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Research article

Quantifying global CH_4 and N_2O footprints

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ABSTRACT

This study aims to quantify global CH_4 and N_2O footprints in 2012 in terms of 181 economies and 20 world regions based on the official national emission accounts from the UNFCCC database and the global multi-region input-output accounts from the EORA database. Global total CH_4 and N_2O emissions increased by 15.0% in 2012 compared to 1990, mainly driven by increasing demands of agricultural and energy products. Mainland China, Western Europe, the USA, Southeast Asia and Sub-Saharan Africa were identified as the largest five CH_4 footprint contributors (55.6% of the global total), while Mainland China, the USA, Western Europe, Brazil and Sub-Saharan Africa as the largest N_2O footprint contributors (59.2% of the global total). In most developed economies, the CH_4 and N_2O footprints were much higher than their emissions on the production side, but opposite picture is observed in emerging economies. 36.4% and 24.8% of the global CH_4 and N_2O emissions in 2012 were associated with international trade, respectively. Substantial energy-related CH_4 and agricultural CH_4 and N_2O emissions were transferred from developed countries to developing countries. Several nations within Kyoto targets have reduced their CH_4 and N_2O emissions significantly between 1990 and 2012, but the generally-believed success is challenged when viewing from the consumption side. Mainland China, Southeast Asia, Sub-Saharan Africa, Brazil, Middle East and India witnessed prominent increase of CH_4 and N_2O footprints in the same period. The structure and spatial patterns of global CH_4 and N_2O footprints shed light on the role of consumption-side actions and international cooperation for future non-CO_2 GHG emission reduction.

1. Introduction

Achieving the Paris target of limiting global warming to well below 2 °C above pre-industrial levels requires not only the mitigation of CO_2 emissions, but also non-CO_2 GHGs, being methane (CH_4) and nitrous oxide (N_2O) the most important (Montzka et al., 2011; IPCC, 2014). Over the past decades, global anthropogenic non-CO_2 GHG emissions have continued to increase (Olivier et al., 2017), which is largely driven by human activities through agriculture, energy and industrial activities (Saunois et al., 2016; EDGAR, 2017). As a first step, inventorying the national non-CO_2 GHG account is crucially important for subsequent measures towards emission mitigation. Proposed by the UNFCCC (the United Nations Framework Convention on Climate Change), territorial-based accounting framework, also entitled production-based accounting, is generally used to compile the national emission inventory, which measures the quantity of emissions directly generated in all the production activities within the territorial borders of a country. Based on territorial-based accounting, some existing studies have established national inventories of CH_4 and N_2O emissions (e.g., Janssens-Maenhout et al., 2017; Zhang et al., 2016, Zhang et al., 2018a). The production-based principle adopts a producer perspective and focuses on the onsite emissions. Nevertheless, this accounting method is unable to reveal the connections of nations and regions in the world economy (Peters, 2008; Fan et al., 2016).

The world has become unprecedently globalized. International trade gives birth to an integrated global supply chain by a reposition of global resources, manufacturing industries, and consumers. Consumption of goods and services in a nation often induces GHG emissions in other regions. To scope out a nation's GHG inventory from a consumer perspective, consumption-based emission accounting is raised for the allocation of onsite emissions to final users. By subtracting emissions embedded in the exports from production-based emissions and adding those in the imports, production-based inventory could be adjusted for consumption-based inventory, which represents

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the total emissions induced to meet domestic final demand, irrespective of where those emissions are actually generated (Pablo-Romero and Sánchez-Braza, 2017). Consumption-based emission inventory is also referred to as the carbon footprint (Peters, 2010; Caro et al., 2017; Jiang and Green, 2017). The CH_4 (or N_2O) footprint of an economy evaluates the CH_4 (or N_2O) emissions generated worldwide to produce the goods and services to satisfy its domestic final demand (e.g., private and public consumption, and investment). Compared with production-based account, carbon footprint identifies the consumer responsibility and is capable of quantifying the phenomenon of carbon leakage via international trade (Davis and Caldeira, 2010).

In practice, Life Cycle Assessment (LCA) and Input-Output Analysis (IOA) are the two most important consumption-based accounting methods. In the study of large-scale systems, such as economy, consumption-based accounting method has been well established based on the input-output model on multiple scales (e.g., Peters, 2008; Peters et al., 2011; Wu et al., 2018; Zhang et al., 2018b), though some authors proposed other allocation methods based on a consumer perspective (e.g., Caro et al., 2014a, 2014b; Gao et al., 2014; Wiedmann and Lenzen, 2018). To reflect the spatial separation of production and consumption among different nations and regions, global multi-region input-output (MRIO) models have been developed. Based on sectoral monetary transactions and emission satellite data, environmental-extended input-output analysis (EEIOA), recognized as the most widely accepted method in research for attributing GHG emissions to final demand in a consistent accounting framework, has been widely used to construct consumption-based emission inventories at the national level (e.g., Hertwich and Peters, 2009; Peters, 2010; Ali, 2017; Andreoni and Galmarini, 2016; Fan et al., 2016; Kanemoto et al., 2016; Deng and Xu, 2017). Environmental emissions embodied in international trade attract overwhelming attention due to the critical role of international trade in shifting environmental burdens across countries (Lenzen et al., 2012b, 2013a; Steen-Olsen et al., 2012; Kanemoto et al., 2014; Liang et al., 2015; Lin et al., 2016; Meng et al., 2016, 2018; Moran and Kanemoto, 2016; Oita et al., 2016; Jiang and Green, 2017; Zhang et al., 2017; Han et al., 2018).

Previous studies have extensively explored global CO_2 emission transfers along with the expanding international trade (e.g., Peters and Hertwich, 2008; Hertwich and Peters, 2009; Peters et al., 2011; Tian et al., 2015; Malik et al., 2016; Jiang and Guan, 2017; Pablo-Romero and Sánchez-Braza, 2017; Wiedmann and Lenzen, 2018), but researches on CH_4 and N_2O emission transfers are still in its infancy (e.g. Jiang and Green, 2017; Han et al., 2019). Kanemoto et al. (2016) quantified the carbon footprint of nations in 2008 with limited CH_4 and N_2O inventory data, and addressed the importance of consumption-based accounting of non-CO_2 GHG emissions in climate policy making. Zhang and his colleagues (Zhang and Chen, 2010; Zhang et al., 2016, Zhang et al., 2018a; Ma et al., 2018) applied a regional perspective to investigate CH_4 emissions induced by China's international and interregional trades. On the global scale, Zhang et al., 2018b undertook the consumption-based accounting of global anthropogenic CH_4 emissions based on the EDGAR4.3.2 emission database. The importance of non-CO_2 GHGs such as CH_4 in the embodiment analysis of trade-related GHG emissions in the global context has been noticed. Nevertheless, there are several questions to be further investigated: What's the difference between production- and consumption-based CH_4 and N_2O emission inventories of major economies or groups of countries? To what extent does the final demand category contribute to global CH_4 and N_2O emission footprints? What is the general pattern of embodied CH_4 and N_2O emission transfers through international trade?

The Kyoto Protocol's first round commitments are the first detailed step taken within the UN Framework Convention on Climate Change, in which the targets apply to all the six GHGs covering CH_4 and N_2O. According to the treaty, Annex I Parties must have fulfilled their obligations of greenhouse gas emissions limitations established for the Kyoto Protocol's first commitment period. For most state parties, 1990 is the assigned base year for their national GHG emission account. The Kyoto Protocol's first commitment period expired on 31 December 2012. Though the emissions limitation commitments listed in Annex B of the Protocol have been explored in the literature, less attention is paid to the comparison of non-CO_2 GHG inventories between 1990 and 2012 from the consumption perspective.

To fill this gap, the aim of this study is to quantify CH_4 and N_2O footprints of major economies and groups of regions by linking on-site emissions to their final receptors. As reliable inventory information serves as the basis for performing the environmental-extended input-output modeling, the latest available national emission accounts from the UNFCCC database and the MRIO tables from the EORA database are adopted. The spatial distribution and structure of global CH_4 and N_2O footprints in 2012 are analyzed. The impacts of international trade on regional CH_4 and N_2O emission requirements are elucidated. The changes of total emission inventories of some Annex I Parties and representative developing economies between 1990 and 2012 in terms of different accounting principles are discussed. Corresponding implications for emission mitigation of non-CO_2 GHGs are addressed.

