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JEL Classification: F18, F64, O44, Q54, Q56

Keywords: methane emissions, MRIO analysis, production-based inventories, methane footprints, decomposition analysis, emissions embodied in trade

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

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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 (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, but international cooperation for the reduction of methane is largely lacking. The Kyoto Protocol (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 Nentjes and Klaassen, 2004, Hagem et al., 2005, Feaver and Durrant, 2008, Aichele and Felbermayr, 2012). 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, those national contributions are not legally binding as the signatories are only required to report on their progress on reaching their NDCs (Jacquet

[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.

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 are implemented, the global median temperature will rise between 2.6 and 3.1 degrees Celsius until 2100 instead of the "well below 2 degrees Celsius" target of the Paris Agreement.

In the context of international trade, emission leakage poses 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 Copeland and Taylor, 2005, Aichele and Felbermayr, 2015). 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 can 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), Wilting and Vringer (2009), Peters et al. (2011a) 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, 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 Peters, 2008, Peters et al., 2011b, Koopman et al., 2014, Fernández-Amador et al., 2016).[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 130% 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-

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

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 the 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.

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 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

[3] An overview of the regions and sectors covered is available in Tables A.1 and A.2 in Appendix A. For calculations, we first aggregated to 78 regions (66 countries and 12 regions) and 57 sectors. After that, we calculated the inventories. Thus, potential aggregation bias can be assumed 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.

to 57 economic sectors (see Rose and Lee, 2008, Rose et al., 2010, Ahmed et al., 2014, Irfanoglu and van der Mensbrugghe, 2015, 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]

[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.

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. Those results reinforce our approach to calculate a dataset based on the same raw data and methodology for all the years in our sample that can be used for panel analyses.

[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 the Appendix B for a detailed description of the estimation methodology used.

[6] On a 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). Those emissions are not distributed across countries in the IPCC national inventories. In contrast, we allocate them to individual countries 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.

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).

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 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 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 thirds countries via global value chains before reaching the final producer or consumer. Details on each of these steps involved 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]

	CH_4 (CO_2e, 100y)		**CH_4** (CO_2e, 20y)		**CO_2**
	Mt	% of CO_2	Mt	% of CO_2	Mt
1997	7982	35%	23947	105%	22702
2001	7880	34%	23641	103%	23054
2004	8312	32%	24935	95%	26359
2007	8731	30%	26193	91%	28652
2011	9229	30%	27686	90%	30930
2014	9428	30%	28283	91%	31011

Table 1: Global CH_4 and CO_2 emissions. 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). This data were recently updated by the authors to include 2014.

The sectoral distribution of methane emissions differs considerably between production-based and footprint-based emission inventories (see Figure 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 Figure 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.

[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. This 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.

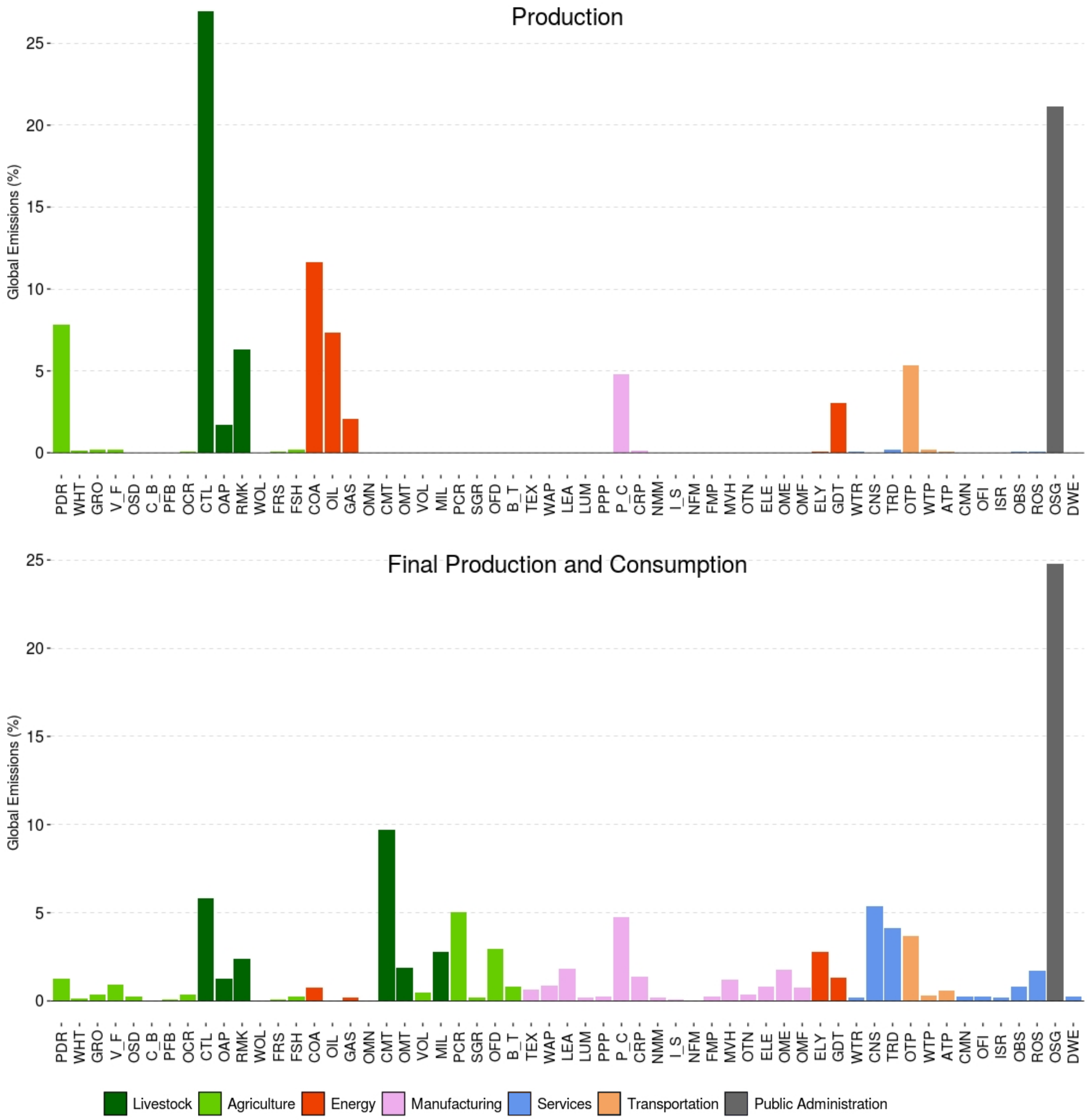

Figure 1: Sector shares of global CH_4 emissions (average 1997–2014). The barplots show CH_4 emissions associated with production (upper plot) and final production and consumption (lower plot) in each of the 57 sectors as shares of global methane emissions. On a global level, methane emissions associated 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.

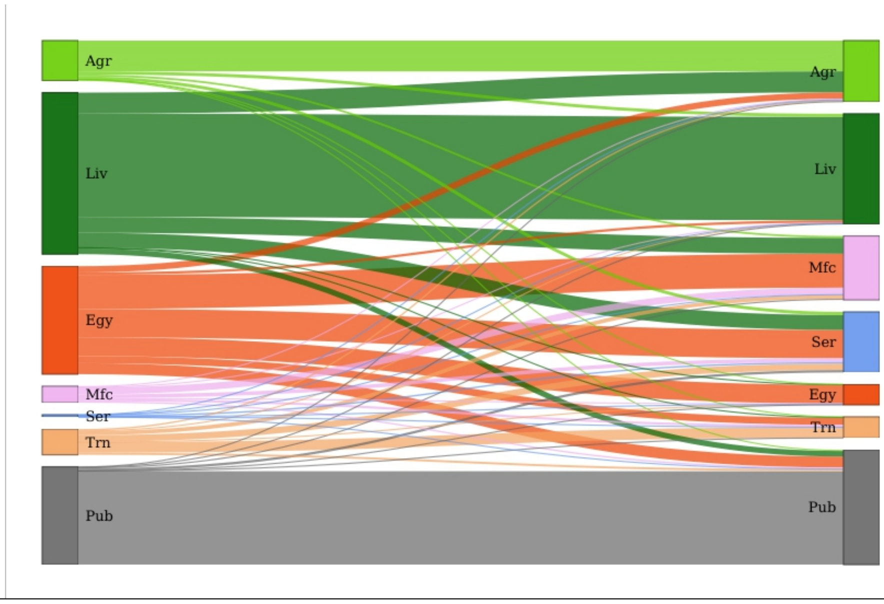

Figure 2: Sectoral emission flows (average 1997–2014). The graph shows the reallocation of emissions across sectors from the sector of production on the left hand-side to the sector of final production and consumption on the right hand-side. Agr. stands for agriculture, Liv. for livestock, Egy. for energy, 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.

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 Figure 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 GHG 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 (IPCC, 1995, Fuglestvedt et al., 2003, Fesenfeld et al., 2018).

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.

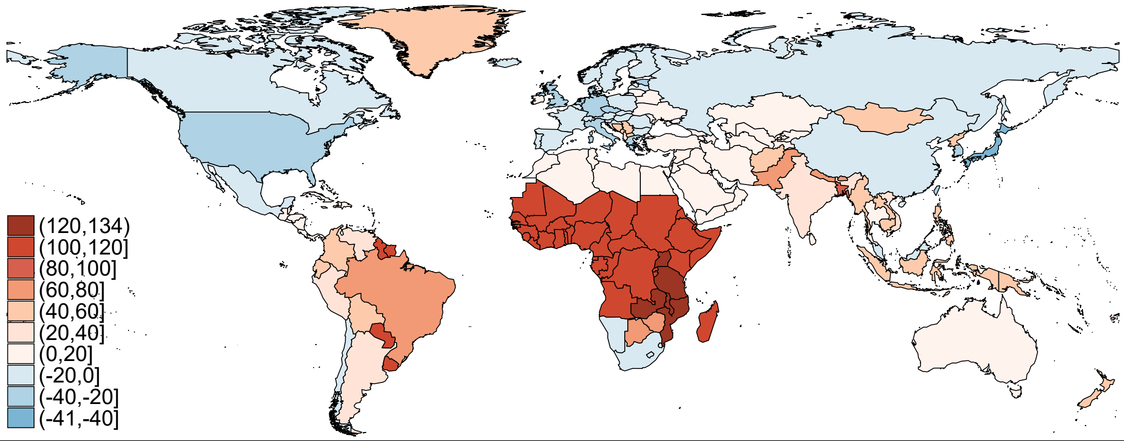

Figure 3: Percentage change of GHG emissions (CO_2 and CH_4) using different GWPs (2014). The figure shows the percentage change in GHG emissions from production (measured as CO_2 equivalents of CO_2 and CH_4) when GWP_{20} is used instead of GWP_{100} to convert emissions to a common scale, as compared 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).

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 value added, as a measure of methane efficiency.[9] Table 2 provides a summary of these three indicators for the four income groups defined by the World Bank and for the most important producers

[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 Leontief-inverse matrix as explained in the methodology section for CH_4 emissions.

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. Exceptions to this general pattern were large producers of 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 and 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 their 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 their methane per value added by approximately 52% and 48%, respectively. The high- and

[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.

	Total CH_4*						CH_4 pc*		CH_4 per VA*	
	production		**final prod.**		**consumption**		**prod.**	**cons.**	**prod.**	**cons.**
	(Mt)	(%)	(Mt)	(%)	(Mt)	(%)	(t per capita)		(kg/USD)	
					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
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

Table 2: Main indicators for CH_4 inventories: 1997 and 2014. Selected regions. Note: *Data reported as CO_2 equivalents with respect to global warming potential for a 100-year period. 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 and 2007, including the upper-middle income countries Bulgaria and Romania, and Croatia; 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.

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 the Appendix), 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 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.

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

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

CH_4 per value added, (ii) the growth rate of value added per capita, and (iii) population growth. The decomposition is implemented as

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

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 approximates growth rates by 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 Figure 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 (Figure 5) revealed that the aggregate pattern described above hides important sector specificities. Although efficiency gains were important on the aggregate level, 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

[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 contributed 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 led to a slight increase in emissions from production (see Figure D.1 in Appendix D).

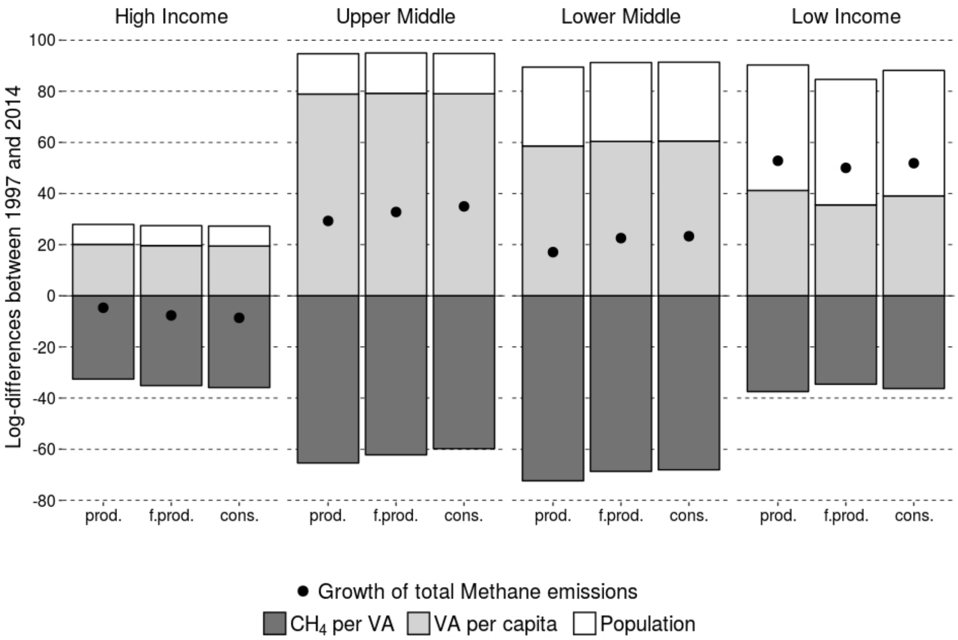

Figure 4: Change in components of the Kaya identity (1997–2014). Note: The barplots show the log differences of the components of the Kaya identity between 1997 and 2014 for the four World Bank income groups. The Kaya identity decomposes total CH_4 emissions into CH_4 per value added, value added per 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.

