Consumption-based accounting of global anthropogenic CH_4 emissions

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Key Points:

- We identify the impacts of final demand and international trade on global anthropogenic CH_4 emissions.
- We quantify consumption-based CH_4 inventories of 181 countries/regions and 19 integrative economies.
- 49.5% of global CH_4 emissions in 2012 were associated with international trade, of which 77.8% were from intermediate trade.

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Abstract

Global anthropogenic CH_4 emissions have witnessed a rapid increase in the last decade. However, how this increase is connected with its socioeconomic drivers has not yet been explored. In this paper, we highlight the impacts of final demand and international trade on global anthropogenic CH_4 emissions based on the consumption-based accounting principle. We find that household consumption was the largest final demand category, followed by fixed capital formation and government consumption. The position and function of nations and major economies to act on the structure and spatial patterns of global CH_4 emissions were systematically clarified. Substantial geographic shifts of CH_4 emissions during 2000-2012 revealed the prominent impact of international trade. In 2012, about half of global CH_4 emissions were embodied in international trade, of which 77.8% were from intermediate trade and 22.2% from final trade. Mainland China was the largest exporter of embodied CH_4 emissions, while the USA was the largest importer. Developed economies such as Western Europe, the USA and Japan were major net receivers of embodied emission transfer, mainly from developing countries. CH_4 emission footprints of nations were closely related to their human development indexes (HDIs) and per capita gross domestic products (GDPs). Our findings could help to improve current understanding of global anthropogenic CH_4 emission increases, and to pinpoint regional and sectoral hotspots for possible emission mitigation in the entire supply chains from production to consumption.

Keywords**:** Anthropogenic CH_4 emissions; Consumption-based accounting; International trade; Multi-regional input-output analysis; Global supply chains

1. Introduction

Methane (CH_4), the second largest greenhouse gas (GHG), has a global warming potential (GWP) 28 times greater than that of carbon dioxide (CO_2) over a 100-year time horizon (IPCC, 2014). Small changes in the atmospheric CH_4 concentration could have significant impacts on climate and environment (Saunois et al., 2016b). Over the past 250 years, CH_4 concentration in the global atmosphere has more than doubled (1845±2 ppb in 2015), responsible for about one fifth of global warming (WMO, 2016). The growth of CH_4 levels in the atmosphere is highly related with increasing emissions from human activities (Montzka et al., 2011; Kirschke et al., 2013; Ghosh et al., 2015; Dalsøren et al., 2016; Hausmann et al., 2016; Nisbet et al., 2016). Saunois et al. (2016a) reported that global total CH_4 emissions were estimated at 558 Tg/yr, of which about 60% were originated from anthropogenic sources such as agricultural production and fossil fuel extraction. Recent bottom-up inventories have shown the rapid rise in anthropogenic CH_4 emissions since 2000 (Rice et al., 2016; Saunois et al., 2016a; Höglund-Isaksson, 2017; Janssens-Maenhout et al., 2017; Olivier et al., 2017), especially in some developing countries such as China. To reduce the uncertainties in future climate projections, world-wide researchers have focused on the inventories of CH_4 emissions and corresponding mitigation strategies at various scales from regional to global (e.g., Schaefer et al., 2016; Schwietzke et al., 2016; Crill and Thornton, 2017; Zhang et al., 2018).

Measuring a country's CH_4 emissions is critical to mitigate GHG emissions and combat climate change. There are two accounting methods of measuring GHG emissions: production-based or consumption-based (Peters, 2008). Production-based emission accounting (PBA) represents the on-site emissions within national territory (sometimes referred to as territorial-based) preferred by the UNFCCC. Existing studies whether regarding national, regional and sectoral CH_4 emissions are all in the scope of PBA circumstance (e.g., Zhang et al., 2014a; Hopkins et al., 2016; Höglund-Isaksson, 2017; Janssens-Maenhout et al., 2017; Du et al., 2018). But GHG emissions from various industrial sectors are induced by economic behaviors (Oliveira and Bourscheidt, 2017). Identification of production-side characteristics alone is insufficient to comprehend the inducements of anthropogenic CH_4 emissions and relevant mitigation potentials. Researches should examine how production-side CH_4 emissions from economic activities are influenced by the consumption-side demands. For that reason, consumption-based emission accounting (CBA) method re-attributes the emissions produced by industrial sectors to the final demand of consumers as embodied emissions related to consumed goods, and therefore the final consumers can be allocated corresponding emission responsibility. Consumption-based national CH_4 emissions, which represent the embodied CH_4 emissions or CH_4 footprint, encompass those emissions from domestic final consumption and those emissions related to the production of its imports in the exporting countries. Key advantages of CBA method include but not limited to "*incorporating embodied emissions, extending emission mitigation options, covering more global emissions through increased participation, and inherently encompassing policies such as the Clean Development Mechanism (CDM)*" (Peters, 2008; Poortinga et al., 2012; IPCC, 2014; Fan et al., 2016). Therefore, it is essential to understand global anthropogenic CH_4 emissions from a consumption perspective and quantify consumption-based CH_4 inventories.

Input-output analysis is an effective tool to reflect the quantitative dependency between all production links in economic sectors. By using the input-output models, environmental emissions caused by the intermediate production and final consumption throughout the supply chain can be attributed to end users (Moran and Kanemoto, 2016; Wu et al., 2018). While a multi-regional input-output (MRIO) model that interconnects multiple regions reflects the interregional and intraregional economic connection (Zhang et al., 2014b, 2016), the global MRIO modelling can provide a robust assessment on the demand-driven resource use and environmental emissions in the production and trade network of the world economy. Extensive studies have been conducted on the global MRIO analyses of resource and emission requirements associated with production, consumption and international trade, such as water (Feng et al., 2011; Chen and Chen, 2013; Lenzen et al., 2013a; Ali, 2017; Han et al., 2018), energy (Chen and Wu, 2017; Chen et al., 2018b), materials (Wiedmann et al., 2013; Tian et al., 2017), land (Chen and Han, 2015; Chen et al., 2018a; Wu et al., 2018), biodiversity (Lenzen et al., 2012b), CO_2 (Davis and Caldeira, 2010; Tian et al., 2015; Andreoni and Galmarini, 2016; Fan et al., 2016; Malik et al., 2016; Jiang and Green, 2017; Pablo-Romero and Sánchez-Braza, 2017; Liddle, 2018), air pollutants (Kanemoto et al., 2014; Lin et al., 2014, 2016; Meng et al., 2016; Zhang et al., 2017), etc. At present, MRIO account and analysis has become a popular approach to measure and assess consumption-based global GHG emissions (e.g., Peters, 2008; Arto and Dietzenbacher, 2014; Caro et al., 2017).

Since international trade plays a key role in global geographic shifts of environmental burdens such as carbon leakage, the environmental indicators most often examined are CO_2 emissions and air pollutants embodied in international trade (e.g., Peters and Hertwich, 2008;

Hertwich and Peters, 2009; Deng and Xu, 2017; Jiang and Guan, 2017). For instance, Peters et al. (2011) reported that the CO_2 emissions from the production of traded goods and services had increased from 20% of global emissions in 1990 (4.3 Gt) to 26% in 2008 (7.8 Gt). Lenzen et al. (2012b) discovered that about 30% of the biodiversity around the world was caused by international trade. Liang et al. (2015) reported that 37% of the mercury emissions in the atmosphere could be attributed to international trade. Oita et al. (2016) found that approximately 1/4 of global nitrogen emissions was embodied in the products of international trade. Previous studies have indicated that international trade has significantly affected the reallocation of industrial distribution and related environmental impacts, and the net embodied transfers of resources and emissions via international trade were identified from developing to developed countries. However, consumption-based global CH_4 accounting and trade-related emission transfers attract little attention (Kanemoto et al., 2016), due to inadequate CH_4 inventories at the global scale. Some researchers calculated the CH_4 emissions embodied in the international trade of agricultural products (e.g., meats) (Caro et al., 2014), but failed to integrate a comprehensive trade relationships into the global MRIO modeling. It necessitates further exploration of the embodied CH_4 emissions associated with goods exchange among nations, including the mechanism whereby the final demand acts on the production and trade distribution across the world.

