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Evolution of methane emissions in global supply chains during 2000-2012

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ABSTRACT

Reduction of methane emissions (CH_4) plays an important role in addressing global climate change. Most previous studies have focused on the direct CH_4 emissions of economies, but overlooked the upstream CH_4 emissions along global supply chains induced by the final consumption of economies. Using a global multi-regional input-output analysis, this study aims to explore the evolution of CH_4 emissions embodied in international trade and final consumption in major economies during 2000–2012. The results show that China, the EU, USA, India and Brazil were the top five economies with high volumes of consumption-based CH_4 emissions from 2000 to 2012. In particular, China's consumption-based CH_4 emissions showed an observable growth trend, while the EU, the USA and Japan showed a downward trend. It's estimated that growing amounts of CH_4 emissions (i.e., the volume increase from 77.1 Mt in 2000 to 95.9 Mt in 2012) were transferred globally via international trade, primarily as exports from China, Russia and other large developing economies to consumers in major developed economies. Russia–EU, China–USA and China–EU formed the main bilateral trading pairs of embodied emission flows. Further analysis found that per capita consumption-based CH_4 emissions was closely related to their per capita GDP. Quantifying the CH_4 emissions embodied in trade and final demand of major economies can provide important basis for understanding economy-wide emission drivers to design global and regional CH_4 reduction scheme from a consumer perspective.

1. Introduction

Over the past few decades, global greenhouse gas (GHG) emissions have been growing rapidly. The total GHG emissions reached 50.9 Gt CO_2 eq (gigatonnes of CO_2 equivalent) in 2017 with an annual growth rate of 1.3% (Olivier, 2018). Olivier (2018) found that global anthropogenic non $-$ CO_2 GHG emissions have exceeded CO_2 emissions in recent years, with CH_4 contributing significantly to the overall radiative forces (Montzka et al., 2011; Saunois et al., 2016). CH_4 is widely acknowledged as the second largest source of GHG emissions, which is responsible for about 18% of the global total GHG emissions (Olivier, 2018). The global warming potential (GWP) of CH_4 is 28 times higher than that of CO_2 over one hundred years (IPCC, 2014), and the atmospheric CH_4 concentration has tripled since 1750 (Peng et al., 2016). CH_4 emission growth is highly related to increasing emissions from human activities, such as agriculture, fossil fuel production and waste/waste water (Du et al., 2018; Ghosh et al., 2015b; Hausmann et al., 2016; Kirschke et al., 2013; Nisbet et al., 2016). Therefore, achieving the Paris Agreement's target to limit global warming to well below 2 °C above pre-industrial levels and to pursue efforts to 1.5 °C requires not only significant efforts in CO_2 emission mitigation, but also more attentions to the CH_4 emissions reduction.

Compiling the national CH_4 emission inventory is the prerequisite to design proper global CH_4 mitigation policy. Regarding the national emissions accounting, the United Nations Framework Convention on Climate Change (UNFCCC) requests the States Parties to report their annual territorial-based national emission inventories in accordance with the IPCC guidelines (IPCC, 2006). The territorial-based national emission inventories preferred by the UNFCCC are considered to be equivalent to the production-based emissions, except for the allocation of international transportation (Peters, 2008). Consequently, many previous studies have compiled global CH_4 emission inventories from direct sources at multiple scales, such as global (Dlugokencky et al., 2011; Ghosh et al., 2015a; Kirschke et al., 2013), national (Zhang and Chen, 2014; Zhang et al., 2014), regional (Janssens-Maenhout et al., 2017; Zhang et al., 2016) as well as inventories for specific sources or sectors, e.g., fossil fuel production (Höglund-Isaksson, 2017; Zhang et al., 2014), agriculture production (Caro et al., 2014), wastewater (Du

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et al., 2018). Such production-based inventories provide basic information for decision making to control and reduce CH_4 emissions from a producer perspective, e.g., strict implementation of CH_4 recovery from municipal solid waste (MSW), organic wastewater and sewage treatment plants, effective utilization of coalbed methane, and technologies upgrades for these key emitters.

It's widely acknowledged that the intensifying globalization increases the spatial separation between production and consumption, leading to the reallocation of resource use and pollutant emissions via international trade (Chen et al., 2018a, b; Li et al., 2017; Meng et al., 2018; Mi et al., 2017). Consequently, the conventional production-based accounting cannot allocate emissions embodied in international trade and ignore the potential for "carbon leakage" (Chen and Chen, 2016; Lenzen et al., 2004; Munksgaard et al., 2005; Peters and Hertwich, 2008a). In order to give a more conprehensive picture of the relation between anthropogenic emissions and economic activities, many scholars believe that the total emission induced to meet a country's final consumption should be taken into account(Barrett et al., 2013; Davis and Caldeira, 2010; Kan et al., 2019; Peters, 2008; Zhang et al., 2018), irrespective of where those emissions are actually generated (i.e., consumption-based accounting). The consumption-based accounting (CBA) method reattributes the emissions from pruducers to the final demand from consumers as embodied emissions.

Consumption-based GHG inventories are more advantageous for reducing carbon leakage because the main motive for consumption-based GHG inventories is to reduce carbon leakage associated with international trade. Many authors have argued that GHG inventories obtained by CBA method are "fairer" than PBA method (Bastianoni et al., 2004; Ferng, 2019; Jesper, 2001; Kondo et al., 2019; Peters and Hertwich, 2006, 2008b). (Peters and Hertwich, 2008b) also argued that consumption-based GHG inventories have greater flexibility towards pollution intensive resource endowments, and encourage different approaches to GHG mitigation. Moreover, consumption-based inventories can also protect clean domestic industries and encourage environmental performance while addressing competitiveness issues. For example, if multiple economies are competing for the same export market, then these exporters can use good environmental performance as a marketing tool.

The global multi-regional input-output (MRIO) model is widely employed to account the emissions embodied in global supply chains, including production, consumption and international trade. At present, the environmentally-extended input-output analysis (EEIOA) has become a popular approach to measure and assess consumption-based emissions, such as CO_2 (Andreoni and Galmarini, 2016; Davis and Ken, 2010; Fan et al., 2016b), atmospheric mercury (Chen et al., 2019a; Li et al., 2017; Liang et al., 2015), $PM_{2.5}$ (Meng et al., 2016), and nitrogen pollution (Oita et al., 2016). However, most of these consumption-based studies focus on carbon (Davis and Ken, 2010; Fan et al., 2016a, b) or GHG emissions (Arto and Dietzenbacher, 2014; Caro et al., 2017), while only a few has paid special attention to tracking CH_4 emissions along global supply chains. For example, (Han et al., 2019) conducted a single year analysis of consumption-based agricultural CH_4 and N_2O emissions from a bilateral trade perspective, but failed to integrate a comprehensive trade relationships into the global MRIO modeling. (Zhang et al., 2018) analyzed the impact of intermediate and final trade activities on the global spatial distribution of CH_4 emissions for one year, and also compared the changes of consumption-based CH_4 inventories between 2000 and 2012, without systematically revealing both the spatial and temporal evolution features of CH_4 emissions in global supply chains. Due to the difficulty of data acquisition, research on CH_4 emissions has rarely addressed both long-term temporal measurement and high space resolutions. An in-depth comparative analysis of the evolution characteristics of the CH_4 emissions among major economies under a continuous time series is in urgent need. Moreover, previous consumption-based studies have focused on the CH_4 emissions from either specific source (e.g., agriculture) or all sources, without a comparison between different CH_4 sources (e.g., agriculture and energy) when conducting the consumption-based accountings. A comparision between different sources could provide specific demand-side insights for regulating the CH_4 emissions.