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 (Kuznets, 1973, Herrendorf et al., 2013). 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.

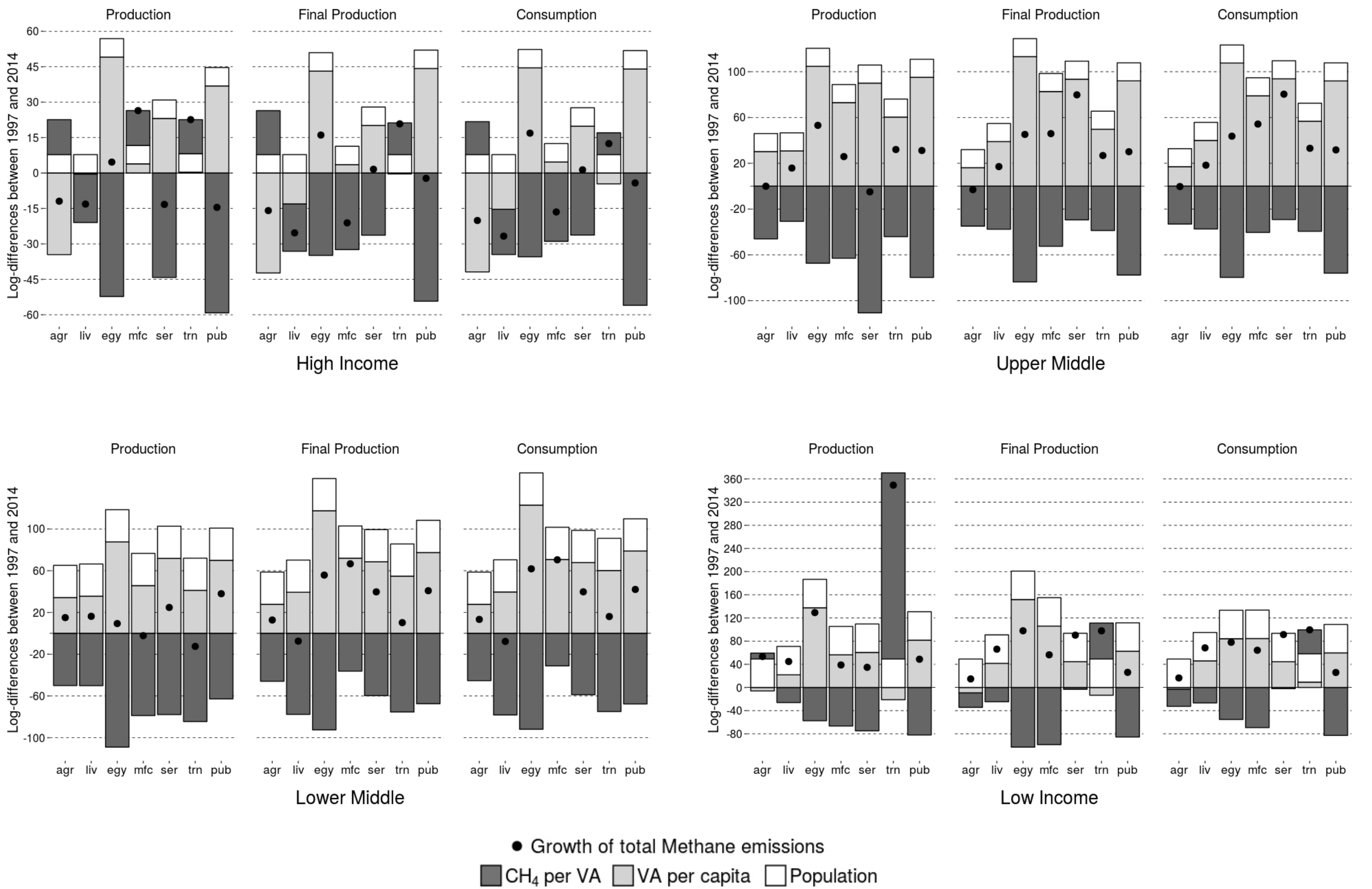

Figure 5: Change in components of the Kaya identity (1997–2014, sectors). Note: The barplots show the log differences of the components of the Kaya identity between 1997 and 2014 for seven sectors of the four World Bank income groups. The Kaya identity decomposes sectoral CH_4 emissions into CH_4 per value added, value added per capita, and population, according to the formula $CH_4 = \frac{CH_4}{VA} \cdot \frac{VA}{pop} \cdot pop$. 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.

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).

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

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.

The results shown in Figure 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. Also, 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 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.

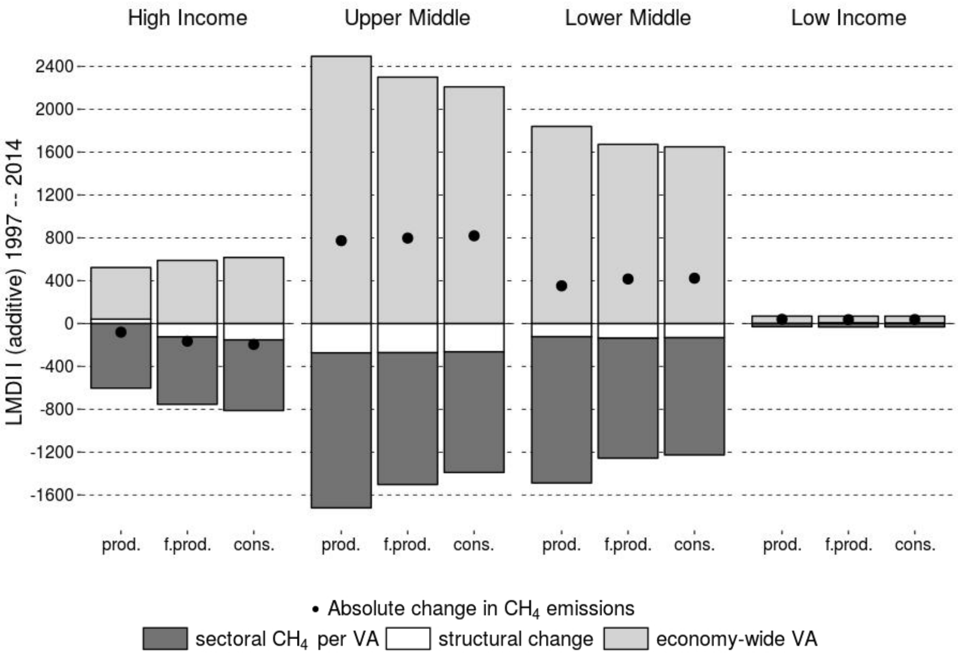

Figure 6: Additive LMDI decomposition of changes in CH_4 emissions (1997–2014). Note: The barplots show the decomposition of changes in CH_4 emissions in physical units (Mt. of CO_2 eq., 100y) between 1997 and 2014 for the four World Bank income groups. The additive LMDI decomposition decomposes changes 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 growth rate of total emissions (in log differences), marked as black dot.

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-

	Embodied CH_4^*				CH_4 non-Annex I*		CH_4 per VA*	
	exports	**imports**	**BEETT**	**BEETI**	**prod.**	**imports**	**exports**	**imports**
		(% of prod.	emissions)		(% of)		(kg/USD)	
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

Table 3: CH_4 emissions embodied in trade: 1997 and 2014. Selected regions and income groups. Note: *Data are reported as CO_2 equivalents with respect to global warming potential for a 100 year time frame. 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). EEU stands for Eastern European Union members joining the Union in 2004 and 2007. EU 15 denotes the member states of the EU before the Eastern European members joined the union. In both groups trade flows between the members have been retained when calculating the aggregated figures. The EU 15 group includes the upper middle income countries Bulgaria and Romania. For the income group aggregates these countries were assigned to the upper-middle-income group. 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.

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 Annex I of 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. For 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. Figure 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 Figure E.1 in the Appendix). Most developing countries in Figure 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 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.

[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.

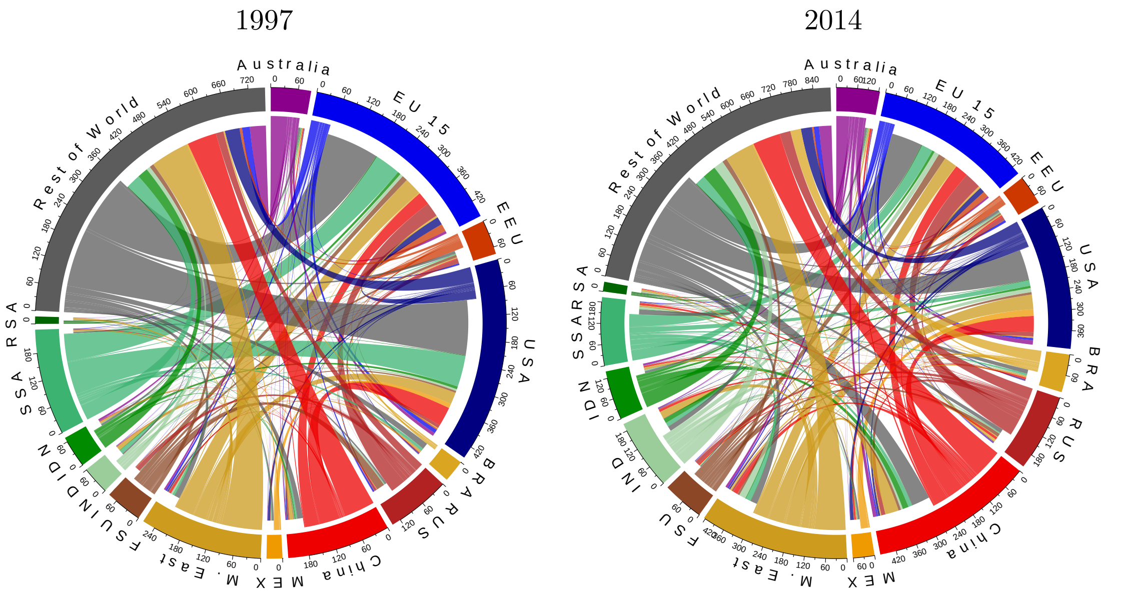

Figure 7: Traded methane emissions by region of origin and destination (1997 and 2014). Note: The circle-plots show traded CH_4 emissions accruing to consumption for the most important producers of CH_4 emissions and the Rest of World aggregate region. Trade-embodied emissions are reported in megatonnes (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. Figure 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).

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 (Myhre et al., 2013, Fesenfeld et al., 2018). Choosing alternative time horizons can substantially alter emission footprints across countries and sectors (Fuglestvedt et al., 2003, Shine, 2009, Myhre et al., 2013, Fesenfeld et al., 2018) 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. Smith et al. (2012), Myhre et al. (2013), 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 to 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 (Höglund-Isaksson, 2012, Estrada et al., 2013, Shindell et al., 2012, 2017). 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 et al., 2008, Lenton, 2011, 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 developing countries (see Jackson, 2009, Fernández-Amador et al., 2016, 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

[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.

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 Peters and Hertwich, 2008c, Wiedmann, 2009, Fesenfeld et al., 2018). 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, Kai et al., 2011, Höglund-Isaksson, 2012, Karakurt et al., 2012). Therefore, the potential for mitigation of individual countries should be considered at a 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 (Wiedmann, 2009, Lenzen et al., 2012). 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 Munksgaard and Pedersen, 2001, Andrew and Forgie, 2008, 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 (Wiedmann, 2009, Lenzen et al., 2012).

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. Weber and Matthews, 2008, Wiedmann, 2009, Lenzen et al., 2012, Karakurt et al., 2012), 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.

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Online Appendices

A Data appendix

Aggregate	Countries and regions included
	Single Countries and Regions:
The 66 single countries and regions	Albania, Argentina, Australia, Austria, Belgium, Bangladesh, Bulgaria, Brazil, Botswana, Canada, Chile, China, Colombia, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hong Kong, Hungary, India, Indonesia, Ireland, Italy, Japan, Korea, Latvia, Lithuania, Luxembourg, Malawi, Malaysia, Malta, Mexico, Morocco, Mozambique, Netherlands, New Zealand, Peru, Philippines, Poland, Portugal, Romania, Russia, Singapore, Slovakia, Slovenia, Spain, Sri Lanka, Sweden, Switzerland, Taiwan, Tanzania, Thailand, Turkey, Uganda, United Kingdom, United States, Uruguay, Venezuela, Vietnam, Zambia, Zimbabwe
	The 12 Composite Regions:
Rest of Andean Pact	Bolivia and Ecuador
Central America, Caribbean	Anguilla, Antigua and Barbuda, Aruba, Bahamas, Barbados, Belize, Cayman Islands, Costa Rica, Cuba, Dominica, Dominican Republic, El Salvador, Grenada, Guatemala, Haiti, Honduras, Jamaica, Netherlands Antilles, Nicaragua, Panama, Saint Helena, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Trinidad and Tobago, and Virgin Islands (US,GB).
Rest of EFTA	Iceland, Liechtenstein and Norway.
Rest of Former Soviet Union	Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Tajikistan, Turkmenistan, Ukraine, and Uzbekistan.
Middle East	Bahrain, Iran (Islamic Republic of), Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, United Arab Emirates and Yemen.
Rest of North Africa	Algeria, Egypt, Libya and Tunisia
Other Southern Africa	Angola and Congo (DPR)
Rest of South African Customs Union	Lesotho, Namibia, South Africa and Swaziland
Rest of South America	Guyana, Paraguay and Suriname
Rest of South Asia (RSA)	Bhutan, Maldives, Nepal and Pakistan
Rest of Sub-Saharan Africa (SSA)	Benin, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Côte d'Ivoire, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Liberia, Madagascar, Mali, Mauritania, Mauritius, Mayotte, Niger, Nigeria, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, Sudan and Togo
Rest of World	Afghanistan, American Samoa, Andorra, Bosnia and Herzegovina, Brunei Darussalam, Cambodia, China, Macao SAR, Cook Islands, Democratic People's Republic of Korea, Falkland Islands (Malvinas), Faroe Islands, Fiji, French Guiana, French Polynesia, Gibraltar, Greenland, Guam, Isle of Man, Kiribati, Lao People's Democratic, Republic, Marshall Islands, Micronesia (Federated States of), Mongolia, Montenegro, Myanmar, Nauru, New Caledonia, Niue, Norfolk Island, Northern Mariana Islands, Occupied Palestinian, Territory, Palau, Papua New Guinea, Pitcairn Islands, Samoa, Serbia, Solomon Islands, The former Yugoslav Republic of Macedonia, Timor-Leste, Tokelau, Tonga, Tuvalu, Vanuatu and Wallis and Futuna Islands.

