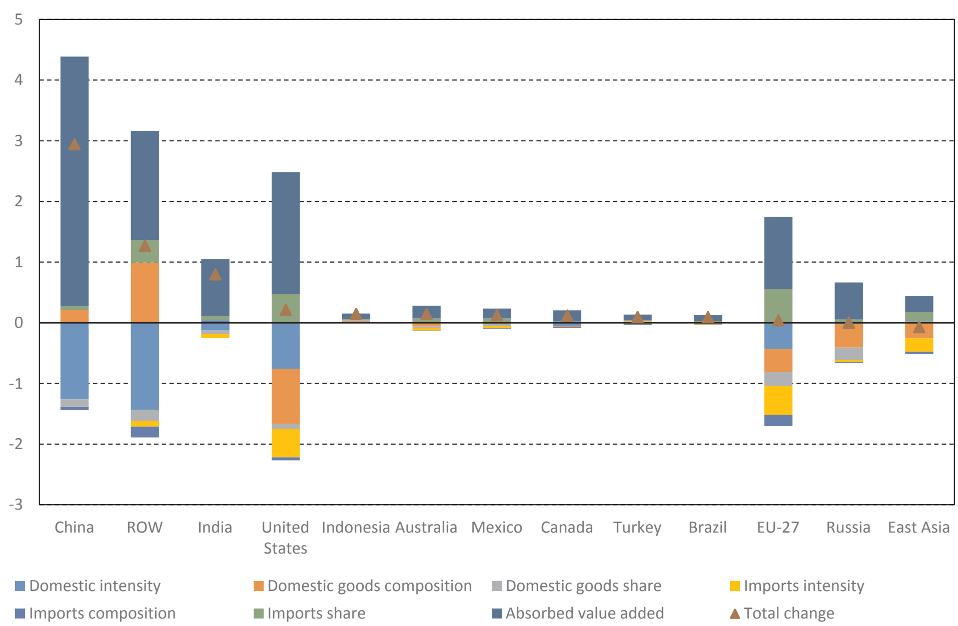

Fig. 6. Consumption-based emissions changes in global economies, 1995–2009 (unit: billion tons of CO_2). Note: data are sorted by the total change in emissions.

emission intensity steadily reduced, its consumption-based emissions. The imports composition gradually became greener over time, particularly in period III. These changes led to reductions in the country's consumption-based emissions since 2006. The development in the EU was fairly similar to that in the United States. The consumption-based emissions increased consistently until 2007, followed by drastic decreases in 2008 and 2009. Changes in imports share could explain a large part of the emission growth. Both imports intensity and imports composition improved, and the former contributed more to limit growth in consumption-based emissions.

4.4. Emission balance

The preceding shows that global economies performed fairly differently in production-based and consumption-based emissions. The difference implies the outsourcing of CO_2 emissions among countries via trade. Fig. 1(c) shows that China and Russia were the largest carbon exporters in 2009, while the EU and the United States were the larger importers. East Asia became a net emission exporter during 1995–2009. On the other hand, Mexico, Australia and Canada transited from net exporters to net importers. The carbon leakage between advanced economies and emerging economies increased in this period. Applying the EB-IDA model directly reveals the driving forces behind countries' emission balance changes. The EB-IDA model can be computed as the difference between the decomposition results of the P-IDA and those of the C-IDA model, and the results are shown in Fig. 8.

The driving forces behind changes in emission balance of countries were mixed, except that the growing trade volume usually widened the emission balance. While the trade structure depends on the specialization and relative competitiveness of economies in international