Therefore, to fill the gaps in the existing research, this paper attempts to quantify the CH_4 emission embodied in trade and final demand of major economies by linking production-side emissions to their final consumers, based on the latest global CH_4 emission inventories from the Emissions Database for Global Atmospheric Research (EDGAR–4.3.2) and the global MRIO table from the WIOD database during 2000–2012. We analyze the temporal and spatial evolution features of CH_4 emissions in global supply chains among major economies by constructing a time series inventories with multiple nationals and industries details. Moreover, this study further elaborate the results by distinguishing different CH_4 sources (e.g., agricultural avtivities and energy exploitation).

The rest of this paper is organized as follows: Section 2 describes the methodology and data used to estimate the embodied emission in trade and final demand of major economies, wherein a EEIOA model is depicted in detail. Results from Section 3.1 provides an overall trend for consumption-based CH_4 emissions. The structure of consumption-based CH_4 emissions are discussed in Section 3.2, followed by the impact of trade on the consumption-based CH_4 emissions in Section 3.3. Conclusions and policy implications are finally proposed in the ending section.

2. Methodology and data sources

2.1. Environmentally-extended input-output analysis

The input-output analysis was first proposed and developed by Wassily Leontief in the late 1930s, in which observed economic data for a particular economic area (nation, province, city, etc.) were used for building up a basic input-output model. This paper explores the consumption-based CH_4 emissions of major economies by applying a fully integrated Environmentally-Extended-Input-Output Analysis (EEIOA), which is an extension of a basic input-output model. Based on the core idea of input-output theory, the total output of an economy X can be broken down into intermediate and final demand, as indicated in Eq. (1):

$$X = AX + F \tag{1}$$

where, column vector X denotes the total output, matrix A is the technology coefficients to describe the relationship between all sectors of the economy, and the column vector of F denotes final demand with its elements being the sum of all items of final demands, including household consumption, non-profit organization consumption, government consumption, gross fixed capital formation and inventory changes.

Considering that Eq. (1) under multiple regions can be further expressed as Eq. (2):

$$\begin{pmatrix} X^1 \\ X^2 \\ X^3 \\ \vdots \\ X^q \end{pmatrix} = \begin{pmatrix} A^{11} & A^{12} & A^{13} & \cdots & A^{1q} \\ A^{21} & A^{22} & A^{23} & \cdots & A^{2q} \\ A^{31} & A^{32} & A^{33} & \cdots & A^{3q} \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ A^{q1} & A^{q2} & A^{q3} & \cdots & A^{qq} \end{pmatrix} \begin{pmatrix} X^1 \\ X^2 \\ X^3 \\ \vdots \\ X^q \end{pmatrix} + \begin{pmatrix} \sum_r f^{1r} \\ \sum_r f^{2r} \\ \sum_r f^{3r} \\ \vdots \\ \sum_r f^{qr} \end{pmatrix} \tag{2}$$

where X^q is a column vector of the total output in region q, where each element x_i^q indicates the total output of sector i (i = 1, 2, ⋯, 56) in region q. And Each block matrix A is a 56 × 56 matrix for the interregional intermediate input coefficients between two regions, where its element a_{ij}^{qp}denotes the ratio of the intermediate demand of sector j

(j = 1, 2, ⋯, 56) in region p supplied by the sector i in region q to the total input of the sector *j in region p*. More simply to say, each diagonal matrix blocks refers to the requirement in the same region between different sectors and each off-diagonal matrix blocks represents the trading patterns between different regions. In addition, the column vector of $\sum_r f^{qr}$denotes final demand in region r provided by region *q*, and its elementf_i^{qr}shows the final demand of sector i in region *q*. To better understand the national consumption-based emissions, the consumption-based emissions in region r (E^r) can be further expressed in Eq. (3):

$$\begin{pmatrix} E^{1r} \\ E^{2r} \\ E^{3r} \\ \vdots \\ E^{qr} \end{pmatrix} = \begin{pmatrix} M^1 & 0 & 0 & 0 & 0 \\ 0 & M^2 & 0 & 0 & 0 \\ 0 & 0 & M^3 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & M^q \end{pmatrix} \left\{ \begin{pmatrix} I & 0 & 0 & \cdots & 0 \\ 0 & I & 0 & \cdots & 0 \\ 0 & 0 & I & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & 0 & I \end{pmatrix} - \begin{pmatrix} A^{11} & A^{12} & A^{13} & \cdots & A^{1q} \\ A^{21} & A^{22} & A^{23} & \cdots & A^{2q} \\ A^{31} & A^{32} & A^{33} & \cdots & A^{3q} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A^{q1} & A^{q2} & A^{q3} & \cdots & A^{qq} \end{pmatrix} \right\}^{-1} \begin{pmatrix} f^{1r} \\ f^{2r} \\ f^{3r} \\ \vdots \\ f^{qr} \end{pmatrix} \tag{3}$$

whereE^{qr}represents the consumption-based emissions which provided by region q to region r ; $M^q$is a diagonal matrix containing domestic CH_4 coefficients for each industry in region q. *I* is the identity matrix; and$L = (I - A)^{-1}$is the total Leontief inverse matrix. A region's consumption-based emissions can be calculated by summing up the embodied emissions in final demand drawn from various countries for use in this region. For instance, the consumption-based emission of the region r is the sum of the vectors $E^{1r}$to E^{qr}.

When the consumption-based emission inventory is extended to multi-regions, it can be further described by Eq. (4):

$$\begin{pmatrix} E^{11} & E^{12} & \cdots & E^{1q} \\ E^{21} & E^{22} & \cdots & E^{2q} \\ \vdots & \vdots & \ddots & \vdots \\ E^{q1} & E^{q2} & \cdots & E^{qq} \end{pmatrix} = \begin{pmatrix} M^1 & 0 & 0 & 0 \\ 0 & M^2 & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & M^q \end{pmatrix} \begin{pmatrix} L^{11} & L^{12} & \cdots & L^{1q} \\ L^{21} & L^{22} & \ldots & L^{2q} \\ \vdots & \vdots & \ddots & \vdots \\ L^{q1} & L^{q2} & \ldots & L^{qq} \end{pmatrix} \begin{pmatrix} f^{11} & f^{12} & \cdots & f^{1q} \\ f^{21} & f^{22} & \cdots & f^{2q} \\ \vdots & \vdots & \ddots & \vdots \\ f^{q1} & f^{q2} & \cdots & f^{qq} \end{pmatrix} \tag{4}$$

The production-based accounting emissions (PBE) is defined as the direct CH_4 emission emitted within the territory of a region, and consumption-based accounting emissions (CBE) as the CH_4 emission embodied in local final demand. Based on Eq. (4), the PBE in region r and CBE in region s can be readily obtained by Eq. (5):

$$\left\{ \begin{array}{l} PBEr = \sum_{s=1}^{q} Ers \\ CBEs = \sum_{r=1}^{q} Ers \end{array} \right\} \tag{5}$$

whereE_{rs}efers to the CH_4 emissions of region r that are embodied in the final consumption of region s, we have defined it as the CH_4 export from region r to region s.