Table A.1: Countries and composite regions in the database. Note: Computations were performed using the regional aggregation of GTAP 5. The table shows also countries which appear in later GTAP databases, which are, however, too small to change results. They are mainly small islands states or territories belonging to the jurisdiction of another country, which show up in one of the later composite regions (Wallis and Futuna, for example). The only notable exceptions are Timor-Leste and Greenland.

Final Dem. Sector	Detailed Sectors
Agriculture (agr.)	Paddy rice (pdr); Wheat (wht); Cereal grains nec (gro); Vegetables, fruit, nuts (v_f); Oil seeds (osd); Sugar cane, sugar beet (c_b); Plant-based fibers (pfb); Crops nec (ocr); Forestry (frs); Fishing (fsh); Sugar (sgr); Food products nec (ofd); Beverages and tobacco products (b_t); Vegetable oils and fats (vol); Processed rice (pcr);
Livestock (liv.)	Cattle, sheep, goats, horses (ctl); Animal products nec (oap); Raw milk (rmk); Wool, silk-worm cocoons (wol); Meat: cattle, sheep, goats, horse (cmt); Meat products nec (omt); Dairy products (mil);
Manufacturing (mfc.)	Textiles (tex); Wearing apparel (wap); Leather products (lea); Wood products (lum); Paper products, publishing (ppp); Chemical, rubber, plastic products (crp); Mineral products nec (nmm); Ferrous metals (i_s); Metals nec (nfm); Metal products (fmp); Motor vehicles and parts (mvh); Petroleum, coal products (p_c); Transport equipment nec (otn); Electronic equipment (ele); Machinery and equipment nec (ome); Manufactures nec (omf);
Transport (trn.)	Transport nec (otp); Sea transport (wtp); Air transport (atp);
Services (ser.)	Water utility services (wtr); Construction (cns); Trade and distribution (trd); Communication (cmn); Financial services nec (ofi); Insurance (isr); Business services nec (obs); Recreation and other services (ros); Dwellings (dwe);
Energy (egy.)	Coal (coa); Oil (oil); Gas (gas); Minerals nec (omn); Electricity (ely); Gas manufacture, distribution (gdt);
Public Administration (pub.)	Public Administration (osg);

Table A.2: Aggregation of sectors into final demand sectors. Note: Original 57 sectors merged into 7 sectors according to final demand uses. This aggregation was used for the econometric analysis of CH_4 drivers.

Category	IPCC	GTAP	1997	2001	2004	2007	2011	2014
FAO CH_4 emissions – *total*			43.77	44.92	43.76	43.13	41.88	40.50
FAO CH_4 categories matched to GTAP sectors:								
Rice Cultivation	4C	pdr	8.08	8.18	7.72	7.56	7.50	7.41
Burning Crops Residues	4F		0.31	0.31	0.30	0.30	0.30	0.30
of which:								
Maize		gro	0.13	0.13	0.13	0.14	0.14	0.15
Paddy Rice		pdr	0.08	0.08	0.08	0.07	0.07	0.07
Sugar Cane		c_b	0.01	0.01	0.01	0.01	0.01	0.01
Wheat		wht	0.09	0.08	0.08	0.08	0.07	0.07
Burning Savanna	4E	ctl	1.59	2.06	1.74	1.63	1.77	1.13
Enteric Fermentation	4A		30.70	31.25	30.95	30.63	29.42	28.79
of which:								
Cattle, dairy		rmk	5.81	5.79	5.68	5.60	5.54	5.33
Cattle, non-dairy[b]		ctl	24.55	25.11	24.93	24.69	23.55	23.12
Swines		oap	0.34	0.35	0.34	0.34	0.34	0.33
Manure Management	4B		3.09	3.12	3.04	3.00	2.89	2.88
of which:								
Cattle, dairy		rmk	0.73	0.71	0.67	0.65	0.63	0.62
Cattle, non-dairy[b]		ctl	1.06	1.06	1.03	1.02	0.98	0.96
Poultry/Swines[c]		oap	1.30	1.35	1.33	1.32	1.29	1.30
EDGAR CH_4 emissions – *total*			56.23	55.08	56.24	56.87	58.12	59.50[a]
EDGAR CH_4 categories matched directly to a single GTAP sector:								
Coal Mining	1B1	coa	8.93	9.23	10.57	11.70	12.79	13.36[a]
Other - Chemicals	2B	crp	0.04	0.05	0.05	0.06	0.08	0.09[a]
Landfilling	6A	osg	9.60	9.71	9.36	9.16	8.79	8.75[a]
Wastewater Treatment	6B	osg	10.27	11.06	11.08	11.21	11.37	11.61[a]
EDGAR CH_4 categories matched to more than one GTAP sector:								
Combustion[d]	1A1 - 1A4		4.97	4.84	4.80	4.68	4.66	4.64[a]
of which:								
Energy Industries	1A1	coa, oil, gas p_c, ely, gdt	0.09	0.09	0.11	0.12	0.13	0.14[a]
Industrial Sectors	1A2	omn, cmt, omt vol, mil, pcr sgr, ofd, b_t tex, wap, lea lum, ppp, crp nmm, i_s, nfm fmp, mvh, otn ele, ome, omf	0.15	0.16	0.16	0.17	0.17	0.17[a]
Transport Sectors	1A3	otp, wtp, atp	0.26	0.24	0.23	0.22	0.24	0.26[a]
Agriculture and Services	1A4	pdr, wht, gro v_f, osd, c_b pfb, ocr, ctl oap, rmk, wol frs, fsh, wtr trd, cmn, ofi isr, obs osg	4.47	4.34	4.30	4.17	4.11	4.07[a]
Oil and Gas Fugitives[e]	1B2	oil, gas, p_c gdt, otp	22.40	20.20	20.37	20.06	20.41	21.01[a]
Other - Metals[f]	2C	i_s, nfm	0.01	0.01	0.01	0.01	0.02	0.02[a]

Table A.3: CH_4 Emissions from FAO and EDGAR categories (percentage of total annual emissions). Note: [a] EDGAR data for 2014 is predicted. See the *Appendix B* for a detailed description of the methodology applied. [b] Includes Asses, Buffalos, Camels, Goats, Horses, Llamas, Mules and Sheep. [c] Includes Chicken, Ducks and Turkeys and Swines. [d] Stationary and mobile combustion. [e] Including exploration, distribution, flaring, leakage at industrial plants, power stations, commercial and residential sectors, refining, storage, venting and transport. [f] Including aluminium, ferroalloys, iron, steel production, and other metals.

		Production inventory							Footprint inventories						
	Sec.	1997	2001	2004	2007	2011	2014	Avg.	1997	2001	2004	2007	2011	2014	Avg.
Agriculture	pdr	8%	8%	8%	8%	8%	8%	8%	3%	2%	1%	1%	1%	1%	1%
	wht	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	gro	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	v_f	-	-	-	-	-	-	-	1%	1%	1%	1%	1%	1%	1%
	osd	-	-	-	-	-	-	-	-	1%	-	-	-	-	-
	c_b	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	pfb	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	ocr	-	-	-	-	-	-	-	-	1%	-	-	-	-	-
	frs	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	fsh	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	pcr	-	-	-	-	-	-	-	5%	6%	5%	5%	5%	5%	5%
	sgr	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	ofd	-	-	-	-	-	-	-	3%	3%	3%	3%	3%	3%	3%
	b_t	-	-	-	-	-	-	-	1%	1%	1%	1%	1%	1%	1%
	vol	-	-	-	-	-	-	-	1%	-	-	1%	1%	1%	1%
	Total	**9%**	**9%**	**8%**	**8%**	**9%**	**8%**	**9%**	**15%**	**15%**	**13%**	**12%**	**13%**	**13%**	**13%**
Livestock	ctl	27%	28%	28%	27%	26%	25%	27%	8%	6%	6%	5%	5%	5%	6%
	oap	2%	2%	2%	2%	2%	2%	2%	1%	2%	1%	1%	1%	1%	1%
	rmk	7%	7%	6%	6%	6%	6%	6%	3%	3%	3%	2%	2%	2%	2%
	wol	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	cmt	-	-	-	-	-	-	-	9%	9%	10%	10%	10%	10%	10%
	omt	-	-	-	-	-	-	-	2%	3%	2%	2%	2%	2%	2%
	mil	-	-	-	-	-	-	-	2%	3%	3%	3%	3%	3%	3%
	Total	**36%**	**37%**	**36%**	**44%**	**34%**	**33%**	**35%**	**26%**	**24%**	**25%**	**35%**	**23%**	**22%**	**24%**
Manufacturing	tex	-	-	-	-	-	-	-	1%	1%	1%	1%	1%	1%	1%
	wap	-	-	-	-	-	-	-	1%	1%	1%	1%	1%	1%	1%
	lea	-	-	-	-	-	-	-	2%	2%	2%	2%	2%	2%	2%
	lum	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	ppp	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	p_c	4%	5%	6%	6%	4%	4%	5%	4%	5%	6%	5%	4%	4%	5%
	crp	-	-	-	-	-	-	-	1%	1%	1%	1%	1%	2%	1%
	nmm	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	i_s	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	nfm	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	fmp	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	mvh	-	-	-	-	-	-	-	1%	1%	1%	1%	1%	1%	1%
	otn	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	ele	-	-	-	-	-	-	-	1%	1%	1%	1%	1%	1%	1%
	ome	-	-	-	-	-	-	-	1%	1%	2%	2%	2%	2%	2%
	omf	-	-	-	-	-	-	-	1%	1%	1%	1%	1%	1%	1%
	Total	**5%**	**5%**	**6%**	**6%**	**4%**	**5%**	**5%**	**14%**	**15%**	**15%**	**17%**	**15%**	**16%**	**15%**
Trn.	otp	6%	6%	4%	5%	6%	6%	5%	4%	4%	3%	4%	4%	4%	4%
	wtp	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	atp	-	-	-	-	-	-	-	1%	1%	1%	1%	1%	1%	1%
	Total	**6%**	**6%**	**5%**	**5%**	**6%**	**6%**	**6%**	**5%**	**5%**	**4%**	**4%**	**5%**	**5%**	**5%**
Services	wtr	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	cns	-	-	-	-	-	-	-	4%	4%	5%	6%	6%	7%	5%
	trd	-	-	-	-	-	-	-	4%	4%	5%	5%	4%	4%	4%
	cmn	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	ofi	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	isr	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	obs	-	-	-	-	-	-	-	1%	1%	1%	1%	1%	1%	1%
	ros	-	-	-	-	-	-	-	2%	2%	2%	2%	2%	2%	2%
	dwe	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Total	**1%**	**0%**	**0%**	**0%**	**1%**	**1%**	**1%**	**12%**	**11%**	**13%**	**14%**	**14%**	**15%**	**13%**
Energy	coa	9%	10%	11%	12%	13%	14%	12%	1%	1%	1%	1%	1%	1%	1%
	oil	9%	6%	8%	7%	7%	7%	7%	-	-	-	-	-	-	-
	gas	2%	2%	2%	2%	2%	2%	2%	-	-	-	-	-	-	-
	omn	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	ely	-	-	-	-	-	-	-	3%	3%	3%	3%	3%	3%	3%
	gdt	3%	3%	3%	3%	3%	3%	3%	1%	1%	2%	2%	1%	2%	1%
	Total	**23%**	**22%**	**24%**	**25%**	**25%**	**26%**	**24%**	**4%**	**6%**	**6%**	**5%**	**5%**	**5%**	**5%**
P.	osg	21%	21%	21%	21%	21%	22%	21%	24%	25%	25%	25%	25%	25%	25%

Table A.4: Sector shares of global methane emissions. Note: The table shows sectoral CH_4 emissions embodied in production and in footprint inventories (final production and consumption) as percentage of global CH_4 emissions. Avg. stands for average across all years. Trn. stands for transport and P. stands for public administration. A - indicates a sector share of less than 0.5%. Sector shares might not sum to 100% due to rounding. For abbreviations of sector names, see Table A.2.

