Ecological Economics 170 (2020) 106528

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Analysis

The methane footprint of nations: Stylized facts from a global panel dataset☆

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ARTICLE INFO

Keywords:
Methane emissions
MRIO analysis
Production-based inventories
Methane footprints
Decomposition analysis
Emissions embodied in trade

JEL classification:
F18
F64
O44
Q54
Q56

ABSTRACT

We develop a global dataset of methane inventories derived from production, supply use (final production), and consumption activities for 1997–2014, disaggregated to 78 countries/regions. Our dataset extends existing data on methane emissions to 2014 and allows to trace emissions embodied in international trade in intermediates and in final goods. Anthropogenic emissions are quantitatively important for global warming and increased by about 18% from 1997 to 2014. The bulk of produced emissions is attributable to developing economies, though a considerable amount is exported mainly via manufactured goods to high income countries, which are net-importers of methane. Trade-embodied emissions increased by 8% more than nationally produced emissions during 1997–2014, with the strongest increase experienced by China, India, and Indonesia. Decompositions of the growth rate of emissions over this period suggest that methane efficiency improved, but the effect of these efficiency gains on total emissions was outweighed by the effect of economic and population growth in low- and middle-income countries. In high-income countries, by contrast, methane efficiency gains were larger the effect of economic and population growth.

1. Introduction

Methane (CH_4) is one of the most important greenhouse gases (GHGs). Anthropogenic methane emissions are responsible for about 20% of the global radiative forcing of GHGs since pre-industrial times, making it the second largest contributor after Carbon Dioxide (CO_2; EPA, 2012). Methane emissions have a much larger global warming potential (GWP) than CO_2, especially over short time-periods (Myhre et al., 2013), and there is evidence of a strong and mostly coincident effect of atmospheric methane concentrations on global temperature trends (Estrada et al., 2013).

Atmospheric methane concentrations result from a mix of natural and anthropogenic sources, which are characterized by changing trends over time (see Kirschke et al., 2013). Methane concentrations from anthropogenic sources experienced an exponential increase in the late 1970s and sustained growth in the 1980s, followed by a slowdown during the 1990s and a general stabilization from 1999 until 2006. Since 2006, atmospheric methane levels started to rise again (Kirschke et al., 2013). Estrada et al. (2013) suggested that a reduction in methane emissions resulting from the application of chemical fertilizers and more efficient water use in rice production in Asia and the reduction of chlorofluorocarbon (CFC) emissions under the Montreal Protocol (which entered into force in 1989) were the main causes for the deceleration of warming in the mid-1990s.

Despite its importance for global warming, methane has neither been a primary focus of recent economic and political debates on greenhouse gas regulation, nor has it been targeted by major environmental policies. There exist national regulations on methane emissions,

☆ The authors thank specially Douglas Nelson, Dominique van der Mensbrugghe, Bernard Hoekman and the audience of the World Trade Forum 2017 for their valuable comments. The authors also thank the members of the Environmental Economics Group of the University of Bern, of the Galbino Collaborative Workshop 2019, and of the SWSR for their comments. All of the authors acknowledge support from the NRP 73 project Switzerland's Sustainability Footprint: Economic and Legal Challenges, grant No. 407340-172437, University of Bern, supported by the Swiss National Science Foundation (SNSF) within the framework of the National Research Programme "Sustainable Economy: resource-friendly, future-oriented, innovative" (NRP 73).

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https://doi.org/10.1016/j.ecolecon.2019.106528
Received 4 July 2018; Received in revised form 26 September 2019; Accepted 7 November 2019
Available online 27 December 2019

but international cooperation for the reduction of methane is largely lacking. The Kyoto Protocol (adopted in 1997) limited emissions of six GHGs including methane, but its design has been highly criticized. For example, it failed to introduce mechanisms to change the behavior of the countries bound by emission targets (Barret, 2008), and the enforcement of compliance with these targets was problematic (see Aichele and Felbermayr, 2012; Feaver and Durrant, 2008; Hagem et al., 2005; Nentjes and Klaassen, 2004). Furthermore, the binding targets for emission reduction specified in it were small and confined to the Annex I members, providing substantial room for emission leakage.[1]

Signed in 2015, the Paris Agreement includes nationally determined contributions (NDCs) from developed and developing countries. However, unlike the emission targets for Annex I members in the Kyoto Protocol, these national contributions are not legally binding as the signatories are only required to report on their progress to reach their NDCs (Jacquet and Jamieson, 2016). Furthermore, many NDCs are subject to considerable uncertainty and do not include all GHGs or sectors responsible for emissions, as described in Rogelj et al. (2016). For example, the NDC of China does not include non-CO_2 emissions at all (see Gallagher et al., 2019), although it is the largest producer and consumer of CH_4 emissions in our dataset. Related to these issues, Rogelj et al. (2016) concluded that even if all NDCs were implemented, the global median temperature would rise between 2.6 and 3.1 °C until 2100 instead of the "well below 2 °C" target of the Paris Agreement.

In the context of international trade, emission leakage will pose a challenge for environmental regulation if such regulation is not universally adopted. Emission leakage occurs when environmental policies implemented in a subgroup of countries change relative good prices, such that countries that are not subject to binding emission constraints raise their emission-intensive output (see Aichele and Felbermayr, 2015; Copeland and Taylor, 2005). Offshoring and vertical trade specialization—the use of imported intermediates in production—allow circumventing national regulation by outsourcing emission-intensive parts of production processes.

Emission leakage could be avoided by globally coordinated action against climate change, but such coordination is hampered by the difficulty to distribute the burdens to mitigate greenhouse gas emissions across countries (Roser et al., 2015). Yet, rapid action is urgently needed to avoid potential irreversible climate effects (IPCC, 2014, 2018). More developed countries are more likely to implement environmental regulation (Dasgupta et al, 2002) but are often net-importers of emissions (Ahmad and Wyckoff, 2003; Aichele and Felbermayr, 2015; Fernández-Amador et al., 2016; Wood et al., 2018). Consumption-based policy instruments in these countries could account for trade-embodied emissions (see e.g. Peters and Hertwich, 2008b). Thus, in order to minimize the circumvention of national policies in the absence of global agreements, countries implementing climate policies should evaluate the impacts of policy instruments that are closer to the final producer and consumer, additionally to standard production-based instruments. A focus on final production or consumption could also prevent production inefficiencies such as those resulting from taxes on intermediates (Diamond and Mirrlees, 1971; OECD, 2011).

In order to analyze policy options targeted at different stages of the supply chain, it is necessary to have global data on embodied emissions at different stages of the production process. For aggregate GHG emissions and for CO_2, databases covering footprint-based and territorial production inventories have already been developed. Hertwich and Peters (2009), Tukker et al. (2013) and Wood et al. (2015) provide data for consumption-based inventories of aggregate GHG emissions (using 100-year GWP for the aggregation); Peters and Hertwich (2008a,b), Peters et al. (2011a), Wilting and Vringer (2009) and Peters et al. (2011b) provide data for consumption-based CO_2 inventories, and Fernández-Amador et al. (2016) offer data for final-production and consumption based CO_2 inventories. For methane, however, existing panel datasets focus on production-based emissions only (FAOSTAT, 2019; EORA, 2019; UNFCCC, 2019; Rose and Lee, 2008, 2009; Rose et al., 2010; EPA, 2012; Genty et al., 2012; Ahmed et al., 2014; Irfanoglu and van der Mensbrugghe, 2015; Janssens-Maenhout et al., 2019), or provide data with a relatively low disaggregation to countries and sectors. For example, the Industrial Ecology Programme (2019) offers data on methane embodied in consumption for 42 countries/regions and 17 sectors, and EORA (2019) provides consumption-footprints for 190 countries but without sectoral disaggregation. Also, a few earlier studies calculated emissions embodied in international trade to evaluate consumption footprints for specific countries (Subak, 1995; Walsh et al., 2009; Zhang and Chen, 2010). Yet, comprehensive analyses of methane footprints across a large number of countries and sectors have so far been limited by the availability of global comparable panel data. An exception is the recent paper by Zhang et al. (2018), who provide an analysis of emissions embodied in trade, covering 181 regions and 26 economic sectors for the years 2000–2012.

We develop a global panel dataset of national inventories of anthropogenic methane emissions, which extends previous research in several dimensions. Our dataset covers 78 countries and regions comprising the global economy. It provides information on 57 sectors for the years 1997, 2001, 2004, 2007, 2011 and 2014, and uses multi-regional input-output (MRIO) analysis to calculate methane emission inventories (see also Fernández-Amador et al., 2016; Koopman et al., 2014; Peters, 2008; Peters et al., 2011b).[2] The MRIO analysis allows us to extend standard (territorial) production inventories to emissions embodied in final production, for which we trace emissions embodied in intermediate input flows, and to emissions embodied in final consumption, for which we map emissions embodied in trade flows of final goods and services. Thus, it contains information about national (and sectoral) sources of emissions at these three stages of the supply chain, which is especially important in the context of rapidly expanding global production networks and increasing vertical specialization. The analysis of cross-border linkages in production chains and the potential for outsourcing provides valuable information for the design of international environmental agreements and the definition of national policy targets.

Based on these comparable inventories, we identify four main stylized facts regarding anthropogenic methane emissions in 1997–2014. First, anthropogenic CH_4 emissions were equivalent to about 30% or 95% of the global warming potential of CO_2 emissions from fossil fuel combustion, depending on whether a 100-year or a 20-year basis is used to compute the equivalence, and they increased by 18% during 1997–2014. Second, low- and middle-income countries accounted for a big part of anthropogenic methane released. Emissions from this group of countries increased between 1997 and 2014 despite considerable gains in methane efficiency (per unit of value added) and structural change towards less methane-intensive sectors; in contrast, high-income countries reduced per-capita emissions. Third, high-income countries were net-importers of embodied emissions, especially in the manufacturing sector. Finally, the EU 15, the USA, the Middle East, China, the Rest of Sub-Saharan Africa region (defined in Appendix Table A.1), and Russia accounted for more than half of the emissions embodied in trade flows; and China, India, and Indonesia more than doubled their emissions embodied in trade between 1997 and 2014.