To fill this gap, this paper makes the first attempt to perform a consumption-based accounting of global anthropogenic CH_4 emissions, based on the latest emission inventories from the Emissions Database for Global Atmospheric Research (EDGAR) and the available global MRIO tables from the EORA database. By linking CH_4 emissions to the economic production, trade and final consumption along the supply chains, the characteristics of global consumption-side CH_4 emissions in the socio-economic context are explored. We identify how the spatial distribution of CH_4 emissions around the world could be affected by intermediate trade and final trade activities. Critical industrial sectors and regions in global consumption and trade are revealed for emission mitigation. The results probe into the impact of final demand and international trade on the structure of global CH_4 emissions.

The remainder of this paper is organized as follows. In Section 2, the global MRIO table, algorithms for MRIO analysis and data sources are introduced. In Section 3, the results of embodied CH_4 emissions in final demand and international trade in 2012 are presented. We also analyze the evolution of consumption-based emission inventories over 2000-2012 in this section. Implications of consumption-based emission accounting are further discussed in Section 4. Concluding remarks will be made in the ending section.

2. Methodology and data

2.1. Global MRIO table

The global MRIO tables describe the economic relationships between producers and consumers within the globalized world economy (Lenzen et al., 2012a). Multiple organizations have prepared the global MRIO tables covering multiple regions of the world. These include the Global Trade Analysis Project (GTAP) database by Purdue University, the input-output database by the Organization for Economic Co-operation and Development (OECD), the EXIOPOL database by the European Union, the WIOD database by University of Groningen, and the EORA database by University of Sydney (Malik et al., 2016). Among these databases, the EORA MRIO table covers the most regions and the longest time spans (Lenzen et al., 2012a, 2013b). A large number of studies have been conducted on embodied resources and emissions in international trade based on the global MRIO table from the EORA database (e.g., Malik et al., 2016; Oita et al., 2016; Li et al., 2017; Xia et al., 2017; Chen et al., 2018a,b; Wu and Chen, 2018). In this study, the EORA database is also adopted to build the global MRIO tables for 2000-2012, which cover 189 countries/regions.

Figure 1 displays the basic framework of a global MRIO table. The economic linkage along supply chains refers to the input (intermediate input and value-added) and the output (intermediate production/use and final consumption/use). The total input of a production sector is equal to its total output. In the input-output accounts, the principal measure of economic output is the total output, which refers to the value of intermediate production plus final consumption. The intermediate production represents the processing of intermediate goods, including primary and other raw materials, for final consumption. The final consumption or final demands include household consumption, non-profit consumption, government consumption, fixed capital formation, inventory increase and acquisitions of valuables (Lenzen et al., 2012a).

The trade of goods and services for intermediate production (intermediate trade) and for final consumption (final trade) are two basic components of international trade in the global MRIO table. The intermediate trade between both sectors and regions is to satisfy the purpose of intermediate production (Johnson and Noguera, 2012), which occupies a considerable share in global trading activities. As displayed in Fig. 1, to illustrate the trade of region 1 with other regions for intermediate production and final demand, the yellow segments indicate the exports in region 1 for intermediate and final trade, and the red segments represent the imports in region 1 from other regions for intermediate production and final consumption.

[Place Figure 1 here]

2.2. MRIO analysis and emission embodiment

The global MRIO model, incorporating direct emission inventories, reveals the emissions induced by final demand and international trade. Assuming regional- and industry-specific data for emissions per unit of output are available, the total amount of emissions for production, consumption and trade can be calculated. The global total production-side emission is equal to the total consumption-side emission. According to the emission balance of global MRIO model, the basic linear equation can be expressed as,

$$e_i^R + \sum_{S=1}^{m} \sum_{j=1}^{n} (\varepsilon_j^S Z_{ji}^{SR}) = \varepsilon_i^R X_i^R \quad (1)$$

$$X_i^R = \sum_{S=1}^{m} \sum_{j=1}^{n} Z_{ij}^{RS} + \sum_{S=1}^{m} f_i^{RS} \quad (2)$$

where e_i^R is the direct CH_4 emissions (Production-based CH_4 emissions, PBM) by sector i in region R; ε_j^S and ε_i^R are termed as embodied emission intensities of the output from sector j in region S and sector i in region R, respectively; Z_{ji}^{SR} represents the intermediate input from sector j in region S to sector i in region R; X_i^R is the total output vector of sector i in region R; Z_{ij}^{RS} is the intermediate production from sector i in region R to sector j in region S; and f_i^{RS} stands for the final consumption of goods or services from sector i in region R to region S.

Introduce $\hat{\mathbf{X}}$ as the matrix diagonalization of X, the MRIO model can be further expressed as

$$\mathbf{E}+\boldsymbol{\varepsilon}\times\mathbf{Z}=\boldsymbol{\varepsilon}\hat{\mathbf{X}} \tag{3}$$

Then with the condition that $(\hat{\mathbf{X}}-\mathbf{Z})$ is reversible, the embodied CH_4 emission intensities can be obtained by

$$\boldsymbol{\varepsilon}=\mathbf{E}(\hat{\mathbf{X}}-\mathbf{Z})^{-1} \tag{4}$$

Based on the embodied emission intensity matrix, the CH_4 emissions embodied in regional final consumption can be acquired by

$$\mathrm{CBM}^{R}=\sum_{S=1}^{m}\sum_{j=1}^{n}(\varepsilon_j^S f_j^{SR}) \tag{5}$$

where CBM^{R} represents the embodied CH_4 emissions (Consumption-based CH_4 emissions, CBM) induced by the final demand of regional R.

To calculate the emissions embodied in international trade, this study pays equal attention to the intermediate trade and final trade, which is consistent with the traditional accounting of monetary trade (Chen and Wu, 2017). Embodied emission transfers via intermediate trade and final trade are considered as intermediate producers' production-driven and final users' consumption-driven trading fluxes, respectively. According to the systems input-output model illustrated by Wu and Chen (2017, 2018), the flows of embodied resources or emissions in both intermediate and final trades can be quantified. The CH_4 emissions embodied in international import (MEIM, the sum of intermediate import and final import) and export (MEEX, the sum of intermediate export and final export) are expressed as

$$\mathrm{MEIM}^{R}=\sum_{i=1}^{n}\sum_{S=1(S\neq R)}^{m}(\sum_{j=1}^{n}\varepsilon_j^S Z_{ji}^{SR}+\varepsilon_j^S f_j^{SR}) \tag{6}$$

$$\mathrm{MEEX}^{R}=\sum_{i=1}^{n}\sum_{S=1(S\neq R)}^{m}(\sum_{j=1}^{n}\varepsilon_i^R Z_{ij}^{RS}+\varepsilon_i^R f_i^{RS}) \tag{7}$$

$$\mathrm{MEEB}^{R}=\mathrm{MEIM}^{R}-\mathrm{MEEX}^{R} \tag{8}$$

where $MEIM^R$ is the total emissions imported to region R from other regions, while $MEEX^R$ is the total emissions embodied in exports to all other regions from region R. The embodied CH_4 emissions in international trade balance (MEEB) can be obtained as the difference of import (MEIM) and export (MEEX). An economy with positive value of MEEB is a net importer of embodied CH_4 emissions, while that with negative MEEB is a net exporter.

2.3. Emission data collection and preparation

Most global inventories of anthropogenic CH_4 emissions are "bottom-up" (Chai et al., 2016), based on summing individual source-category estimates. A well-developed bottom-up inventory can be used to reveal the emission source and composition. Unlike CO_2 emissions, the estimation of anthropogenic CH_4 emissions at the Country level is extremely challenging, due to the fact that large amount of activity-level data and emission factors are hard to obtain. The global GHG emission inventories in the EDGAR database have been widely adopted for related environmental and climate research. This database has updated the bottom-up inventories of anthropogenic GHG emissions of nations to the year of 2012 (EDGAR, 2017; Janssens-Maenhout et al., 2017). Specifically, the most recently available anthropogenic CH_4 emission inventories at the Country level can be obtained from the EDGAR4.3.2 emission database, which make it possible for a more systematic study on time-series consumption-based accountings of global CH_4 emissions during 2000-2012. Based on the emission data availability, all the 189 countries/regions in the MRIO model are merged into 181 economies (see Table S1) with 26 sectors (see Table S2) included for each economy. The population and gross domestic product (GDP) data of the economies are available from the statistical database of the World Bank (World Bank, 2017).