	Agr.	Liv.	Egy.	Mfc.	Ser.	Trn.	Pub.
				Production			
High Income	2%	34%	27%	4%	0%	7%	26%
Upper Middle	8%	33%	28%	6%	0%	6%	20%
Lower Middle	16%	38%	17%	5%	1%	4%	19%
Low Income	7%	55%	8%	4%	2%	1%	24%
Global	**9%**	**35%**	**24%**	**5%**	**1%**	**6%**	**21%**
				Final Production			
High Income	5%	20%	7%	17%	18%	6%	27%
Upper Middle	10%	26%	5%	17%	13%	5%	25%
Lower Middle	28%	25%	3%	12%	7%	3%	22%
Low Income	11%	49%	2%	7%	5%	1%	26%
Global	**13%**	**24%**	**5%**	**15%**	**13%**	**5%**	**25%**
				Consumption			
High Income	6%	19%	7%	20%	17%	6%	26%
Upper Middle	10%	27%	6%	14%	14%	5%	26%
Lower Middle	27%	26%	2%	12%	7%	3%	22%
Low Income	11%	49%	2%	8%	5%	1%	26%
Global	**13%**	**24%**	**5%**	**15%**	**13%**	**5%**	**25%**

Table A.5: Sector shares of total CH_4 emissions, global and by income groups (average 1997–2014). Note: Sector shares of CH_4 emissions averaged over all years (1997, 2001, 2004, 2007, 2011, 2014). 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 a detailed definition of these sectors and their correspondence with the 57 detailed sectors see Table A.2. Sector shares might not sum to 100% due to rounding. On a global level, sector shares of final production and final consumption are equal.

B Forecasts of methane emissions for EDGAR categories in 2014

Methane emissions corresponding to the FAO categories are available for 2014 from the FAO database. However, emissions from the EDGAR database are only available until 2012. Therefore, we extend methane emissions corresponding to the categories from the EDGAR database to 2014 by using univariate time series forecasting methods. These methods perform rather well when forecasting in short term horizons, and, importantly, since the forecasts only rely on the properties of the series, the data can be used in further research where emissions are related to other variables, avoiding problems of circularity. For a subset of the countries for which we forecast methane emissions, figures of total CH_4 emissions for 2013 and 2014 are available from the OECD. Therefore, we implement two procedures, depending on whether such OECD information is available.[16]

[16] The territories for which OECD series are available are Austria, Czech Republic, Estonia, France, Germany, Hungary, Iceland, Italy, Japan, Lithuania, Latvia, Netherlands, New Zealand, Poland, Portugal, Russian Federation, Spain, Sweden, United Kingdom, United States. For the other territories only EDGAR series are available.

For the countries for which OECD emission data are available for 2014, we condition our forecasts on that information. The procedure is carried out as follows. First, we calculate an aggregate of non-agricultural sectors from the EDGAR series (EDGAR-based non-agricultural aggregate) by subtracting the EDGAR categories corresponding to FAO categories from total emissions from the EDGAR database. A proxy for the same aggregate is obtained from the OECD series (OECD-based non-agricultural aggregate) by subtracting emissions contained in the FAO categories from OECD total emissions. EDGAR and OECD measurements are not equal but show high correlation. We regress the EDGAR-based non-agricultural aggregate on its 1-year lagged value and the OECD-based non-agricultural aggregate using ARIMAX models. Specifically, we estimate the following model:

$$Y_t = \alpha + \rho Y_{t-1} + \beta X_t + \epsilon_t \ , \tag{B.1}$$

where Y_t refers to the EDGAR-based non-agricultural aggregate in period t, Y_{t-1} to the EDGAR-based non-agricultural aggregate in period $t-1$, X_t is the OECD-based non-agricultural aggregate in period t, and ϵ_t is the error term.[17] Therefore, the forecasts for the EDGAR non-agricultural aggregate will be based on its own dynamics and on available OECD information when the correlation between both non-agricultural aggregates is high. The inspection of the residuals did not report any specification problem and thus, based on the estimated ARIMAX specification, we forecast the EDGAR-based non-agricultural aggregate for the periods 2013 and 2014.

In parallel, we forecast the emissions for the EDGAR categories that are not available from the FAO database. The large amount of sectoral series and the short forecast horizon required make it convenient to use exponential smoothing techniques. For each category, we estimated an exponential smoothing model with additive damped trend (see Gardner and McKenzie, 1985, Hyndman et al., 2002, 2008a):

$$\hat{Y}_{t+h|t} = l_t + (1 + \phi + \ldots + \phi^{h-1}) b_t \tag{B.2}$$

$$l_t = \alpha Y_t + (1-\alpha)(l_{t-1} + \phi b_{t-1}) \tag{B.3}$$

$$b_t = \beta(l_t - l_{t-1}) + (1-\beta)\phi b_{t-1} \, , \tag{B.4}$$

where $\hat{Y}_{t+h|t}$ is the forecast of the series—i.e., the corresponding EDGAR category not available from the FAO database—in period $t+h$ conditioned on information in t, Y_t

[17] In two cases, Spain and Italy, the estimate of the autoregressive parameter ρ was outside the region of stationarity. In those cases, we estimated a similar model in first-differences.

is such an EDGAR category in period t, l_t is the level of the series, b_t is the damped trend, α and β are the smoothing parameters, and ϕ is the damping parameter. The parameters were estimated by minimizing the mean square error. Additive damped trends have shown a good performance in forecasting, being often the benchmark among the class of exponential smoothing models, while they are still conservative in comparison to multiplicative damped trends.[18]

Finally, we must reconcile the aggregate forecasts and the forecasts for the categories. Since the aggregate forecasts rely on available information for 2014 from the OECD, we consider them as the reference for sectoral (category) emission forecasts. Therefore, we normalize the sectoral forecasts to the forecast of the non-agricultural EDGAR aggregate.

For each of the countries without total emissions available from the OECD data for 2014, we calculate the non-agricultural EDGAR aggregate as the sum of the EDGAR categories that do not correspond to FAO categories. We forecast this series using the exponential smoothing model with additive damped trend as explained above for the model (B.2)-(B.4). In parallel, we estimate exponential smoothing models using the model (B.2)-(B.4) and forecast EDGAR sectoral emissions as we did for the countries with available information from the OECD. To be consistent with the normalization carried out for the countries for which OECD data were available, the sectoral forecasts are normalized to the forecast of the non-agricultural EDGAR aggregate.

As a measure of robustness to the benchmark for national aggregate emissions, we computed the discrepancy between the benchmark used for normalization (top-down) and a bottom-up alternative using the sum of the sectoral forecasts as a benchmark. The divergences between the two alternatives were mostly below 2% for the countries for which only EDGAR information was available, where the method of estimation was the same for aggregate and sectoral emission series. In the countries were OECD information was available, divergences were slightly larger but mostly below 4%, probably as a result of the different estimation methods for aggregate and sectoral emission series.

[18] See Gardner and McKenzie (1985, 2010, 2011), Hyndman et al. (2002, 2008b), and Taylor (2003). Traditional restrictions on the parameters are $\alpha, \beta, \phi \in (0,1)$; Hyndman et al. (2002, 2008b) restrict them further in the state-space model used for estimation. The errors enter the model in either additive or multiplicative form, the selection being made by using the Bayesian Information Criterion (BIC, Schwarz, 1978). This is only relevant for the determination of the confidence intervals, being the point-wise forecasts identical for the two models.

C Calculation of footprint-based emission inventories

Footprint-based CH_4 inventories are derived using MRIO techniques, which combine the production-based emission inventories calculated with input-output (IO) and trade data sourced from GTAP.

This is done in three steps. First, we construct a global intermediate input requirements matrix based on IO and trade data. From this matrix we derive the Leontief-inverse matrix, which collects the direct and indirect input requirements to generate a unit of output for each sector in each region. Finally, we rescale the Leontief-inverse matrix with emission-intensities and multiply it with the matrices of final production or consumption to derive final production- and consumption-based emission inventories for each sector and at the national level. As a side-product, we also obtain two measures of emissions embodied in trade flows, namely emissions embodied in intermediates used for final production and emissions embodied in inputs for final consumption. In what follows we describe the steps to derive the footprint inventories in detail.

Let us define the vector of sectoral gross outputs in region i as $x_i = (x_{i,1}, x_{i,2}, \ldots, x_{i,s})'$, where the dimension s is the number of sectors defined in the economy (57 in our case) and $i \subseteq [1, n]$, where n denotes the total number of regions considered (78 in our case). The gross output of a sector is used as intermediate input for another sector or as final demand. The companion vector of sectoral gross output for all the n regions, x, is equal to the intermediates required as inputs from all sectors in all regions, Ax, plus final demands from all regions, $Y\iota_n$. That is,

$$x = Ax + Y\iota_n \tag{C.1}$$

or

$$\begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_n \end{pmatrix} = \begin{pmatrix} A_{11} & A_{12} & A_{13} & \cdots & A_{1n} \\ A_{21} & A_{22} & A_{23} & \cdots & A_{2n} \\ A_{31} & A_{32} & A_{33} & \cdots & A_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A_{n1} & A_{n2} & A_{n3} & \cdots & A_{nn} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_n \end{pmatrix} + \begin{pmatrix} y_{11} & y_{12} & \cdots & y_{1n} \\ y_{21} & y_{22} & \cdots & y_{2n} \\ y_{31} & y_{32} & \cdots & y_{3n} \\ \vdots & \vdots & \ddots & \vdots \\ y_{n1} & y_{n2} & \cdots & y_{nn} \end{pmatrix} \begin{pmatrix} 1 \\ 1 \\ 1 \\ \vdots \\ 1 \end{pmatrix} \tag{C.2}$$

The matrix A with elements A_{rp} is the global intermediate input requirements matrix, which collects all the intermediate input requirements of all sectors in all regions. Following input–output conventions the first subscript in A_{rp} denotes the region of origin of a transaction (or exporter) and the second subscript denotes the region of destination (or importer). Each A_{rp} is a $s \times s$ matrix of trade in intermediates from region r to region p (which refers to domestic flows wherever $r = p$). The components of the A_{rp} matrices are normalized to sectoral gross output; thus, each element a_{kj} in A_{rp} denotes the direct inputs from sector k in region r needed for a sector j in region p to produce one dollar of output, where $k, j \subseteq [1, s]$. We calculate A for each year from IO and trade data, following Peters et al. (2011a).[19]

Each element y_{rp} in the last matrix appearing on the right-hand side of equation (C.2), Y, denotes the final demand in region p for products from region r. More specifically, $y_{rp} = (y_{rp,1}, y_{rp,2}, \ldots, y_{rp,s})'$ is a column vector of dimension s, where each element, $y_{rp,z}$, is the demand in region p for final products from sector z in region r. The product of the final demand matrix, Y, and a column vector of ones of length n, ι_n, results in the column vector of total final demands, y, produced in each region r.

Solving equation (C.1), $x = Ax + y$, for the companion vector of gross output, we obtain $x = (I - A)^{-1}y$. The matrix $(I - A)^{-1}$ is the Leontief-inverse matrix, where I is the identity matrix. Both matrices are of dimension $(n \cdot s) \times (n \cdot s)$. The Leontief-inverse matrix in the multi-regional framework is the matrix of total (direct and indirect) unit input requirements of each sector in each region for intermediates from each sector in each region. The columns of the Leontief-inverse matrix show the unit input requirements (direct and indirect) from all other producers (rows), to generate one dollar of output. Denoting its sub-matrices as $(I - A)^{-1}_{rp}$, each element $\tilde{a}_{kj}$ in $(I - A)^{-1}_{rp}$ contains the direct and indirect inputs needed from sector k in region r to produce one dollar of output in sector j in region p.

Next, the final production- and consumption-based emission inventories are derived for each sector and region in our sample. For this, we first calculate the flux of emissions required for final production and consumption in region r (which also serves to construct emissions embodied in trade flows), and based on them, we derive final production- and consumption-based inventories for each sector and region.

To derive the flux of emissions required for final production and consumption in region r (i.e. F^o_r and F^c_r), we rescale the Leontief-inverse matrix by a matrix of emission-intensities (E) and multiply it, alternatively, with the matrices of final goods produced (O_r) and consumed (C_r) in region r.

$$F^o_r = E\,(I - A)^{-1}\,O_r \tag{C.3}$$

[19] Kanemoto et al. (2012) discussed several methods to compute emissions embodied in trade. A broader discussion of MRIO methodologies can be found in Davis and Caldeira (2010), Davis et al. (2011), and Peters (2008), among others.

$$F_r^c = E\,(I-A)^{-1}\,C_r \tag{C.4}$$

The diagonal matrix E of dimension $(n\cdot s)\times(n\cdot s)$ is the matrix of regional CH_4 emission-intensities, with main-diagonal elements $e=(e_1,e_2,\ldots,e_n)$. Each of its elements e_i is also a diagonal matrix with the diagonal consisting of the s-dimensional sectoral emission-intensities, $e_i=(e_{i,1},e_{i,2},\ldots,e_{i,s})$, where $e_{i,z}$ are CH_4 emissions from production processes per gross output of the corresponding sector $(x_{i,z})$. Thus, the term $E\,(I-A)^{-1}$ is the matrix of total (direct and indirect) CH_4 emissions embodied in global transactions of intermediates between each sector in each region.

The matrices O_r and C_r compile, respectively, the final goods produced and consumed in region r, disaggregated to each sector j. In order to construct them, we define the column vectors o_r and c_r, which are both of dimension $(n\cdot s)\times 1$ and contain all final goods that are produced (o_r) or consumed (c_r) in region r. Final good production by region r is collected in the s rows of Y that correspond to region r, while final good consumption by region r is collected in the r^{th} column of Y. Thus, o_r and c_r are defined as $o_r=(R\circ Y)\iota_n$ and $c_r=(P\circ Y)\iota_n$, where R and P are selection matrices of dimension $(n\cdot s)\times n$, ι_n is defined as above, and $\circ$ denotes the Hadamard (entrywise) product. Specifically, R contains ones in the s rows corresponding to region r and zeroes otherwise and P contains ones in the r^{th} column and zeroes otherwise. The elements of o_r and c_r, which are vectors of length s (e.g. $o_i=(0_s,\ \ldots,\ 0_s,\ (y_{i1}+y_{i2}+\ldots+y_{in}),\ 0_s,\ \ldots,0_s)'$ and $c_i=(y_{1i},\ y_{2i},\ y_{3i},\ldots,\ y_{ni})'$, for $r=i$), capture production and consumption of final goods in region r, by region and sector of origin.