The rest of the paper is organized as follows. The next section describes the methodology applied to construct the data for methane production, final production, and consumption inventories. Section 3 provides an overview of the inventories and derives some stylized facts for the period 1997–2014. We conclude in Section 4.

[1] The Annex I countries were originally defined by the United Nations Framework Convention on Climate Change (UNFCCC). The Kyoto Protocol determined emission targets for all Annex I countries but Turkey in its Annex B.

[2] The dataset is available from the authors upon request.

2. Construction of emission inventories

The construction of our emission dataset proceeds in two steps. The first step is to generate national (standard) production-based emission inventories maintaining consistency over time, by mapping methane emissions from several sources to the 57 sectors of the 78 regions covered in our dataset.[3] The second step is to calculate inventories of CH_4 emissions embodied in final production and final consumption activities (i.e. footprint-based emissions) by applying MRIO techniques. As a side product, we obtain two types of bilateral trade flow data: emissions embodied in traded intermediates for final production, and emissions embodied in traded intermediates and final products for final consumption, respectively.

2.1. Production-based emission inventories

In order to create a consistent panel of sectoral methane emissions spanning the years 1997, 2001, 2004, 2007, 2011 and 2014, we modify and extend the methodology developed by the Global Trade Analysis Project (GTAP) to elaborate different cross-sectional methane emissions databases. Methane releases are included in the several versions of the GTAP non-CO_2 Emissions database, which exist for 2001, 2004, 2007 and 2011, disaggregated to 57 economic sectors (see Ahmed et al., 2014; Irfanoglu and van der Mensbrugghe, 2015; Rose et al., 2010; Rose and Lee, 2008, for the details of the methodologies followed to generate the different releases). However, the different releases of methane data from GTAP cannot directly be used in panel-data analyses, since the sources of raw data and/or the methodology for data construction differ across the releases.

The 2001 release of methane data from GTAP was constructed in cooperation between GTAP and the US Environmental Protection Agency (EPA), resulting in a highly disaggregated database of methane and other GHG emissions linked to economic activity (see Rose et al., 2007; Rose and Lee, 2008). This undertaking has not been repeated for the other releases, but the 2001 data was extrapolated to 2004 based on growth rates of detailed GHG emission categories provided by EPA projections, and to 2007 using growth rates based on EDGAR (2011, for non-agricultural activities) and FAOSTAT (2014, for agricultural activities) data. Because no EDGAR data was available to project the 2001 emissions to 2007 for three sectors (mineral production, manufactures n.e.c, and paper products and publishing), an output growth approach was used instead. For the 2011 release, GTAP changed the methodology again: they extrapolated emissions in the EDGAR (2011) categories, which were available until 2010, to 2011, using average growth rate of emissions between 2007–2010, and matched the extrapolated EDGAR data and FAOSTAT (2014) data directly to the 57 sectors (Irfanoglu and van der Mensbrugghe, 2015).

In order to construct our database, we apply a consistent procedure for all years. We directly match emission data from FAOSTAT (2014) and EDGAR (2011) to the 57 sectors included in our dataset, using concordance tables provided by Irfanoglu and van der Mensbrugghe (2015). About 75% of global methane emissions can be directly matched to a single sector. These are all the emissions sourced from FAO and about half of the emissions sourced from EDGAR. The remaining 25% can be mapped to the sectors by using information on the sectoral allocation of emissions provided by the GTAP non-CO_2 Emissions database releases, which report sectoral CH_4 emissions and the activity causing them: output production by industry, endowment usage by industry, input use by industry, and input use by households. Each EDGAR emissions category can be attributed to one of these four activities (see Irfanoglu and van der Mensbrugghe, 2015).[4]

The mapping process is the same for all years, but two adjustments apply to 1997 and 2014. First, for these two years there is no information on the sectoral allocation of emissions, which is needed to match the 25% of emissions that cannot be directly allocated to a single sector. Thus, we extrapolate the sector shares to 1997 and 2014 by applying moving averages on the sector shares for 2001–2011. Second, since EDGAR data are available only until 2012, we estimate emissions in the EDGAR categories for 2014 by using univariate time series models.[5] FAOSTAT data are matched directly to the sectors for every year and no adjustment was required.

This procedure results in a dataset of comparable production-based CH_4 emissions for the years 1997, 2001, 2004, 2007, 2011, and 2014 disaggregated to 57 economic sectors covering emissions from activities of firms and residential emissions from private households. The resulting production-based CH_4 inventories assign emissions to the sector and region in which emissions are released. National production-based emissions can be derived by aggregating across sectors, yielding a balanced panel dataset of 468 observations. They are close to the standard territorial based inventories defined by the IPCC (for details see the discussion in Fernández-Amador et al., 2016), which constitute the standard measure of national emissions relevant for multilateral agreements on emission reduction such as the Kyoto Protocol.[6]

In Appendix F, we offer a detailed comparison of our dataset on production-based methane emissions with the ones of GTAP in the years 2001, 2004, 2007, and 2011. Here, we confine ourselves to a short summary of the results. On the global level, we find substantial differences between the datasets in the year 2011, while on the country level we observe considerable differences in all the years. Such differences are to be expected given the differences in the raw data and methodologies applied. In contrast, in both datasets the allocation of methane emissions to sectors is very similar. These results reinforce our approach to calculate a dataset based on the same raw data and methodology for all the years in our sample, which can be used for panel analyses.

Once emission inventories based on standard production are calculated, we trace emissions embodied in international and inter-sectoral transactions and extend the production-based data with footprint-based CH_4 inventories, which assign emissions that are generated over the whole supply chain to the sector and region in which the final product is produced (final production inventories) or consumed (consumption-based inventories).

[3] An overview of the regions and sectors covered is available in Tables A.1 and A.2 in Appendix A. To derive the inventories, we first aggregated emissions to 78 regions (66 countries and 12 regions) and 57 sectors. After that, we calculated the inventories. Thus, potential aggregation bias can be assumed to be constant over time. The number of regions is constrained by the regional disaggregation of the raw data used, specifically the input-output tables corresponding to the GTAP release for 1997.

[4] When an EDGAR category has to be distributed to several sectors we rely on the sector shares corresponding to the matching activity. For example, emissions from the EDGAR category 1A1 and its sub-categories (combustion by energy industries) originate from input usage, while emissions from EDGAR category 1B2 (oil and gas fugitives) result from output production. Accordingly, emissions from category 1A1 are distributed to sectors using sector shares provided by the data from input usage, while emissions from 1B2 are distributed to sectors using information on output production. An overview on how we matched the emissions categories of FAO and EDGAR to the 57 sectors is given in Table A.3 in Appendix A.

[5] Two reasons underlie our choice of univariate time series methods to forecast emissions. First, these methods perform well when forecasting in the short term. Second, since they only rely on the properties of the series to forecast, the data can be used in further research in which emissions are related to other variables, avoiding problems of circularity. See Appendix B for a detailed description of the estimation methodology used.

[6] On the national level, differences between standard territorial inventories as defined by IPCC and our definition result from the allocation of emissions from the usage of bunker fuels for international shipping and aviation (see also Peters, 2008). These emissions are not distributed across countries in the IPCC national inventories. In contrast, we allocate them to individual countries or regions according to their usage of international shipping services. In 1997–2014, global CH_4 emissions from such activities range between 0.22% (2004) and 0.27% (2014) of world totals. As a result, any difference on the national totals between both definitions is small.

2.2. Footprint-based emission inventories

Footprint-based CH_4 emission inventories are derived using MRIO techniques. The steps are summarized as follows. First, we construct a global intermediate input requirements matrix based on IO and trade data, sourced from GTAP. The global intermediate input requirements matrix collects all the intermediate input requirements for all sectors in all regions. From this matrix, we derive the Leontief-inverse matrix, which collects the direct and indirect input requirements to generate one dollar of output for each sector in each region. Next, we rescale the Leontief-inverse matrix with emission-intensities, which are derived from the standard production emission inventories, calculated as explained in the previous subsection. In order to derive final production- and consumption-based emission inventories for each sector and at the national level, we multiply the rescaled Leontief-inverse matrix with the matrices of final production and consumption, respectively. As a side-product, we also obtain two measures of emissions embodied in bilateral trade flows, namely emissions embodied in intermediates used for final production and emissions embodied in inputs (intermediates and final goods) for final consumption. The derived methane trade flows differ from the traditional definition of trade by taking into account that intermediates may be traded indirectly through third countries via global value chains before reaching the final producer or consumer. Details on each of these steps are provided in Appendix C.

3. Stylized facts from national methane emission inventories

3.1. Global methane emissions and their sources

Methane is the second most important warming agent after CO_2 (Shindell et al., 2017). Despite its relatively short atmospheric life-time of 12.4 years, the global warming potential (GWP) of methane is substantially higher than that of CO_2 (84 times higher over a 20-year period, and 28 times higher over a 100-year period, respectively; see IPCC, 2014). Between 1997 and 2014, anthropogenic methane emissions were equivalent to about a third of CO_2 emissions from fossil fuel combustion when using the conversion factor corresponding to a 100-year period; using the conversion factor corresponding to a 20-year period, however, the relative global warming potential of methane was substantially higher, about 95% of that of CO_2 emissions (see Table 1). Methane emissions increased by 18% during 1997–2014, a much lower increase than the one experienced by CO_2 emissions during the same period (37%).[7]

The sectoral distribution of methane emissions differs considerably between production-based and footprint-based emission inventories (see Fig. 1).[8] Methane emissions embodied in territorial production (upper plot) are concentrated in relatively few economic sectors, which correspond to heterogeneous economic processes such as livestock breeding (35%), drilling and transporting fossil fuels (24%), public administration (21%, which is mainly waste management), and rice cultivation (8%). By contrast, emissions embodied in final production and consumption patterns (lower plot), are spread across sectors more evenly as a result of domestic and international inter-sectoral supply-chain relations. Specifically, as it can be observed in Fig. 2 for flows between broad sectors, much of the methane produced by rice cultivation and livestock breeding passes on to food processing sectors, while emissions from fossil fuel drilling go to industrial activities, services, and transportation.

Table 1
Global CH_4 and CO_2 emissions.