To perform the MRIO modeling, we should extract the direct emission data that are related to economic activities and reallocate these data to each industrial sector of different economies. Direct CH_4 emission sources refer to enteric fermentation, manure management, rice cultivation, fugitive emissions from solid fuels, fugitive emissions from oil & gas, solid waste disposal on land, wastewater handling, fossil fuel combustion and others, which are further divided into detailed emission categories in the EDGAR database. For instance, 82 emission categories are covered for the sources of anthropogenic CH_4 emissions in China. Since global inventories do not specify for distinguishing the emission categories considered here, mixed methods are used to prepare the sectoral emission inventories and obtain concrete emission data for different economic sectors. Most production-side emissions can be allocated into a concrete industrial sector. For instance, the emissions from agricultural activities, and fugitive emissions from solid fuels and oil & gas can be directly categorized into corresponding economic sectors of *Agriculture* and *Mining and quarrying*, respectively. If the emission category is related to multiple departments, we reallocate the emission data to industrial sectors. In addition, several minor emission sources are neglected, mainly referring to the fuel combustion of commercial and public services and non-specified industrial sectors.

3. Results

3.1. Production- versus consumption-based CH_4 emissions in 2012

The world economy generated 348.5 Tg CH_4 emissions into the atmosphere in 2012.

Figure 2 shows the production-side CH_4 emissions (PBMs) and the consumption-side CH_4 emissions (CBMs) of the 181 economies. For the accounting results of national emission inventories, there was a great difference between the PBM and the CBM for most economies. With respect to regional distribution, Mainland China had the largest PBM value of 63.8 Tg, which was two times as large as that of India (32.3 Tg, ranked 2nd), followed by the USA (25.5 Tg), Brazil (19.2 Tg) and Russia (17.4 Tg).

From the consumption-based perspective, Mainland China was also the largest emitter of CBM (65.0 Tg), accounting for 18.6% of the global total. The USA had the second largest CBM (38.4 Tg), which was 50.6% larger than its PBM. India (30.9 Tg), Brazil (19.2 Tg) and Japan (12.1 Tg) were important embodied emission contributors. These top five economies together contributed 47.5% of global total CBM. In addition, Germany possessed relatively high value of CBM (7.2 Tg), approximately 2.6 times that of its PBM. The economies with large consumption-based emissions were mostly those with large population and consumption volumes. By contrast, the CBM (8.9 Tg) in Russia was only half of its PBM. Therefore, both production- and consumption-based accounting methods of CH_4 emissions should be considered in identifying mitigation opportunities.

[Place Figure 2 here]

The world economy can be further divided into 19 integrative economies (see the regional information in Table S3). China was the largest direct CH_4 emitter, followed by Sub-Saharan Africa, India, Southeastern Asia and the USA. Agriculture, energy and waste related emission sources were the three main contributors to the global production-side CH_4 emissions (see Figure 3a). As one of the most important emission categories, agricultural activities accounted for 45.9% of the global total PBMs, followed by energy (30.0%) and waste (19.6%). As to agriculture-related PBMs, China's contribution amounted to 25.9 Tg, followed by India of 20.3 Tg, Sub-Saharan Africa of 19.1 Tg, Southeastern Asia of 17.4 Tg and Brazil of 14.7 Tg. For energy-related PBMs, China (21.8 Tg), Middle East (15.5 Tg) and Russia (11.4 Tg) ranked the top three of the integrated economies. Particularly, the PBMs of Middle East and Russia were both dominated by energy activities, due to their large-scale oil & gas exploitations.

As to final demand category (see Figure 3b), household consumption accounted for 65.6% (228.5 Tg) of the global total CBM, followed by fixed capital formation (53.6 Tg), government consumption (44.1 Tg), non-profit consumption (13.0 Tg), inventory increase (6.7 Tg) and acquisitions of valuables (2.7 Tg). China's household consumption took up the largest share of 51.8% in its CBM, while fixed capital formation also contributed a comparable share. Western Europe ranked second in terms of the CBM, which was 1.2 times larger than that of the PBM. Like Western Europe, the USA, Rest Europe and Japan had higher CBMs than their PBMs.

[Place Figure 3 here]

Figure 4 shows the compositions of the PBM and the CBM by industrial sector (also see Table S4). The sector of *Agriculture* (S1, 160.1 Tg) was the largest emitter of PBM, followed by *Mining and quarrying* (S3, 104.6 Tg) and *Education, health and other services* (S23, 68.4 Tg). The above-mentioned three sectors together accounted for 95.6% of the global total PBM. China's *Agriculture*, *Mining and quarrying*, and *Education, health and other services* each took the share of 16.2%, 20.8% and 16.6% of the world-wide sectoral total, respectively.

[Place Figure 4 here]

From the consumption-based perspective, the CBM of *Education, health and other services* amounted to 74.7 Tg, followed by *Agriculture* (64.7 Tg)，*Food and beverages* (S4, 57.0 Tg), *Construction* (S14, 30.8 Tg) and *Petroleum, chemical and non-metallic mineral* (S7, 17.5 Tg). *Agriculture* and *Food and beverages* contributed massive agriculture-related CBMs. Notably, *Construction* contributed large proportions in the CBMs of some developing countries. Particularly, China contributed 46.9% of the global total CBM of the *Construction* sector.

3.2. Embodied CH_4 emissions in global trade network in 2012

Trade globalization has led to close economic connection. A region's consumption can cause CH_4 emissions in other regions through the import trade of commodities. In 2012, the CH_4 emissions embodied in international trade (total MEIM or MEEX, 172.4 Tg) were equivalent to 49.5% of the global total PBM. Figure 5 displays the top 20 economies for the MEIM, MEEX and MEEB. 58.9% of global total MEIM and 39.8% of global total MEEX can be attributed to the top 10 economies, respectively. Mainland China ranked first in terms of the MEEX (14.4 Tg), which was equal to 22.2% of its CBM. Meanwhile, the USA had the largest value of MEIM (21.0 Tg), which was equal to 54.6% of its CBM. Detailed data are listed in Tables S5 and S6.

The embodied emission in international trade balance (MEEB) is an important indicator to reflect the profit or loss of environmental pressure from international trade (Peters, 2008; Peters et al., 2011). The top 20 net importers and net exporters accounted for 90.8% and 69.9% of the total MEEB (62.5 Tg, the total net import or export), respectively. Mainland

China had high volume of MEEX and MEIM, but its MEEB was relatively small. The USA, Japan, Germany, South Korea, the UK and other Western European countries were significant net importers of embodied CH_4 emissions. Russia, Ethiopia, Nigeria, Iran and Qatar were the top five net exporters. Russia, Nigeria, Iran and Qatar were prominent net exporters of embodied energy-related CH_4 emissions, due to the dominating export of energy commodities. By contrast, Ethiopia was a net exporter, mainly associated with agriculture-related emissions induced by international trade.

[Place Figure 5 here]

Among the emissions embodied in international trade, intermediate trade and final trade contributed to 77.8% (134.1 Tg) and 22.2% (38.4 Tg) of the total, respectively. Figure 6 displays the major fluxes of embodied CH_4 emissions in the intermediate trade and final trade among the 19 integrative economies (excluding intraregional trade within the economy). As shown in Fig. 6(a), Western Europe, China, the USA and Japan were the major destinations for trading embodied emission flows. Prominently, Western Europe occupied the largest portion in intermediate trade with an import volume of 30.2 Tg. In Russia, Sub-Saharan Africa, Middle East, Northern Africa and Rest Europe, 17.9%, 15.7%, 14.0%, 11.0% and 10.0% of their intermediate trade-related CH_4 emissions could be linked to the production of exported goods for the consumption of Western Europe, respectively. Middle East was the largest exporters of embodied emissions in intermediate trade, followed by Sub-Saharan Africa and Russia, which accounted for 12.9%, 11.6% and 10.8% of the global total, respectively. The largest bilateral trading flow in the intermediate trade was related to the exports from Russia to Western Europe (5.4 Tg), which was equal to 30.9% of Russia's PBM, followed by the trading flow from Sub-Saharan Africa to Western Europe (4.7 Tg).