A region produces final goods either for domestic use or for exporting. Accordingly, the non-zero entries of the vector o_r (i.e. y_{rn}) denote region r's exports of final goods in each sector to all n possible export destinations, including its own market (i.e. y_{rr}). The remaining $(n-1)$ elements of o_r, 0_s, are zero vectors of dimension s. On the other hand, regions typically consume final goods originated in several other regions. Accordingly, the elements of c_r (i.e. y_{nr}) denote imports of final products by region r from all n possible source regions and all possible sectors, including its own market (i.e. y_{rr}). The elements are zero only if there is no trade in final goods between the two regions.

The vectors o_r and c_r capture the production and consumption of final goods of all sectors in a given region r in one column. In order to organize the elements such that a specific sector appears in column j, we define ι_s' as a row vector of ones with length s and I_s as the identity matrix of dimension $s\times s$, and derive $O_r=(o_r\iota_s')\circ(\iota_n\otimes I_s)$ and $C_r=(c_r\iota_s')\circ(\iota_n\otimes I_s)$. Thus, O_r and C_r stack the $s\times s$ regional emission matrices and are of dimension $(n\cdot s)\times s$. The nonzero elements of the j^{th} column of matrix O_r capture the final goods produced by region r in sector j. Similarly, the nonzero elements of the j^{th} column of matrix C_r capture the final goods produced in sector j consumed by region r, accounting for the region of origin of these final goods.

Thus, the flux of emissions required for final production (F_r^o) and consumption (F_r^c) in region r (see equations (C.3) and (C.4)) is a function of the methane intensities collected in E, the bundle of intermediates that are used in the global supply chain of a specific sector, determined by the Leontief-inverse $(I-A)^{-1}$, and the pattern of production and consumption of final goods in region r. More specifically, the components of $F_r^o = (F_{1r}^o, F_{2r}^o, \ldots, F_{nr}^o)'$, which are of dimension $s \times s$, show the emissions embodied in final goods produced in region r, accounting for the emissions embodied in all processed domestic and imported intermediates from sectors 1 to s in regions 1 to n. Similarly, the components of $F_r^c = (F_{1r}^c, F_{2r}^c, \ldots, F_{nr}^c)'$, which are of dimension $s \times s$, show the emissions embodied in consumption of final goods in region r, accounting for the emissions embodied in all processed domestic and imported intermediates and final goods from sectors 1 to s in regions 1 to n. At this step, we add residential emissions from households (corresponding to the sectors oil, coal, gas, gas manufacture and distribution, and petroleum and coal products) to the domestic ($r = p$) elements of F_r^o and F_r^c.

The elements of F_r^o and F_r^c can be used to track exports and imports of methane emissions embodied in intermediates and final goods between all and each of the sectors and regions whenever $r \neq p$. Whenever $r = p$ the elements of F_r^o and F_r^c denote purely domestic emissions, which are the same for final production and consumption. A given element of F_r^c (i.e. F_{ir}^c) captures methane emissions embodied in intermediates and final goods exported from all sectors in region i (independent of i's position within the global supply chain) to all sectors in region r, where the embodied emissions are consumed. This type of trade flow differs 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 consumer in region r. Similarly, accounting for indirect trade via global supply chains, an element of F_r^o (i.e. F_{ir}^o) captures methane emissions embodied in exported intermediates from all sectors in region i to region r, which uses these intermediates to produce final goods (either for consumption at home or for export).

Finally, we derive final production- and consumption-based emission inventories for each sector j in each region r. To obtain these inventories, we depart from F_r^o for production-based inventories (or from F_r^c for consumption-based inventories, respectively) and aggregate across the sectors and regions which contribute intermediates to the final goods produced (or consumed) in sector j in region r; i.e. $\phi_r^o = \iota_{ns}' F_r^o$ (or $\phi_r^c = \iota_{ns}' F_r^c$, respectively), where ι_{ns}' is a row vector of ones of length $n \cdot s$. The resulting row vectors ϕ_r^o and ϕ_r^c are of length s. Staking the regions r, the matrices ϕ^o and ϕ^c, both of dimension

$(n \times s)$, capture the final production and consumption inventories for the regions and sectors covered in our dataset. Furthermore, we can operate $\Phi^o = \phi^o \iota_s$ and $\Phi^c = \phi^c \iota_s$, where ι_s is a column vector of ones of length s, such that for each row (region) we sum across all columns (sectors) of ϕ^o and ϕ^c. Φ^o and Φ^c constitute the aggregated national emission inventories embodied in final production and consumption.

D Details on decompositions and further results

D.1 Decomposition based on the Kaya identity

The decomposition implemented in section 3.3 in the main text of the article builds on the Kaya-identity (see e.g. Raupach et al., 2007)

$$CH_4 = \frac{CH_4}{VA} \cdot \frac{VA}{pop} \cdot pop \tag{D.1}$$

where CH_4 measures total CH_4 emissions, VA stands for value added, and pop is the population size. Taking natural logarithms (ln)

$$ln(CH_4) = ln\left(\frac{CH_4}{VA}\right) + ln\left(\frac{VA}{pop}\right) + ln\,(pop) \tag{D.2}$$

and computing changes over time (Δ, from 1997–2014), we derive at

$$\Delta ln(CH_4) = \Delta ln\left(\frac{CH_4}{VA}\right) + \Delta ln\left(\frac{VA}{pop}\right) + \Delta ln\,(pop), \tag{D.3}$$

which corresponds to the equation in the main text.

Further decomposition results based on the Kaya-identity

Decompositions based on the sub-periods between 1997 and 2014, shown in Table D.1, mainly correspond to the patterns for the whole time period. Notable exceptions occurred (i) between 1997 and 2001, when low value added growth contributed 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

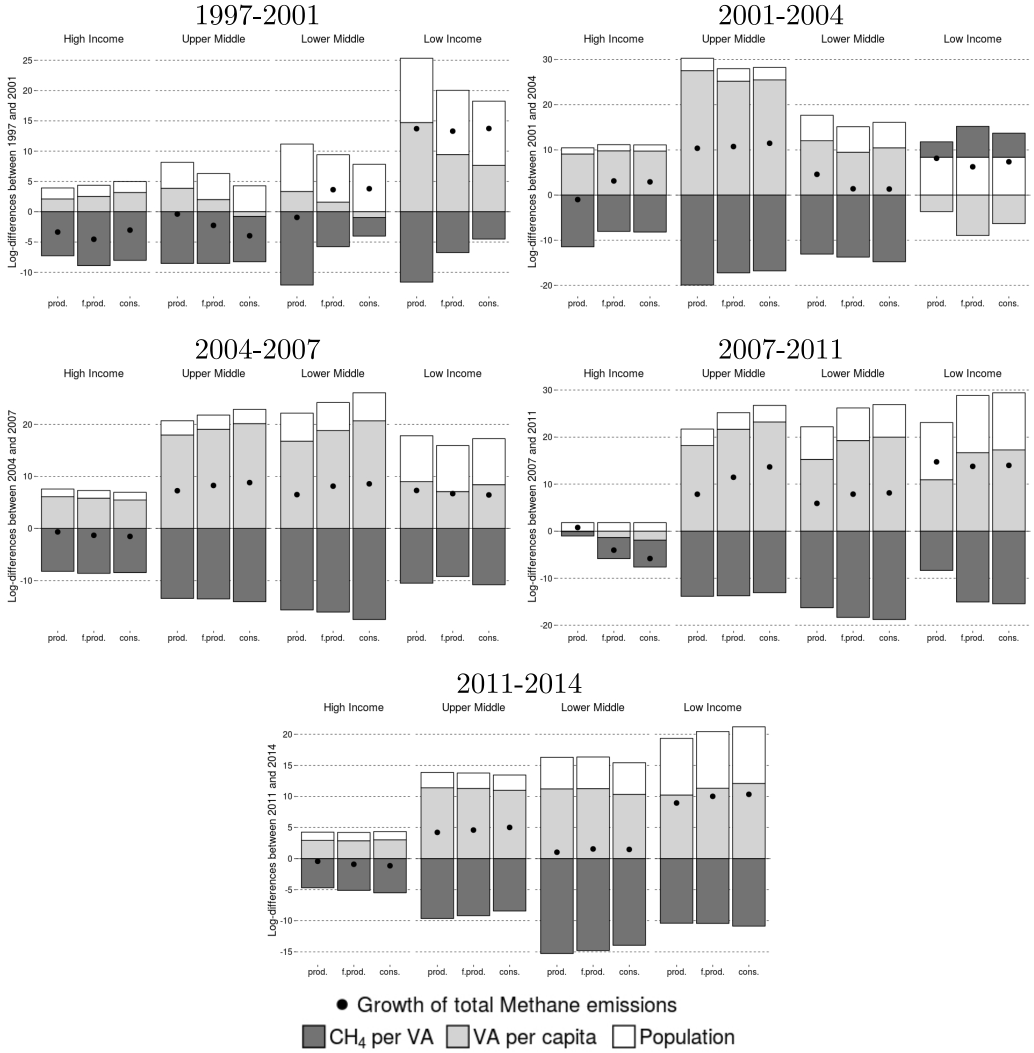

Figure D.1: Change in components of the Kaya identity. Note: The barplots show the log differences of the components of the Kaya identity between all subperiods from 1997–2014 for the four World Bank income groups. The Kaya identity decomposes total CH_4 emissions into CH_4 per value added, value added 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.

methane per value added; and (iii) between 2007 and 2011, when low efficiency gains in high-income countries led to a slight increase in emissions from production.

Figure D.2 reports the results of the Kaya-based decomposition for the period 1997–2014 for selected regions.

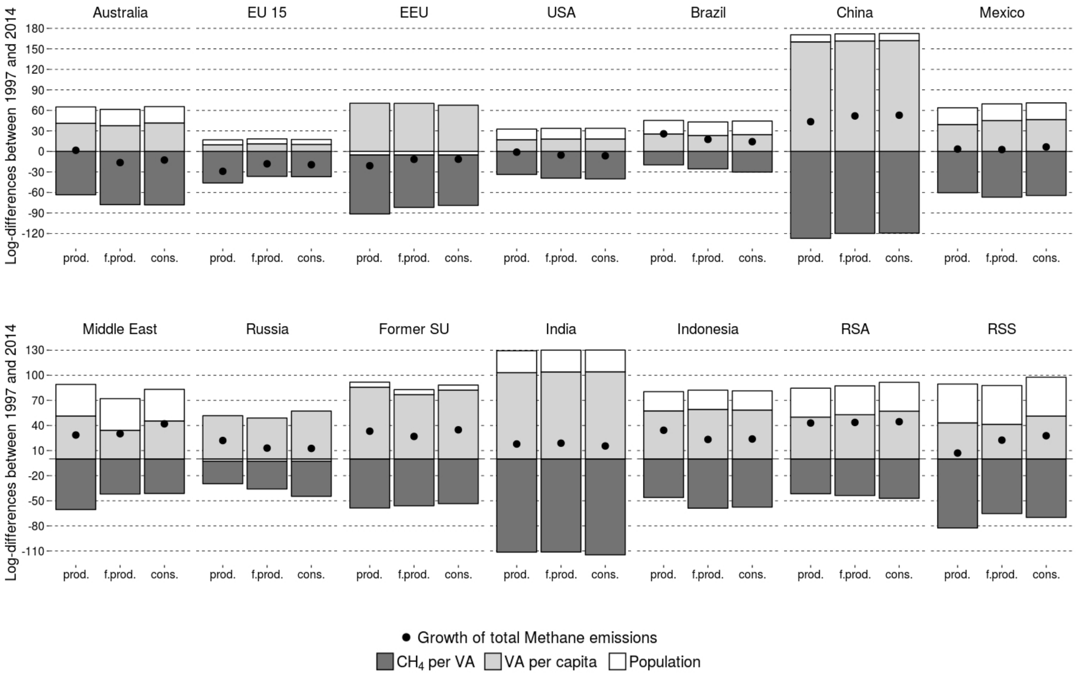

Figure D.2: Change in components of the Kaya-identity (1997–2014, selected regions). Note: The barplots show the log-differences of the components of the Kaya-identity between 1997 and 2014 for the 14 most important producers of CH_4 emissions. The Kaya identity decomposes total CH_4 emissions into CH_4 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 per country (in log-differences), marked as black dot.

D.2 Decomposition based on the Logarithmic Mean Divisia Index

Decompositions based on the Logarithmic Mean Divisia Index (LMDI) allow to quantify the contribution of sectoral changes to economy-wide emissions. There exist different models to compute the LMDI decomposition, from which we implement the two most relevant in our context: Since our outcome-variable of interest, the level of economy-wide methane emissions, is a quantitative indicator, we implement the additive and multiplicative versions of the LMDI-I decomposition for quantity indicators (see Ang, 2015, for details).

The main difference between the additive and the multiplicative versions of the decomposition is that the additive model decomposes the (arithmetic) change of an aggregate indicator in physical units in its components, whereas the multiplicative version decomposes the ratio change of an aggregate indicator in components expressed as indexes. Yet, the results of both versions of the decomposition are closely related, and it is possible to convert the results of one version of the decomposition to those of the other (Ang, 2015).

Both versions of the decomposition depart from the equation

$$CH_4 = \sum_i CH_4^i = \sum_i \frac{CH_4^i}{VA^i} \cdot \frac{VA^i}{VA} \cdot VA \tag{D.4}$$

where i stands for sector i and everything else is defined as before. The additive version of the decomposition, which corresponds to the one in the main text, is derived as

$$\Delta CH_4 = \left[\sum_i L^i \cdot \Delta ln\left(\frac{CH_4^i}{VA^i}\right)\right] + \left[\sum_i L^i \cdot \Delta ln\left(\frac{VA^i}{VA}\right)\right] + \left[\sum_i L^i \cdot \Delta ln\,(VA)\right] \tag{D.5}$$

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 $\Delta CH_4^i = 0$. ΔCH_4 is the change in methane emissions in physical units (see also Ang et al., 1998).