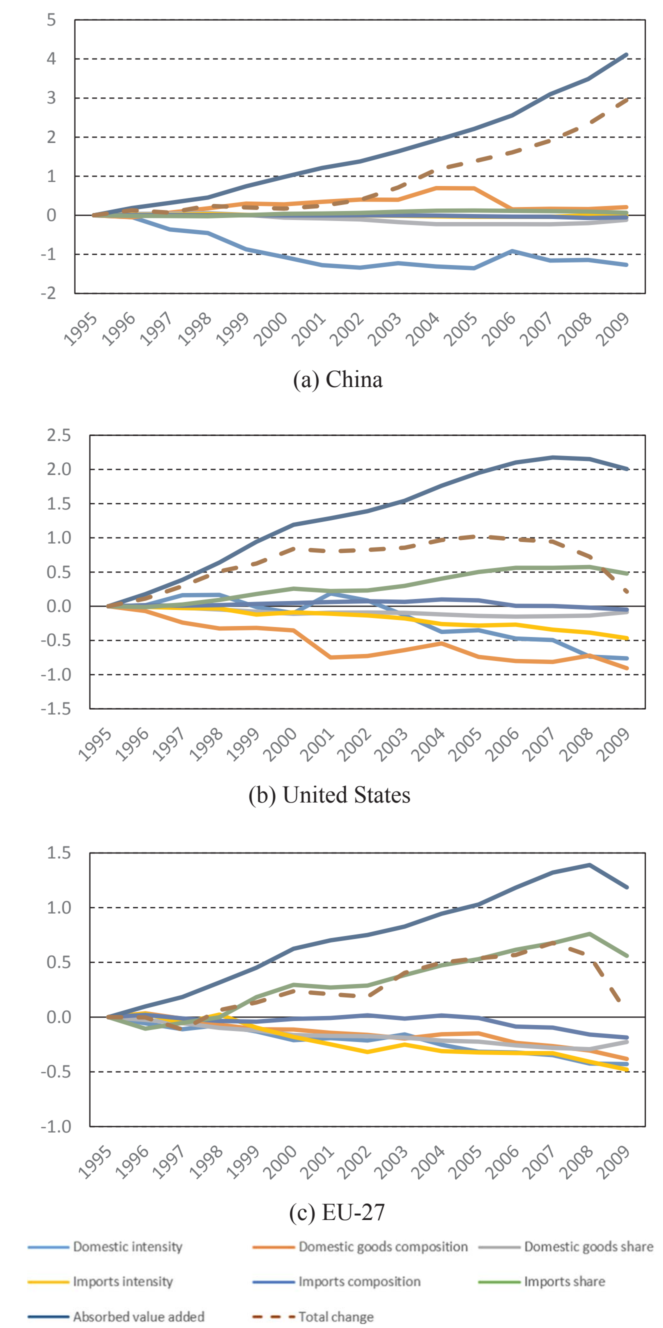

Fig. 7. Cumulative changes in consumption-based emissions in China, United States and EU, 1995–2009 (unit: billion tons of CO_2).

production, intensity effect reflects the difference between economies' production technology. As the largest net emission exporter, China saw a narrowing gap between exports and imports in terms of emission intensity, while at the same time the traded products structure became slightly more emission intensive. Top contributors to the change in China's emission balance were the emission intensive industrial sectors, including the electricity sector (S17), the basic metals and fabricated metal sector (S12) and the chemical sector (S9). These results are consistent with those reported in Zhang and Tang [59] and Liu et al. [17]. East Asia, Russia and India exhibited similar patterns since their trade structure became less emission intensive but the emission intensity increased. On the other hand, the net emission importers usually exhibited patterns opposite to emission exporters. For instance, the trade of the EU and the United States became more emission intensive over time, while the gap between emission intensity of imports and exports widened the emission balance. The results are contrary to those of China, which was a main trade partner of the EU and the United States. Similar findings are also observed at the sectoral level.

5. Conclusion

The objective of this study is to assess the role of international trade in global/national emissions using the IDA approach. Based on the emission accounting from MRIO analysis, three inter-linked IDA models are proposed. The production-based IDA (P-IDA) model adopts the production-based accounting principle and examines the emissions embodied in all the products of economies, including both domestic goods and exports. Similarly, the consumption-based (C-IDA) model investigates the emissions embodied in all the demands of economies that cover both domestic goods and imports. These two models are extensions of the conventional IDA model by distinguishing between domestic goods and imports/exports. The impact of international trade can therefore be quantified from different perspectives. Further, the EB-PDA model, which is essentially the difference between the P-IDA and the C-IDA model, can be applied to reveal changes in an economy's emission balance. The proposed models can also be extended to study intensity indicators and domestic trade. Compared to SDA, the three IDA models are simpler and more flexible in analyzing the impacts of trade.