2. Methods and data

2.1. EEIOA model

Environmental-extended input-output analysis (EEIOA) is a well-established method for consumption-based emission accounting (Peters and Hertwich, 2008; Arto and Dietzenbacher, 2014; Liddle, 2018). The Eora database provides time-series high-resolution IO tables from 1990 to 2015 for 189 economies with 26 industrial sectors (Lenzen et al., 2012a, 2013b). Since the EORA MRIO table covers the most regions and the longest timespan as compared to other MRIO databases such as WIOD (Arto and Dietzenbacher, 2014; Jiang and Guan, 2017), GTAP (Davis and Caldeira, 2010; Meng et al., 2018) and EXIOPOL (Moran and Wood, 2014; Wood et al., 2018), a large number of studies have examined resource and environmental footprints of nations based on the Eora MRIO models (e.g., Wiedmann et al., 2013; Chen and Han, 2015; Arto et al., 2016; Chen and Wu, 2017; Li et al., 2017; Chen et al., 2018a, 2018b; Xia et al., 2017; Wu and Chen, 2017, 2018; Wu et al., 2018). In this study, the initial MRIO tables are also adopted from the EORA database. Detailed regional and sectoral information for the EEIOA analysis is shown in Tables S1 and S2 in the supplementary materials.

The total balance of MRIO model can be expressed in matrix form as:

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

$$\begin{pmatrix} x_1 \\ \vdots \\ x_u \\ \vdots \\ x_V \end{pmatrix} = \begin{pmatrix} a_{1a} & \cdots & a_{1s} & \cdots & a_{1V} \\ \vdots & \ddots & \vdots & \iddots & \vdots \\ a_{u1} & \cdots & a_{us} & \cdots & a_{uV} \\ \vdots & \iddots & \vdots & \ddots & \vdots \\ a_{V1} & \cdots & a_{Vs} & \cdots & a_{VV} \end{pmatrix} \begin{pmatrix} x_1 \\ \vdots \\ x_u \\ \vdots \\ x_V \end{pmatrix} + \sum_{u=1}^{V} \begin{pmatrix} y_{1u} \\ \vdots \\ y_{su} \\ \vdots \\ y_{Vu} \end{pmatrix} \tag{2}$$

where x_u is the column vector of the total output of region u ($u = 1, \ldots, V$); A_{us} is the inter-industrial matrix between region u and region s, where the elements are measurement of per unit output; and y_{su} is the vector of final demand required by region u provided by region s, while the elements include household final consumption, non-profit institutions serving households, government final consumption, gross fixed capital formation, changes in inventories and acquisitions less disposals of valuables.

Equation (1) can be further expressed under the MRIO framework:

$$X = (I - A)^{-1}Y = LY \tag{3}$$

where $L = (I - A)^{-1}$ is the Leontief inverse matrix which captures the total economic inputs to satisfy one unit of final demand in monetary value.

By means of EEIOA method stamped by demand-pull principle, the non-CO_2 GHG emissions can be assigned to final users. Here we take the dimensions of multiple-regions as an example to illustrate the IO model and obtain the embodied emission matrix C, as expressed below:

$$\begin{pmatrix} C_{1a} \cdots C_{1s} \cdots C_{1V} \\ \vdots \ \ddots \ \vdots \ \iddots \ \vdots \\ C_{u1} \cdots C_{us} \cdots C_{uV} \\ \vdots \ \iddots \ \vdots \ \ddots \ \vdots \\ C_{V1} \cdots C_{Vs} \cdots C_{VV} \end{pmatrix} = \begin{pmatrix} E_1 & 0 & \cdots & \cdots & 0 \\ \vdots & \ddots & \vdots & \vdots & \vdots \\ 0 & \cdots & E_u & \cdots & 0 \\ \vdots & \cdots & \cdots & \ddots & \vdots \\ 0 & \cdots & \cdots & 0 & E_V \end{pmatrix} \begin{pmatrix} L_{1a} \cdots L_{1s} \cdots L_{1V} \\ \vdots \ \ddots \ \vdots \ \iddots \ \vdots \\ L_{u1} \cdots L_{us} \cdots L_{uV} \\ \vdots \ \iddots \ \vdots \ \ddots \ \vdots \\ L_{V1} \cdots L_{Vs} \cdots L_{VV} \end{pmatrix} \begin{pmatrix} y_{1a} \cdots y_{1s} \cdots y_{1V} \\ \vdots \ \ddots \ \vdots \ \iddots \ \vdots \\ y_{u1} \cdots y_{us} \cdots y_{uV} \\ \vdots \ \iddots \ \vdots \ \ddots \ \vdots \\ y_{V1} \cdots y_{Vs} \cdots y_{VV} \end{pmatrix} \quad (4)$$

where C_{us} refers to the emissions of region u that are embodied in the final consumption of region s, which is the embodied emission export of region u to region s; E_u is the direct emission intensity, which means the emissions induced by per output of industries in region u.

Two key indicators could help evaluate the impact of international trade on regional non-CO_2 GHG emissions. The total exported emissions from region u are the sum of the amount of production-based emissions of regions u which are allocated to the final consumption of all other regions in the global supply chain, as derived in Eq. (5):

$$C_u^e = \sum_{s \neq u}^{V} C_{us} \quad (5)$$

where C_u^e represents the total emissions of region u as embodied in the final consumption of all other regions, which is the export of embodied emissions of region u.

The total imported emissions into region u are represented by the sum of emissions from all other regions in the global supply chain, as indicated by Eq. (6):

$$C_u^i = \sum_{s \neq u}^{V} C_{su} \quad (6)$$

where C_u^i indicates that the induced emissions in all other regions that are driven by the final consumption of the region u.

The emission embodied in international trade balance (CETB) of region u, denoted as C_u^{net}, is defined as below:

$$C_u^{net} = C_u^e - C_u^i \quad (7)$$

A positive CETB indicates that the amount of emissions produced by region u to meet other regions' consumption is larger than that in other regions induced by the final consumption of region u. A positive value of the CETB means that a region's production-based emissions are larger than its consumption-based emissions (or emission footprints).

2.2. Data sources and preparation

Estimations of CH_4 and N_2O emissions are more uncertain than CO_2, with fewer global estimates. The uncertainties of EEIOA can also be largely affected by the accuracy of territory-based emission estimates (Lenzen et al., 2010). To build authorized CH_4 and N_2O emission inventories, we firstly resort to the satellite accounts provided in the UNFCCC database (UNFCCC, 2019). All the official GHG emission data for the Annex I Parties in the Kyoto Protocol are available from this database covering various kinds of gases and different emission sources. In addition, some non-Annex I Parties have officially released their national GHG inventories by source for a few years. For instance, China as the world's largest GHG emitter unveiled the latest officially released inventory for the year of 2012. Many non-Annex I Parties, however, haven't submitted their national emission inventories in recent years to the UNFCCC. A well-developed global bottom-up GHG budget in the EDGAR database can be used as a supplement, which have been widely adopted to support existing researches on environment and climate. The EDGAR4.3.2 database provides complete national CH_4 and N_2O emission inventories as categorized by different sources during 1970–2012, which are derived from highly disaggregated country-level emission sources. Therefore, hybrid CH_4 and N_2O emission inventories for the year of 1990 and 2012 from the UNFCCC and EDGAR databases are adopted. Detailed description of emission data preparation can be referred to Table S3.

To perform the MRIO modeling, the first step is to extract the direct emission data that are related to economic activities and to reallocate the emissions to economic sectors in the revised MRIO tables covering 181 economies. To be consistent with the reliable emission data, this study only focuses on the world economy in 1990 and 2012. Source-level emissions for each economy are allocated to the corresponding economic sectors covered in the global MRIO table, supported by IPCC emission source definitions and descriptions of economic sectors (see Table S1). Fugitive CH_4 emissions occurring during the transmission of fuels over pipelines are associated with fuel input levels. Several minor emission sources such as fuel combustion emissions of some service sectors are not taken into consideration. The CH_4 and N_2O emissions are measured in tons of CO_2-equivalents based on their respective global warming potentials (GWP) of 25 and 298 over 100-year horizon.