As to the final trade, China turned to the leading exporter by exporting products to the USA (1.4 Tg), Western Europe (1.0 Tg), Japan (0.7 Tg) and other economies. Western Europe was the largest importer of embodied emissions (5.8 Tg), followed by the USA (5.5 Tg). Russia had relatively low embodied CH_4 emissions in the final trade. The largest bilateral trading flows through final trade were from China to the USA and from China to Western Europe. As shown in Fig. 6(b), China, Southeastern Asia, India, Sub-Saharan Africa and Other Southern Asia were the important source regions, while Western Europe, the USA and Japan were the major destinations for trading embodied emissions flows in the final trade.

[Place Figure 6 here]

Figure 7 highlights the net transfer of embodied CH_4 emissions in terms of intermediate net trade and final net trade. Russia (5.0 Tg) accounted for one fourth of the total net embodied CH_4 inflows in the intermediate trade of Western Europe, followed by Sub-Saharan Africa (4.4 Tg), Middle East (3.1 Tg) and Northern Africa. The main exporting regions of net embodied CH_4 inflow into the USA were Sub-Saharan Africa, Rest South America, Middle East and Canada, together accounting for 67.9% of its total net inflows through intermediate trade. China was also an important net importer. In the final net trade, Western Europe and the USA were net importers, but China turned into a net exporter. Sub-Saharan Africa, Southeastern Asia, India and Asia Stan were important net exporters of embodied CH_4 emissions. Middle East, Japan, Russia, Rest Europe and Northern Africa were net importers of embodied emission transfer in the final net trade.

[Place Figure 7 here]

3.3. Evolution of consumption-based CH_4 inventories over 2000-2012

The total CH_4 emissions by the world economy increased by 20.5%, from 289.3 Tg in 2000 to 348.5 Tg in 2012. Table 1 presents a comparison of production- and consumption-based CH_4 inventories of 19 integrative economies in 2000 and 2012. China, Western Europe and the USA had the largest CBM values among all the 19 economies during 2000-2012 (see Table S7). Meanwhile, the CBMs of the USA, Western Europe and Japan were much higher than their PBMs, but the values of CBM in the USA, Western Europe, Japan and Oceania decreased from 2000 to 2012. For instance, the PBM and the CBM of Japan decreased by 20.4% and 12.6%, respectively. As the largest emitter in the world, the evolution of China's CH_4 emission inventories revealed increasing larger gap between its PBM and CBM over the same period. Significant increases of CBMs can be observed in most developing regions during 2000-2012. In addition, there were remarkable disparities on the growth rate of CH_4 emissions among selected economies. Asia Stan was the area with the fastest growing PBM of 71.5%, while Sub-Saharan Africa had the fastest growing CBM of 64.5% over 2000–2012. China and Middle East also witnessed rapid growth in PBMs, though their CBMs grew more prominently. Overall, the CH_4 inventory changes of 19 integrative economies from a consumption perspective were quite different from those from a production perspective.

[Place Table 1 here]

Economic globalization led to the growth of international trade and corresponding emission leakage during 2000-2012. The gross scale of embodied emissions in international trade was only 132.9 Tg (45.9% of the total PBM) in 2000, compared to 172.4 Tg (49.5% of the total PBM) in 2012. Displayed in Table 2 are the trade-related CH_4 emission changes between 2000 and 2012. After comparing the change of trade structure, a large share of the CH_4 emissions generated in the production of certain exported products in many economies were transferred to the consumers in developed countries and large developing countries over 2000-2012. It is worth noting that intermediate trade change contributed the major shares to the trade-related CH_4 emission changes of most economies. Global total intermediate trade increased from 103.4 Tg in 2000 to 134.1 Tg in 2012, while final trade increased from 29.6 Tg to 38.4 Tg. Most economies such as China and Western Europe showed a rapid growth of trade-induced CH_4 emissions over this period. Particularly, the MEEBs of China and Rest Europe increased by 5.7 and 2.9 Tg over this period, respectively. Developed economies such as Western Europe, the USA and Japan were the major net receivers of embodied emission transfer in international trade, mainly from developing countries. However, the USA and Japan had a negative growth of embodied emissions in both intermediate and final imports. Detailed results of the embodied CH_4 emissions in international exports and imports of the 19 integrative economies during 2000–2012 are listed in Tables S8 and S9, respectively.

[Place Table 2 here]

4. Discussion

In the context of accelerated globalization, the production-side environmental emission within one country's territory is not anymore a suitable indicator for measuring its real emission requirements. Several studies have claimed that embodied energy, carbon and water footprints can give a more accurate picture of resources and emissions associated with the degree of development of a country (e.g., Steinberger et al., 2012; Lamb et al., 2014; Arto et al., 2016; Prell, 2016; Hubacek et al., 2017). Unlike CO_2 emissions, the studies estimating consumption-based CH_4 inventories or CH_4 footprints of nations are scarce and, to date, no one has focused on the development issues. CBM or CBM per capita can also be used as an important indicator for more in-depth studies of the global environmental patterns and human development.

Figure 8 shows the relationships between per capita gross domestic product (GDP) and per capita CBM as well as human development index (HDI) and per capita CBM among major economies (see Table S10 for details). The world-average per capita CBM was calculated as 49.2 kg/cap in 2012. The economies with higher per capita CBM were mainly in the developed regions with larger GDP values, such as Singapore, Hong Kong, the USA and Canada. Most of the economies with high HDIs were grouped at larger per capita CBMs. Importantly, most of the developing countries with lower HDIs had low per capita CBMs or embodied CH_4 emission requirements, such as India, Pakistan, Indonesia and Nigeria. The per capita CBM or household consumption-driven CBM of Mainland China, the largest CH_4 emitter, was still much lower than those of the developed world. Thereafter, the per capita CBM reflects the environmental inequality among different economies to a certain extent.

[Place Figure 8 here]

In view of the importance of international trade for understanding global CBM inventories, the transfers of embodied CH_4 emissions in an economy were found to be determined by its industrial position in the global supply chain. Figure 9 presents the net trade pattern of embodied CH_4 emissions for major economies in 2012, by revealing the emission imbalance of intermediate trade and final trade. Prominently, embodied CH_4 emission transfers via international trade were mainly related to intermediate production rather than final consumption. For example, Mainland China was an intermediate net importer but a final net exporter. As a "world factory', Mainland China imported a large number of agricultural products and industrial raw materials such as fossil fuels via intermediate trade and then produced manufactured goods to meet demands of both local consumption and foreign countries via export trade. Totally, 83.5% of its direct emissions in 2012 were used to satisfy local final demand, and the other 16.5% was used for the final demand of foreign regions. By contrast, Russia was an intermediate net exporter, due to its vast volume of intermediate exports. 65.6% of its CH_4 emissions were generated by production to meet the trade demand of global market. This can be explained by the fact that the exports of Russia were dominated by energy and industrial raw materials, mostly used for intermediate production in Western Europe and other large economies. Meanwhile, Russia was a final net importer as a result of the import trade of manufactured goods and consumer goods for its final consumption.

Embodied CH_4 emissions in the intermediate and final imbalances of the USA exceeded those of any other regions. The trade patterns were similar in Japan and Western European Countries (e.g., the UK, Germany and France) with substantial embodied emissions in goods imports to meet the demand for final consumption. Japan had extremely low CH_4 emissions from local production, but its embodied emissions to support its final demand amounted to 12.1 Tg in 2012, of which 16.6% from Middle East, 13.0% from Sub-Saharan Africa, 12.9% from Southeastern Asia, 11.6% from China, 9.9% from Russia and 21.6% from other foreign countries. Over the period of 2000-2012, the top net importers in both intermediate and final trade were all concentrated in developed economies, while the leading net exporters in the third quadrant were underdeveloped or developing economies such as Ethiopia and India. It is clear that by consumption-based accounting principle, many developed countries should take a greater share of CH_4 emissions.