The proposed models are useful to energy and environmental policy development and assessment related to trade. Understanding the impact of international trade in global/national emissions assists the debate on climate issues, e.g. addressing the carbon leakage between countries. The determinants specified in our models, e.g. emission intensity of traded goods and trade structure, are closely related to policy measures that have been widely debated or undertaken to control EET [2]. The trade related results shed lights on the linkage between trade and climate responsibilities, which can help to resolve the trade-climate dilemma in major emission exporters such as China. The results at the sectoral level further pinpoint key sectors that deserve greater attention in emission mitigation. Moreover, studying changes in countries' emission balance shows the dynamics of carbon leakage among economies, which is closely related to the design of border carbon adjustments that aim to strengthen the competitiveness of domestic industries.

We apply the proposed models to evaluate the impacts of international trade on global CO_2 emissions. From the production perspective, it is found that the growing share of exports in GDP drove up the total emissions, while the exports composition became marginally greener, particularly after 2005. From the consumption perspective, it is shown that imports had larger impact on the advanced economies, e.g. the EU and the United States, that rely heavily on imports to satisfy demand. Both the intensity and composition of imports contributed to emission mitigation. The different performances of economies in production-based and consumption-based emissions led to the outsourcing of CO_2 emissions. From the viewpoint of emission balance, it is found that the expansion of carbon leakage between advanced economies and emerging economies occurred in the study period was driven by the widening trade balance and more emission-intensive trade structure.

The present study deals with some basic issues and it can be extended in the following aspects. First, our proposed models take the simplest form and more factors, e.g. population, fuel type and sub-regions in economies, can be incorporated. Such extensions can offer results which are more detailed than those presented in this study. Second, stemming from the IDA technique that is an accounting approach, our proposed models cannot provide inferential information and do not take (energy, commodity, etc) prices into consideration. Such extensions can be made by combining IDA with econometric models. Third, due to data availability, our case study covers the period up to 2009. Empirical analyses can be conducted using more recent data to provide results with more timely policy implications.

Fig. 8. Changes in emission balance of economies, 1995–2009 (unit: million tons of CO_2).

Appendix A. Calculation of C-IDA model

Applying the additive LMDI-I method to Eq. (11) yields the follows:

$$\Delta C_{dint}^{r,con} = \sum_{i} w_{ri} \ln \frac{f_i^{rr,T}}{f_i^{rr,0}} \tag{A1}$$

$$\Delta C_{imint}^{r,con} = \sum_{k \neq r,i} w_{ki} \ln \frac{f_i^{kr,T}}{f_i^{kr,0}} \tag{A2}$$

$$\Delta C_{dcom}^{r,con} = \sum_{i} w_{ri} \ln \frac{Q_i^{rr,T}}{Q_i^{rr,0}} \tag{A3}$$

$$\Delta C_{imcom}^{r,con} = \sum_{k \neq r,i} w_{ki} \ln \frac{Q_i^{kr,T}}{Q_i^{kr,0}} \tag{A4}$$

$$\Delta C_{dshare}^{r,con} = \sum_{i} w_{ri} \ln \frac{P^{r,T}}{P^{r,0}} \tag{A5}$$

$$\Delta C_{imshare}^{r,con} = \sum_{k \neq r,i} w_{ki} \ln \frac{P^{kr,T}}{P^{kr,0}} \tag{A6}$$

$$\Delta C_{AVA}^{r,con} = \sum_{k,i} w_{ki} \ln \frac{AVA^{r,T}}{AVA^{r,0}} \tag{A7}$$

where $w_{ki} = L(C_i^{kr,T}, C_i^{kr,0})$.