Along with the process of regionalization and globalization, major developed countries and developing economies can be covered in a more comprehensive way. All the nations and regions covered in this study can be further divided into 20 world regions or groups of regions, i.e., Asia Stan, Australia, Brazil, Canada, Central America, Mainland China, India, Japan, Middle East, North Africa, Other East Asia, Other

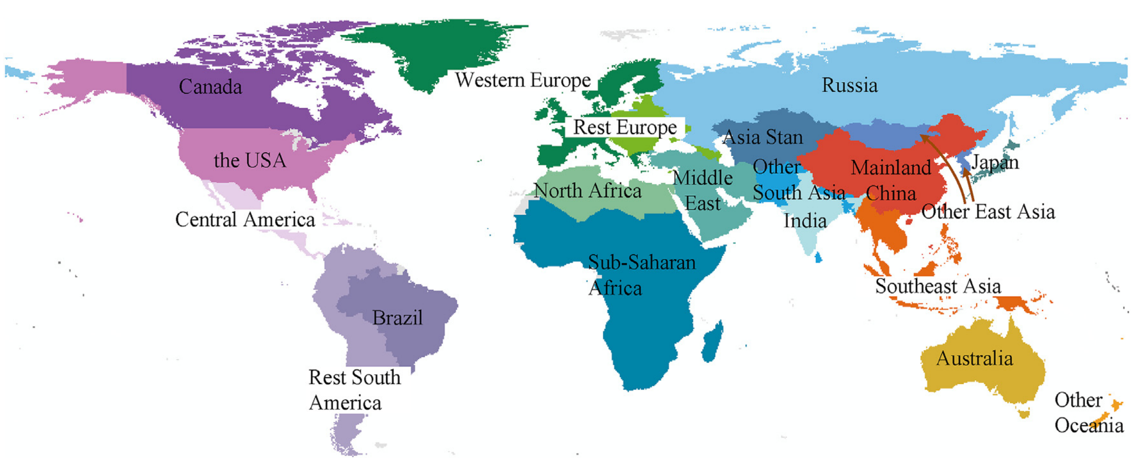

Fig. 1. Geographical distribution of the 20 world regions.

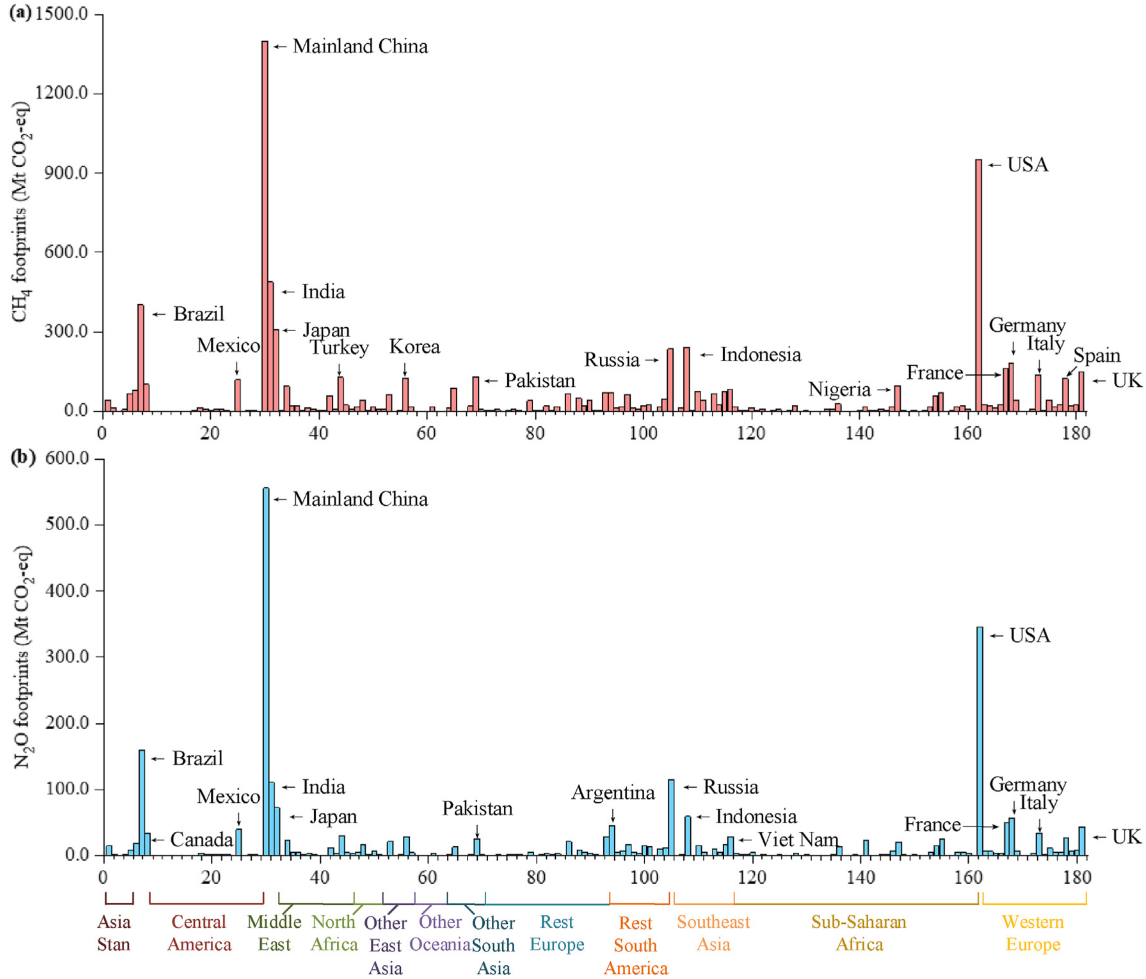

Fig. 2. Total (a) CH_4 footprints and (b) N_2O footprints of the 181 economies in 2012.

Oceania, Other South Asia, Rest Europe, Rest South America, Russia, Southeast Asia, Sub-Saharan Africa, the USA, and Western Europe, as shown in Fig. 1. The data for population and gross domestic product (GDP) are adopted from the World Bank (2017). The unit of GDP data is constant 2010 US$. Detailed regional information is listed in Tables S1 and S4.

3. Results

3.1. Total CH_4 and N_2O footprints

Fig. 2 shows the CH_4 and N_2O footprints of 181 economies. In 2012, global CH_4 emissions reached 8127.5 Mt CO_2-eq. Mainland China had the largest CH_4 footprint of 1399.3 Mt CO_2-eq, accounting for about one-fifth of the global total. Western Europe ranked the second, with the CH_4 footprint reaching 1021.5 Mt CO_2-eq, followed by the USA (951.2 Mt CO_2-eq), Southeast Asia (631.5 Mt CO_2-eq) and Sub-Saharan Africa (511.9 Mt CO_2-eq). These five world regions accounted for 55.6% of the global total. Global N_2O emissions reached 2531.2 Mt CO_2-eq in 2012. Mainland China had the largest N_2O footprint (555.7 Mt CO_2-eq) sharing about one-fifth of global N_2O emissions. The USA ranked the second, with the N_2O footprint amounting to 345.5 Mt CO_2-eq, followed by Western Europe (279.2 Mt CO_2-eq), Brazil (159.7 Mt CO_2-eq) and Sub-Saharan Africa (157.9 Mt CO_2-eq). The total N_2O footprint of these above-mentioned 5 regions accounted for 59.2% of the global total. In addition, Japan, Russia, Indonesia and some developed countries such as Germany, France and the UK also contributed significantly to the global CH_4 and N_2O footprints.