The emissions embodied in imports (EEI) and exports (EEE) of region r can be expressed as Eq. (6):

$$\left\{ \begin{array}{l} EEIr = \sum_{r \neq s}^{q} Esr \\ EEEr = \sum_{r \neq s}^{q} Ers \end{array} \right\} \tag{6}$$

where EEI_r is the emissions embodied in international import of region r from other regions, while EEE_r denotes the emissions embodied in international exports of region r to all other regions.

2.2. Data sources

In this study, the anthropogenic CH_4 emissions are derived from the latest EDGAR-4.3.2 emission database, which have been widely adopted for related environmental and climate research (Madrazo et al., 2018; Zhang et al., 2018). The database reports detailed CH_4 emissions for more than 80 sources, such as enteric fermentation, manure management, rice cultivation, fugitive emissions from solid fuels, fugitive emissions from oil and gas, solid waste disposal on land, wastewater handling, fossil fuel combustion, and others. This database has updated the bottom-up inventories of anthropogenic GHG emissions of nations to the year of 2012 (Janssens-Maenhout et al., 2017). Therefore, we can obtain a time series CH_4 emission inventories at the national level from the EDGAR 4.3.2 emission database and then adopt a hybrid approach to redistribute emissions data to 56 sectors in each economy of WIOD. This makes it possible for a more systematic study on time-series consumption-based accountings of global CH_4 emissions via the methods of EEIOA. If we use other national GHG inventories with limited data (especially for developing economies), the uncertainty of input-output analysis will be greatly affected.

We adopt the global input-output tables from the WIOD database, which includes 44 economies (43 countries or regions plus a Rest of World) and 56 sectors (see supporting information Table S2). Due to the availability of CH_4 emission account, this paper selects the global MRIO data during 2000–2012 in order to keep consistency. The EU in this article includes 28 countries (see Table S1). In addition, due to the complexity of the data and the inter-departmental correlation, some small emission sources such as public services, fuel combustion of commercial and non-specified industrial sectors are ignored. The population and GDP of the major economies are obtained from the World Bank (World Bank, 2017). However, since the World Bank data does not include Taiwan Province of China, we use United Nations Conference On Trade And Development (UNCTAD) data when calculating demographic and economic-related indicators for Taiwan Province of China.

3. Results and discussions

3.1. Overall trend of consumption-based CH_4 emissions of major economies

The evolution features about consumption-based CH_4 emissions in major economies are shown in Fig. 1. During the period 2000–2012, there were 12 economies showing an upward trend in their consumption-based CH_4 emissions (see Table S3 for details). The economy with the highest average annual growth rate of consumption-based CH_4 emissions was China (4.2%), followed by Russia (4.1%) and Indonesia (4.1%). In particular, during the period 2006–2012, the consumption-based CH_4 emissions of China, India and Indonesia experienced rapid annual growth rates of 6.0, 5.4 and 4.0%, respectively. On the contrary, the consumption-based CH_4 emissions of the EU, the USA, Taiwan of China and Japan showed a slightly decreasing trend. For example, the EU reduced from a historical peak at 47.7 Mt in 2006 to 38.6 Mt in 2012, the USA decreased from a historical peak at 41.1 Mt in 2005 to 35.5 Mt in 2012. In detail, EU was the economy with the largest consumption-based CH_4 emissions (43.6 Mt) in 2000, followed by China (39.5 Mt) and the USA (39.2 Mt). Since 2007, however, China has surpassed the EU and the USA to become the largest driver of global

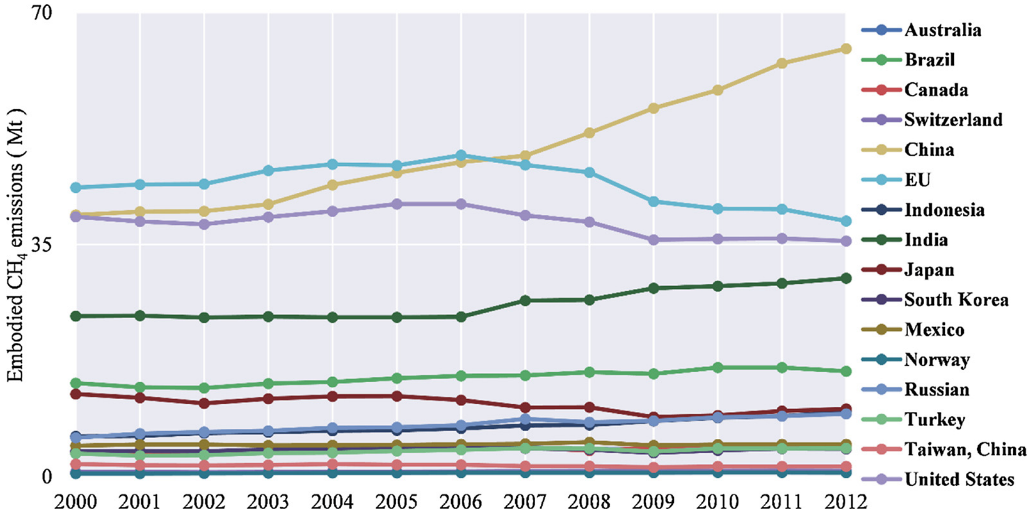
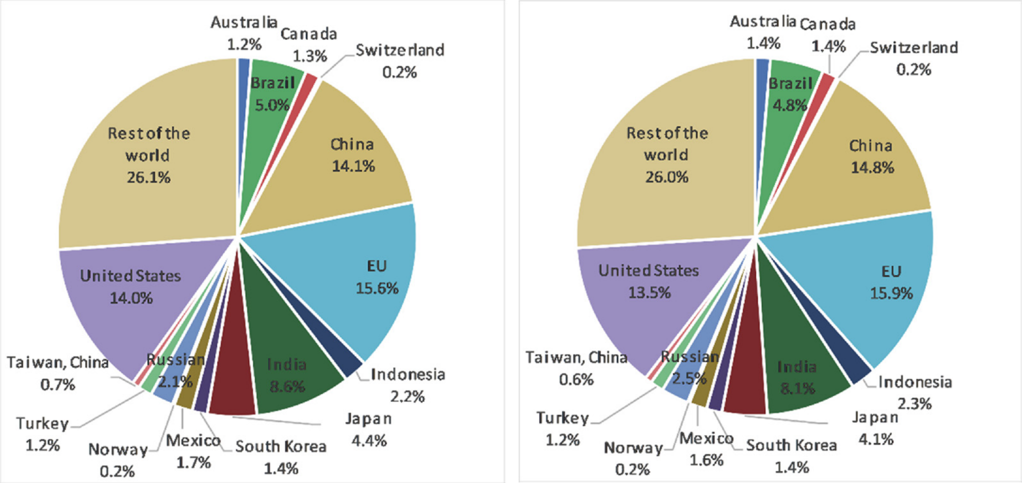
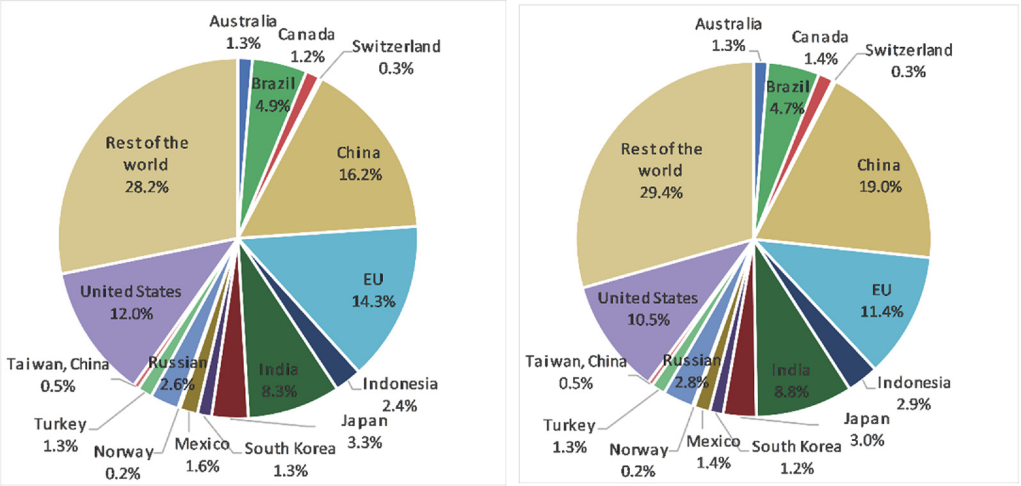


Fig. 1. Consumption-based CH_4 emissions of major economies during 2000–2012.