	CH_4 Mt	(CO_2e, 100y) % of CO_2	CH_4 Mt	(CO_2e, 20y) % of CO_2	CO_2 Mt
1997	7,982	35%	23,947	105%	22,702
2001	7,880	34%	23,641	103%	23,054
2004	8,312	32%	24,935	95%	26,359
2007	8,731	30%	26,193	91%	28,652
2011	9,229	30%	27,686	90%	30,930
2014	9,428	30%	28,283	91%	31,011

Note: CO_2e, 100y and CO_2e, 20y stand for CO_2 equivalents based on a global warming potential over 100 and 20 years, using the conversion factors of 28 and 84, respectively (IPCC, 2014). CO_2 data are available from Fernández-Amador et al. (2016). These data were recently updated by the authors to include 2014.

The sectoral heterogeneity in terms of methane emissions and the choice of a specific time-period to compute CO_2 equivalents, which are the prevalent GHG indicator in environmental agreements, have important implications on overall GHG emission budgets across countries and economic sectors, as exemplified in Fig. 3. The figure shows the percentage change in national emission budgets (based on production) when GWPs over 20 years (GWP_{20}) are used to compute CO_2 equivalents of methane and CO_2 emissions instead of GWPs over 100 years (GWP_{100}). The focus on a shorter time-period substantially raises the contribution of agriculture, livestock, and waste sectors to overall emissions and leads to a particularly pronounced increase in the emission budgets of some countries, especially in Africa, Latin America, and Asia (see also Fesenfeld et al., 2018). Because these changes can affect national and international climate policy negotiations and imply trade-offs between different mitigation options, it has been suggested to simultaneously report CO_2 equivalents based on GWPs over alternative time periods; this would allow to spot countries and sectors with a particularly high potential to mitigate shorter-lived GHGs such as methane (Fesenfeld et al., 2018; Fuglestvedt et al., 2003; IPCC, 1995).

Apart from the choice of the time-period to compute CO_2 equivalents, aggregate GHG emission budgets may be affected by the choice of the conversion metric to compute the equivalents (see Myhre et al., 2013). An example for an alternative conversion metric to the GWP is the Global Temperature change Potential (GTP). GTPs reflect the temperature effects of emissions at a chosen point in time and are thus more closely related to climate impacts than GWPs. Nevertheless, GTPs are connected to larger uncertainty than GWPs, because they are based on assumptions about climate sensitivity and heat uptake by the ocean (Myhre et al., 2013), and GWPs are the most commonly used conversion metric to calculate CO_2 equivalents. Thus, we report methane emissions as CO_2 equivalents based on GWP.

3.2. National methane emissions

A first picture of the responsibility for global methane emissions can be obtained from the analysis of three indicators calculated from the emission inventories: (i) total CH_4 emissions, (ii) CH_4 emissions per capita, and (iii) CH_4 emissions per unit of value added, as a measure of methane efficiency.[9] Table 2 provides a summary of these three

[7] Since the focus of this study is on methane emissions, our findings are not affected by the use of a specific conversion factor. In what follows, we report methane emissions as CO_2 equivalents based on 100-year GWP, because this is the most widely used metric in international environmental agreements. The choice of the conversion factor does not affect our conclusions, only the comparison with other GHGs.

[8] For the sectoral analyses throughout the paper, we aggregated the 57 sectors in our dataset to seven broader sectors: agriculture, livestock, energy, manufacturing, services, transport, and public-administration. A detailed definition of these sectors is available in Table A.2 in Appendix A. Table A.4 in Appendix A provides details on sector shares of global methane emissions and their evolution over time.

[9] Pollution intensity (efficiency) is often measured as pollution per GDP. We measure it in terms of value added produced, finally produced, or consumed to better align the definition of the economic aggregate and the inventory of reference. All the monetary indicators used throughout this text are in constant 1997 prices. In order to stay consistent with consumption-based inventories, we derive constant value added embodied in final consumption by means of the

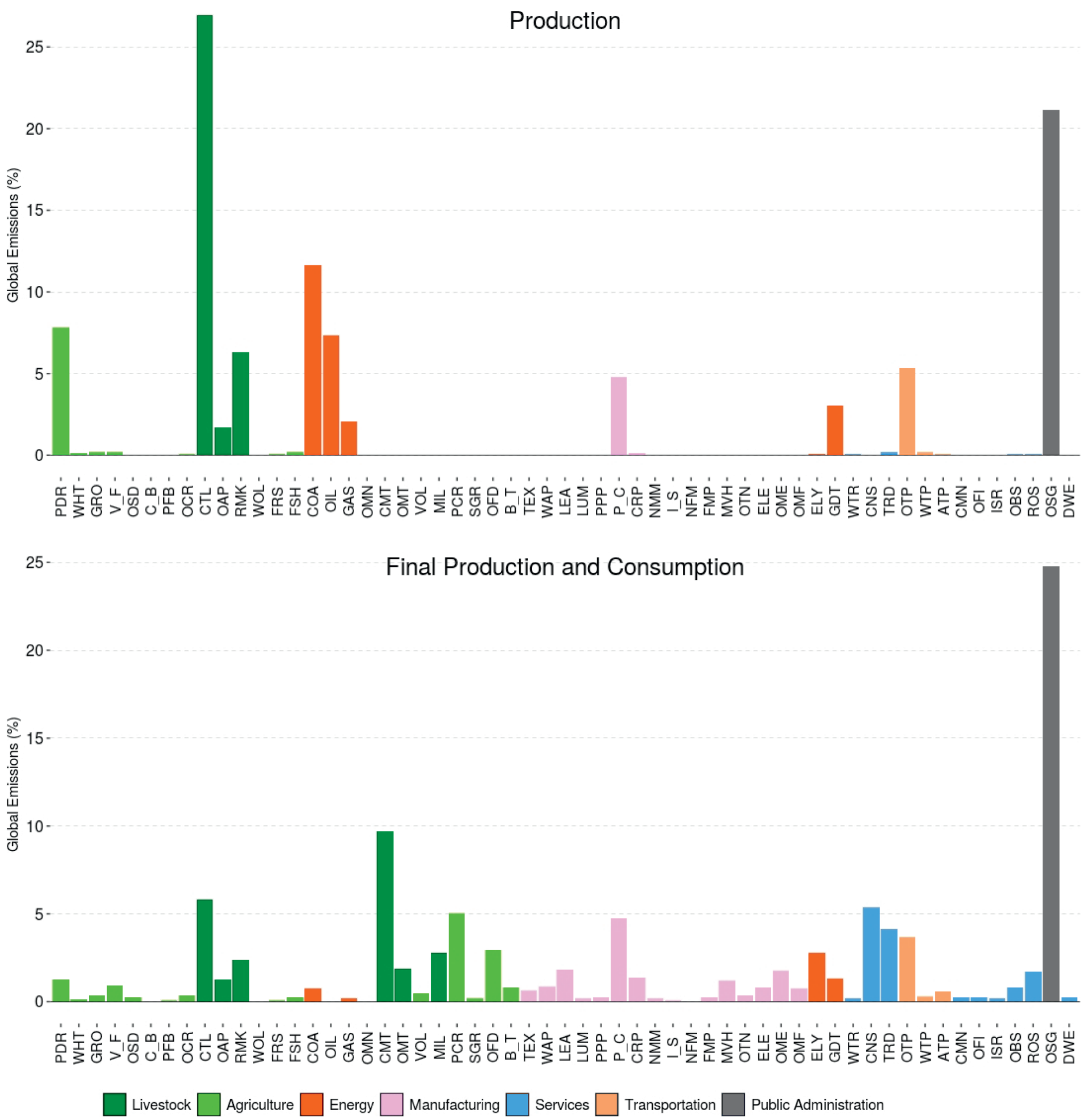

Fig. 1. Sector shares of global CH_4 emissions (average 1997–2014). The barplots show CH_4 emissions associated with production (upper plot) and final production and consumption (lower plot) in each of the 57 sectors as shares of global methane emissions. On the global level, methane emissions associated with final production and final consumption are equal. For a definition of sector abbreviations and for the assignment of the 57 sectors to the 7 broad sectors represented by the different colors, see Table A.2 in Appendix A. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

indicators for the four income groups defined by the World Bank and for the most important producers and consumers of methane, which, taken together, represented slightly more than 75% of produced emissions between 1997 and 2014.

The bulk of total CH_4 emissions was concentrated in developing economies, especially in the upper- and lower-middle-income groups; together, these groups accounted for about 70% of produced and 60% of consumed CH_4 in 1997. This contrasts with CO_2 from fossil-fuel combustion, in which high-income economies historically accounted for a larger share of emissions (see Fernández-Amador et al., 2016). During 1997–2014, the dynamics of emissions differed substantially between developed and developing economies: While emissions in developing countries (especially in upper-middle-income and low-income countries) grew considerably for all three methane inventories, the opposite was observed in high-income countries, where production-based inventories experienced the greatest decline (columns 1–6).

Unlike total emissions, CH_4 emissions per capita were the highest in high-income countries, followed by upper-middle- and lower-middle-income countries. High-income countries were also net importers of emissions, as evidenced by the fact that their emissions for consumption-based inventories were higher than for production-based inventories; the other income groups were net exporters of embodied emissions. Exceptions to this general pattern were large producers of

(*footnote continued*)
Leontief-inverse matrix as explained in the methodology section for CH_4 emissions.

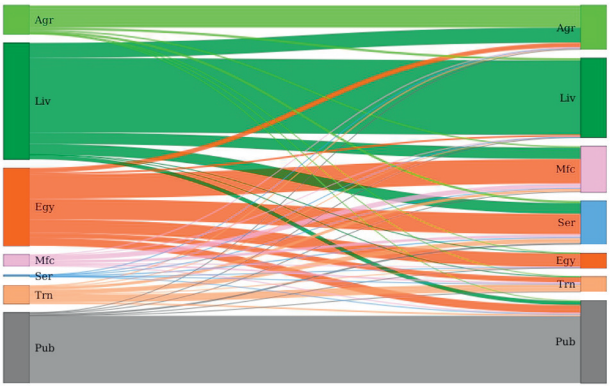

Fig. 2. Sectoral emission flows (average 1997–2014). The graph shows the reallocation of emissions across sectors from the sector of production on the left hand-side to the sector of final production and consumption on the right hand-side. Agr. stands for agriculture, Liv. for livestock, Egy. for energy, Mfc. for manufacturing, Ser. for services, Trn. for transport, and Pub. for public administration. For the assignment of the 57 sectors to the 7 broad sectors represented by the different colors, see Table A.2 in Appendix A. (For interpretation of color in this figure, the reader is referred to the web version of this article.)

agricultural products and livestock such as Australia and Brazil, and large fossil fuel producers such as Russia, the Middle East, and the Former Soviet Union, which produced rather high emissions per capita compared to other countries in their respective income groups; they were typically also net exporters of emissions. Focusing on the evolution of per-capita emissions over 1997–2014, emissions grew most strongly in upper-middle-income countries, while they remained quite the same in the low-income group and experienced a decrease in the high-income and lower-middle-income groups (columns 7–8).