Fig. 3 further presents the compositions of CH_4 and N_2O footprints of 20 world regions in terms of different final demand categories. Totally, household consumption was the dominant demand category with the CH_4 footprint of 5305.3 Mt CO_2-eq (65.3% of the total), followed by fixed capital formation (1320.6 Mt CO_2-eq, 16.2%) and government consumption (985.8 Mt CO_2-eq, 12.1%). Meanwhile, household consumption, fixed capital formation and government consumption contributed 1921.4 Mt CO_2-eq of N_2O footprints (75.9% of the global total), 298.7 Mt CO_2-eq (11.8%) and 160.5 Mt CO_2-eq (6.3%), respectively. Obviously, household consumption was the dominant contributor, whose induced emissions were mainly related with the economic sectors of *Agriculture*, *Food and beverages*, and *Hotels and restaurants*. Particularly, Mainland China had prominent fixed capital formation-driven CH_4 and N_2O emissions, mainly associated with the *Construction* sector.

Fig. 4 shows the compositions of CH_4 and N_2O footprints by emission source. The emission sources of CH_4 are classified into *Agriculture*, *Coal*, *Oil and Gas*, and *Others*, with the total emissions of 3547.4 (43.6% of the total), 1001.9 (12.3%), 1935.9 (23.8%), and 1642.3 (20.2%) Mt CO_2-eq, respectively. Mainland China, India, Western Europe, Southeast Asia, and the USA had prominent *Agriculture*-related CH_4 footprints, respectively 606.6, 359.2, 352.7, 307.2, and 303.5 Mt CO_2-eq, together accounting for 54.4% of the total *Agriculture*-related CH_4 footprints. This category also had the leading share of CH_4 footprints in India (73.5%), Brazil (72.9%), Other South Asia (64.3%), Rest South America (62.3%), and Other Oceania (58.6%).

Meanwhile, in Mainland China, the CH_4 footprints associated with *Coal* reached 477.7 Mt CO_2-eq (34.1% of its total), accounting for 47.7% of the global total *Coal*-related CH_4 footprints. *Coal*-related CH_4

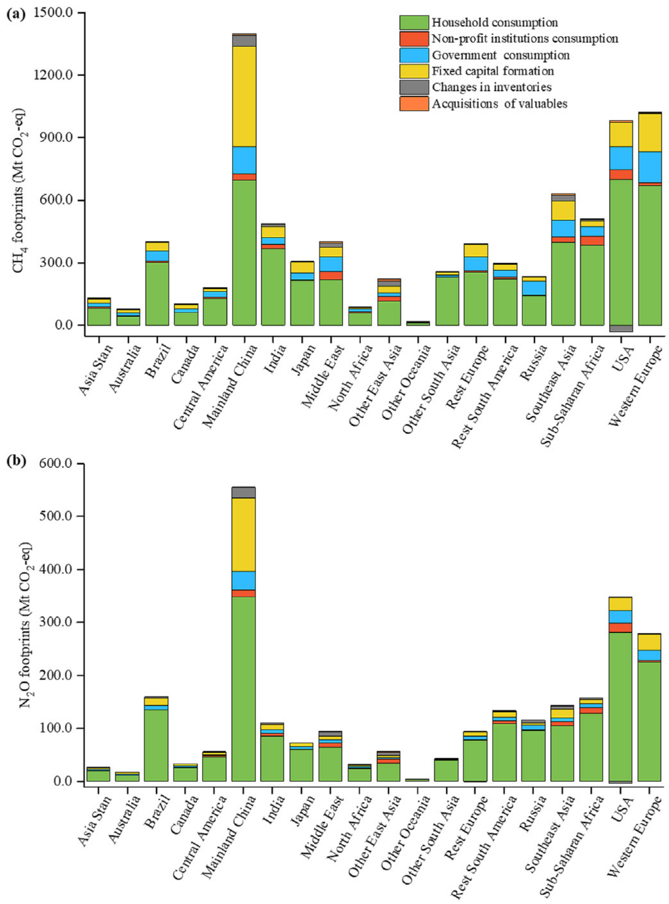

Fig. 3. Compositions of (a) CH_4 footprints and (b) N_2O footprints of the 20 world regions by final demand categories in 2012.

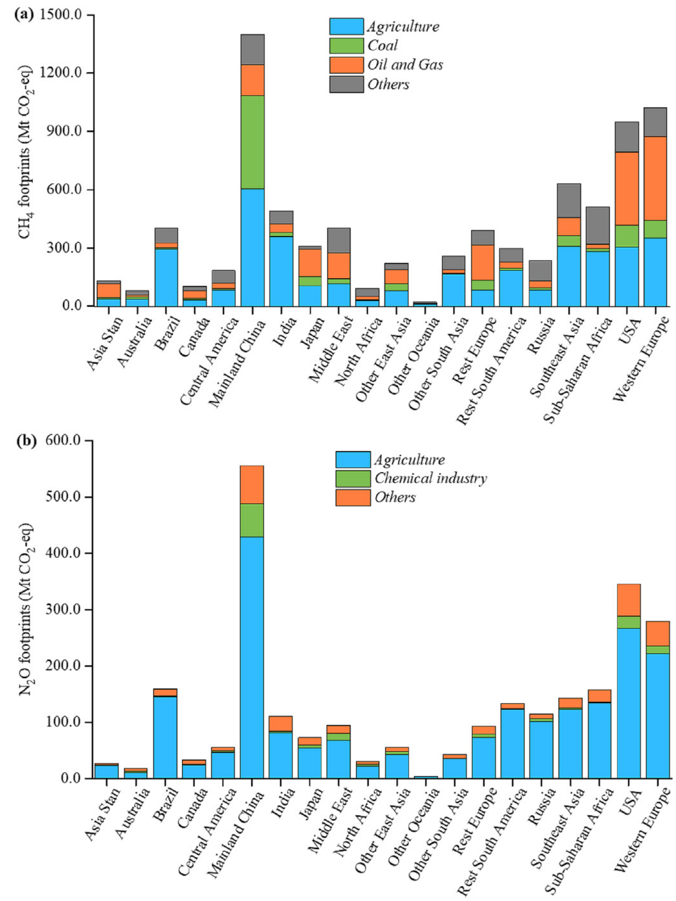

Fig. 4. Compositions of (a) CH_4 footprints and (b) N_2O footprints of the 20 world regions by emission source category in 2012.

also took up a relatively large proportion in the footprints of Other East Asia (17.2%), Japan (15.7%) and Australia (14.5%). In terms of *Oil and Gas*, Western Europe and the USA had prominent CH_4 footprints of 429.4 and 379.3 Mt CO_2-eq respectively, followed by Rest Europe, Mainland China and Japan. The proportions of *Oil and Gas* in the CH_4 footprints of Asia Stan (54.9%), Rest Europe (46.2%), Japan (45.2%), Western Europe (42.0%) and the USA (39.9%) were also significant.

The major sources of N_2O emissions can be divided into *Agriculture*, *Chemical industry* and *Others*, with the emissions of 2033.0 (80.3% of the total), 149.6 (5.9%) and 348.6 (13.8%) Mt CO_2-eq. *Agriculture* had a dominant position in the footprint structure of most regions, especially in Rest South America (91.7%), Brazil (91.2%) and Russia (88.1%). Mainland China, the USA, Western Europe, Brazil and Sub-Saharan Africa had significant *Agriculture*-related N_2O footprints, amounting to 429.2, 266.4, 222.5, 145.6 and 134.3 Mt CO_2-eq, respectively. These five regions together contributed to 58.9% of the total *Agriculture*-related N_2O footprints. Mainland China's embodied *Agriculture*-related N_2O footprints were 1.6 times those of the USA and 5.3 times those of India. In addition, Mainland China, the USA, Western Europe and Middle East had significant N_2O footprints associated with *Chemical industry*, namely 58.5, 22.0, 13.0 and 12.0 Mt CO_2-eq, together accounting for 70.5% of the total N_2O footprints of this sector. *Chemical Industry* also held important shares in the N_2O footprints of North Africa (15.1%), Middle East (12.7%), Australia (11.1%) and Mainland China (10.5%).