(a) 2000 (b) 2004



(c) 2008 (d) 2012

Fig. 2. The emission shares of major economies in the global total consumption-based CH_4 emissions.

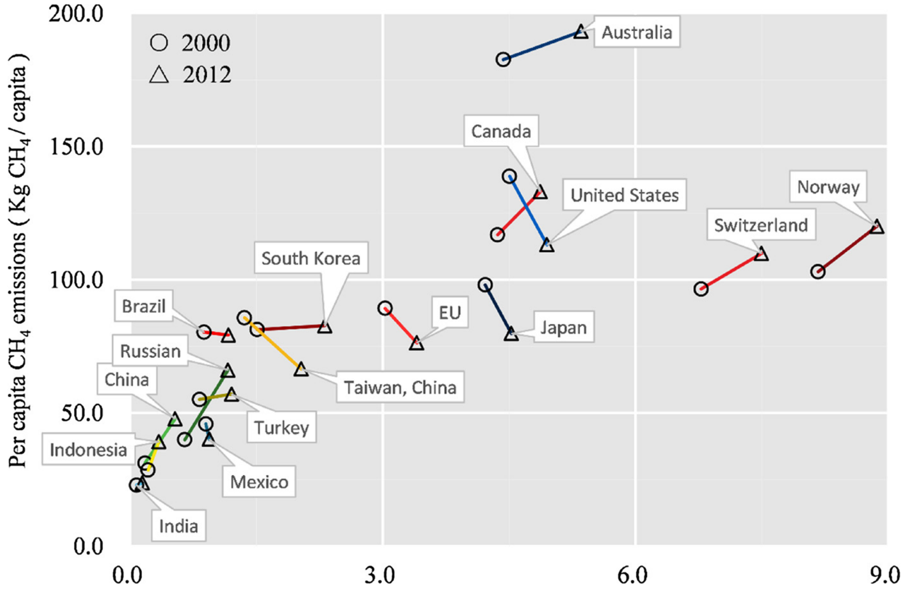
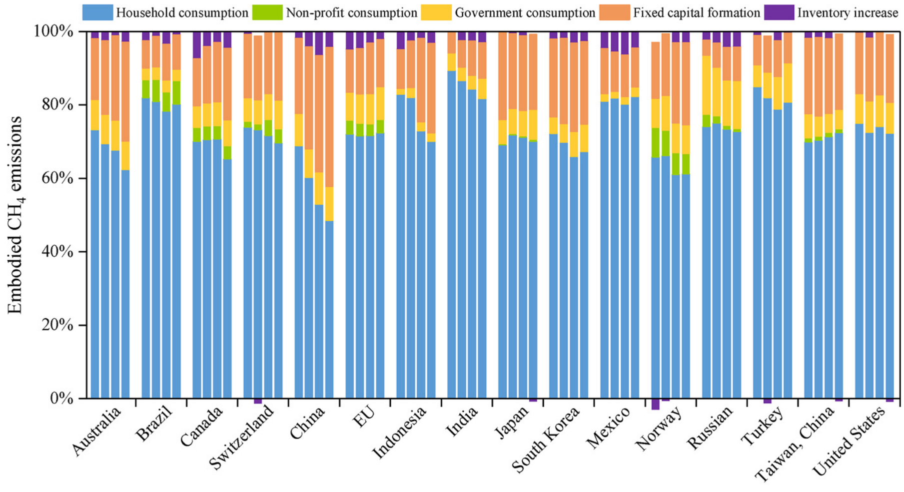
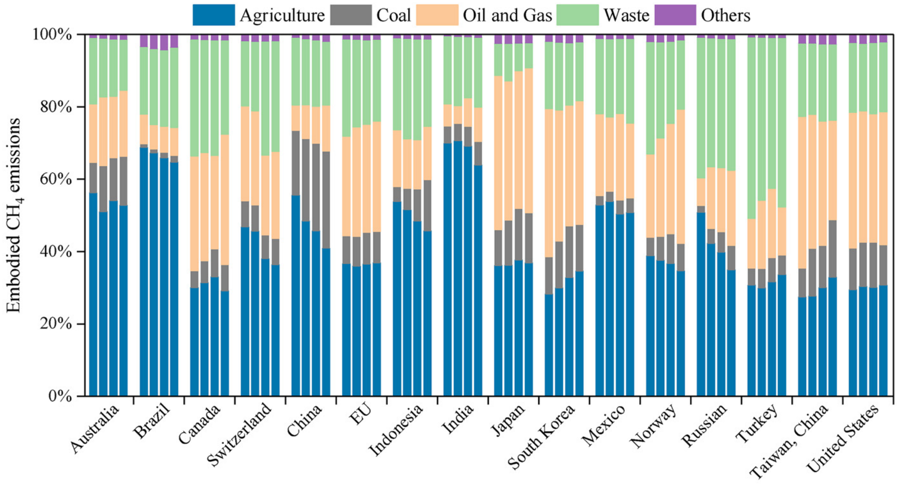


Fig. 3. The relationship between per capita GDP and per capita CH_4 emissions for major economies in 2000 and 2012.