Turning to CH_4 emissions per unit of value added (columns 9–10), high-income economies showed by far the highest methane efficiency, followed by upper-middle- and lower-middle-income countries, while low-income economies were particularly methane intensive.[10] The methane intensity of the group of high-income countries was lower for production- than for consumption-based inventories, which reflects the importation of methane from less methane-efficient countries; the reverse was the case in the other income groups. The largest improvements in methane efficiency between 1997 and 2014 occurred in the lower-middle-income and upper-middle-income countries, which were able to reduce methane per value added by approximately 52% and 48%, respectively. The high- and low-income countries showed slightly smaller improvements in methane efficiency, about 27% and 31%, respectively.

On the sectoral level (Tables E.1-E.7 in Appendix E), the share of total sectoral emissions produced by low- and middle-income countries in 2014 was particularly high in the agriculture (94%), services (91%), manufacturing (80%), and livestock sectors (77%).[11] In the remaining sectors, high-income countries accounted for more than a quarter of emissions released by production (27% from energy and public administration, and 33% in the transport sector). Similar to the economy-wide pattern, emission shares of high-income countries increased when moving down the supply chain in all sectors, indicating methane intensive imports, while it was the opposite in the other income groups. Exceptions where the livestock sector in low-income and upper-middle-income countries, and the service sector in upper-middle-income countries, where footprint-emission shares were larger than production-emission shares. In high-income countries, footprint-emission shares based on consumption accounted for more than a third of total sectoral emissions in all sectors but livestock (25%) and agriculture (14%), with especially large shares in the energy and transport sectors (46% and 50%, respectively). From 1997 to 2014, the contribution of low- and middle-income countries to global sectoral emissions increased relative to high-income countries in all sectors but the manufacturing and the transport sectors. For the footprint-inventories, the share of emissions of low- and middle-income countries increased in all sectors by more than for production-based emissions, indicating a catch-up process in terms of consumption.

3.3. Decomposition of changes in methane emissions

To investigate the drivers of changes in methane emissions in more detail, we performed two different decomposition analyses of the changes observed between 1997 and 2014 for all emission inventories and income groups. First, we implemented a decomposition based on the Kaya identity to analyze changes in economy-wide methane emissions and in emissions in each of the seven broad economic sectors. Afterwards, we analyzed the results of a decomposition based on the Logarithmic Mean Divisia Index (LMDI) method, which allows to evaluate the contribution of changes in sectoral structures to economy-wide changes in emissions.

3.3.1. Decomposition based on the Kaya identity

We used the Kaya-identity (see e.g. Raupach et al., 2007) to decompose the growth rate of total CH_4 emissions between 1997 and 2014 into three components: (i) the growth rate of CH_4 per value added, (ii) the growth rate of value added per capita, and (iii) population growth. The decomposition is implemented as

$$\underbrace{\Delta \ln(CH_4)}_{\text{CH}_4\text{ growth}} = \underbrace{\Delta \ln\left(\frac{CH_4}{VA}\right)}_{\text{growth of CH}_4\text{ per VA}} + \underbrace{\Delta \ln\left(\frac{VA}{pop}\right)}_{\text{growth of VA per capita}} + \underbrace{\Delta \ln(pop)}_{\text{population growth}} \tag{1}$$

where Δ measures changes over time, $\ln(\cdot)$ is the natural logarithm operator, CH_4 measures total CH_4 emissions, VA stands for value added, and pop is the population size. The decomposition is based on growth rates in log-differences. More details on the decomposition are provided in Section D.1 in Appendix D.

The decomposition revealed a coherent pattern across all emission inventories and income groups (see Fig. 4). Expansions in value added per capita and population contributed to higher emissions, whereas efficiency gains reduced emissions. Despite this uniform pattern, the net effect of the three components on total emissions differed across income groups. In high-income countries, the efficiency gains—the decrease of CH_4 per value added—outweighed the comparably low growth rates of value added per capita and population, resulting in a decrease in total emissions. In low- and middle-income countries, however, the expansion of value added per capita and population surpassed efficiency gains, yielding a net increase in methane releases.[12]

A similar decomposition at the sectoral level (Fig. 5) revealed that the aggregate pattern described above hides important sector specificities. Although efficiency gains were important on the aggregate level,

[10] The higher methane content of value added in countries with lower income levels might result from less efficient techniques or from the sectoral structure of their economies. Here, we use methane-efficiency or -intensity to refer to both channels.

[11] Table A.5 in Appendix A provides information on the contribution of sectoral emissions to economy-wide emissions for each income group.

[12] Decompositions for the five sub-periods between 1997 and 2014 mainly resembled the patterns for the whole time period. The only differences occurred (i) between 1997 and 2001, when low value added growth was connected to a decrease in total emissions also for the group of upper-middle-income countries, and for production-based emissions in lower-middle-income countries; (ii) between 2001 and 2004, when higher value added growth contributed to larger emission-footprints in high-income countries, whereas low-income countries experienced a decline in value added per capita but increases in methane per value added; and (iii) between 2007 and 2011, when low efficiency gains in high-income countries contributed to a slight increase in emissions from production (see Fig. D.1 in Appendix D).

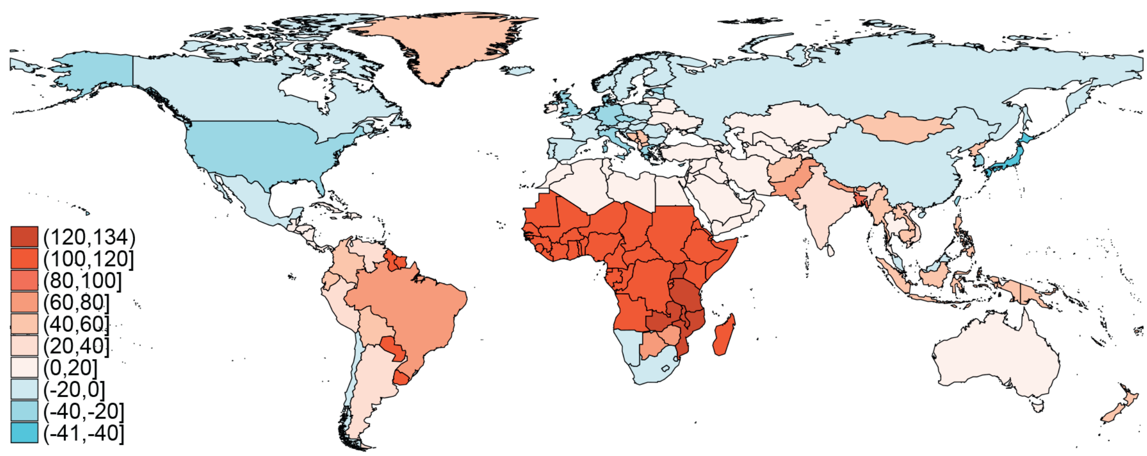

Fig. 3. Percentage change of GHG emissions (CO_2 and CH_4) using different GWPs (2014). The figure shows the percentage change in GHG emissions from production (measured as CO_2 equivalents of CO_2 and CH_4) when GWP_{20} is used instead of GWP_{100} to convert emissions to a common scale, as compared to the global average change in 2014. Red shades indicate an increase in emissions above the global average of 46.6%, blue shades indicate an increase in emissions below the global average of 46.6%. Some countries in the map form part of composite regions (see Table A.1 in Appendix A); the values for these countries are based on emissions data for the composite regions. Data on CO_2 emissions are based on Fernández-Amador et al. (2016). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Main indicators for CH_4 inventories: 1997 and 2014. Selected regions.

	Total CH_4[a] Production (Mt)	(%)	Final prod. (Mt)	(%)	Consumption (Mt)	(%)	CH_4 pc[a] Prod. (t per capita)	Cons.	CH_4 per VA[a] Prod. (kg/USD)	Cons.
1997										
High income	**2358**	**30%**	**2978**	**37%**	**3152**	**39%**	**2.03**	**2.71**	**0.11**	**0.15**
Australia	152	2%	118	1%	97	1%	8.19	5.25	0.45	0.29
EU 15	621	8%	913	11%	980	12%	1.65	2.61	0.09	0.15
EEU	182	2%	187	2%	183	2%	1.64	1.65	0.65	0.59
USA	702	9%	915	11%	990	12%	2.58	3.63	0.09	0.13
Upper middle	**3030**	**38%**	**2740**	**34%**	**2608**	**33%**	**1.35**	**1.16**	**0.89**	**0.76**
Brazil	396	5%	418	5%	418	5%	2.36	2.50	0.57	0.58
Russia	390	5%	319	4%	333	4%	2.63	2.25	1.08	0.92
China	1058	13%	1003	13%	922	12%	0.86	0.75	1.58	1.37
Mexico	134	2%	133	2%	133	2%	1.38	1.36	0.41	0.41
Middle East	443	6%	269	3%	267	3%	2.57	1.55	1.03	0.62
Lower middle	**2518**	**32%**	**2189**	**27%**	**2149**	**27%**	**1.06**	**0.91**	**2.01**	**1.65**
Former SU	231	3%	204	3%	184	2%	1.72	1.38	2.22	1.71
India	747	9%	755	9%	744	9%	0.75	0.75	2.24	2.19
Indonesia	241	3%	208	3%	209	3%	1.19	1.03	1.31	1.13
RSA	141	2%	142	2%	141	2%	0.92	0.92	2.43	2.29
SSA	684	9%	489	6%	476	6%	1.67	1.16	4.93	3.35
Low income	**76**	**1%**	**74**	**1%**	**73**	**1%**	**0.82**	**0.79**	**3.07**	**2.72**
2014										
High income	**2250**	**24%**	**2758**	**29%**	**2892**	**31%**	**1.79**	**2.30**	**0.08**	**0.11**
Australia	154	2%	100	1%	86	1%	6.56	3.65	0.24	0.13
EU 15	464	5%	763	8%	807	9%	1.15	2.00	0.06	0.10
EEU	148	2%	167	2%	163	2%	1.40	1.55	0.28	0.28
USA	695	7%	867	9%	929	10%	2.18	2.92	0.07	0.09
Upper middle	**4062**	**43%**	**3804**	**40%**	**3700**	**39%**	**1.55**	**1.41**	**0.46**	**0.42**
Brazil	512	5%	499	5%	482	5%	2.51	2.36	0.47	0.43
Russia	486	5%	363	4%	378	4%	3.38	2.63	0.82	0.61
China	1634	17%	1686	18%	1566	17%	1.20	1.15	0.44	0.42
Mexico	139	2%	137	2%	142	2%	1.12	1.14	0.22	0.21
Middle East	589	6%	363	4%	406	4%	2.34	1.61	0.56	0.41
Lower middle	**2987**	**32%**	**2744**	**29%**	**2713**	**29%**	**0.92**	**0.84**	**0.97**	**0.84**
Former SU	321	3%	266	3%	261	3%	2.26	1.84	1.23	1.00
India	893	10%	911	10%	868	9%	0.69	0.67	0.73	0.69
Indonesia	340	4%	263	3%	265	3%	1.33	1.04	0.82	0.64