Appendix B. Linkages between P-IDA, C-IDA and EB-IDA models

Emission balance of a country is defined as the difference between its production-based emissions and consumption-based emissions. With reference to the P-IDA model, i.e. Eq. (7), and C-IDA model, i.e. Eq. (11), the change in the emission balance of country r during year 0 and T can be formulated as:

$$\begin{aligned} EB^{r,T} - EB^{r,0} &= (C^{r,prd,T} - C^{r,con,T}) - (C^{r,prd,0} - C^{r,con,0}) = (C^{r,prd,T} - C^{r,prd,0}) - (C^{r,con,T} - C^{r,con,0}) = (\Delta C_{int}^{r,prd} + \Delta C_{dcom}^{r,prd} + \Delta C_{excom}^{r,prd} + \Delta C_{dshare}^{r,prd} + \Delta C_{exshare}^{r,prd} + \Delta C_{GDP}^{r,prd}) \\ &\quad - (\Delta C_{dint}^{r,con} + \Delta C_{imint}^{r,con} + \Delta C_{dcom}^{r,con} + \Delta C_{dshare}^{r,con} + \Delta C_{imcom}^{r,con} + \Delta C_{imshare}^{r,con} + \Delta C_{AVA}^{r,con}) = \left(\sum_{k \neq r,i} w_{ki} \ln \frac{f_i^{r,T}}{f_i^{r,0}} + \sum_{k \neq r,i} w_{ki} \ln \frac{S_i^{rk,T}}{S_i^{rk,0}} + \sum_{k \neq r,i} w_{ki} \ln \frac{V^{rk,T}}{V^{rk,0}} \right) \\ &\quad - \left(\sum_{k \neq r,i} w_{ki}^* \ln \frac{f_i^{k,T}}{f_i^{k,0}} + \sum_{k \neq r,i} w_{ki}^* \ln \frac{Q_i^{kr,T}}{Q_i^{kr,0}} + \sum_{k \neq r,i} w_{ki}^* \ln \frac{V^{kr,T}}{V^{kr,0}} \right) = (\Delta EEE_{exint}^r + \Delta EEE_{exstr}^r + \Delta EEE_{exv}^r) - (\Delta EEI_{imint}^r + \Delta EEI_{imstr}^r + \Delta EEI_{imv}^r) \\ &= \Delta EB_{int}^r + \Delta EB_{str}^r + \Delta EB_{tb}^r \end{aligned} \tag{B1}$$

where $w_{ki} = L(C_i^{rk,T},C_i^{rk,0})$ and $w_{ki}^* = L(C_i^{kr,T},C_i^{kr,0})$ when LMDI-I is applied. The last four lines in Eq. (B1) are the same as that in Eq. (15).

Appendix C. Structure effects in the P-IDA model

As shown in Ang (2015), the production-based emissions is usually modelled as:

$$C = \sum_i \frac{C_i}{V_i}\frac{V_i}{V}V = \sum_i I_i S_i V \tag{C1}$$

and the conventional three-factor IDA model is specified as follows:

$$\Delta C = C^T - C^0 = \Delta C_{int} + \Delta C_{str} + \Delta C_{act} \tag{C2}$$

The economy structure effect can be calculated as:

$$\Delta C_{str} = \sum_i w_i \ln\left(\frac{V_i^T/V^T}{V_i^0/V^0}\right) \tag{C3}$$

where w_i is the weight function. Given the application of additive LMDI-I, $w_i = L(C_i^T,C_i^0)$.