[Place Figure 9 here]

Globally, economic driving forces, such as household consumption increase, accelerated fixed investment and international trade expansion play important roles in determining the structure of anthropogenic CH_4 emission requirements. As major emission sources of production-side CH_4, industrial activities of energy, agriculture and waste sectors are induced by final consumption demands of local and foreign consumers. In 2012, household consumption contributed 65.6% (228.5 Tg) of the global total CBMs, followed by fixed capital formation (53.6 Tg) and government consumption (44.1 Tg). As the largest final demand category for the CBMs, household consumption is closely related to residents' daily life such as *Agriculture* and *Food and beverages*. In fact, rural and urban household consumption were agricultural-CH_4 intensive. The energy-related CBMs were predominantly driven by investment demand or gross capital formation, especially in some developing countries. For instance, the energy-related CBMs of China's *Construction* sector were remarkable. In addition, the waste-related CH_4 emissions were largely driven by local consumption, living standards of people and waste management levels. At present, reduction of CH_4 emissions on the consumption side has been far less attended to by policy makers and researchers than that of CO_2 emissions (Zhang et al., 2016, 2018). Consumption-based accounting conducted in this study provides new insights on where to focus policy responses to reduce global anthropogenic CH_4 emissions and pinpoints the regional and sectoral hotspots for possible emission mitigation associated with production, consumption and international trade.

5. Concluding remarks

Reducing CH_4 emissions has become an important global agenda in energy, environmental and climate fields. The generation and increase of anthropogenic CH_4 emissions are related with regional economic development, industrial structure, population, people's diets and living standard, energy mix, technological advance, etc. Consumption-based accountings thereafter are more suitable for the illustration of real CH_4 footprint for an economy. In order to better understand how final demand and international trade influence production as well as related CH_4 emissions, a systematic accounting for global CH_4 emissions from the consumption-based perspective is conducted in this study. We not only identified the spatial separation of production and consumption, but also how the virtual transfer of CH_4 emissions along global supply chains was associated with the intermediate trade and final trade. The position and function of 181 economies to act on the structure and spatial patterns of global CH_4 emissions were revealed. Substantial geographic shifts of CH_4 emissions during 2000-2012 revealed the significant impact of international trade on national CH_4 emissions. Owing to the increasing embodied emission transfers via international trade, there were remarkable regional disparities on the growth rate of consumption-side CH_4 emissions among the 19 integrative economies over 2000-2012. Consumption-based accounting of global anthropogenic CH_4 emissions in this study reveals the CH_4 footprints of nations and major economies, and helps to identify corresponding emission responsibilities along global supply chains for climate change mitigation.

Acknowledgements

See Tables S1-10 in Supplementary information associated with this article. All the CH_4 emission data can be available from the EDGAR database at http://edgar.jrc.ec.europa.eu/overview.php?v=432_GHG&SECURE=123. This study has been supported by the National Natural Science Foundation of China (Grant no. 71774161), the Foundation of State Key Laboratory of Coal Resources and Safe Mining (Grant no. SKLCRSM16KFC06), and the Yue Qi Young Scholar Project, China University of Mining & Technology (Beijing). Very helpful comments by the editor Michael Ellis and the anonymous reviewer are highly appreciated.

Nomenclature

GHG	Greenhouse gas emissions
PBA	Production-based emission accounting
CBA	Consumption-based emission accounting
PBM	Production-based methane emission
CBM	Consumption-based methane emission
MRIO	Multiregional input-output model
MEIM	Methane emission embodied in international import
MEEX	Methane emission embodied in international export

MEEB	Embodied methane emission in international trade balance
EDGAR	Emissions Database for Global Atmospheric Research
UNFCCC	United Nations Framework Convention on Climate Change
HDI	Human development index
GDP	Gross domestic product

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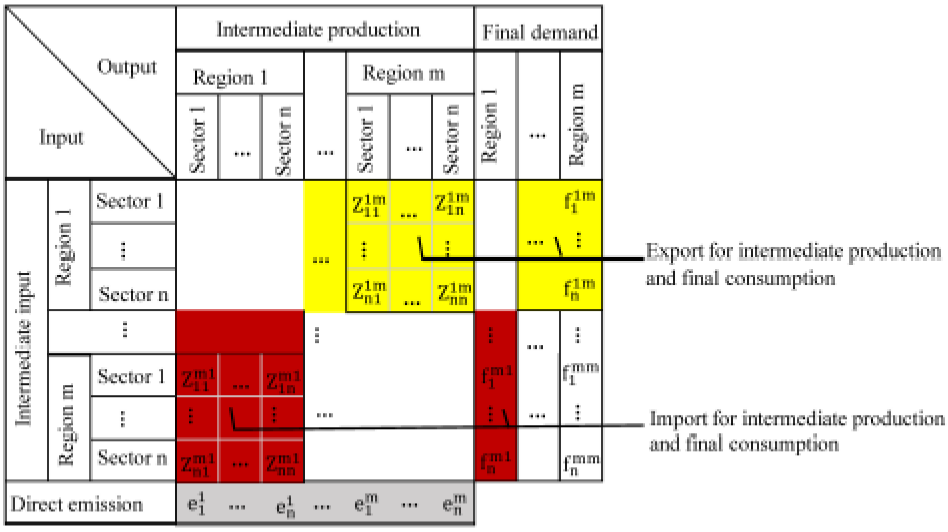


Fig. 1. The structure of MRIO table for the world economy. Revised from Wu and Chen (2017).

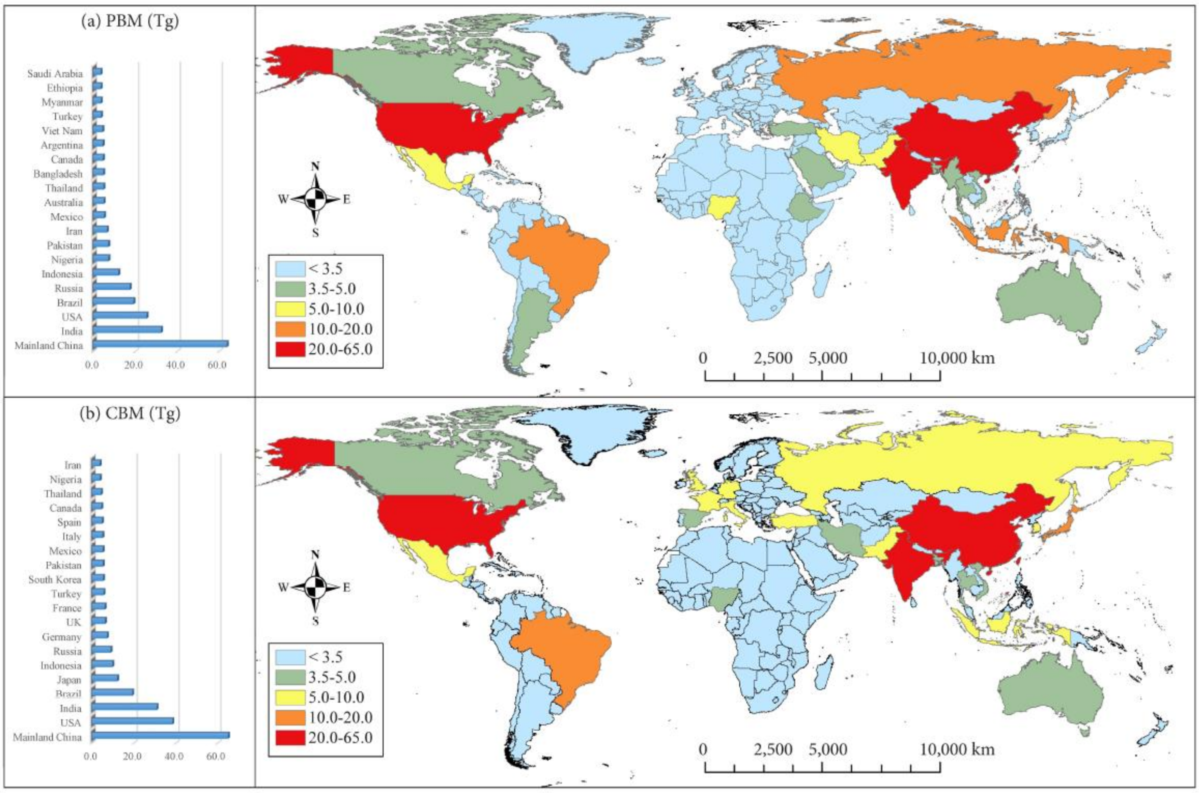


Fig. 2. The PBMs and CBMs of the top 20 economies in 2012.