(*continued on next page*)

Table 2 (*continued*)

	Total CH_4[a] Production (Mt)	(%)	Final prod. (Mt)	(%)	Consumption (Mt)	(%)	CH_4 pc[a] Prod. (t per capita)	Cons.	CH_4 per VA[a] Prod. (kg/USD)	Cons.
RSA	216	2%	220	2%	220	2%	1.00	1.02	1.60	1.43
SSA	734	8%	612	7%	628	7%	1.13	0.96	2.16	1.67
Low income	**128**	**1%**	**122**	**1%**	**123**	**1%**	**0.85**	**0.82**	**2.11**	**1.89**

Note: VA stands for value added in constant 1997 prices, pc stands for per capita, Mt stands for megatons, % for percent of world total, t for ton, kg for kilogram. EU 15 stands for the first historical members of the European Union. EEU stands for Eastern European Union members joining the Union in 2004, 2007, and 2013, including the upper-middle income countries Bulgaria and Romania; for the group totals, these countries are assigned to their respective income group. RSA stands for the Rest of South Asia, SSA for the Rest of Sub-Saharan Africa. For details on the countries covered in these regions, see Table A.1 in Appendix A.

[a] Data reported as CO_2 equivalents with respect to global warming potential for a 100-year period.

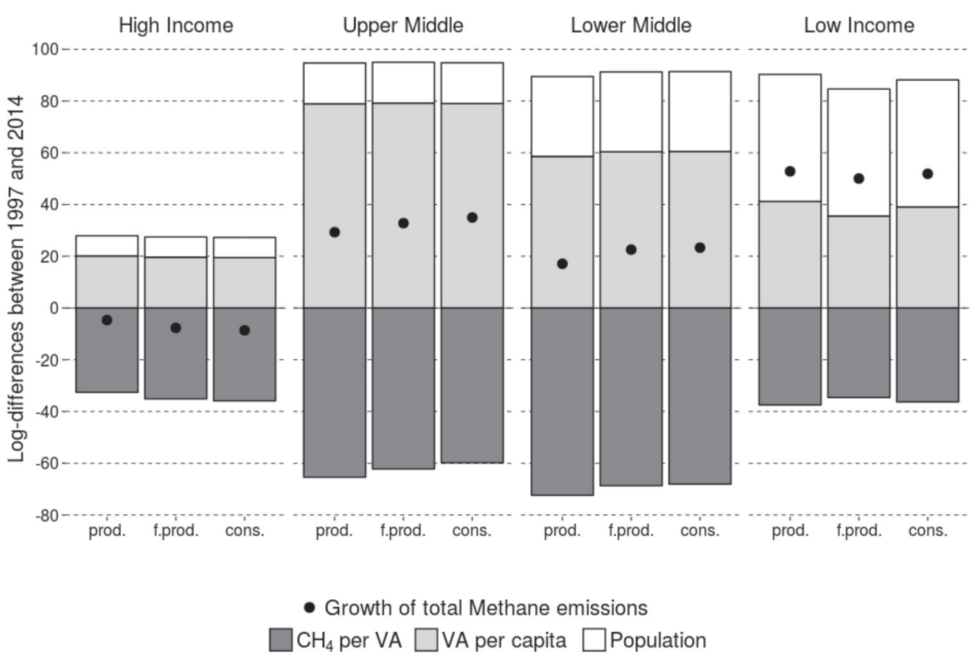

Fig. 4. Change in components of the Kaya identity (1997–2014). Note: The barplots show the log differences of the components of the Kaya identity between 1997 and 2014 for the four World Bank income groups. The Kaya identity decomposes total CH_4 emissions into CH_4 per value added, value added per capita, and population, according to the formula $CH_4 = \frac{CH_4}{VA} \cdot \frac{VA}{pop} \cdot pop$. We show the decomposition results for the three inventories in our dataset: standard production (prod.), final production (f.prod.) and consumption (cons.). Additionally, we show the growth rate of total emissions (in log differences), marked as black dot.

they were not realized to the same extent in every economic sector, which suggests sectoral differences in abatement potential. Focusing on production inventories, improvements in efficiency were particularly relevant in the services, public administration, and energy sectors, whereas the transport and manufacturing sectors showed more limited efficiency gains or even increased methane intensity. The primary sectors also demonstrated lower mitigation potential than other sectors. Moreover, the agriculture sector in low-income and high-income economies experienced a slight increase in methane intensity. These patterns generally were also observed for final production and consumption inventories. The only relevant exceptions were the manufacturing sector in high-income economies and the agriculture sector in low-income countries, which turned to realize efficiency gains once we move down in the supply chain. More generally, upper-middle-income and lower-middle-income groups tended to show larger efficiency gains at the production stage than at the final production or consumption stages.

Finally, the results of the decomposition suggest that the economy-wide changes in value added per capita may have been influenced by sectoral shifts in production and consumption patterns that are consistent with the structural shifts usually associated with economic development (Herrendorf et al., 2013; Kuznets, 1973). The energy and the public-administration sectors (the latter includes landfills and sewage treatment) experienced strong growth from 1997 to 2014 in all income groups and notably in low-income countries. The services sector was also among the sectors that grew more strongly. In low-income countries, the manufacturing sector expanded considerably, whereas for the other income groups it lost weight in terms of value added. The primary and transport sectors decreased their shares in value added.

3.3.2. *Decomposition based on the Logarithmic Mean Divisia Index method*

To quantify the contribution of sectoral shifts to economy-wide emissions for the respective country groups, we implemented a further decomposition, based on the Logarithmic Mean Divisia Index (LMDI) method (see Ang, 2015). The additive version of the decomposition breaks down changes in methane emissions into (i) a sectoral CH_4 intensity term (CH_4 per value added at the sectoral level); (ii) a structural change term (sector shares of value added); and (iii) an economic activity term (economy-wide value added).

$$\underbrace{\Delta CH_4}_{\text{Change in CH}_4} = \underbrace{\sum_i L^i \cdot \Delta \ln\left(\frac{CH_4^i}{VA^i}\right)}_{\text{sectoral CH}_4\text{ intensity}} + \underbrace{\sum_i L^i \cdot \Delta \ln\left(\frac{VA^i}{VA}\right)}_{\text{structural change}} + \underbrace{\sum_i L^i \cdot \Delta \ln(VA)}_{\text{economic activity}}, \quad (2)$$

where $L^i = \Delta CH_4^i / \Delta \ln(CH_4^i)$ for $\Delta CH_4^i \neq 0$ and $L^i = CH_4^i$ for $\Delta CH_4^i = 0$ is the logarithmic mean weight function, *i* stands for sector *i*, and all other terms are defined as before.