3.2. Trade-induced CH_4 and N_2O emission transfers

Fig. 5 depicts the trade of embodied CH_4 and N_2O emissions among 181 world regions in 2012. Total embodied CH_4 and N_2O emissions in international trade (import or export) amounted to 3591.0 Mt CO_2-eq, of which CH_4 were 2962.1 Mt CO_2-eq and N_2O were 628.9 Mt CO_2-eq. Then trade-induced CH_4 emissions were equivalent to 36.4% of the global total, while trade-induced N_2O were 24.8% of the global total.

As for the total trade of embodied CH_4 emissions, Russia (720.6 Mt CO_2-eq) ranked first, followed by the USA, Mainland China, Japan and Germany, with the volumes of 543.0, 532.6, 277.3 and 173.2 Mt CO_2-eq, respectively. In the whole, Western Europe accounted for 26.0% (716.0 Mt CO_2-eq) of the total imports of embodied CH_4 emissions, followed by the USA (415.9 Mt CO_2-eq, 15.1%), Mainland China (286.3 Mt CO_2-eq, 10.4%) and Japan (275.7 Mt CO_2-eq, 10.0%). Some developed countries, such as Germany, France, Italy, the UK and Korea had large embodied CH_4 imports. By contrast, Russia (654.3 Mt CO_2-eq, 23.7% of the global total), Sub-Saharan Africa (347.0 Mt CO_2-eq, 12.6%), Middle East (283.2 Mt CO_2-eq, 10.3%), Mainland China (246.3 Mt CO_2-eq, 8.9%) and Southeast Asia (215.1 Mt CO_2-eq, 7.8%) had large export volumes of embodied CH_4 emissions. For instance, Nigeria, Indonesia, Qatar and Iran had large embodied CH_4 exports.

The top five economies with the largest trade volume of embodied N_2O emissions were the USA (148.4 Mt CO_2-eq), Mainland China (133.9 Mt CO_2-eq), Japan, Germany and France. Western Europe accounted for 23.2% (128.3 Mt CO_2-eq) of the total imports of embodied N_2O emissions, followed by the USA (14.4%, 79.4 Mt CO_2-eq), Japan (9.6%, 53.2 Mt CO_2-eq), Mainland China (8.3%, 46.1 Mt CO_2-eq) and Other East Asia (7.2%, 39.8 Mt CO_2-eq). By contrast, Sub-Saharan Africa (88.8 Mt CO_2-eq, 16.1%), Mainland China (87.8 Mt CO_2-eq, 15.9%), the USA (69.0 Mt CO_2-eq, 12.9%), Rest South America (44.5 Mt CO_2-eq, 8.1%) and Rest Europe (35.5 Mt CO_2-eq, 6.4%) had relatively large exports of embodied N_2O emissions.

Fig. 6 shows the trading flows of embodied CH_4 and N_2O emissions

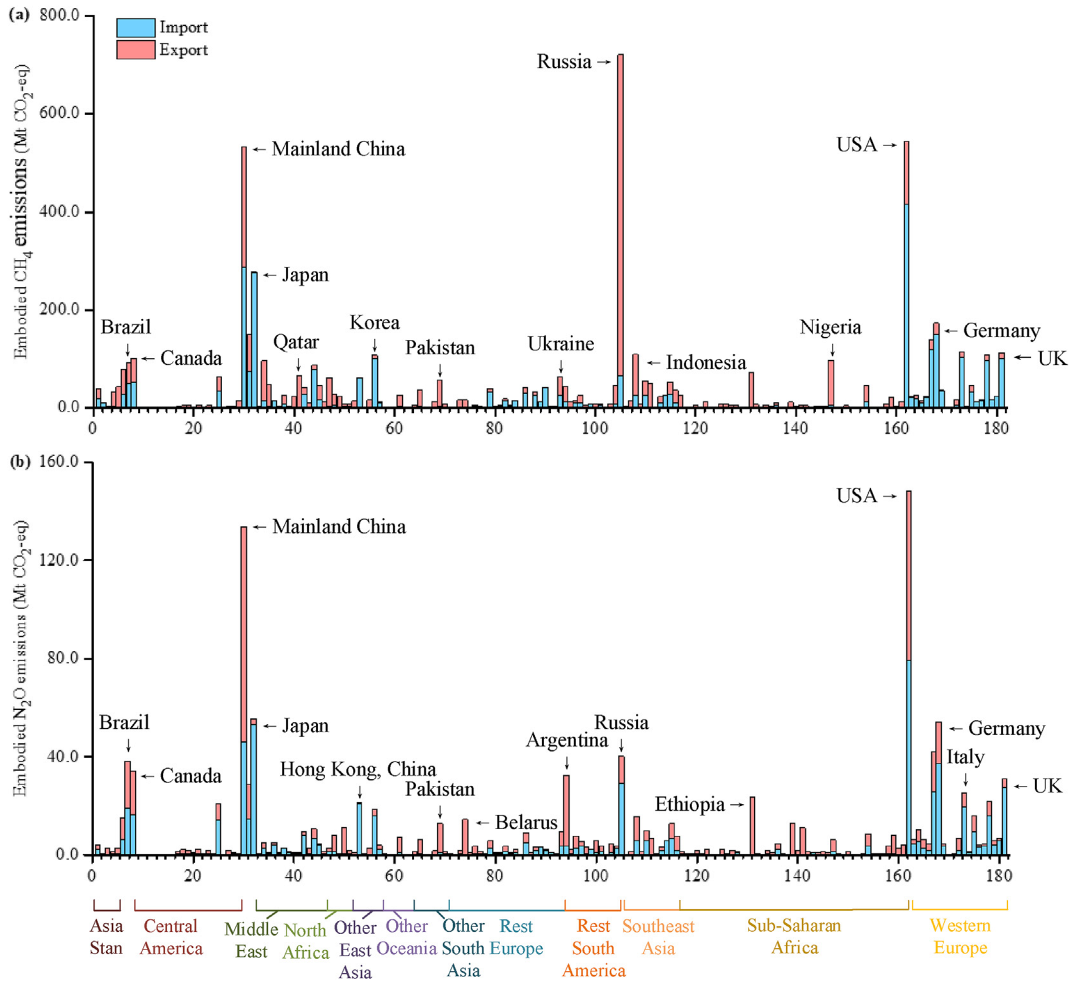

Fig. 5. Embodied (a) CH_4 emissions and (b) N_2O emissions in the international trade of the 181 economies in 2012.

among 20 world regions. As for the CH_4 trading flows (see Fig. 6a), the imported embodied emissions of Western Europe were mainly from Russia (246.6 Mt CO_2-eq), Sub-Saharan Africa (106.5 Mt CO_2-eq), Middle East (65.8 Mt CO_2-eq), North Africa (58.9 Mt CO_2-eq) and Mainland China (48.0 Mt CO_2-eq), together accounting for 73.4% of its total embodied CH_4 imports. The source regions of the USA's imports were mainly Sub-Saharan (61.9 Mt CO_2-eq), Mainland China (50.1 Mt CO_2-eq), Russia (45.0 Mt CO_2-eq), Rest South America (44.3 Mt CO_2-eq) and Middle East (40.5 Mt CO_2-eq), together accounting for 58.1% of its total. Japan had a relatively large imports of CH_4 from Russia, Middle East and Southeast Asia. Embodied emission exports from Russia to Rest Europe were particularly significant, reaching 133.6 Mt CO_2-eq. Important trading flows from Sub-Saharan Africa to the USA and Mainland China, as well as those from Russia to Japan and Middle East, were also identified. In addition to the relatively high exports of embodied CH_4 to Western Europe, Middle East also had high export volumes to Mainland China, Japan and the USA.

As for the N_2O trading flows (see Fig. 6b), Western Europe's imported embodied emissions of N_2O were mainly from Sub-Saharan Africa (31.2 Mt CO_2-eq), while the USA mainly imported from Mainland China (18.3 Mt CO_2-eq), Canada (10.1 Mt CO_2-eq) and Sub-Saharan Africa (9.0 Mt CO_2-eq). Russia had relatively large imports of N_2O from Rest Europe (15.4 Mt CO_2-eq), while Mainland China had relatively large exports of N_2O to Other East Asia (15.9 Mt CO_2-eq) and Japan (12.2 Mt CO_2-eq).