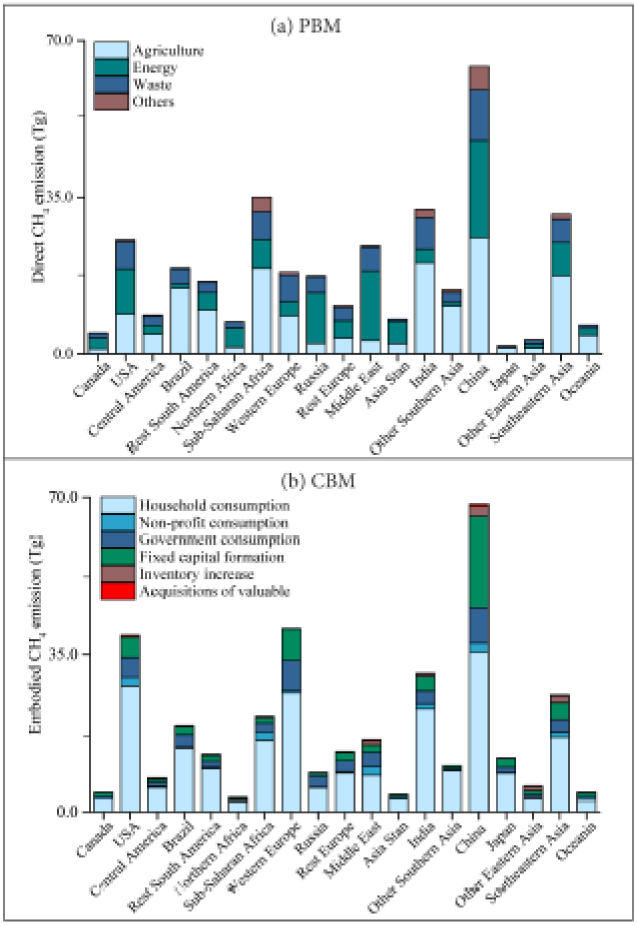


Fig. 3. The PBMs and CBMs of 19 integrative economies in 2012.

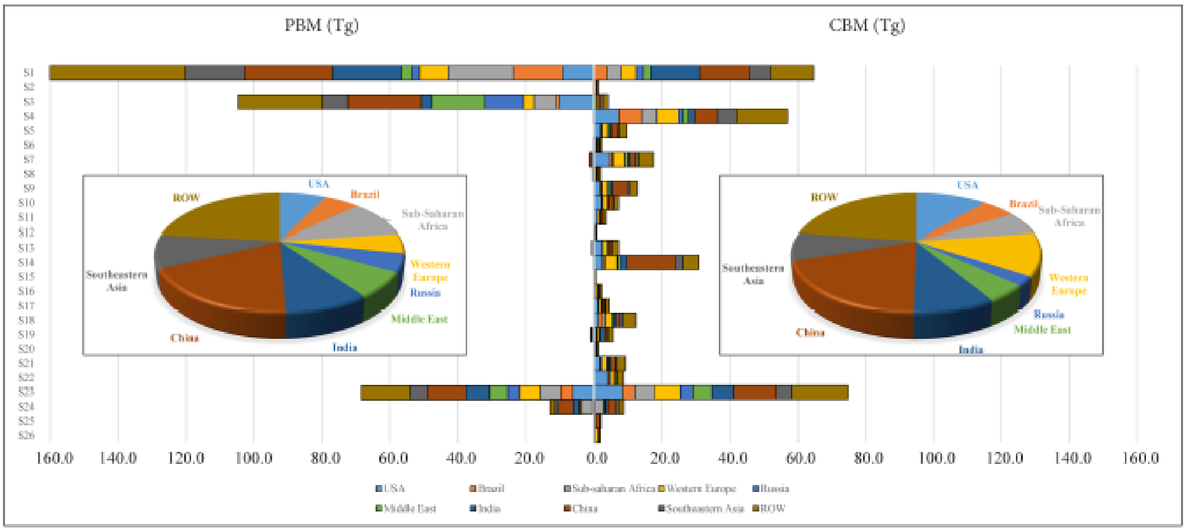


Fig. 4. Sectoral production- and consumption-based CH_4 emissions by the world economy in 2012.

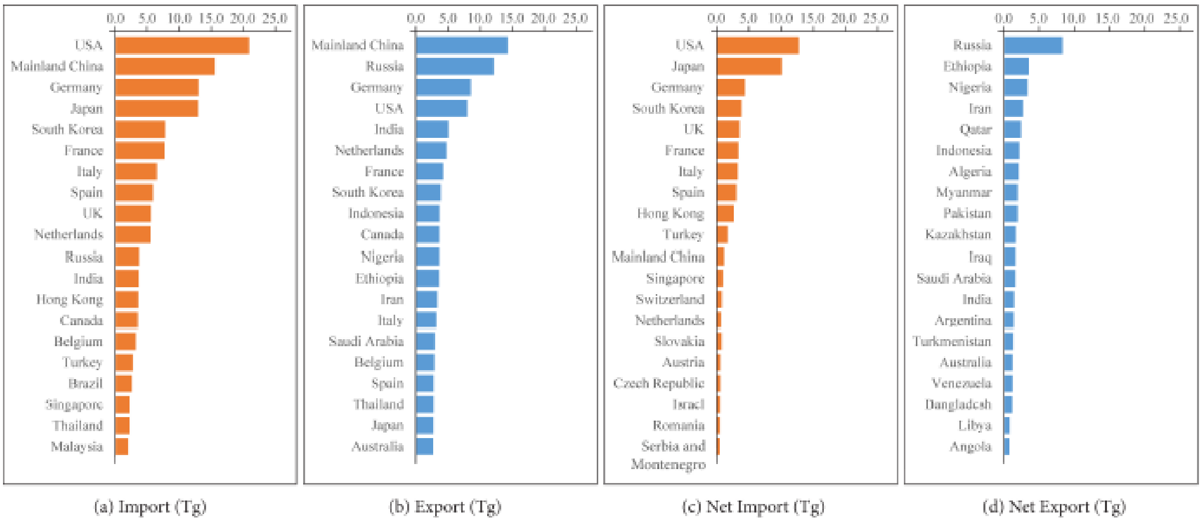


Fig. 5. The MEIMs, MEEXs and MEEBs of the top 20 economies in 2012.

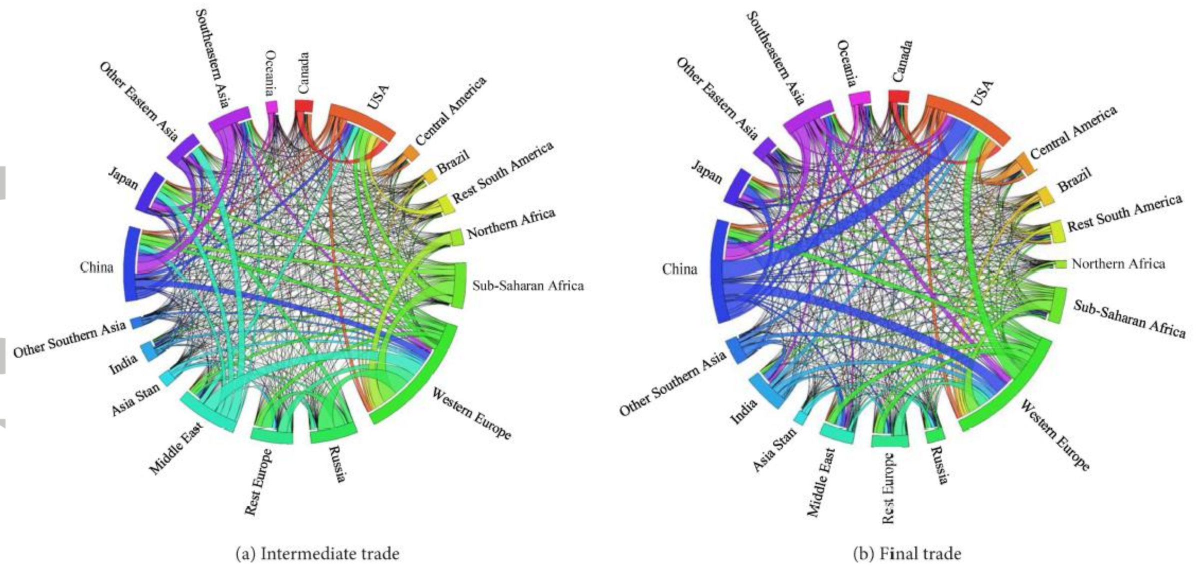


Fig. 6. Embodied CH_4 emissions in international trade among 19 integrative economies in 2012. The connection between economies represents the transfer of embodied emissions, and the color of the connecting line is consistent with the exporter. The width of the connecting line represents the size of trade volume.