The multiplicative version is given by

$$\frac{CH_4^T}{CH_4^0} = exp\left[\sum_i \frac{L^i}{L} \cdot \Delta ln\left(\frac{CH_4^i}{VA^i}\right)\right] \cdot exp\left[\sum_i \frac{L^i}{L} \cdot \Delta ln\left(\frac{VA^i}{VA}\right)\right] \cdot exp\left[\sum_i \frac{L^i}{L} \cdot \Delta ln(VA)\right] \tag{D.6}$$

where T and 0 stand for the last and first periods, respectively, such that CH_4^T/CH_4^0 is an index-change over time, and $L{=}\Delta CH_4/\Delta ln(CH_4)$ for $\Delta CH_4{\neq}0$ and $L{=}CH_4$ for $\Delta CH_4{=}0$ at the economy-wide level (see also Ang and Liu, 2001). In equations D.4 to D.6, the first term on the right-hand side corresponds to changes in sectoral CH_4 intensities, the second term to the structural change component, and the third term to economy-wide value added growth.

Results from the multiplicative LMDI decomposition

Table D.1 shows the results of the multiplicative LMDI decomposition. The table reports economy-wide (ratio) changes in CH_4 emissions in column 1, which are decomposed into sectoral CH_4 per value added (column 2), structural change (column 3), and changes in economy-wide value added (column 4). The three terms of the decomposition enter multiplicatively in the computation of aggregate (ratio) changes in emissions. Multiplying the values in columns 2 to 4—which correspond to the three terms at the right-hand side of equation D.6—gives the value in column 1. Values smaller than one indicate a decrease in emissions over time (column 1) or a negative contribution to economy-wide emissions (i.e. they contribute to lower emissions, columns 2–4).

The results in Table D.1, reported as index-changes, are in line with the results from the additive LMDI decomposition in the main text (see Figure 6), which are represented as changes in physical units.

CH_4 inventory	(1) (Ratio) change of CH_4 emissions	(2) Sectoral CH_4 intensities	(3) Structural change	(4) Economy-wide VA
High income countries				
Production	0.954	0.705	1.024	1.322
Final Production	0.926	0.746	0.944	1.315
Consumption	0.917	0.747	0.935	1.313
Upper middle income countries				
Production	1.340	0.578	0.902	2.572
Final Production	1.388	0.603	0.894	2.574
Consumption	1.419	0.618	0.894	2.569
Lower middle income countries				
Production	1.186	0.515	0.942	2.443
Final Production	1.253	0.545	0.928	2.479
Consumption	1.262	0.547	0.930	2.481
Low income countries				
Production	1.696	0.672	1.028	2.453
Final Production	1.649	0.636	1.116	2.322
Consumption	1.680	0.645	1.083	2.405

Table D.1: LMDI decomposition of the growth index for total CH_4 emissions – income groups. Note: The table shows the growth index for total methane emissions by income group for each inventory with respect to 1997 – 2014 (Total) and its decomposition into sectoral CH_4 per value added, structural change and economy-wide value added using the multiplicative LMDI approach as described in Ang (2015). The total growth index is the result of the product of the three components.

Further decomposition results from the additive LMDI decomposition

The results for the sub-periods based on the LMDI decomposition, reported in Figure D.3, are similar to those based on the Kaya-identity in Figure D.1. Changes in CH_4 intensity typically contributed to lower emissions, whereas growth in value added contributed positively to increases in emissions in all sub-periods. Table D.3 reveals that structural change contributed to lower emissions in all income-groups in most sub-periods, with the exception of 1997–2001 (all income-groups) and 2007–2011 (high-income countries).

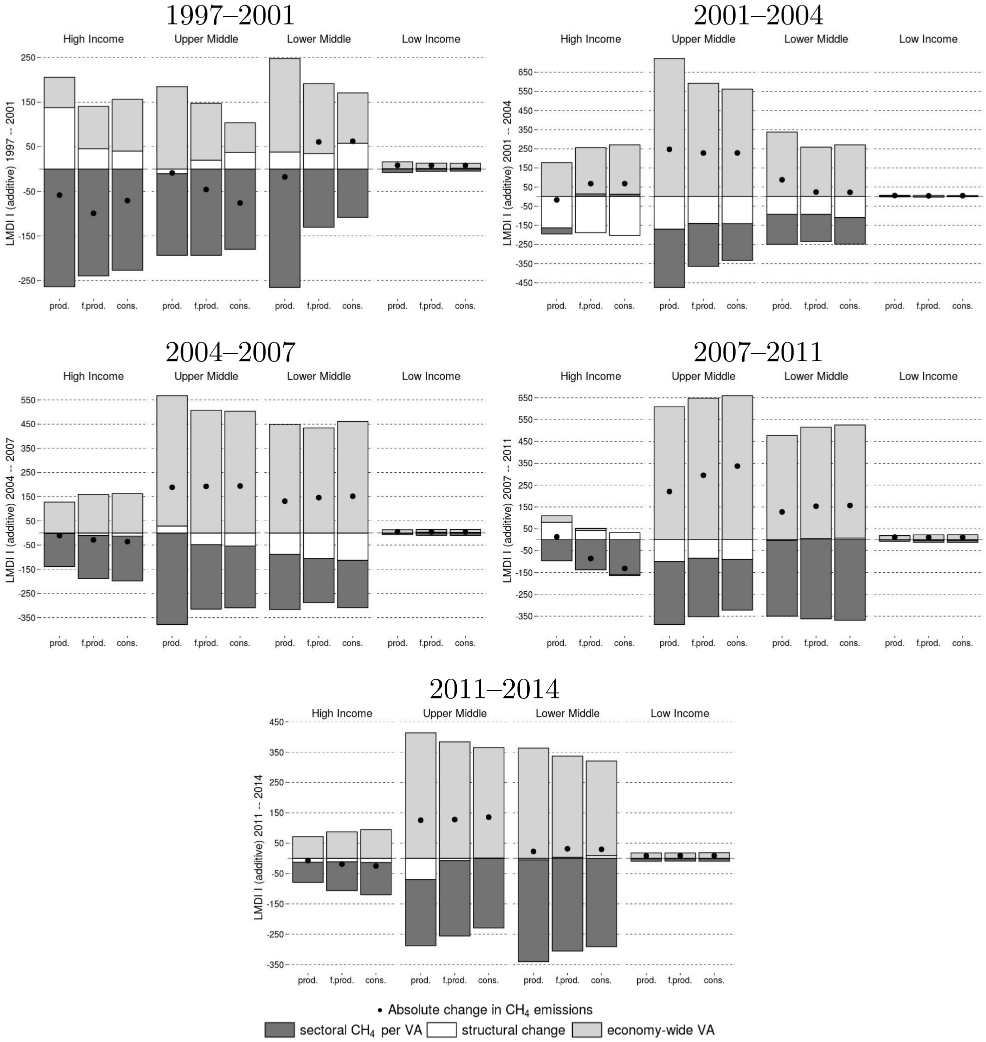

Figure D.3: Additive LMDI decomposition for changes in CH_4 emissions Note: The barplots show the decomposition of changes in CH_4 emissions in physical units (Mt. of CO_2 eq., 100y) between all subperiods from 1997–2014 for the four World Bank income groups. The additive LMDI decomposition decomposes 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 growth rate of total emissions (in log differences), marked as black dot.

E Further results

E.1 Traded emissions accruing to final production and consumption

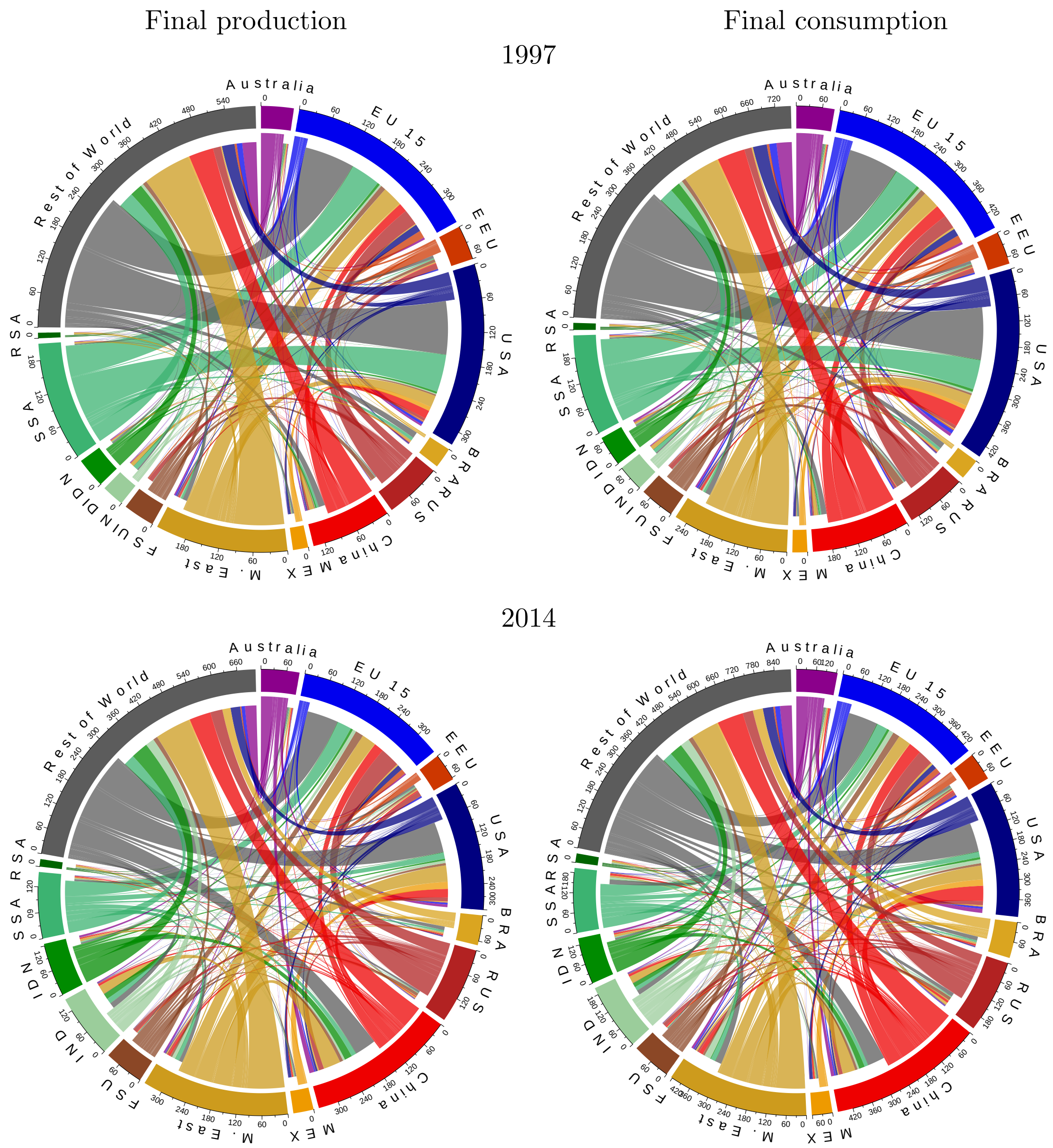

Figure E.1: Traded methane emissions by region of origin and destination (1997 and 2014). Note: The circle-plots show traded CH_4 emissions accruing to consumption and final production for the most important producers of CH_4 emissions and the Rest of World aggregate region. Trade-embodied emissions 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 this 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 produced (plots on the left panel) and consumed (plots on the right side of the panel).

E.2 Detailed sectoral results

	Total CH_4^*						CH_4 pc*		CH_4 per VA*	
	production		**final prod.**		**consumption**		**prod.**	**cons.**	**prod.**	**cons.**
	(Mt)	(%)	(Mt)	(%)	(Mt)	(%)	(t per capita)		(kg/USD)	
1997										
High Income	40	7%	129	15%	152	17%	0.03	0.13	0.05	0.15
Australia	1	0%	4	1%	4	0%	0.08	0.23	0.10	0.25
EU 15	6	1%	32	4%	41	5%	0.02	0.11	0.02	0.12
EEU	2	0%	11	1%	11	1%	0.02	0.10	0.06	0.31
USA	12	2%	32	4%	35	4%	0.04	0.13	0.05	0.13
Upper Middle	203	37%	266	30%	255	29%	0.09	0.11	0.49	0.60
Brazil	6	1%	17	2%	17	2%	0.03	0.10	0.08	0.23
Russia	2	0%	14	2%	16	2%	0.02	0.11	0.06	0.38
China	140	25%	149	17%	147	17%	0.11	0.12	1.11	1.22
Mexico	1	0%	4	0%	4	0%	0.01	0.04	0.03	0.09
Middle East	4	1%	14	2%	16	2%	0.02	0.09	0.21	0.51
Lower Middle	305	55%	469	54%	458	52%	0.13	0.19	1.17	1.53
Former SU	3	0%	10	1%	8	1%	0.02	0.06	0.55	1.18
India	107	19%	157	18%	152	17%	0.11	0.15	1.26	1.78
Indonesia	52	9%	52	6%	52	6%	0.26	0.26	1.34	1.42
RSA	12	2%	26	3%	26	3%	0.08	0.17	0.78	1.42
SSA	20	4%	90	10%	86	10%	0.05	0.21	0.58	2.01
Low Income	4	1%	8	1%	8	1%	0.04	0.08	0.44	0.79
2014										
High Income	36	6%	110	12%	124	14%	0.03	0.10	0.06	0.18
Australia	1	0%	3	0%	4	0%	0.04	0.16	0.05	0.20
EU 15	6	1%	45	5%	48	5%	0.02	0.12	0.03	0.21
EEU	2	0%	7	1%	7	1%	0.02	0.07	0.08	0.25
USA	12	2%	22	2%	27	3%	0.04	0.08	0.06	0.13
Upper Middle	203	34%	258	28%	254	28%	0.08	0.10	0.31	0.43
Brazil	5	1%	9	1%	9	1%	0.02	0.04	0.08	0.17
Russia	2	0%	6	1%	7	1%	0.01	0.05	0.09	0.27
China	134	22%	145	16%	143	16%	0.10	0.11	0.39	0.55
Mexico	1	0%	6	1%	6	1%	0.01	0.05	0.02	0.13
Middle East	4	1%	16	2%	26	3%	0.01	0.10	0.11	0.42
Lower Middle	355	59%	533	59%	523	57%	0.11	0.16	0.71	0.97
Former SU	2	0%	10	1%	10	1%	0.02	0.07	0.11	0.38
India	108	18%	245	27%	227	25%	0.08	0.18	0.61	1.31
Indonesia	65	11%	61	7%	61	7%	0.25	0.24	1.08	1.27
RSA	15	2%	25	3%	25	3%	0.07	0.12	0.55	0.58
SSA	31	5%	45	5%	55	6%	0.05	0.08	0.30	0.46
Low Income	7	1%	9	1%	9	1%	0.05	0.06	0.49	0.59

Table E.1: Main indicators for CH_4 inventories of the agriculture sector: 1997 and 2014. Selected regions. Note: *Data reported as CO_2 equivalents with respect to global warming potential for a 100-year period. 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 and 2007, including the upper-middle income countries Bulgaria and Romania, and Croatia; 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.