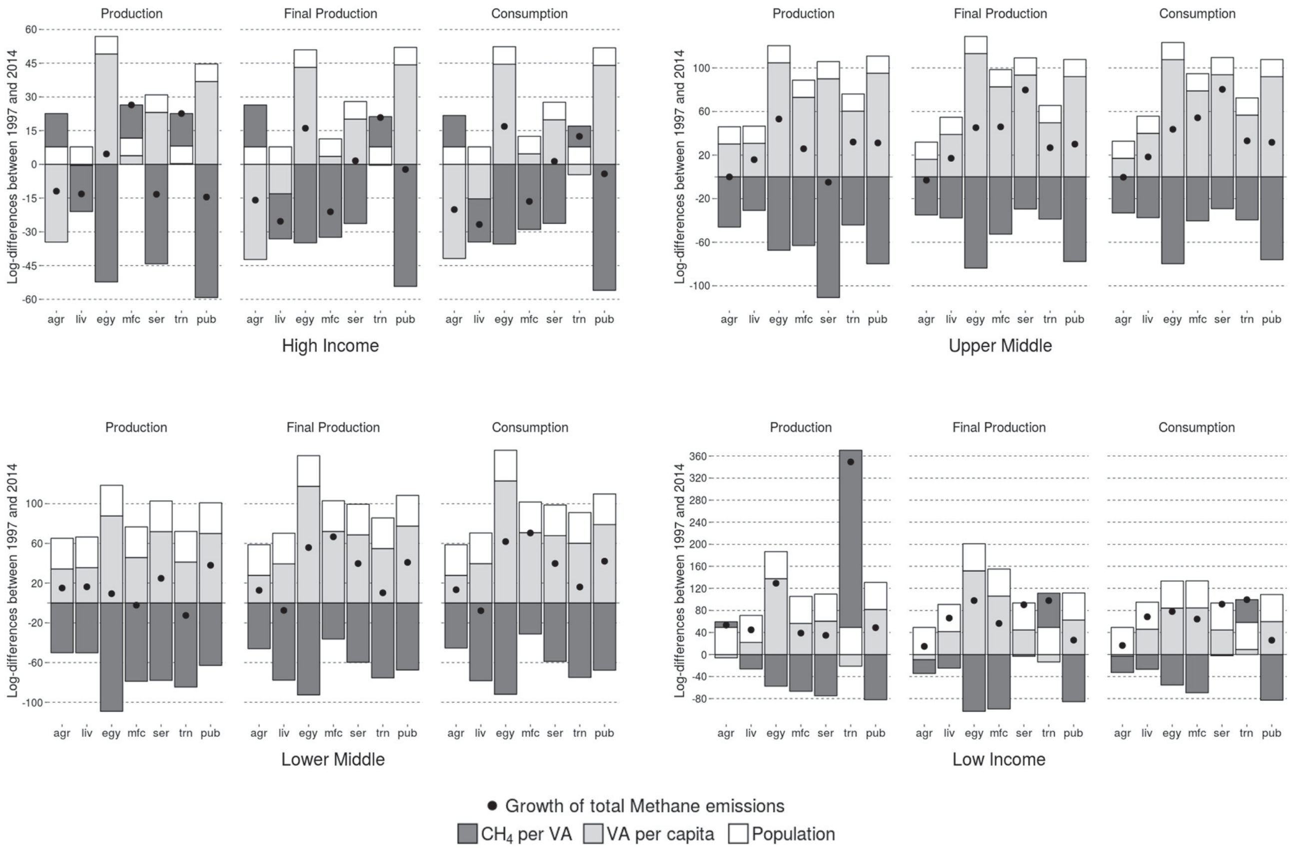

Fig. 5. Change in components of the Kaya identity (1997–2014, sectors). Note: The barplots show the log differences of the components of the Kaya identity between 1997 and 2014 for seven sectors of the four World Bank income groups. The Kaya identity decomposes sectoral CH_4 emissions into CH_4 per value added, value added per capita, and population, according to the formula $CH_4 = \frac{CH4}{VA} \cdot \frac{VA}{pop} \cdot pop$. Except for population, all the variables in the formula are measured at the sectoral level. We show the decomposition results for the three inventories in our dataset: standard production, final production and consumption. Additionally, we show the growth rate of total sectoral emissions (in log differences), marked as black dot.

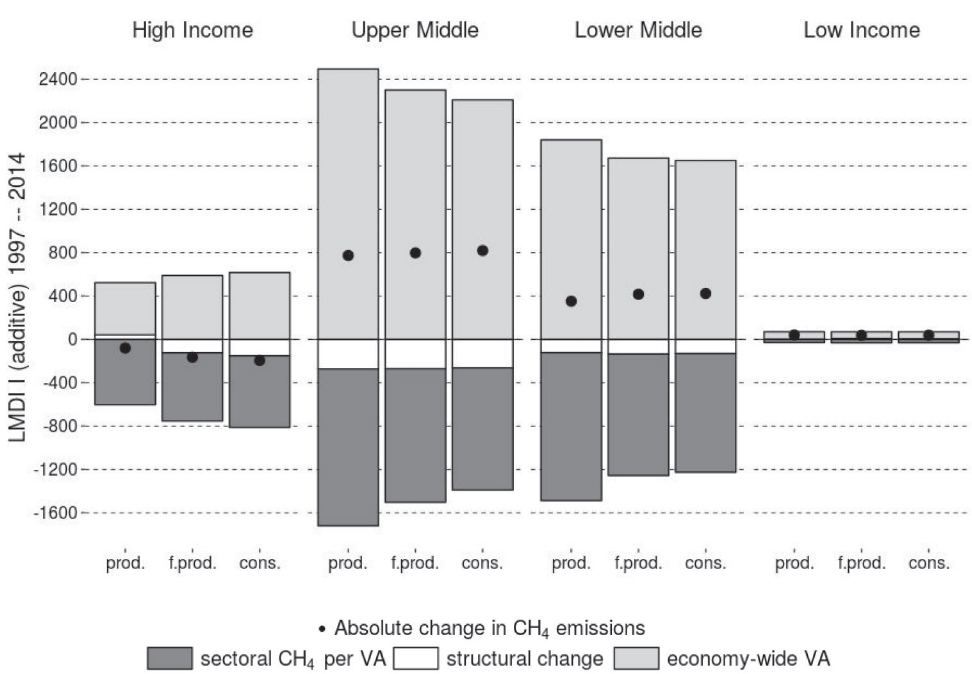

Fig. 6. Additive LMDI decomposition of changes in CH_4 emissions (1997–2014). Note: The barplots show the decomposition of changes in CH_4 emissions in physical units (Mt of CO_2 eq., 100y) between 1997 and 2014 for the four World Bank income groups. The additive LMDI decomposition decomposes changes in CH_4 emissions into sectoral CH_4 per value added, structural change, and economy-wide value added. We show the decomposition results for the three inventories in our dataset: standard production (prod.), final production (f.prod.) and consumption (cons.). Additionally, we show the change of total emissions marked as black dot.

Table 3
CH_4 emissions embodied in trade: 1997 and 2014. Selected regions and income groups.

	Embodied CH_4[a] Exports (% of prod. emissions)	Imports	BEETT	BEETI	CH_4 non-Annex I[a] Prod. (% of)	Imports	CH_4 per VA[a] Exports (kg/USD)	Imports
1997								
High income	**22%**	**56%**	**−34%**	**−26%**	**42%**	**75%**	**0.16**	**0.41**
Australia	47%	11%	36%	22%	9%	78%	1.30	0.30
EU 15	19%	77%	−58%	−47%	51%	66%	0.08	0.33
EEU	23%	23%	−1%	−3%	9%	38%	0.53	0.39
USA	11%	52%	−41%	−30%	46%	89%	0.12	0.50
Upper middle	**23%**	**9%**	**14%**	**10%**	**6%**	**73%**	**1.02**	**0.37**
Brazil	3%	9%	−6%	−6%	8%	90%	0.27	0.53
Russia	25%	11%	14%	18%	3%	30%	1.52	0.66
China	17%	4%	13%	5%	3%	76%	1.28	0.32
Mexico	13%	12%	1%	0%	11%	85%	0.25	0.25
Middle East	50%	10%	40%	39%	7%	67%	1.74	0.36
Lower middle	**19%**	**5%**	**15%**	**13%**	**4%**	**75%**	**2.35**	**0.48**
Former SU	27%	7%	20%	12%	1%	15%	2.76	0.63
India	4%	4%	0%	−1%	3%	90%	0.99	0.76
Indonesia	21%	8%	13%	14%	5%	65%	1.24	0.46
RSA	6%	6%	0%	−1%	5%	89%	1.06	0.73
SSA	32%	2%	30%	29%	1%	80%	6.58	0.32
Low income	**9%**	**5%**	**3%**	**2%**	**5%**	**88%**	**1.65**	**0.63**
2014								
High income	**27%**	**56%**	**−28%**	**−23%**	**40%**	**71%**	**0.13**	**0.28**
Australia	62%	18%	44%	35%	15%	84%	0.84	0.23
EU 15	25%	99%	−74%	−64%	60%	60%	0.06	0.24
EEU	28%	38%	−11%	−13%	15%	40%	0.22	0.25
USA	13%	46%	−34%	−25%	39%	84%	0.10	0.30
Upper middle	**23%**	**15%**	**9%**	**6%**	**11%**	**77%**	**0.50**	**0.29**
Brazil	13%	8%	6%	3%	7%	86%	0.59	0.29
Russia	34%	12%	22%	25%	8%	68%	1.22	0.34
China	16%	12%	4%	−3%	9%	76%	0.39	0.26
Mexico	21%	23%	−2%	1%	21%	90%	0.22	0.20
Middle East	52%	20%	31%	38%	15%	74%	0.72	0.33
Lower middle	**19%**	**10%**	**9%**	**8%**	**8%**	**83%**	**0.99**	**0.39**
Former SU	28%	9%	19%	17%	4%	46%	1.11	0.36
India	13%	10%	3%	−2%	9%	91%	0.64	0.42
Indonesia	32%	10%	22%	23%	7%	71%	1.28	0.38
RSA	6%	7%	−2%	−2%	6%	90%	0.88	0.48
SSA	20%	6%	14%	17%	5%	87%	2.12	0.41
Low income	**10%**	**6%**	**4%**	**5%**	**5%**	**93%**	**1.06**	**0.45**

Note: BEETT and BEETI stand for net balance of emissions embodied in total trade and in traded intermediates, respectively, scaled to production-based emissions. CH_4 non-Annex I is defined as emissions embodied in imports from non-Annex I countries either as percent of emissions from territorial production (prod) or of total imported emissions (imports). EU 15 stands for the first historical members of the European Union. EEU stands for Eastern European Union members joining the Union in 2004, 2007, and 2013, including the upper-middle income countries Bulgaria and Romania; for the group totals, these countries are assigned to their respective income group. In the EU 15 and the EEU, trade flows between the members have been retained when calculating the aggregated figures. RSA stands for the Rest of South Asia area, SSA for the Rest of Sub-Saharan Africa region. For details on the countries covered in these regions please refer to Table A.1 in Appendix A. Income groups are based on World Bank definitions.

[a] Data are reported as CO_2 equivalents with respect to global warming potential for a 100-year period.

The results, shown in Fig. 6, indicate that similar to the Kaya-based decomposition, the growth of value added contributed positively to increases in emissions across all income groups and inventories, whereas efficiency gains had the opposite effect. The overall contribution of sectoral shifts to changes in economy-wide methane emissions was rather limited. These sectoral shifts contributed to a decrease in emissions from all inventories in middle-income countries, and to lower footprint-based emissions in high-income countries. By contrast, they contributed to higher emissions in low-income countries and for production-based emissions in high-income countries, mainly because of the expansion of the energy and public administration sectors.[13]

[13] More details on the LMDI decomposition and results for the multiplicative version of the decomposition are reported in Appendix D.2.

3.4. Methane embodied in international trade

Table 3 describes the flows of methane emissions embodied in international trade aggregated across sectors. It reports the CH_4 content of exports and imports as percent of production-based emissions, net-exports of emissions embodied in total trade and in traded intermediates, shares of CH_4 imported from non-Annex I countries, and measures of the methane intensity of international trade flows.