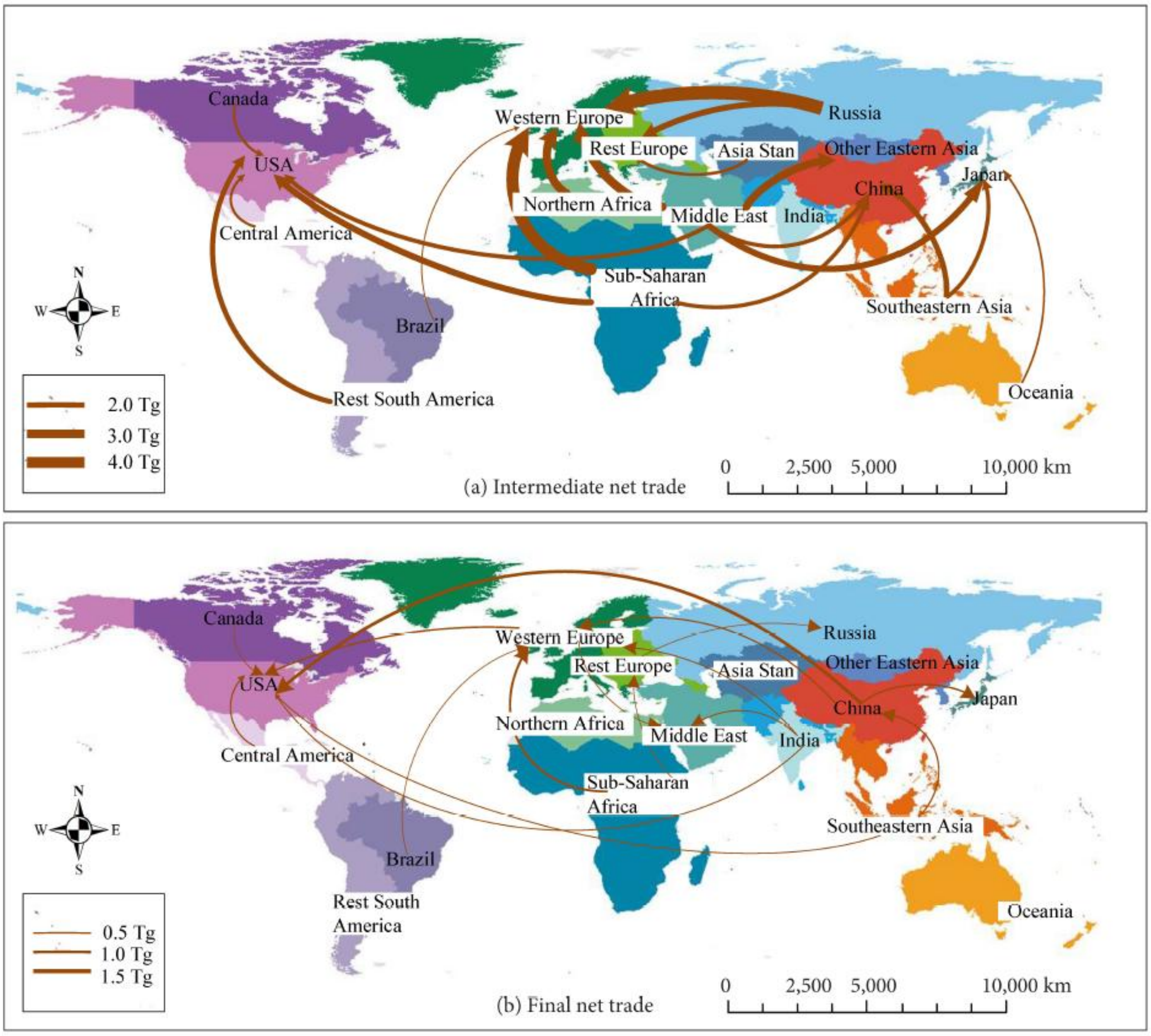
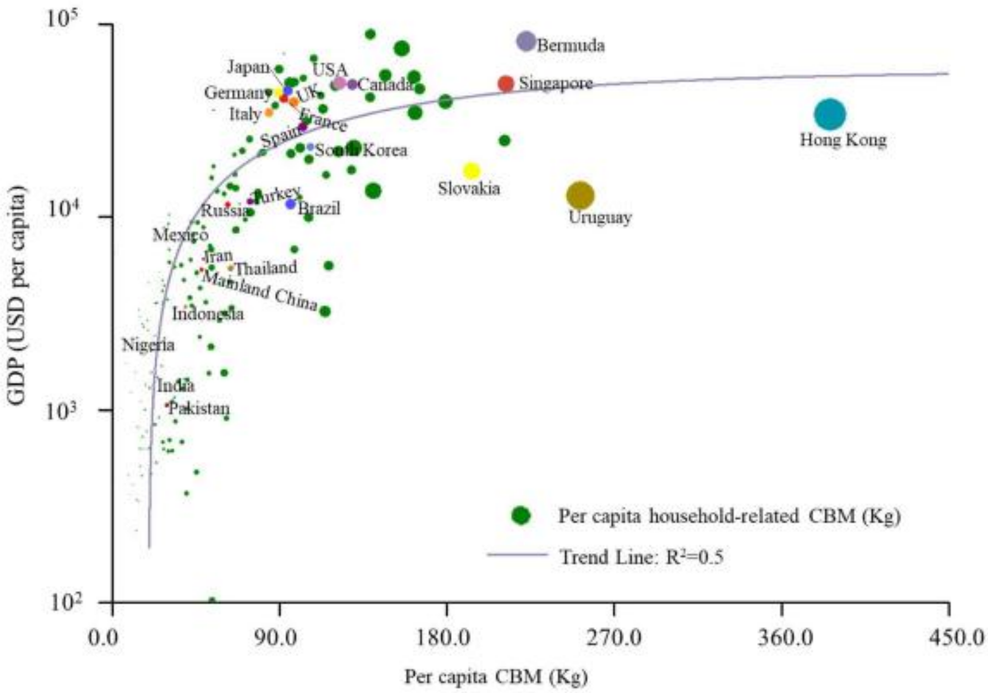
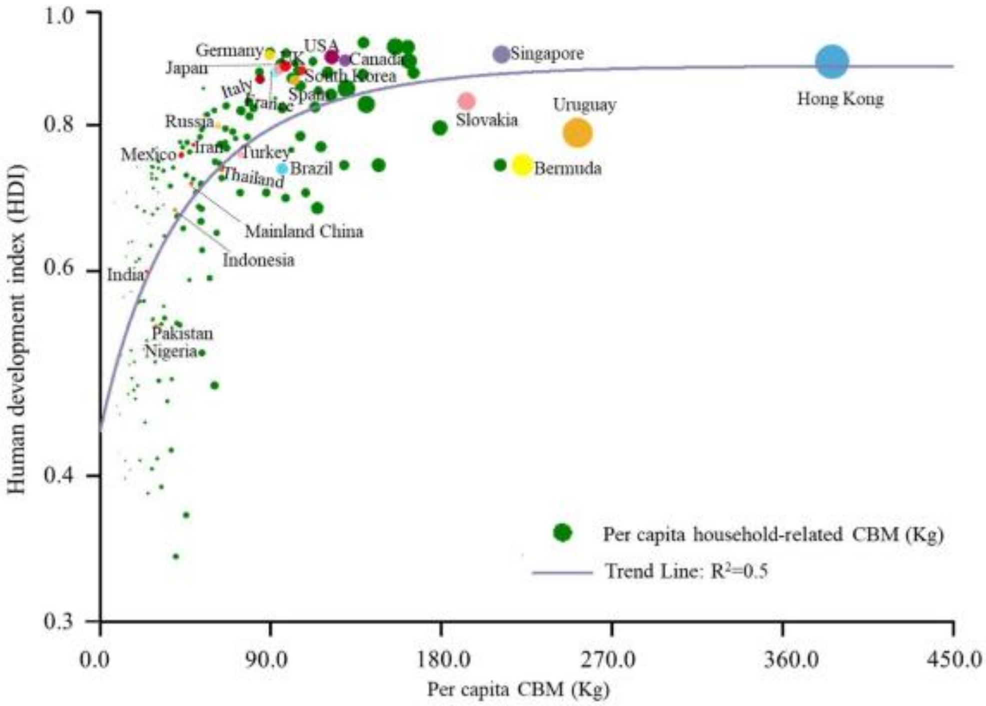