It is noticed that the consumption demands of agricultural and energy products were the dominant contributor of trade-related emission transfer. Fig. 6c further presents the virtual trade of agriculture-related CH_4 and N_2O emissions among 20 world regions. Sub-Saharan Africa had the largest embodied agriculture-related CH_4 and N_2O exports of 253.5 Mt CO_2-eq, followed by Southeast Asia, Other South Asia, Mainland China and the USA, with the export volumes of 128.6, 125.0, 115.9 and 112.9 Mt CO_2-eq, respectively. Sub-Saharan Africa's exports to Western Europe and Japan amounted to 90.1 and 38.6 Mt CO_2-eq, respectively, while Southeast Asia's exports to Mainland China were 46.9 Mt CO_2-eq. Western Europe was the leading importer, with the imports reaching 297.9 Mt CO_2-eq, followed by the USA, Mainland China and Japan, with the imports of 173.3, 139.9 and 128.0 Mt CO_2-eq, respectively.

As to the trade of embodied energy-related CH_4 emissions (see Fig. 6d), Russia was the most important exporting region, with an export volume of 645.4 Mt CO_2-eq. Middle East, Mainland China and Sub-Saharan Africa followed with the exports reaching 270.4, 164.2 and 142.5 Mt CO_2-eq, respectively. Western Europe was the most important importing region, with an import of 500.7 Mt CO_2-eq, followed by the USA, Japan, Mainland China and Rest Europe, with the imports of 289.8, 186.2, 175.6 and 171.8 Mt CO_2-eq, respectively. Russia, Middle East and North Africa had significant exports to Western Europe. As main exporters of oil & natural gas in the world, Middle East's exports to Western Europe, Mainland China, Japan, the USA and Other East Asia were very significant. Russia's exports to Rest Europe were up to 132.4 Mt CO_2-eq, while Mainland China's exports to the USA were 35.6 Mt CO_2-eq. This study also proves that the transfers of embodied GHG emissions of an economy were determined by the international trade network and its industrial position in global supply chains.

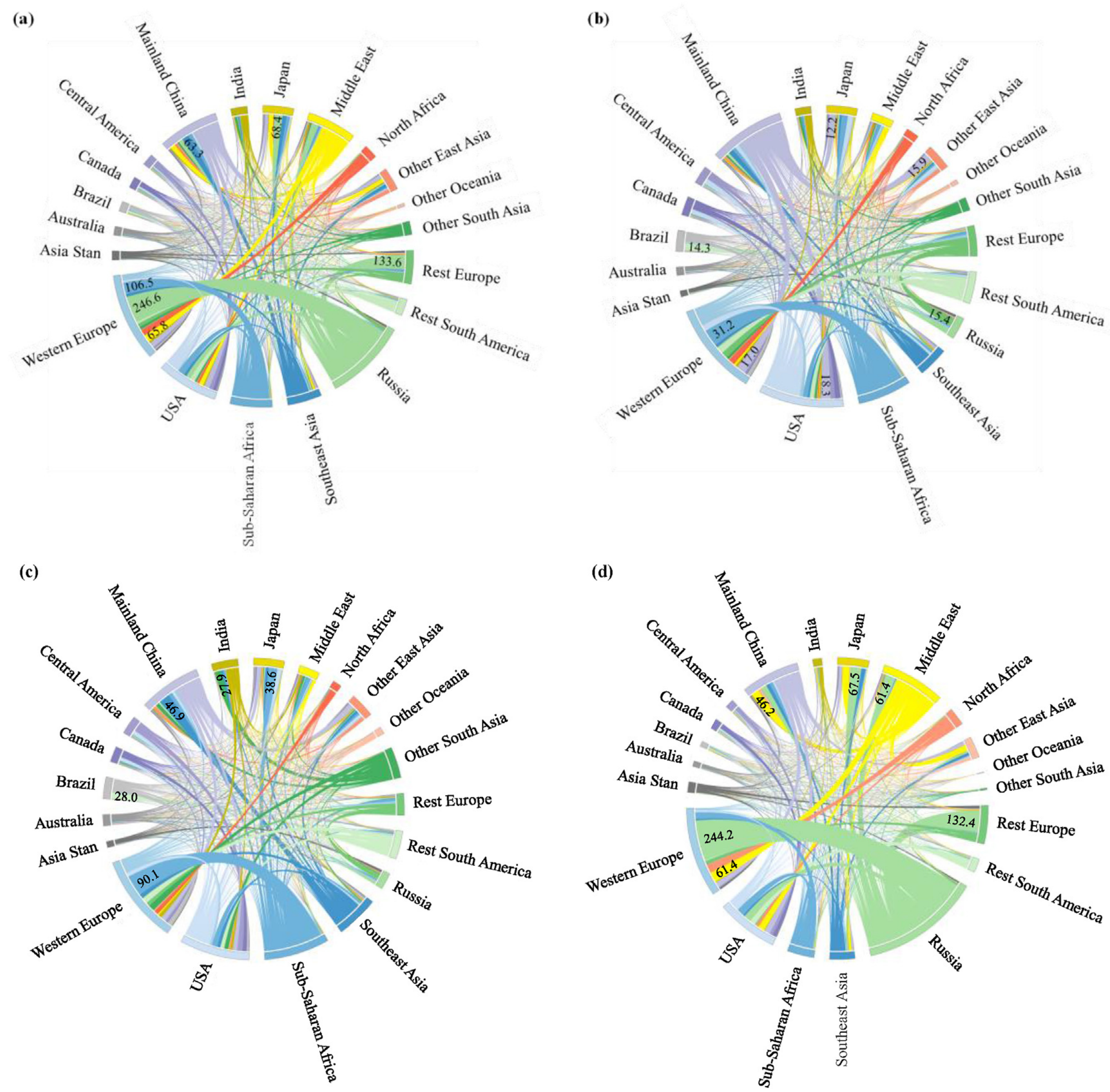

Fig. 6. Trade-induced transfers of embodied emissions among the 20 world regions in 2012: (a) CH_4 emissions; (b) N_2O emissions; (c) agriculture-related CH_4 and N_2O emissions; (d) energy-related CH_4 emissions (Unit: Mt CO_2-eq). *Note*: Energy-related CH_4 emissions cover fugitive CH_4 emissions from *Coal* and *Oil and gas*. The color of the connecting line is consistent with the exporter; the width of the connecting line represents the size of trade volume. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

4. Discussions

Different from production-based emission inventories, consumption-based accountings are more suitable for illustrating actual emission requirements induced by an economy (Peters, 2008; Zhang et al., 2018b). Fig. 7 displays the relationship between per capita GDP and total per capita CH_4 and N_2O emissions of 181 economies by different accounting principles in 2012. Global average per capita non-CO_2 GHG footprint was 1.5 t/cap. Guyana (16.3 t/cap) had the largest consumption-based emissions, followed by Hong Kong (11.8 t/cap), Slovakia (8.7 t/cap), Uruguay (8.1 t/cap), Greenland (7.9 t/cap), Virgin Islands_British (7.0 t/cap), Bermuda (6.9 t/cap), Lithuania (6.4 t/cap), Singapore (6.0 t/cap) and Paraguay (5.6 t/cap), while Qatar (31.5 t/cap) had the largest production-based emissions, followed by Trinidad and Tobago (12.0 t/cap), Brunei (10.5 t/cap), New Zealand (9.9 t/cap) and Uruguay (9.6 t/cap). Developed economies were observed to have higher per capita CH_4 and N_2O footprints than developing economies. Mainland China had high CH_4 and N_2O footprints, but it had relatively low per capita emission footprints. Production-based emissions per capita in representative developing countries were always much greater than their emission footprints per capita. Thereafter, the consumption-based accountings can generate a more accurate picture of CH_4 and N_2O emission inventory of an economy.