	Total CH_4^*						CH_4 pc*		CH_4 per VA*	
	production		**final prod.**		**consumption**		**prod.**	**cons.**	**prod.**	**cons.**
	(Mt)	(%)	(Mt)	(%)	(Mt)	(%)	(t per capita)		(kg/USD)	
					1997					
High Income	614	29%	499	32%	500	32%	0.53	0.43	2.50	1.12
Australia	75	4%	46	3%	29	2%	4.06	1.56	9.41	4.66
EU 15	192	9%	166	11%	170	11%	0.51	0.45	1.58	0.83
EEU	42	2%	33	2%	32	2%	0.38	0.29	3.11	1.45
USA	160	8%	127	8%	126	8%	0.59	0.46	3.17	1.16
Upper Middle	781	37%	562	36%	556	35%	0.35	0.25	5.75	2.96
Brazil	210	10%	170	11%	169	11%	1.26	1.01	8.92	5.22
Russia	70	3%	75	5%	87	6%	0.48	0.59	5.69	2.43
China	181	8%	91	6%	90	6%	0.15	0.07	4.77	1.79
Mexico	44	2%	38	2%	39	2%	0.45	0.40	3.44	1.75
Middle East	28	1%	25	2%	29	2%	0.16	0.17	2.78	1.98
Lower Middle	699	33%	492	31%	498	32%	0.29	0.21	10.93	6.05
Former SU	69	3%	56	4%	47	3%	0.52	0.35	42.31	15.36
India	281	13%	210	13%	209	13%	0.28	0.21	12.42	7.95
Indonesia	21	1%	17	1%	20	1%	0.10	0.10	3.83	2.94
RSA	63	3%	44	3%	44	3%	0.41	0.29	16.19	9.19
SSA	197	9%	117	7%	118	7%	0.48	0.29	49.27	19.31
Low Income	33	2%	24	2%	24	1%	0.36	0.26	28.58	18.00
					2014					
High Income	538	23%	387	25%	383	25%	0.43	0.30	2.04	0.93
Australia	72	3%	29	2%	13	1%	3.05	0.55	7.74	2.04
EU 15	171	7%	113	7%	115	7%	0.42	0.28	1.78	0.83
EEU	31	1%	23	2%	22	1%	0.30	0.21	2.37	0.87
USA	149	6%	127	8%	128	8%	0.47	0.40	1.79	0.94
Upper Middle	914	39%	667	43%	668	43%	0.35	0.25	4.23	2.03
Brazil	275	12%	223	14%	207	13%	1.35	1.01	9.75	5.79
Russia	42	2%	48	3%	57	4%	0.29	0.40	3.01	1.76
China	235	10%	93	6%	96	6%	0.17	0.07	2.31	0.73
Mexico	47	2%	34	2%	35	2%	0.38	0.28	4.10	1.45
Middle East	33	1%	38	2%	51	3%	0.13	0.20	2.83	1.89
Lower Middle	822	35%	457	29%	461	30%	0.25	0.14	6.62	2.77
Former SU	65	3%	65	4%	64	4%	0.46	0.45	5.53	2.46
India	308	13%	86	6%	83	5%	0.24	0.06	5.93	1.23
Indonesia	24	1%	17	1%	18	1%	0.09	0.07	4.20	2.36
RSA	102	4%	26	2%	26	2%	0.48	0.12	7.14	2.05
SSA	222	10%	198	13%	196	13%	0.34	0.30	11.51	7.41
Low Income	52	2%	47	3%	47	3%	0.34	0.31	22.02	13.80

Table E.2: Main indicators for CH_4 inventories of the livestock sector: 1997 and 2014. Selected regions. Note: *Data reported as CO_2 equivalents with respect to global warming potential for a 100-year period. 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 and 2007, including the upper-middle income countries Bulgaria and Romania, and Croatia; 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.

	Total CH_4^*						CH_4 pc*		CH_4 per VA*	
	production		**final prod.**		**consumption**		**prod.**	**cons.**	**prod.**	**cons.**
	(Mt)	(%)	(Mt)	(%)	(Mt)	(%)	(t per capita)		(kg/USD)	
					1997					
High Income	467	34%	134	52%	138	53%	0.40	0.12	0.86	0.78
Australia	23	2%	3	1%	2	1%	1.24	0.13	1.06	0.81
EU 15	68	5%	33	13%	37	14%	0.18	0.10	0.59	0.74
EEU	50	4%	19	7%	20	8%	0.45	0.18	4.65	3.60
USA	167	12%	40	16%	40	16%	0.61	0.15	0.88	0.65
Upper Middle	549	40%	92	36%	91	35%	0.24	0.04	2.09	2.93
Brazil	13	1%	3	1%	3	1%	0.08	0.02	0.96	0.84
Russia	101	7%	21	8%	20	8%	0.68	0.13	2.11	2.33
China	212	15%	51	20%	50	20%	0.17	0.04	5.80	12.54
Mexico	9	1%	1	0%	1	0%	0.09	0.01	0.40	0.95
Middle East	173	13%	10	4%	10	4%	1.01	0.06	1.71	1.89
Lower Middle	363	26%	32	12%	28	11%	0.15	0.01	4.08	2.76
Former SU	49	4%	14	5%	14	5%	0.36	0.10	3.20	2.40
India	29	2%	6	2%	6	2%	0.03	0.01	1.78	1.95
Indonesia	33	2%	3	1%	3	1%	0.16	0.01	1.68	2.03
RSA	3	0%	3	1%	3	1%	0.02	0.02	2.58	4.27
SSA	174	13%	5	2%	5	2%	0.43	0.01	10.31	9.49
Low Income	3	0%	0	0%	0	0%	0.03	0.00	3.43	2.36
					2014					
High Income	490	27%	158	44%	163	46%	0.39	0.13	0.51	0.55
Australia	32	2%	3	1%	3	1%	1.35	0.11	0.47	0.36
EU 15	43	2%	38	11%	43	12%	0.11	0.11	0.21	0.51
EEU	32	2%	15	4%	16	4%	0.30	0.15	1.19	1.06
USA	187	10%	59	16%	58	16%	0.59	0.18	0.61	0.59
Upper Middle	933	51%	144	40%	142	40%	0.36	0.05	1.07	1.32
Brazil	15	1%	2	0%	2	0%	0.07	0.01	0.19	0.13
Russia	145	8%	22	6%	21	6%	1.01	0.15	1.21	0.97
China	500	27%	74	21%	75	21%	0.37	0.05	2.75	3.10
Mexico	8	0%	2	0%	2	0%	0.06	0.01	0.34	0.22
Middle East	223	12%	21	6%	20	5%	0.88	0.08	0.58	0.76
Lower Middle	399	22%	55	15%	52	15%	0.12	0.02	1.37	1.10
Former SU	84	5%	29	8%	26	7%	0.59	0.18	1.89	2.83
India	53	3%	14	4%	14	4%	0.04	0.01	0.64	0.67
Indonesia	84	5%	5	1%	4	1%	0.33	0.02	1.59	1.33
RSA	5	0%	4	1%	4	1%	0.02	0.02	1.40	1.05
SSA	133	7%	15	4%	15	4%	0.20	0.02	2.72	5.52
Low Income	9	1%	1	0%	1	0%	0.06	0.01	1.93	1.36

Table E.3: Main indicators for CH_4 inventories of the energy sector: 1997 and 2014. Selected regions. Note: *Data reported as CO_2 equivalents with respect to global warming potential for a 100-year period. 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 and 2007, including the upper-middle income countries Bulgaria and Romania, and Croatia; 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.

	Total CH_4^*						CH_4 pc*		CH_4 per VA*	
	production		**final prod.**		**consumption**		**prod.**	**cons.**	**prod.**	**cons.**
	(Mt)	(%)	(Mt)	(%)	(Mt)	(%)	(t per capita)		(kg/USD)	
					1997					
High Income	50	18%	403	47%	479	56%	0.04	0.41	0.01	0.13
Australia	0	0%	6	1%	8	1%	0.02	0.43	0.01	0.16
EU 15	5	2%	127	15%	151	18%	0.01	0.40	0.00	0.11
EEU	1	0%	18	2%	16	2%	0.01	0.15	0.02	0.22
USA	4	1%	137	16%	179	21%	0.01	0.65	0.00	0.13
Upper Middle	131	48%	303	36%	236	28%	0.06	0.11	0.17	0.29
Brazil	6	2%	26	3%	26	3%	0.03	0.16	0.04	0.17
Russia	35	13%	22	3%	20	2%	0.24	0.14	0.74	0.43
China	28	10%	141	17%	86	10%	0.02	0.07	0.12	0.55
Mexico	8	3%	15	2%	14	2%	0.08	0.14	0.10	0.18
Middle East	51	19%	38	4%	33	4%	0.30	0.19	0.96	0.36
Lower Middle	90	33%	142	17%	133	16%	0.04	0.06	0.48	0.54
Former SU	5	2%	13	2%	13	2%	0.04	0.10	0.31	0.55
India	13	5%	42	5%	42	5%	0.01	0.04	0.25	0.56
Indonesia	21	8%	17	2%	16	2%	0.10	0.08	0.68	0.49
RSA	2	1%	7	1%	7	1%	0.01	0.05	0.25	0.61
SSA	23	8%	38	4%	35	4%	0.06	0.09	1.94	1.70
Low Income	2	1%	4	0%	4	0%	0.03	0.04	1.22	1.08
					2014					
High Income	65	20%	326	30%	406	37%	0.05	0.32	0.02	0.09
Australia	0	0%	5	0%	9	1%	0.01	0.39	0.01	0.11
EU 15	6	2%	94	9%	116	11%	0.02	0.29	0.01	0.09
EEU	1	0%	17	2%	16	2%	0.01	0.16	0.01	0.12
USA	4	1%	103	10%	145	13%	0.01	0.45	0.00	0.08
Upper Middle	169	52%	479	44%	406	37%	0.06	0.15	0.09	0.19
Brazil	7	2%	30	3%	31	3%	0.03	0.15	0.04	0.14
Russia	49	15%	33	3%	34	3%	0.34	0.24	0.85	0.28
China	41	13%	310	28%	219	20%	0.03	0.16	0.04	0.23
Mexico	7	2%	14	1%	16	1%	0.06	0.13	0.06	0.11
Middle East	67	21%	42	4%	50	5%	0.27	0.20	0.40	0.19
Lower Middle	88	27%	276	25%	269	25%	0.03	0.08	0.22	0.39
Former SU	10	3%	14	1%	16	2%	0.07	0.11	0.36	0.32
India	19	6%	93	9%	83	8%	0.01	0.06	0.12	0.31
Indonesia	15	4%	19	2%	21	2%	0.06	0.08	0.20	0.27
RSA	3	1%	75	7%	75	7%	0.01	0.35	0.26	1.64
SSA	24	7%	37	3%	43	4%	0.04	0.07	0.87	0.56
Low Income	4	1%	7	1%	8	1%	0.02	0.05	0.63	0.54

Table E.4: Main indicators for CH_4 inventories of the manufacturing sector: 1997 and 2014. Selected regions. Note: *Data reported as CO_2 equivalents with respect to global warming potential for a 100-year period. 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 and 2007, including the upper-middle income countries Bulgaria and Romania, and Croatia; 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.