Fig. 7. Major net trading flows of embodied CH_4 emissions in 2012.



(a) Per capita GDP and per capita CBM.



(b) HDI and per capita CBM.

Fig. 8. The relationship between the HDI, per capita GDP and per capita CBM by country/region in 2012. Note: Guyana is excluded, due to its per capita CBM amounting to 470.2 kg (higher than 450). Luxembourg is also excluded due to its per capita GDP larger than 102,404.6 USD.

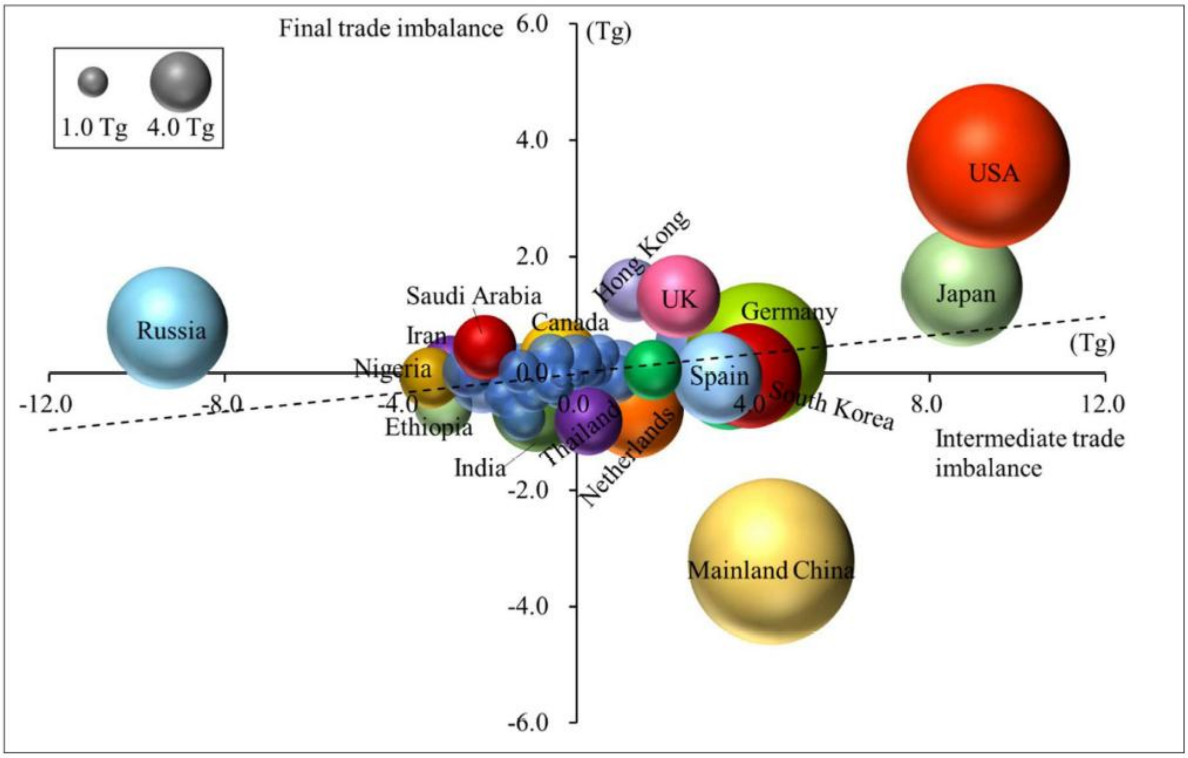


Fig. 9. Trade imbalances of embodied CH_4 emissions of major economies in 2012. Note: The size of the sphere represents the total trade volume of embodied CH_4 emissions (the total import or export). Regions closer to the vertical axis tend to be final consumption-oriented, while those closer to the horizontal axis tend to be intermediate production-oriented. Regions have positive values are net importers, and vice versa.

Table 1

Production- and consumption-based CH_4 inventories of 19 integrative economies in 2000 and 2012

Economy	PBM (Tg)		Changes (%)	CBM (Tg)		Changes (%)
	2000	2012		2000	2012	
Canada	5.0	4.7	-6.3	3.8	4.5	19.4
USA	24.6	25.5	3.6	40.2	38.4	-4.5
Central America	7.4	8.7	17.7	7.0	7.7	9.8
Brazil	15.6	19.2	23.5	15.3	19.2	25.5
Rest South America	14.7	16.2	9.9	12.4	12.9	4.4
Northern Africa	6.7	7.2	6.4	2.7	3.4	27.5
Sub-Saharan Africa	28.7	35.1	22.1	12.9	21.3	64.5
Western Europe	21.9	18.2	-16.7	44.1	40.3	-8.7
Russia	13.6	17.4	28.0	6.7	8.9	33.0
Rest Europe	10.6	10.8	2.0	10.3	13.5	30.2

Middle East	17.8	24.2	36.2	11.2	16.1	44.1
Asia Stan	4.5	7.7	71.5	2.8	4.1	47.1
India	26.7	32.3	21.0	25.4	30.9	21.4
Other Southern Asia	11.2	14.4	28.8	7.8	10.4	32.3
China	45.7	64.3	40.7	44.2	68.5	54.9
Japan	2.3	1.8	-20.4	13.8	12.1	-12.6
Other Eastern Asia	2.7	3.1	13.8	5.0	5.9	18.6
Southeastern Asia	23.2	31.3	34.9	18.9	26.1	37.9
Oceania	6.4	6.4	0.5	4.8	4.5	-5.3
Total	289.3	348.5	20.5	289.3	348.5	20.5

Table 2

Trade-related CH_4 emission changes of 19 integrative economies between 2000 and 2012 (Tg)

Economy	Intermediate trade change		Final trade change		Change of net trade
	MEIM	MEEX	MEIM	MEEX	(MEEB)
Canada	0.5	-0.2	0.2	-0.1	1.0
USA	-0.6	0.8	-1.0	0.4	-2.7
Central America	0.2	0.9	0.2	0.1	-0.6
Brazil	0.9	0.5	0.2	0.3	0.3
Rest South America	0.6	1.6	0.5	0.3	-0.9
Northern Africa	0.2	0.0	0.2	0.1	0.3
Sub-Saharan Africa	0.2	-1.7	0.4	0.2	2.0
Western Europe	6.4	6.2	1.6	1.8	-0.2
Russia	1.1	3.3	0.6	0.0	-1.6
Rest Europe	4.3	1.9	1.2	0.6	2.9

Middle East	2.0	4.3	1.1	0.3	-1.5
Asia Stan	0.2	1.8	0.2	0.5	-1.9
India	1.3	1.3	0.6	0.8	-0.2
Other Southern Asia	0.1	0.5	0.1	0.4	-0.7
China	9.1	3.5	2.0	1.9	5.7
Japan	-0.2	0.8	-0.2	0.1	-1.3
Other Eastern Asia	2.6	2.2	0.3	0.3	0.5
Southeastern Asia	1.9	2.5	0.4	0.6	-0.9
Oceania	0.0	0.4	0.3	0.2	-0.3