Kyoto Protocol is the only international binding treaty on GHG emissions cuts. During the first commitment period, 37 industrialized countries and the European Community committed to reduce GHG emissions to around 5% relative to 1990 levels by 2012. Table 1 shows the changes of total CH_4 and N_2O inventories of some Annex I Parties and representative developing economies between 1990 and 2012 in terms of different accounting principles. Global total CH_4 and N_2O emissions increased by 15.0% in 2012 compared to 1990, from 9267.5 Mt CO_2-eq to 10658.7 Mt CO_2-eq. Some nations with Kyoto targets reduced their CH_4 and N_2O emissions significantly between 1990 and 2012, as listed in Table 1. For instance, Russia, the USA, Ukraine, the UK, Germany, France, Romania, Poland and Netherlands witnessed notable decline in the total production-based CH_4 and N_2O emissions over this period. Once the consumption-based emission inventories are taken into account, the generally-believed successes of such countries are challenged. In most Annex I Parties, their CH_4 and N_2O footprints were much higher than their production-based

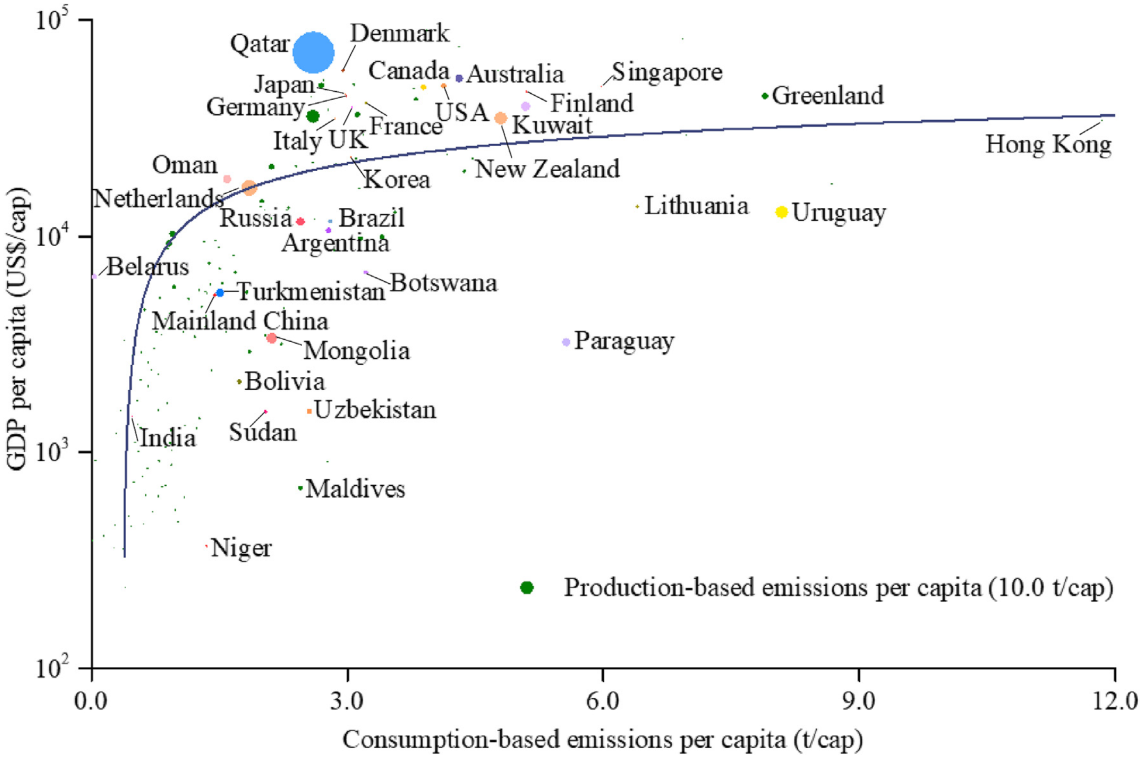

Fig. 7. Relationships among per capita GDP and CH_4 and N_2O footprints of 181 economies in 2012. *Note*: The regions with the largest GDP per capita (Luxembourg, 102404.6 US$/cap) and the smallest (Somalia, 88.3 US$/cap) are removed.

emissions, and the mitigation achievements based on the consumption-based accounting principle were dwarfed by their targets.

In the meantime, both production- and consumption-based CH_4 and N_2O emissions have increased sharply in several large emerging economies. Regarding production-based emissions, Mainland China had an increase of 899.3 Mt CO_2-eq, from 1990 to 2012, followed by Brazil (180.0 Mt CO_2-eq) and India (95.7 Mt CO_2-eq). By contrast, Mainland China had a total footprint increase of 1029.2 Mt CO_2-eq, followed by Brazil (194.9 Mt CO_2-eq), India (106.7 Mt CO_2-eq) and Turkey (63.9 Mt CO_2-eq). Mainland China had the most significant increase of embodied CH_4 and N_2O imports, with an amount of 311.9 Mt CO_2-eq. India and Brazil also had relatively large increases of embodied CH_4 and N_2O imports, with the total volumes of 68.5 and 46.5 Mt CO_2-eq, respectively. Therefore, many developed countries listed in Annex I Parties and representative large emerging economies have outsourced their CH_4 and N_2O emissions to other countries.

The CH_4 and N_2O footprints of a nation or region can be explained by its resource endowment, industrial structures, household consumption levels and economic development modes. After addressing the effect of consumption patterns on CH_4 and N_2O emissions and the impact of trade on global emissions, CH_4 and N_2O footprint accountings provide new insights on where to focus policy responses to reduce global anthropogenic non-CO_2 GHG emissions. The consumers and importers of embodied CH_4 and N_2O emissions could reduce the extravagant consumption of their residents, accept responsibility for the embodied emissions of imported goods and services, and contribute to mitigation efforts in foreign countries. The producers and exporters of embodied CH_4 and N_2O emissions could strengthen emission reductions associated with the production within their territories, attach great importance to the trade-off between economic benefits and environmental impacts caused by their exports, and optimize trade structures. For instance, the trades of agricultural and energy products not only redistribute production-based emissions among the economies, but also may increase global total emissions by considering the backwardness of production technology in developing countries. Further CH_4 and N_2O emissions reductions call for international cooperation to increase mitigation options, encourage environmental comparative advantages, address environmental concerns and speed up technology diffusion. Examining emission drivers and responsibility mechanism based on national CH_4 and N_2O footprints provide multi-gas strategies including reduction targets and action plans.

It is worthy of noting that consumption-based accountings contain different levels of uncertainty. The selection of CH_4 and N_2O emission inventory data would affect the accuracy of consumption-based accounting, especially for some developing and emerging countries with limited official national GHG inventories. A recent study by Zhang et al., 2018b reported that trade-induced CH_4 emissions accounted for about half of global anthropogenic CH_4 emissions in 2012 by separating international trade into intermediate trade and final trade. Their consumption-based accounting was performed based on the CH_4 emission inventories directly adopted from the EDGAR database, resulting in large uncertainties. Table S5 lists the results of consumption-based CH_4 inventories of economies in this study and Zhang et al., 2018b to make a comparison. For instance, the CH_4 footprints of India, Mainland China and Brazil in Zhang et al., 2018b were 771.6, 1624.1 and 481.1 Mt CO_2-eq, much higher than corresponding results of 489.0, 1399.3 and 402.1 Mt CO_2-eq in this study. To improve the performance of global MRIO modeling, more efforts in the future are required to compile reliable time-series inventories of CH_4 and N_2O emissions at the national and regional levels. In addition, the EEIOA method may introduce inaccuracy into the footprint analysis in consideration of the reliability and uncertainty of the Eora MRIO table, though the sensitivity analysis resulted from the bilateral trade statistics and the treatment of MRIO tables is not within the scope of the present paper. Even considering such uncertainties in data, models or methods, the results of this study may offer fundamental information to the knowledge and understanding of global CH_4 and N_2O footprints.

Table 1
Changes of total CH_4 and N_2O emission inventories of 41 Annex I Parties and 3 representative emerging economies between 1990 and 2012 (Mt CO_2-eq).