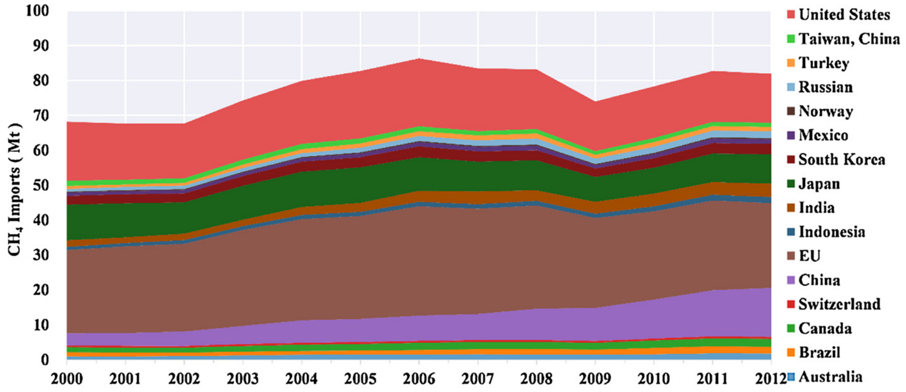


(a) Embodied emissions by final demand category

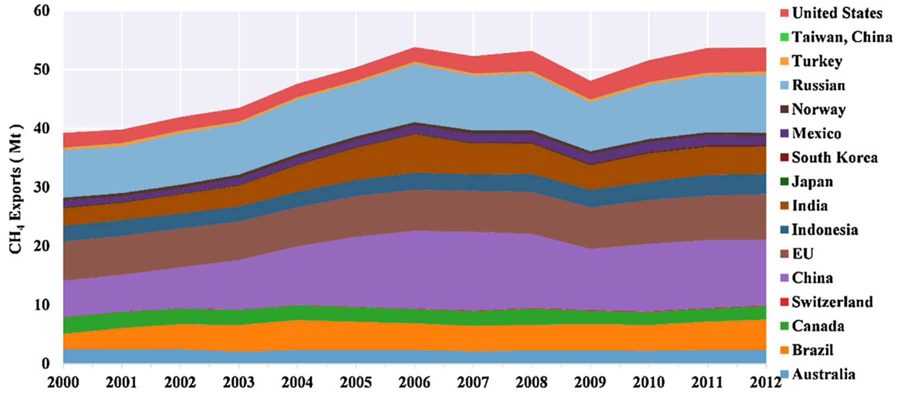


(b) Embodied emissions by source

Fig. 4. Consumption-based CH_4 emissions structures of major economies in 2000, 2004, 2008 and 2012.



(a) Imports



(b) Exports

Fig. 5. CH$_4$ emissions embodied in international trade of major economies during 2000–2012.

CH$_4$ emissions. China's total consumption-based CH$_4$ emissions reached 64.5 Mt in 2012, which was 1.8 and 1.7 times that of the US and the EU, respectively.

As illustrated in Fig. 2, the total consumption-based CH$_4$ emissions of the 16 major economies accounted for more than 70% of the global total. The EU, China and the USA were the only three economies which were responsible for more than 10% of global CH$_4$ emissions. The next major economies were India and Brazil, accounting for about 8% and 5%, respectively. For other economies, their contributions were less than 5%. The share of China maintained an obvious increasing trend in the accounting period, climbing up from 14.1% in 2000 to 19.0% in 2012. The shares of India, Indonesia, Russia and Canada also increased in varying degrees. In contrast, the EU, the USA, Brazil, Japan, Mexico, South Korea and Taiwan of China have all experienced a decline, among which the EU, the USA and Japan decreased most significantly.

To shed light on the relationship between economic growth and CH$_4$ emissions, per capita consumption-based CH$_4$ emissions and per capita GDP for the major economies in 2000 and 2012 are showed in Fig. 3 (see Table S4). Results show a positive correlation between per capita GDP and per capita consumption-based CH$_4$ emissions in general. For example, India, Indonesia and China demonstrated a type of economies with low GDP and low per capita CH$_4$ emissions, while Australia, Canada, Norway and the USA belonged to a different type of economies with high per capita GDP and high per capita emissions. Likewise, a positive correlation also exists in the changes of per capita GDP and the changes of per capita consumption-based CH$_4$ emissions. For instance, the per capita consumption-based CH$_4$ emissions of Russia (65.1%) and China (52.9%) increased significantly comparing to 2000, and their corresponding per capita GDP increased by 201.2% and 79.0%, respectively. However, exceptions do exist. For example, the per capita GDP of the USA, Japan, the EU and Mexico changed relatively little from 2000 to 2012, and their corresponding per capita embodied emissions revealed an overall downward trend.

3.2. Consumption-based CH4 emission structures of major economies

From the global perspective, approximately 70% of the global consumption-based CH$_4$ emissions were induced by household consumption, followed by gross fixed capital formation (about 15%) and government consumption (about 6%). The contributions of changes in inventories and non-profit organization consumptions were negligible in most economies. The share of household consumption declined from 76.1% in 2000 to 68.0% in 2012, while the share of fixed capital formation increased steadily from 13.3% in 2000 to 18.7% in 2012. This can be partly attributed to the decrease in the share of household consumption and the simultaneous increase in the share of fixed capital formation in China, Australia and India.

In terms of the final demand structure in each economy, household consumption accounted for the highest share of consumption-based CH$_4$ emissions in India (see Fig. 4a), reaching 89.7% in 2000. However, its share saw annual decline trend since then, falling continuously from 86.6% in 2004 to 81.8% in 2012. The contribution of household consumption in China experienced a similar continuous decline from 68.9% in 2000 to 48.5% in 2012, making China the economy with the lowest proportion of household consumption among these economies in 2012. Comparing to 2000, the contribution of household consumption declined in most economies, with China, Indonesia and Australia falling the most significantly, at 20.3%, 12.9% and 10.9%, respectively. Fixed capital formation generally exerted its ever-increasing impact on consumption-based CH$_4$ emissions in China during the whole period, reaching up to the maximum of 38.1% in 2012. It is also worth noting that the composition in final demand categories of the EU and the USA have not changed much overall.

With regard to emission source category, agriculture-, waste-, and oil and gas-related emission sources were the main contributors to the global CH_4 emissions (see Fig. 4b). In term of agriculture-related CH_4 emissions, they constituted more than 60% of total consumption-based CH_4 emissions in India and Brazil, the two largest consumers of global agriculture-related CH_4 emissions. The contribution of agriculture-related emissions in Russia, China, Switzerland, Indonesia, Norway and Brazil all showed a slight downward trend during 2000–2012. As for the embodied oil and gas-related emissions in each economy, oil and gas-related emissions accounted for the highest share of consumption-based CH_4 emissions in Japan, followed by the USA, Taiwan of China, Canada and the EU. The contribution of waste-related emissions driven by final demand in Turkey is more than 40% of its total embodied CH_4 emissions, followed by Russia (more than 35%).

3.3. Impacts of trade on embodied CH_4 emissions

Fig. 5 depicts the trend of CH_4 emissions embodied in international trade of major economies during 2000–2012, which vary within a narrow range between 77.1 and 95.5 Mt. Total CH_4 emissions embodied in imports of the 16 economies increased from 77.1 Mt in 2000 to 95.1 Mt in 2007, followed by a consecutive two years decrease due to the global financial crisis and fell to 85.9 Mt in 2009. After that, the embodied emissions begin to soar again, reaching a historical peak at 95.9 Mt in 2012. This shows that CH_4 flows of an economy are constrained by external economic situations. Furthermore, this also suggests that the continuous time series analysis could offer more informative insights than the analysis in individual years. Among the 16 major economies, the EU consistently ranked the top in CH_4 emissions embodied in imports during 2000–2012 (see Table S5 for details). Its imports volume experienced a steady increase trend from 23.9 Mt in 2000 to its highest point of 30.7 Mt in 2007, and then reduced to 24.3 Mt in 2012. The CH_4 imports of the EU accounted for 25.3%–33.3% of the total global CH_4 imports in 2000–2012, indicating that more than a quarter of the world's CH_4 trade came from the consumption of the EU. The USA ranked second in general, its import volume increased from 15.7 Mt in 2002 to 19.3 Mt in 2005, followed by a continuous decline to 14.0 Mt in 2012. Imports from China have more than quadrupled from 2000 to 2012 and grew steadily at 12.5% per year over the whole period. Contrary to this, the shares of the EU and the USA in the global CH_4 imports declined during 2006–2012, with the shares of the EU decreasing from 32.3% to 25.3% and that of Japan from 20.2% to 14.6% over the same time period.