With reference to the P-IDA model,

$$\Delta C_{dcom}^{r,prd} + \Delta C_{dshare}^{r,prd} = \sum_i w_i' \ln\left(\frac{V_i^{rr,T}/V^{r,T}}{V_i^{rr,0}/V^{r,0}}\right) \tag{C4}$$

and

$$\Delta C_{excom}^{r,prd} + \Delta C_{exshare}^{r,prd} = \sum_{k\neq r,i} w_{ki}'' \ln\left(\frac{V_i^{rk,T}/V^{r,T}}{V_i^{rk,0}/V^{r,0}}\right) \tag{C5}$$

Summing Eqs. (C4) and (C5) yields:

$$\Delta C_{dcom}^{r,prd} + \Delta C_{dshare}^{r,prd} + \Delta C_{excom}^{r,prd} + \Delta C_{exshare}^{r,prd} = \sum_{ki} w_{ki}^* \ln\left(\frac{V_i^{rk,T}/V^{r,T}}{V_i^{rk,0}/V^{r,0}}\right) \tag{C6}$$

where $w_{ki}^* = L(C_i^{rk,T},C_i^{rk,0})$. Both Eqs. (C3) and (C6) capture the impact of production structure change in country r, with the difference that the latter further distinguishes the destination of goods produced in the country. Numerically the two structure effects may not be exactly same due to different disaggregation levels in the two models, i.e. only sector (i) in Eq. (C3) while both sector (i) and destination of goods (country k) in Eq. (C6).

Appendix D. SDA modelling and its linkage with IDA when studying quantity indicator

Taking the production-based emissions as an example and with reference to Eq. (3), the aggregate emissions is modelled as:

$$C = \mathbf{f}'\mathbf{H}\mathbf{Y} = \mathbf{f}'\mathbf{H}\mathbf{S}y_{tot} \tag{D1}$$

where $\mathbf{S} = \mathbf{Y}/y_{tot}$ denotes the final demand structure and y_{tot} is the total final demand. Defining the ratio between total final demand and aggregate GDP as $p = y_{tot}/AGDP$, Eq. (D1) can be rewritten as:

$$C = \mathbf{f}'\mathbf{H}\mathbf{S}_{fdstr}y_{tot} = \mathbf{f}'\mathbf{H}\mathbf{S}pAGDP \tag{D2}$$

It is easy to verify that $\mathbf{V}_{str} = \mathbf{HS}p$ denotes the economy structure in terms of value added share of sectors within countries. With the data in year 0 and T, the change in emissions during the period can be decomposed as:

$$C^T - C^0 = \Delta C = \Delta C_{int} + \Delta C_H + \Delta C_{fdstr} + \Delta C_p + \Delta C_{AGDP} \tag{D3}$$

The effects other than the emission intensity effect (ΔC_{int}) and total activity effect (ΔC_{AGDP}) give the economy structure effect, which is nonetheless different from that yielded by the P-IDA model due to aggregation issues. More detailed explanations are given in Wang et al. [55].

Appendix E. Sector classification in WIOD

S1	Agriculture, Hunting, Forestry and Fishing
S2	Mining and Quarrying
S3	Food, Beverages and Tobacco
S4	Textiles and Textile Products
S5	Leather, Leather and Footwear
S6	Wood and Products of Wood and Cork
S7	Pulp, Paper, Paper, Printing and Publishing
S8	Coke, Refined Petroleum and Nuclear Fuel
S9	Chemicals and Chemical Products
S10	Rubber and Plastics
S11	Other Non-Metallic Mineral
S12	Basic Metals and Fabricated Metal
S13	Machinery, n.e.c
S14	Electrical and Optical Equipment

S15	Transport Equipment
S16	Manufacturing, n.e.c; Recycling
S17	Electricity, Gas and Water Supply
S18	Construction
S19	Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel
S20	Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles
S21	Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods
S22	Hotels and Restaurants
S23	Inland Transport
S24	Water Transport
S25	Air Transport
S26	Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies
S27	Post and Telecommunications
S28	Financial Intermediation
S29	Real Estate Activities
S30	Renting of M&Eq and Other Business Activities
S31	Public Admin and Defense; Compulsory Social Security
S32	Education
S33	Health and Social Work
S34	Other Community, Social and Personal Services
S35	Private Households with Employed Persons

Note: n.e.c denotes not elsewhere classified

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