Economies	Total CH_4 and N_2O emissions		Embodied CH_4 and N_2O emissions	
	Production-based	Consumption-based	Imports	Exports
Australia	−10.3 (−7.6%)	−17.8 (−15.3%)	12.2	19.7
Austria	−4.3 (−29.5%)	−1.9 (−5.8%)	2.7	0.3
Belarus	−4.3 (−12.2%)	0.2 (362.3%)	0.1	−4.4
Belgium	−7.6 (−34.2%)	−7.5 (−20.7%)	−2.3	−2.5
Bulgaria	−13.6 (−53.9%)	−9.5 (−46.5%)	0.2	−3.9
Canada	4.1 (3.2%)	−0.8 (−0.6%)	15.4	20.3
Croatia	−1.0 (−14.5%)	−1.1 (−11.2%)	−0.1	0.0
Cyprus	0.2 (22.5%)	0.8 (40.4%)	0.6	0.0
Czech Republic	−13.1 (−39.5%)	8.5 (22.7%)	13.3	−8.3
Denmark	−3.4 (−21.7%)	−3.3 (−16.7%)	0.3	0.2
Estonia	−1.4 (−40.9%)	−3.8 (−47.5%)	−2.3	0.0
Finland	−4.4 (−31.3%)	−23.5 (−46.0%)	−18.3	0.8
France	−36.1 (−26.4%)	−83.2 (−28.3%)	−51.1	−3.9
Germany	−90.2 (−48.8%)	−116.8 (−32.7%)	−30.7	−4.1
Greece	−2.9 (−15.8%)	−0.8 (−1.6%)	3.3	1.2
Hungary	−8.1 (−40.4%)	−0.5 (−2.3%)	6.1	−1.4
Iceland	0.0 (−2.1%)	0.1 (10.0%)	0.2	0.1
Ireland	−4.0 (−17.9%)	−1.2 (−8.9%)	4.5	1.6
Italy	−9.8 (−13.2%)	−37.0 (−17.9%)	−24.5	2.7
Japan	−21.6 (−28.4%)	−36.1 (−8.7%)	−14.9	−0.4
Kazakhstan	−13.8 (−19.2%)	−22.0 (−27.8%)	8.2	16.3
Latvia	−3.0 (−45.3%)	−7.9 (−52.2%)	−5.2	−0.3
Lithuania	−5.6 (−45.4%)	−20.2 (−51.3%)	−14.5	0.1
Luxembourg	−0.1 (−6.1%)	1.8 (51.5%)	2.0	0.1
Malta	0.1 (32.2%)	0.2 (19.5%)	0.1	0.0
Netherlands	−23.2 (−46.6%)	−2.5 (−4.7%)	10.6	−10.0
New Zealand	4.0 (10.2%)	−2.4 (−10.3%)	1.3	7.7
Norway	−2.3 (−22.5%)	1.2 (6.6%)	2.9	−0.6
Poland	−25.0 (−27.4%)	15.0 (20.5%)	27.7	−12.3
Portugal	0.3 (2.3%)	−2.9 (−8.7%)	−2.9	0.3
Romania	−35.5 (−48.8%)	−20.5 (−26.4%)	10.9	−4.0
Russia	−185.3 (−16.8%)	−152.8 (−30.3%)	7.8	−24.7
Slovakia	−5.4 (−46.4%)	−48.5 (−50.8%)	−43.2	−0.1
Slovenia	−0.4 (−12.5%)	−0.7 (−10.5%)	−0.2	0.1
Spain	1.1 (2.2%)	1.6 (1.1%)	2.7	2.2
Sweden	−3.8 (−28.6%)	−2.8 (−9.8%)	0.7	−0.3
Switzerland	−1.4 (−15.7%)	1.6 (5.0%)	3.1	0.1
Turkey	22.0 (34.6%)	63.9 (68.3%)	45.2	3.3
Ukraine	−128.0 (−53.1%)	−143.7 (−58.6%)	−13.9	1.8
UK	−100.4 (−55.4%)	−46.4 (−19.3%)	31.0	−23.0
USA	−136.1 (−12.0%)	−32.0 (−2.4%)	122.3	18.3
Brazil	180.0 (48.2%)	194.9 (53.1%)	46.5	31.6
Mainland China	899.3 (85.1%)	1029.2 (111.2%)	311.9	182.0
India	95.7 (19.0%)	106.7 (21.6%)	68.5	57.5

Note: Detailed information about CH_4 and N_2O footprints in 1990 and 2012 is listed in Table S4.

5. Concluding remarks

Accounting for national non-CO_2 GHG emissions should not be confined to one country's territory. As important assessment metrics and environmental indicators, CH_4 and N_2O footprints provide important basis for understanding global non-CO_2 GHG emissions from the consumption side. This paper identifies the structure and spatial patterns of global CH_4 and N_2O footprints in 2012 to reflect actual contribution of 181 economies and 20 world regions for driving global non-CO_2 GHG emissions. There are significant regional disparities on CH_4 and N_2O footprints in 2012. Mainland China (1399.3 Mt CO_2-eq), Western Europe (1021.5 Mt CO_2-eq), the USA (951.2 Mt CO_2-eq), Southeast Asia (631.5 Mt CO_2-eq) and Sub-Saharan Africa (511.9 Mt CO_2-eq) together accounted for 55.6% of the global total CH_4 footprints, while Mainland China, the USA, Western Europe (279.2 Mt CO_2-eq), Brazil (159.7 Mt CO_2-eq) and Sub-Saharan Africa (157.9 Mt CO_2-eq) together accounted for 59.2% of the global total N_2O footprints. As to the structure of CH_4 and N_2O footprints, *Agriculture*-related CH_4 and N_2O emissions was the dominant source category for most regions, but the proportions of *Oil and Gas*-related CH_4 emissions were significant in Asia Stan, Rest Europe, Japan, Western Europe and the USA. Household consumption was the most significant one for inducing CH_4 and N_2O emissions in most economies. In some developing countries such as China, capital formation played important roles in their footprint structures.

International trade plays an important role in determining the spatial distribution of global CH_4 and N_2O emissions. The CH_4 and N_2O emissions embodied in international trade were equivalent to 36.4% and 24.8% of the global total in 2012, respectively. In the whole, Western Europe accounted for 25.5% of the total imports of embodied CH_4 and N_2O emissions, followed by the USA (15.0%) and Mainland China (10.1%) and Japan (9.9%). By contrast, Russia (20.1% of the total), Sub-Saharan Africa (13.2%), Mainland China (10.1%) and Middle East (8.9%) had large export volumes of embodied CH_4 and N_2O emissions. The leading net exporters were underdeveloped or developing economies, while the top net importers were all concentrated in developed economies. The trade-induced embodied emission transfers were dominated by energy-related CH_4 and agriculture-related CH_4 and N_2O emissions. For instance, Middle East exported embodied CH_4 emissions through *Oil and Gas*-related trade and imported large amounts of agricultural products and related embodied N_2O emissions through *Agriculture*. The growth of international trade led to the increase of CH_4 and N_2O emission leakage during 1990–2012. Overall, the progress of most developed countries made under the Kyoto Protocol and several large emerging economies over 1990–2012 looks extremely poor from the consumption perspective, owing to the fact that international trade has induced a large amount of CH_4 and N_2O emission transfer. Some large emerging economies such as Mainland China, Brazil, India and Turkey also witnessed rapid growth of CH_4 and N_2O footprints.

Global mitigation of non-CO_2 GHG emissions generate significant opportunity to tackle near-term warming, lower the costs, and achieve long-run climate change stabilization. In an increasingly globalized world, sector-level and production-based non-CO_2 GHG emission mitigation is insufficient. Apart from production-side CH_4 and N_2O reduction focused on some major emission sectors such as agricultural and energy activities, more attention should be paid on consumption-side emission mitigation by considering the impacts and effects of growing final consumption demand and international trade. The formulation of emission reduction strategies from the consumption side will redefine the emission responsibility of each country, which can help policy-making to reduce global CH_4 and N_2O footprints and related emission leakage. A more ambitious step covering both production- and consumption-side emission mitigation from the producers to final consumers could help in reducing atmospheric concentrations of CH_4 and N_2O with beneficial effects on climate change.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2019.109566.

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