With regard to export (see Table S6 for details), emissions increased by 24.3% from 2000 to 2012. Exported emissions from Russia and the EU were the largest in 1990, with 10.5% and 8.7%, respectively, before exports from China started to grow rapidly from 2002 following the accession of China to the World Trade Organization. Meanwhile, it indicates that China's accession to the World Trade Organization not only promoted world economic trade, but also triggered China's CH_4 emissions for other economies. Since 2004, China has surpassed Russia as the largest exporter. Its exports volume grew rapidly from 6.2 Mt in 2000 to 13.4 Mt in 2012 with an average annual growth rate of 11.6%. However, a fluctuation has also been witnessed in the period of 2008–2012 potentially due to the shock of global financial crisis. In addition to China, Brazil, Russia, the USA, India and the EU also experienced a slight growth trend from 2000 to 2012. For the remaining economies, their CH_4 exports maintained stable trends and the volumes were relatively low, with an annual volume of 2 million tons and below.

To further present regional tele-connection among major economies, Table 1 describes the evolution of embodied CH_4 emissions transfer network. As shown in Table 1, the EU, the USA, China and Japan were the major destinations for trading embodied emission flows. Obviously, China reinforces its position as the dominant contributor of interregional transfers of embodied CH_4 emissions from 1.1 Mt in 2000 to 5.2 Mt in 2012.

The largest bilateral trading flows took place from Russia to the EU among the major economies. This trading flows increased from 3.5 Mt in 2000 to 5.5 Mt in 2004, followed by a long-term decrease due to the global financial crisis, and fell to 4.3 Mt in 2012. China, as the largest exporter of embodied CH_4 emissions, also exported substantial embodied emissions to the USA and the EU. The trading flows from Canada and Mexico to the USA, and from Brazil and Russia to China were also essential ties in the embodied emission transfer network. In sum, the most important trade flows were related to China, the USA, the EU, Japan, and Brazil.

Agriculture and energy-related CH_4 emissions transfers among major economies are portrayed in Fig. 6. In these chord figures, the 16 economies are arranged in a circle, and the embodied CH_4 emissions in exports of each economy are consistent with the size of the sector occupied by the economy. The curve connecting any two economies in the chord figure represents the embodied CH_4 emissions in trade between the two economies. The amount of embodied CH_4 emissions exported to each other by the connected economies is represented by different line widths at both ends of the curve, respectively. And the color of the curve is consistent with the economies with larger exports in the two connected economies.

Presented in Fig. 6(a)(c)(e)(g) are major inter-regional trade flows in terms of agriculture-related CH_4 emissions. The EU was the economy with the largest embodied agricultural CH_4 emissions inflows during 2000–2012. It experienced an overall increase trend, increasing from 62.1 Mt in 2000 to 81.5 Mt in 2004, followed by a long-term decline to 58.2 Mt in 2012. In addition, China gradually ranked the second place in embodied agricultural CH_4 emissions inflows, i.e. from 8.3 Mt in 2000 to 56.3 Mt in 2012. In contrast, as the global CH_4 emissions trade increased, the agriculture-related CH_4 import of the EU and Japan experienced an overall decreasing trend over time. Brazil had the biggest outflows of agricultural-related CH_4 emissions. Its CH_4 outflows in agricultural exports increased from 43.8 Mt in 2000 to 86.7 Mt in 2004, which was subsequently reduced by the global financial crisis and fell to 68.6 Mt in 2008. After that, the embodied emissions began to rise again, reaching 81.1 Mt in 2012. And the largest receiver was the EU, accounting for an overwhelming 56.1% of Brazil's total exports in 2000. The agriculture-related CH_4 export of China also increased significantly with time. Indeed, it grew from 38.8 Mt in 2000 to 60.3 Mt in 2012, reaching the highest point of 75.9 Mt in 2008. Additionally, the corresponding CH_4 export of Australia experienced an overall decreasing trend during 2000–2012 (i.e. from 28.0 Mt in 2000 to 19.4 Mt in 2012). Major export-import pairs supporting the large flows were Brazil–EU, China–Japan, China–USA, India–EU in 2000, and Brazil–China, Brazil–EU, China–USA, China–EU in 2012. Remarkably, for the USA, the agriculture-related CH_4 exports was relatively stable, which varied within a narrow range between 4.0 Mt to 4.5 Mt.

Energy-related emissions are presented in Fig. 6(b)(d)(f)(h), the export volume of the Russia consistently ranked top during the whole period. It experienced an overall increasing trend, from 129.9 Mt in 2000 to 189.6 Mt in 2008, followed by a slight decline to 184.9 Mt in 2012. Russia had the biggest embodied energy-related emission outflows, more than 56% of which flowed into EU. Total outflows of energy-related emissions from China have experienced a continuous rise (i.e. from 45.9 Mt in 2000 to 94.6 Mt in 2008), followed by a short-term sharp fall due to the global financial crisis (i.e. from 94.6 Mt in 2008 to 84.2 Mt in 2012). It mainly flow into EU (more than 23%), the USA (more than 15%) and Japan (more than 14%). In comparison, the EU and the USA were the two leading economies with the biggest inflows. The difference is that the inflow of the EU increased significantly in general, while the USA experienced an overall decreasing trend. Over time, China's energy demand has been growing at a high rate, ranking third in 2012. Major inflow-outflow couples of energy-related emissions

Table 1
Interregional transfers of embodied CH_4 emissions via international trade among major economies. (a) 2000; (b) 2004; (c) 2008; (d) 2012.

(a) 2000

Economy	Australia	Brazil	Canada	Switzerland	China	EU	Indonesia	India	Japan	South Korea	Mexico	Norway	Russian	Turkey	Taiwan, China	United States	Total
Australia	0	17	35	8	190	350	107	50	561	145	20	3	8	15	84	256	1850
Brazil	30	0	33	20	94	1084	16	31	197	31	40	32	52	14	17	411	2100
Canada	12	15	0	6	40	260	9	9	200	36	48	3	4	13	12	1915	2580
Switzerland	0	0	1	0	1	31	0	1	2	0	0	0	0	1	0	4	43
China	115	36	124	28	0	1072	91	49	1062	276	42	20	67	21	80	1144	4227
EU	36	41	79	149	137	0	22	50	187	40	38	54	84	58	31	581	1588
Indonesia	61	20	61	6	177	368	0	51	679	197	17	3	8	10	58	371	2087
India	23	33	44	15	174	1064	25	0	238	26	16	7	69	62	20	428	2243
Japan	2	1	1	1	6	12	1	1	0	4	1	0	0	0	5	20	55
South Korea	2	2	3	0	21	19	4	2	48	0	2	0	2	1	6	36	151
Mexico	3	8	23	2	9	95	3	4	42	7	0	1	2	2	4	663	868
Norway	2	4	36	3	8	319	1	2	15	5	2	0	3	2	2	92	495
Russian	41	75	41	82	226	3481	54	72	392	97	35	21	0	214	50	771	5649
Turkey	2	3	3	5	5	170	1	31	11	2	1	1	11	0	1	35	280
Taiwan, China	1	0	1	0	5	7	0	2	8	1	1	0	0	1	0	10	38
United States	30	37	311	15	65	496	24	17	448	93	344	6	17	21	71	0	1994
Total	361	291	794	339	1158	8828	359	372	4090	960	607	152	325	436	440	6736	