Emissions embodied in trade relative to produced emissions tended to increase with income, particularly on the side of imports (columns 1–2). The group of high-income countries traded embodied emissions more intensively than countries from other (lower income) groups. This was largely driven by the big share of CH_4 contained in imports of high-income countries, whereas the share of emissions embodied in exports of high-income group was comparable to that of the middle-income groups. In low-income countries, the methane content of trade was particularly low. Between 1997 and 2014, as a result of intensifying globalization, the ratio of traded to nationally produced methane emissions increased by about 8%. Emissions embodied in exports increased most strongly in high-income countries and declined slightly in the lower-middle-income group (25% and −2%, respectively). By contrast, emissions embodied in imports increased across all income groups, notably in lower-middle-income and upper-middle-income countries (105% and 68%).

The larger share of emissions embodied in imports relative to the share of emissions embodied in exports in high-income countries confirms that they were net-importers of methane. This is also visible from their negative trade balance of emissions embodied in total trade (BEETT, i.e. the difference between exported and imported emissions), reported in column 3. Net-imports of emissions in high-income countries were sourced from countries in the other income-groups, which were net-exporters of emissions (positive BEETT). Total trade can be broken down into trade in final goods and trade in intermediates. Column 4 displays the balance of emissions embodied in traded intermediates (BEETI). The patterns of the BEETI explained the patterns of the BEETT to a large extent. For most income groups the magnitude of the BEETT was larger than that of the BEETI, indicating that net-trade in final goods reinforced the patterns observed for net-trade in intermediates. In regions where the BEETT was smaller than the BEETI in magnitude, net-trade in final goods counteracted the BEETI. This was the case in EEU countries, which were net-importers of methane embodied in intermediates but net-exporters of methane embodied in final goods, the fossil fuel exporters Russia and (in 2014) the Middle East, for which it was the opposite, and some countries in the lower-middle- and low-income groups. Between 1997 and 2014, the trade-related net positions of embodied emissions generally decreased for all income groups, except for the group of low-income countries, indicating that a process of convergence in methane trade balances across income levels may have taken place.

The net-importation of methane in high-income countries described above, may reflect specialization patterns, since methane emissions are realized from specific sectors, but it may also result from methane leakage, since many high-income countries were bound by emission targets specified in the Kyoto Protocol. In this regard, columns 5–6 show emissions embodied in imports from non-Annex I countries, scaled alternatively to domestic production-based emissions or to emissions embodied in total imports. Imported emissions from non-Annex I countries scaled to production-based emissions were the highest in the group of high-income countries and the lowest in the low-income group. A different picture emerges when focusing on imported emissions from non-Annex I scaled to emissions embodied in total imports, which was the highest in low-income countries. Thus, high-income countries imported more CH_4 from all countries, independently of the trading partners' Annex I status. Between 1997 and 2014, imported emissions from non-Annex I countries decreased in high-income countries, whereas they increased in all other income groups, probably as a consequence of the expansion of South-South trade.

Finally, the methane intensity of trade flows tended to decrease with development (columns 7–8). In the group of high-income countries, imports had a larger CH_4 content per unit of value added than exports, while the opposite was true for the other income groups. A comparison of the CH_4 intensities embodied in trade to the CH_4 intensities reported in Table 2 reveals that exports of the high- and middle-income groups were typically more CH_4 intensive than their national production, whereas the CH_4 intensity of imports was higher than the one of consumption only in the high-income group. In the low-income group, trade flows were less methane intensive than domestic production and consumption. Between 1997 and 2014, the CH_4 intensity of trade decreased in all income groups, reflecting the gains in methane efficiency that were also visible from Table 2.

3.5. Bilateral flows of methane embodied in trade

Aggregate flows of methane embodied in trade can be further broken down into bilateral trade relationships. Fig. 7 displays the trade network of embodied methane; it shows emissions embodied in bilateral trade flows of inputs of consumption (i.e. traded intermediates and final goods) for the years 1997 and 2014, aggregated across sectors. Thus, it allows to analyze the sources and destinations of traded emissions and to analyze changes in trade patterns of embodied emissions over time.

Few regions accounted for the bulk of embodied-emissions trade. The main exporters of embodied emissions were China, the Middle-East, Russia, and the Rest of Sub-Saharan Africa, while the EU 15 and the USA stood out as the main export destinations. Together, these regions accounted for more than half of embodied-emissions trade in the period from 1997 to 2014.

Some specific patterns concerning the sources and destinations of trade-embodied emissions deserve to be highlighted. The two most important destinations for developing countries' methane exports, the EU 15 and the USA, were equally important for most exporters. Exceptions were Mexico, which mainly exported emissions embodied in manufacturing intermediates to the USA, and Russia and the former Soviet Union, which mainly exported emissions to the EU 15. Russia was also the main source of imported emissions in the countries of the Eastern European Union (EEU). By contrast, the export destinations of Australia (also a net-exporter of emissions) were quite diversified across regions, with Japan accounting for a large share of Australian emissions embodied in exports to the Rest of the World.

The comparison of methane embodied in traded intermediates and in final goods also reveals interesting patterns (see also Fig. E.1 in Appendix E). Most developing countries in Fig. 7 (Russia, Mexico, the Middle East, the former Soviet Union, Indonesia, the Rest of Sub-Saharan Africa, and the Rest of South Asia) were primarily exporters of methane embodied in intermediates such as fossil fuels. In these regions, the amount of emissions contained in exports for final production and consumption were virtually identical. By contrast, Brazil, China and, to a lesser extent, India exported a considerable amount of emissions embodied in final goods (besides intermediates). Also, in the high-income countries a significant share of emissions embodied in exports was associated with final products. The pattern of methane imports looks somewhat more homogeneous across groups, with final goods accounting for an important part of overall imported emissions in all regions. Still, emissions embodied in final goods imported were particularly large in the high-income countries, as well as in Russia, the Middle East, Indonesia, the Rest of Sub-Saharan Africa, and the Rest of the World region.

There were important changes in the trade network of embodied methane between 1997 and 2014. Most regions experienced a sizable increase in traded methane emissions; in Australia, Brazil, and Russia this was mainly because of exports. Noteworthy, China, India, and Indonesia more than doubled their emissions embodied in trade in this period. By contrast, traded emissions remained at a fairly constant level in the EU 15 and the Eastern European Union, and decreased in the USA (driven by lower imports) and the Rest of Sub-Saharan Africa (driven by lower exports).[14]

On the sectoral level, methane embodied in manufactured goods accounted for the largest component of traded methane emissions, followed by emissions embodied in traded services, livestock, and agricultural products. The main exporters of emissions embodied in

[14] In China, the increase in traded emissions was mainly driven by exports between 1997 and 2007. After 2007, emissions embodied in exports started to decline, whereas emissions embodied in imports experienced a substantial increase. Traded emissions first increased between 1997 and 2004 in the EU 15 and the USA but started to decrease again, most notably after 2007. The detailed graphs for all the years covered in the dataset and graphs at the sectoral level, analyzed in the next paragraph, are available from the authors upon request.

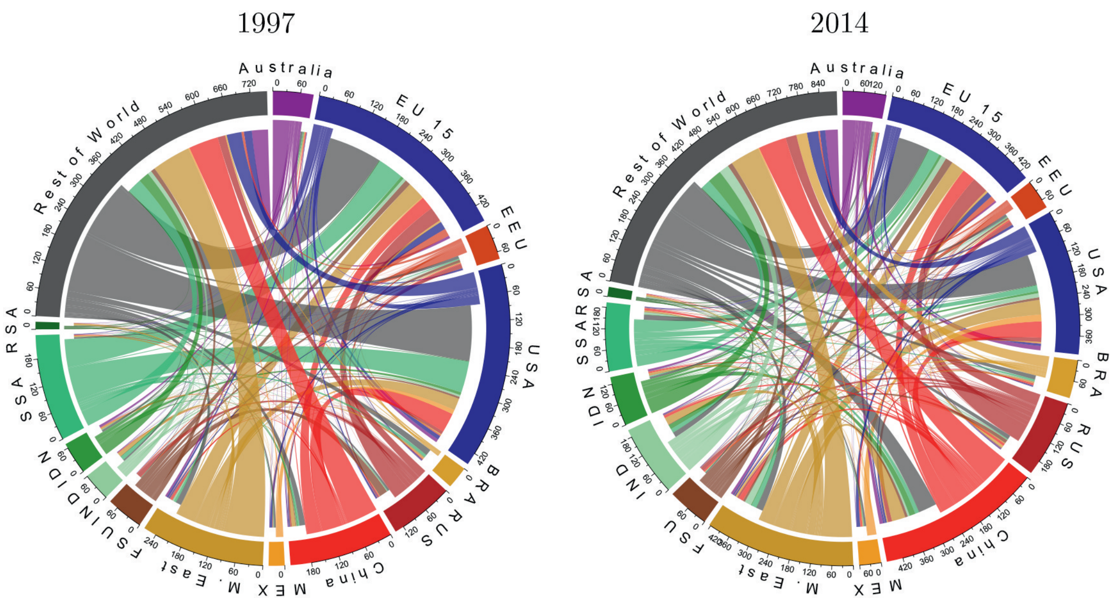

Fig. 7. Traded methane emissions by region of origin and destination (1997 and 2014). Note: The circle-plots show traded CH_4 emissions accruing to consumption for the most important producers of CH_4 emissions and the Rest of World aggregate region. Trade-embodied emissions are reported in megatonnes (Mt) of CO_2 equivalents (100y) for the years 1997 and 2014. The outer circle shows the sum of traded emissions of a region. Brazil (BRA), India (IND), Indonesia (IDN), Russia (RUS), Mexico (MEX), and the United States (USA) are denoted by their ISO codes. EU 15 stands for the members of the European Union before the new Eastern European member states, denoted as EEU, joined in 2004, 2007, and 2013, respectively. M. East stands for the Middle East, FSU for the former Soviet Union, SSA for Sub-Saharan Africa and RSA for Rest of South Asia. A detailed description of the countries included in reach region is found in Table A.1 in the Appendix. Bilateral flows are shown in the color of the exporting region. Connections starting closer to the outer circle refer to exports, while imports are depicted with an indentation. The reported flows account for global value chains in a sense that emissions embodied in intermediates may cross several sectors and borders before being assembled into a final good. They accrue to the region where final goods are consumed. Fig. E.1 in the Appendix reports traded methane emissions accruing to final production (corresponding to traded intermediates) additionally to consumption (corresponding to traded intermediates and final goods). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

manufacturing and in services were China and the Middle East, and to a somewhat lesser extent the Rest of Sub-Saharan Africa and Russia. By contrast, the main exporters of emissions embodied in livestock where Australia and Brazil, whereas India accounted for the largest part of emissions embodied in agricultural exports. Regarding emissions embodied in transport and public administration, the most important exporter was the Middle East, followed by the Rest of Sub-Saharan Africa and Russia. Emissions embodied in exports in the energy sector were dominated by Russia and the Middle East, followed by Indonesia, the Rest of Sub-Saharan, and China. The main importers of emissions throughout all sectors where the EU15 and the USA.