(b) 2004

Economy	Australia	Brazil	Canada	Switzerland	China	EU	Indonesia	India	Japan	South Korea	Mexico	Norway	Russian	Turkey	Taiwan, China	United States	Total
Australia	0	12	36	6	275	304	99	97	537	139	14	3	11	11	69	208	1819
Brazil	30	0	61	30	452	1831	50	68	316	107	94	36	186	28	78	597	3965
Canada	11	9	0	4	50	213	8	11	115	18	52	3	5	6	10	1855	2372
Switzerland	0	0	1	0	1	31	0	1	2	0	0	0	1	0	0	4	43
China	237	78	252	42	0	1981	182	187	1460	448	97	39	192	54	177	1975	7400
EU	42	28	77	131	158	0	17	112	135	36	29	61	106	68	25	517	1542
Indonesia	91	17	24	5	263	301	0	112	697	188	15	3	12	11	109	300	2149
India	41	44	60	17	711	1253	67	0	547	58	22	10	34	52	41	491	3447
Japan	2	1	2	1	11	14	1	1	0	5	1	0	1	0	7	17	65
South Korea	2	1	3	0	22	18	2	4	31	0	1	0	2	1	4	25	117
Mexico	3	4	30	5	12	86	2	11	27	4	0	1	1	1	2	811	1001
Norway	2	3	28	4	10	430	1	3	9	4	2	0	6	3	1	92	598
Russian	44	39	71	67	402	5488	36	148	297	107	30	35	0	310	43	756	7872
Turkey	2	2	3	3	7	165	2	35	6	1	1	2	13	0	1	26	269
Taiwan, China	1	0	1	0	8	7	0	3	7	1	1	0	0	0	0	9	41
United States	29	28	335	11	158	429	26	27	309	79	289	6	16	24	55	0	1822
Total	537	265	983	326	2539	12551	493	820	4496	1197	649	200	585	569	623	7686	

(c) 2008

Economy	Australia	Brazil	Canada	Switzerland	China	EU	Indonesia	India	Japan	South Korea	Mexico	Norway	Russian	Turkey	Taiwan, China	United States	Total
Australia	0	19	28	5	357	241	88	86	503	111	12	3	24	11	47	165	1699
Brazil	33	0	48	32	616	1332	41	50	234	89	33	27	173	29	28	398	3163
Canada	14	20	0	5	75	239	14	17	144	28	63	4	11	15	9	1847	2507
Switzerland	1	1	4	0	3	57	1	4	2	1	1	1	1	1	1	8	86
China	273	179	345	49	0	2611	197	308	1207	499	140	47	452	100	140	2237	8784
EU	47	46	80	126	153	0	20	82	121	39	36	78	152	92	22	427	1521
Indonesia	92	35	27	6	384	365	0	99	692	175	19	4	27	20	41	293	2279
India	35	96	47	11	1107	1728	50	0	142	65	19	9	35	55	63	335	3799
Japan	3	1	2	1	15	15	2	1	0	6	1	0	3	1	7	17	75
South Korea	4	3	3	0	31	27	5	6	23	0	3	1	5	2	4	25	140
Mexico	6	10	43	3	23	128	3	14	37	6	0	1	4	3	3	985	1271
Norway	2	4	17	4	9	450	1	3	8	3	3	0	7	4	1	61	578
Russian	58	62	70	60	496	5279	47	108	326	156	51	43	0	414	32	704	7907
Turkey	2	4	3	3	13	139	5	33	6	2	1	2	22	0	1	18	254
Taiwan, China	1	1	2	0	9	7	1	5	5	1	1	0	1	1	0	7	41
United States	38	55	447	15	278	598	48	38	409	149	437	10	37	50	74	0	2683
Total	609	535	1164	320	3570	13218	520	855	3860	1330	821	229	954	799	475	7529	

(d) 2012

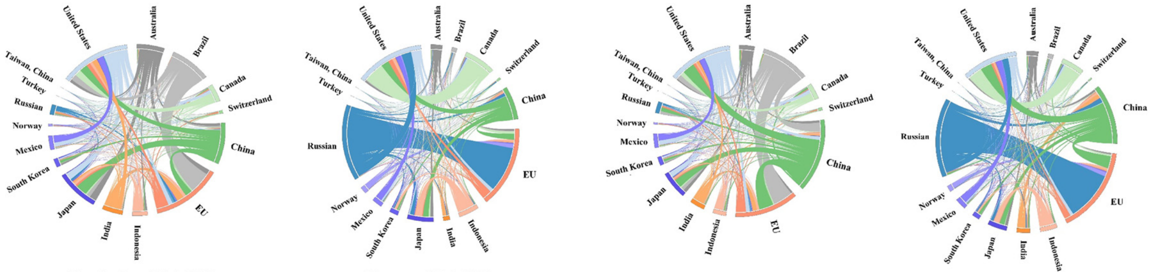
Economy	Australia	Brazil	Canada	Switzerland	China	EU	Indonesia	India	Japan	South Korea	Mexico	Norway	Russian	Turkey	Taiwan, China	United States	Total
Australia	0	20	25	5	564	185	97	104	370	111	10	3	24	13	64	139	1733
Brazil	34	0	60	21	1245	994	73	63	310	151	32	25	122	49	102	394	3677
Canada	14	21	0	4	158	173	11	18	123	23	60	4	12	9	13	1353	1999

(continued on next page)

Table 1 (*continued*)

(d) 2012

Economy	Australia	Brazil	Canada	Switzerland	China	EU	Indonesia	India	Japan	South Korea	Mexico	Norway	Russian	Turkey	Taiwan, China	United States	Total
Switzerland	2	2	4	0	7	43	1	2	3	1	0	1	1	1	1	9	79
China	308	226	320	58	0	1740	229	321	989	391	140	30	427	103	129	1888	7300
EU	65	70	87	147	304	0	30	98	145	62	34	89	192	104	25	435	1887
Indonesia	88	45	30	6	642	292	0	173	496	156	18	4	35	26	128	273	2414
India	46	95	48	12	1031	872	78	0	137	70	23	11	49	54	45	402	2972
Japan	2	1	2	0	15	9	2	2	0	5	1	0	2	1	5	14	61
South Korea	6	4	4	1	47	23	9	6	35	0	3	0	6	2	6	30	180
Mexico	10	15	59	3	56	134	4	31	41	11	0	1	7	12	4	1011	1400
Norway	3	6	9	5	18	359	2	4	10	8	2	0	11	5	2	42	484
Russian	81	92	70	63	1060	4283	87	145	611	218	47	53	0	178	63	667	7717
Turkey	4	8	5	4	44	137	4	14	8	3	2	2	32	0	2	24	294
Taiwan, China	1	2	2	0	14	7	1	3	7	2	1	0	1	1	0	8	49
United States	51	95	554	14	523	598	51	53	369	117	481	10	39	56	54	0	3065
Total	716	703	1279	343	5726	9850	678	1037	3654	1331	854	233	960	612	644	6689	