4. Discussion

Our dataset provides detailed information about methane emission footprints worldwide. It supplements existing data on GHG footprints that cover aggregates of various GHGs. Although a focus on various GHGs is important for reaching climate objectives, aggregating across GHGs implies equal treatment of emissions generated by very diverse processes, which relate to economic growth in a different manner and may have different potential for mitigation or abatement. Moreover, the aggregation depends on subjective choices concerning the method to transfer emissions of different gases to a common scale. The common approach of using CO_2 equivalents based on GWPs requires the choice of a time horizon for the aggregation, usually 100 years, though there is no conclusive scientific evidence why this horizon should be preferred (Fesenfeld et al., 2018; Myhre et al., 2013). Choosing alternative time horizons can substantially alter emission footprints across countries and sectors (Fesenfeld et al., 2018; Fuglestvedt et al., 2003; Myhre et al., 2013; Shine, 2009), with important implications for international climate debates. Thus, focusing only on aggregate GHG inventories based on 100-year GWPs could hide important sources of pollution that are particularly relevant for climate outcomes in the nearer term (Jackson, 2009). Furthermore, also alternatives to aggregations based on GWPs have been suggested by e.g. Myhre et al. (2013), Smith et al. (2012), and Edwards and Trancik (2014), which could affect aggregate emission budgets. Thus, reporting emissions of different GHGs separately rather than aggregated allows decision makers and researchers to take into account the peculiarities of different GHGs when evaluating mitigation options (see also Jackson, 2009; Shindell et al., 2017). Furthermore, methane inventories from our dataset can be aggregated with other comparable GHG datasets such as CO_2 inventories from Fernández-Amador et al. (2016) using GWPs or other conversion metrics over alternative time horizons.

Methane emissions differ from CO_2 emissions in at least three aspects. First, methane has a relatively shorter atmospheric life, and its abatement is particularly relevant for controlling climate change in the near term (Estrada et al., 2013; Höglund-Isaksson, 2012; Shindell et al., 2017, 2012). Rapid abatement of methane emissions could delay global temperature rise (Bowerman et. al, 2013) and reduce the risk of reaching climate tipping points in the near future, beyond which warming is self-accelerating (Hansen et al., 2007; Lenton, 2011; Lenton et al., 2008; Shindell et al., 2017; Steffen et al., 2018). This would gain time for technological breakthroughs or behavioral changes necessary for decarbonization, which may take many years—or decades—despite global efforts (Steffen et al., 2018).[15]

Second, a larger share of CH_4 as compared to CO_2 is released from

[15] It has been argued that the mitigation of short-lived GHGs like methane is important to reach the goals of the Paris Agreement (e.g. Ramanatha and Xu, 2010; Shindell et al., 2017). Yet, the timing of mitigation of short-lived GHGs plays a minor role in peak temperatures in the long run (Bowerman et. al, 2013). Thus, a rapid reduction of short-lived GHGs should supplement CO_2 abatement policies rather than delay their implementation.

developing countries (see Fernández-Amador et al., 2016; Jackson, 2009, for CO_2). The relatively strong economic growth that developing countries experienced between 2001 and 2014 and their significant population growth contributed to the larger increase in methane emissions from this group, which could only be partially offset by methane efficiency gains. However, a similitude with CO_2 emissions emerges concerning footprints: High-income countries are responsible for a larger part of methane emissions than their production structures suggest. The USA and the EU 15 are net-importers of emissions, especially of emissions embodied in manufacturing, services, and primary products (see also Subak, 1995; Walsh et al., 2009; Zhang and Chen, 2010, for country case studies). Yet, between 1997 and 2014, high-income countries were able to reduce their emission footprints, mainly because efficiency gains outweighed slow economic and population growth.

Third, also in contrast to CO_2, the bulk of methane emissions originates from few economic sectors—livestock breeding, rice cultivation, extraction and transport of fossil fuels, and waste management. A large share of CH_4 emissions is released from agricultural activities and livestock breeding. A growing world population will further raise the demand for food on a global scale. Provided that developing countries continue growing by expanding their primary sector activities to meet this demand, methane emissions will increase unless considerable gains in methane efficiency counteract the effect of increasing demand. Thus, for effective climate change control in the near term, climate negotiations should explicitly take into account the implications of policies for the primary sectors.

Effective methane abatement calls for cooperation to share the mitigation burdens between developing countries, where the bulk of emissions is produced, and high-income countries, the main consumers of embodied emissions. Collective action is an option. This collective action can take the form of knowledge and technology transfers and financial assistance by high-income countries to speed up abatement in developing countries (see Fesenfeld et al., 2018; Peters and Hertwich, 2008c; Wiedmann, 2009). Such collaboration is especially relevant for methane-intensive primary sectors where methane efficiency gains could be realized by changes in water management and the use of fertilizers in rice production, and improvements in manure management and dietary changes of ruminants. Such collaboration can also be of relevance to introduce improvements in waste management such as separation of waste, recycling, and improvement of waste treatment systems (e.g. Frolking et al., 2004; Höglund-Isaksson, 2012; Kai et al., 2011; Karakurt et al., 2012). Therefore, the mitigation potential of individual countries should be considered at the sectoral level in order to define cost-effective, coordinated mitigation strategies (see also Höglund-Isaksson, 2012, for mitigation costs).

The information contained in our dataset can be used to evaluate alternative policy options targeted at different stages of production processes and to assess their potential to limit emission leakage in the absence of climate regulation adopted universally. This information can also reduce the uncertainty concerning the potential impacts of alternative policy instruments by explicitly accounting for indirect effects via international trade linkages. Specifically, this information can contribute to empirical research and policy-making in three ways. First, our data allow to track methane emissions through international supply chains and to visualize the methane-trading network. Thus, it can be used to link emissions embodied in consumption in one country with the country and sector where these emissions were released. Furthermore, using Structural Path Analysis (SPA) in an MRIO framework, it is possible to isolate individual supply chains that originate, pass through, or terminate in specific countries and sectors (Lenzen et al., 2012; Wiedmann, 2009). This information could facilitate the negotiation of international transfers of technologies and funds from high-income consumers to lower-income producers (see Peters and Hertwich, 2008c; Wiedmann, 2009).

Second, the data developed in this paper can be used in a general equilibrium framework to evaluate the impact of multi- or unilateral policy instruments on a global scale, explicitly accounting for methane leakage. Within these models, it is possible to determine not only the direct but also the indirect costs associated with such policy instruments that may be passed to other countries via international trade linkages. Also, our data can be used to investigate the determinants of sectoral methane emissions from production, final production, and consumption in a global panel data framework. The results from this research, together with projections of demographic and economic variables, could feed into scenarios to analyze the effects of environmental polices on future emissions.

International coordinated action on climate change mainly concerns the determination of property rights on responsibilities for damage, and costs and rents from policies (see also Andrew and Forgie, 2008; Munksgaard and Pedersen, 2001; Wiedmann, 2009). By adding a footprint-based perspective for methane emissions, our data and the research building on it may facilitate cooperation between developing and developed countries for methane mitigation. The information contained in our dataset contributes to reducing scientific uncertainty regarding the origins of global methane pollution at a regional level; and thus it contributes to reducing the transaction costs associated with enforcement of policies (see Libecap, 2014). Therefore, it can be valuable for the design and enforcement of policy instruments, and for the evaluation of potential inter-sectoral and international spillovers of the environmental policies to be applied.

Finally, the information derived from our MRIO-based analysis could supplement alternative approaches to evaluate consumption-based responsibility for methane emissions such as process-based life-cycle assessment (PB-LCA). MRIO techniques are widely used to evaluate emission footprints in the context of complex international trade networks. They address one important problem inherent to PB-LCA, which is the cut-off error that arises from the exclusion of processes that are mistakenly believed to be irrelevant (Suh et al., 2004; Weber and Matthews, 2008). Yet, the downside of MRIO-based evaluations of emission footprints is the smaller sectoral detail and the resulting aggregation bias if the number of sectors is small. Thus, if the objective is to evaluate abatement policies that require more detailed information about specific products and production processes, hybrid approaches that combine top-down MRIO approaches with bottom-up PB-LCA are promising (Lenzen et al., 2012; Wiedmann, 2009).

Like all MRIO-based footprint inventories, our data inherits different sources of uncertainty from the underlying MRIO tables. This uncertainty includes the quality of survey data used for the construction of IO tables, imputations, balancing, proportionality and homogeneity assumptions, sectoral aggregation, and the treatment of exchange rates, among others (see e.g. Wiedmann, 2009, for a discussion). Despite this, MRIO methods have been shown to be the appropriate methodological framework for the estimation of emission footprints (e.g. Karakurt et al., 2012; Lenzen et al., 2012; Weber and Matthews, 2008; Wiedmann, 2009), and the uncertainty issues are gradually overcome as the coverage and quality of MRIO tables improves.

All in all, the increase methane emissions have experienced since the turn of the millennium, together with their strong impact on global temperature trends, highlight the need to start a strong policy strategy to mitigate and abate CH_4 emissions to avoid reaching climate tipping-points in the near future. In this article, we aimed to bring methane emissions closer to the focus of policy discussions and to facilitate research in that area by providing a comprehensive and easily accessible dataset on methane emissions.

Declaration of competing interest

The authors declare that they have no relevant or material financial interests or conflict of interest that relate to the research described in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2019.106528.

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