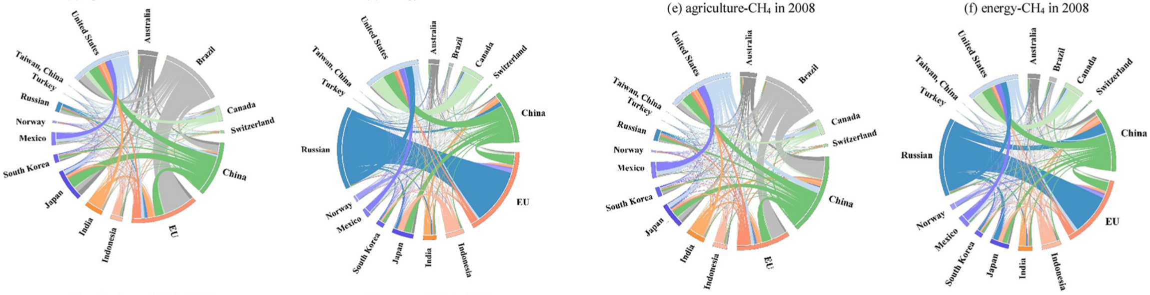


(a) agriculture-CH_4 in 2000

(b) energy-CH_4 in 2000

(e) agriculture-CH_4 in 2008

(f) energy-CH_4 in 2008



(c) agriculture-CH_4 in 2004

(d) energy-CH_4 in 2004

(g) agriculture-CH_4 in 2012

(h) energy-CH_4 in 2012

Fig. 6. Embodied CH_4 emission via international trade transfers among major economies by source.

were Russia–EU, China–EU, and Canada–USA. The trading flows from China to the USA and the EU were also important ties in the embodied energy-related emission transfer network. This indicates that as the largest economic entity in the world, the EU requires large amounts of energy products imported from other economies.

4. Conclusions and policy implications

This study uses the environmentally-extended input-output analysis (EEIOA) method to present the most comprehensive overview of CH_4 emissions in global supply chains for major economies from 2000 to 2012, based on the most updated global CH_4 emission inventories from the Emissions Database for Global Atmospheric Research (EDGAR) and the global MRIO table from the WIOD database. Furthermore, we elaborate the evolution features of embodied emissions from the perspective of final demand structure (i.e., household consumption, gross fixed capital formation, government consumption, changes in inventories and non-profit organization consumption) and source emission structure (i.e., agriculture, waste, and oil and gas). When tracking the CH_4 emissions embodied in international trade, we also distinguish the contributions from agriculture and energy-related CH_4 emissions. Based on the results, some CH_4 reduction policy recommendations are proposed for major economies from both the regional and global perspectives.

With regard to consumption-based CH_4 emissions, except for the EU, the USA, Taiwan of China and Japan, the major economies maintained a growing trend from 2000 to 2012. The EU had the largest consumption-based CH_4 emissions in 2000, which had been outpaced by China since 2007. China (4.2%), Russia (4.1%) and Indonesia (4.1%) had the highest average annual growth rate of consumption-based CH_4 emissions among major economies. Clearly, accounting for the embodied CH_4 emissions of major economies plays a significant role in reducing consumption-induced CH_4 emissions and mitigation policy instruments in each economy. For example, encouraging green consumption and increasing CH_4 label of products can be good practices. Especially in India and Brazil, agriculture-related CH_4 emissions constituted more than 60% of their corresponding total consumption-based CH_4 emissions. Encouraging agricultural products to develop CH_4 labels is important in the context of reducing current and future global warming. We expect CH_4 labeling to have a role in increased supply chain pressures by manufacturers and large chain stores (e.g. food industry) to reduce the CH_4 emissions of products they carry. Meanwhile, CH_4 labels can also promote transparency of related CH_4 emissions and guide consumers to choose low CH_4 products (Chen et al., 2017; Li et al., 2018). While the methodological and legal challenges to the establishment of effective CH_4-labeling programs are significant, careful analysis and selection of product categories to be labeled could ultimately bring about significant reductions in CH_4 emissions in a manner that is cost-effective and consistent with the international trade standards (Cohen and Vandenbergh, 2012). Moreover, proper adjustment of diet habits (e.g. reducing red beet intake) and reductions of food waste can greatly help to ensure a healthy diet and reduce embodied agricultural emissions (Bajzelj et al., 2014).

From our results, it seems clearly that the consumer side presents the greatest mitigation potentiality. It was found that household consumption accounts for about 70% of the total emissions embodied in final consumption. The scope of CH_4 reduction efforts can be further narrowed to residential consumption, such as improving thermal insulation and more efficient heating equipment (Long et al., 2018). In contrast to the decreasing contribution from household consumption, the share of consumption-based CH_4 emissions caused by investment activity increased by 7.6% during the 2000–2012 period. Investment activities generally exerted its ever-increasing impact on consumption-based CH_4 emissions in China, Australia and India with time. Especially, investment activities are of great importance for China, a nation experiencing both rapid urbanization and industrialization processes. It reflected that China were shifting from a society that struggled to satisfying basic household needs to responding to higher standard life styles and demand for advanced investment (Tian et al., 2014). Consequently, further exploring how to determine the energy-saving and emission-reduction potentials of improving investment-driven energy consumption practices (especially for energy industry) is a vital approach to curb the rapid growth of consumption-based CH_4 emissions for investment-driven economies like China (Fu et al., 2014). For instance, large projects should not be blindly invested. Instead, rational planning processes in advance to encourage more investment in clean and green projects should be advocated. Promoting low CH_4 design, using low CH_4 materials, and guiding the public sector towards a low CH_4 investment direction are essential (Tian et al., 2014).

The total transfer of embodied CH_4 emissions via international trade showed a significant upward trend, suggesting that the globalized world economy had generated adverse environmental impacts. Developed countries and large economies played essential roles in embodied CH_4 emission transfers. Therefore, when designing emission reduction strategies for these major economies, attention should be paid not only to local emission reduction, but also to consider emission flows in external trade (Chen et al., 2019b; He and Hertwich, 2019; Tian et al., 2018). From the consumption-based CH_4 imports, total imported CH_4 emissions in 2012 came primarily from the EU, the USA, China and Japan. The CH_4 imports of the EU accounted for 25.3%–33.3% of the total global CH_4 imports in 2000–2012, indicating that more than a quarter of the world's CH_4 trade comes from the consumption of the EU. For important importing economies like the EU (e.g. the USA, China and Japan), tax incentives can be offered for imports with low CH_4 intensity, thereby encouraging upstream industries to produce cleaner products. Meanwhile, encouraging the importing economies to cooperate with the exporting economies to reduce emission intensity of exported commodities by providing financial and advanced technical support are also encouraged (Han et al., 2019). As for the export volume of CH_4 emissions, total CH_4 exports increased by 24.3% from 2000 to 2012, among which Russia, the EU and China contributed the most. The consumption of agricultural commodities in the EU and the USA caused large emissions which were released in Brazil, China, and Mexico. For these large agricultural economies, their national governments should coordinate design and implement effective mechanisms and channels to increase public agricultural R&D investments, thereby stimulating innovation and adopting agricultural technologies and practices that reduce agricultural CH_4 emissions (Lybbert and Sumner, 2012). For example, adopting advanced irrigation management methods, planting hybrid rice with lower CH_4 generation than common rice, and shifting towards more intensive management in agricultural sector (Zhang et al., 2016). Russia, China and Canada also released large CH_4 emissions due to energy-related commodities consumed by the EU and the USA. These economies with large energy-related exports (e.g. Russia, the EU and China) have considerable potentials for climate change mitigation. Future policy priorities are hence recommended to encourage research in low-methane technology by increasing investments and subsidies for the energy-related industry. Furthermore, these economies can transform their industrial structures and changing positions in the international supply chain by developing technology-intensive and high-value-added industries, thereby decreasing the exported emissions of products. Moreover, an alternative direction to decrease energy-related emissions is to encourage the use of energy-saving, clean energy and new energy transportation tools (Ma et al., 2019).

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ReferencesUncategorized References

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.resconrec.2019.104414.

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