	Total CH_4^*						CH_4 pc*		CH_4 per VA*	
	production		**final prod.**		**consumption**		**prod.**	**cons.**	**prod.**	**cons.**
	(Mt)	(%)	(Mt)	(%)	(Mt)	(%)	(t per capita)		(kg/USD)	
					1997					
High Income	5	11%	379	54%	381	54%	0.00	0.33	0.00	0.04
Australia	0	0%	12	2%	12	2%	0.00	0.65	0.00	0.07
EU 15	2	4%	94	13%	95	13%	0.00	0.25	0.00	0.03
EEU	1	3%	18	2%	17	2%	0.01	0.15	0.01	0.16
USA	1	2%	143	20%	143	20%	0.00	0.53	0.00	0.04
Upper Middle	18	43%	212	30%	211	30%	0.01	0.09	0.01	0.17
Brazil	0	1%	16	2%	17	2%	0.00	0.10	0.00	0.07
Russia	1	2%	25	4%	25	4%	0.00	0.17	0.01	0.21
China	15	36%	97	14%	96	14%	0.01	0.08	0.09	0.41
Mexico	0	1%	6	1%	6	1%	0.00	0.06	0.00	0.05
Middle East	0	0%	28	4%	28	4%	0.00	0.16	0.00	0.17
Lower Middle	18	43%	114	16%	113	16%	0.01	0.05	0.04	0.25
Former SU	0	1%	19	3%	18	3%	0.00	0.14	0.01	0.39
India	8	18%	28	4%	27	4%	0.01	0.03	0.07	0.28
Indonesia	2	4%	21	3%	21	3%	0.01	0.10	0.02	0.25
RSA	1	3%	5	1%	5	1%	0.01	0.03	0.06	0.30
SSA	5	11%	23	3%	23	3%	0.01	0.06	0.10	0.52
Low Income	1	3%	2	0%	2	0%	0.01	0.02	0.14	0.28
					2014					
High Income	4	9%	385	37%	386	37%	0.00	0.31	0.00	0.03
Australia	0	0%	17	2%	17	2%	0.00	0.73	0.00	0.05
EU 15	2	3%	104	10%	104	10%	0.00	0.26	0.00	0.03
EEU	1	2%	17	2%	16	2%	0.01	0.16	0.00	0.07
USA	1	1%	126	12%	126	12%	0.00	0.40	0.00	0.02
Upper Middle	17	38%	470	46%	471	46%	0.01	0.18	0.00	0.13
Brazil	0	1%	18	2%	18	2%	0.00	0.09	0.00	0.04
Russia	0	0%	37	4%	38	4%	0.00	0.26	0.00	0.15
China	13	28%	305	30%	304	30%	0.01	0.22	0.01	0.18
Mexico	0	1%	7	1%	7	1%	0.00	0.05	0.00	0.02
Middle East	0	0%	42	4%	43	4%	0.00	0.17	0.00	0.11
Lower Middle	24	51%	169	16%	168	16%	0.01	0.05	0.02	0.14
Former SU	0	1%	32	3%	32	3%	0.00	0.22	0.00	0.34
India	9	19%	62	6%	62	6%	0.01	0.05	0.02	0.13
Indonesia	2	4%	25	2%	25	2%	0.01	0.10	0.01	0.12
RSA	2	3%	6	1%	6	1%	0.01	0.03	0.03	0.25
SSA	8	16%	29	3%	29	3%	0.01	0.04	0.07	0.29
Low Income	2	3%	5	1%	5	1%	0.01	0.03	0.06	0.27

Table E.5: Main indicators for CH_4 inventories of the services sector: 1997 and 2014. Selected regions. Note: *Data reported as CO_2 equivalents with respect to global warming potential for a 100-year period. 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 and 2007, including the upper-middle income countries Bulgaria and Romania, and Croatia; 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.

	Total CH_4^*						CH_4 pc*		CH_4 per VA*	
	production		**final prod.**		**consumption**		**prod.**	**cons.**	**prod.**	**cons.**
	(Mt)	(%)	(Mt)	(%)	(Mt)	(%)	(t per capita)		(kg/USD)	
					1997					
High Income	111	32%	110	40%	122	44%	0.10	0.11	0.11	0.19
Australia	1	0%	2	1%	2	1%	0.04	0.09	0.04	0.12
EU 15	14	4%	23	8%	28	10%	0.04	0.08	0.04	0.15
EEU	7	2%	5	2%	5	2%	0.06	0.04	0.38	0.42
USA	35	10%	36	13%	39	14%	0.13	0.14	0.14	0.22
Upper Middle	145	42%	105	38%	97	35%	0.06	0.04	0.73	0.61
Brazil	8	2%	9	3%	9	3%	0.05	0.05	0.23	0.25
Russia	34	10%	16	6%	16	6%	0.23	0.11	1.09	0.80
China	19	5%	6	2%	6	2%	0.02	0.00	0.65	0.55
Mexico	19	6%	15	6%	15	5%	0.20	0.15	0.74	0.66
Middle East	34	10%	25	9%	23	8%	0.20	0.13	1.42	1.06
Lower Middle	88	26%	62	22%	58	21%	0.04	0.02	0.99	0.87
Former SU	25	7%	15	5%	11	4%	0.19	0.08	2.67	1.93
India	6	2%	7	3%	7	3%	0.01	0.01	0.27	0.46
Indonesia	16	5%	9	3%	8	3%	0.08	0.04	1.29	1.11
RSA	5	1%	4	1%	4	1%	0.03	0.02	1.17	1.01
SSA	29	8%	23	8%	22	8%	0.07	0.05	2.40	1.88
Low Income	0	0%	0	0%	0	0%	0.00	0.00	0.02	0.30
					2014					
High Income	139	33%	135	40%	138	40%	0.11	0.11	0.13	0.21
Australia	0	0%	2	1%	3	1%	0.02	0.14	0.01	0.13
EU 15	13	3%	41	12%	41	12%	0.03	0.10	0.04	0.16
EEU	8	2%	8	2%	7	2%	0.08	0.07	0.26	0.30
USA	49	12%	30	9%	30	9%	0.15	0.09	0.16	0.21
Upper Middle	200	48%	137	40%	135	40%	0.08	0.05	0.47	0.41
Brazil	10	2%	9	3%	11	3%	0.05	0.05	0.21	0.24
Russia	48	12%	30	9%	30	9%	0.34	0.21	1.44	0.89
China	37	9%	28	8%	27	8%	0.03	0.02	0.21	0.32
Mexico	17	4%	16	5%	17	5%	0.14	0.13	0.43	0.35
Middle East	44	11%	36	10%	35	10%	0.18	0.14	1.61	0.78
Lower Middle	77	19%	69	20%	68	20%	0.02	0.02	0.43	0.41
Former SU	48	12%	11	3%	9	3%	0.34	0.06	1.57	0.91
India	11	3%	22	6%	22	6%	0.01	0.02	0.14	0.27
Indonesia	10	2%	8	2%	8	2%	0.04	0.03	0.85	0.58
RSA	8	2%	2	1%	2	1%	0.04	0.01	0.35	0.35
SSA	16	4%	9	3%	9	3%	0.02	0.01	1.37	0.78
Low Income	1	0%	1	0%	1	0%	0.01	0.01	0.57	0.45

Table E.6: Main indicators for CH_4 inventories of the transport sector: 1997 and 2014. Selected regions. Note: *Data reported as CO_2 equivalents with respect to global warming potential for a 100-year period. 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 and 2007, including the upper-middle income countries Bulgaria and Romania, and Croatia; 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.

	Total CH_4^*						CH_4 pc*		CH_4 per VA*	
	production		**final prod.**		**consumption**		**prod.**	**cons.**	**prod.**	**cons.**
	(Mt)	(%)	(Mt)	(%)	(Mt)	(%)	(t per capita)		(kg/USD)	
					1997					
High Income	483	38%	580	40%	593	41%	0.42	0.51	0.14	0.14
Australia	13	1%	16	1%	16	1%	0.71	0.84	0.25	0.21
EU 15	179	14%	210	15%	213	15%	0.48	0.57	0.16	0.14
EEU	32	3%	37	3%	37	3%	0.29	0.33	0.78	0.63
USA	148	12%	172	12%	181	13%	0.54	0.66	0.10	0.11
Upper Middle	446	35%	516	36%	510	35%	0.20	0.23	1.15	0.89
Brazil	53	4%	72	5%	72	5%	0.32	0.43	0.42	0.39
Russia	48	4%	66	5%	66	5%	0.33	0.45	0.89	0.73
China	199	16%	217	15%	216	15%	0.16	0.18	3.87	2.22
Mexico	19	1%	20	1%	20	1%	0.19	0.20	0.66	0.58
Middle East	41	3%	61	4%	62	4%	0.24	0.36	0.60	0.57
Lower Middle	325	26%	331	23%	324	22%	0.14	0.14	2.74	2.22
Former SU	22	2%	27	2%	27	2%	0.16	0.20	1.74	1.64
India	116	9%	116	8%	115	8%	0.12	0.12	3.43	3.11
Indonesia	36	3%	37	3%	37	3%	0.18	0.18	3.06	2.27
RSA	19	1%	19	1%	18	1%	0.12	0.12	3.00	2.61
SSA	66	5%	70	5%	68	5%	0.16	0.17	5.97	4.32
Low Income	14	1%	17	1%	17	1%	0.15	0.18	6.42	4.87
					2014					
High Income	417	27%	567	32%	568	32%	0.33	0.45	0.08	0.08
Australia	11	1%	15	1%	16	1%	0.45	0.66	0.10	0.10
EU 15	108	7%	137	8%	138	8%	0.27	0.34	0.08	0.08
EEU	35	2%	38	2%	38	2%	0.34	0.36	0.51	0.39
USA	120	8%	184	10%	182	10%	0.38	0.57	0.05	0.06
Upper Middle	609	40%	697	39%	700	39%	0.23	0.27	0.52	0.42
Brazil	72	5%	83	5%	84	5%	0.35	0.41	0.38	0.29
Russia	78	5%	95	5%	95	5%	0.54	0.66	0.98	0.74
China	265	17%	310	17%	310	17%	0.19	0.23	0.60	0.48
Mexico	23	2%	25	1%	25	1%	0.19	0.20	0.28	0.24
Middle East	72	5%	78	4%	80	4%	0.28	0.32	0.58	0.49
Lower Middle	475	31%	498	28%	494	28%	0.15	0.15	1.46	1.13
Former SU	31	2%	38	2%	38	2%	0.22	0.27	1.06	0.86
India	161	11%	161	9%	160	9%	0.12	0.12	1.14	1.04
Indonesia	56	4%	61	3%	61	3%	0.22	0.24	1.83	1.24
RSA	28	2%	28	2%	27	2%	0.13	0.13	2.82	1.42
SSA	116	8%	127	7%	125	7%	0.18	0.19	5.30	2.89
Low Income	22	1%	22	1%	22	1%	0.15	0.14	2.83	2.13

Table E.7: Main indicators for CH_4 inventories of the public administration sector: 1997 and 2014. Selected regions. Note: *Data reported as CO_2 equivalents with respect to global warming potential for a 100-year period. 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 and 2007, including the upper-middle income countries Bulgaria and Romania, and Croatia; 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.

F Data Comparison

This appendix reports the results of comparisons of our CH_4 data (production inventory) with emissions from the GTAP non-CO_2 emissions database, along three different dimensions. The three dimensions include (i) a comparison of global CH_4 emissions, (ii) a comparison at the regional/country level, and (iii) a comparison at the sectoral level. More specifically, we compare the data on CH_4 emissions in the four available releases of the GTAP non-CO_2 emissions database in 2001, 2004, 2007, and 2011 with our own calculations, described in Section 2. The comparison is restricted to production based inventories due to the lack of footprint data in the GTAP releases. For both databases, we calculate CH_4 emissions in terms of CO_2 equivalents on 100-year basis, setting the global warming potential (GWP) of methane to 28 as in the latest IPCC report.

The results of the first comparison, focusing on global CH_4 emissions reported in the two databases, are summarized in Table F.1. Column 1 shows the years for which the comparison is conducted, column 2 reports global CH_4 emissions based on the GTAP database, column 3 reports the corresponding value based on our CH_4 database, and column 4 shows the difference between the two series (calculated as two times the absolute difference between the two series as percentage of the sum of the two series). As it can be seen from the table, in the years 2001, 2004, and 2007 the differences between the two databases are rather low on the global level, ranging between 2.7 and 5.2 percent; such differences are small, given the different raw data used to construct the databases. In the year 2011, the difference between the databases is much larger. In this year, the sources of the raw data and the methodology applied in both datasets are the closest over all the years; yet, the raw data sourced from EDGAR and FAOSTAT have been updated since GTAP calculated the emission inventories, and our calculations rely on the updated raw data. Moreover, a large part of the difference detected for 2011 seems to be driven by differences in the national CH_4 emissions of China, which shows an unreasonably high amount of national emissions in the GTAP dataset (2,514 Mt. in 2011 after being only 1,157 Mt. in 2007). Even considering that GTAP changed its methodology between the 2007 and 2011 releases it seems unlikely that China more than doubled its emissions in just four years. In comparison, in our dataset the national emissions of China increase from 1,397 to 1,556 Mt. in the same time period. Overall, the differences between the datasets shown in Table F.1 are to be expected given the differences of raw data and methodologies applied to construct the datasets and supports our approach not to use the GTAP dataset directly to make comparisons over time, but to calculate CH_4 inventories in each year following the same methodology in order to obtain a dataset that can be used for panel analyses.

Year	$\mathbf{CH_4}$ (CO_2e, Mt. 100y) GTAP	own Calc.	Difference in %
2001	7587	7880	3.79%
2004	7891	8312	5.20%
2007	8497	8731	2.72%
2011	11736	9229	23.92%

Table F.1: Comparison with GTAP CH_4 emissions. In Table F.1 we compare the differences between GTAP's non-CO_2 emissions database releases for the years that data is available with our own calculations on a global level. We calculate the difference, δ_t, between both databases in each year, t, as $\delta_t = (|e_t^g - e_t^o| * 2)/(e_t^g + e_t^o)$, denoting global emissions in GTAP by e_t^g and our own global totals as e_t^o. The global warming potential in both databases applied is 28, which is the same as used in the main text.

In the second comparison, reported in Table F.2, we focus on differences in CH_4 on the country/region level. For this analysis, we first aggregated national CH_4 emission from the GTAP databases to the 78 countries/regions covered in our dataset (see also Table A.1 in the appendix). Then, we calculated the difference in national/regional CH_4 emissions for the 78 regions, like we did for global emissions. The descriptive statistics reported in Table F.2 show that there are substantial differences between GTAP data and our CH_4 data on the regional level, which may again result from the use of different raw data. The differences in national/regional CH_4 emissions across the datasets are larger than the differences Fernández-Amador et al. (2016) found when comparing alternative databases on production-based CO_2 emissions on a country level. Anthropogenic methane emissions are subject to high uncertainties as discussed in Schwietzke et al. (2016), whereas anthropogenic CO_2 emissions accounted for in Fernández-Amador et al. (2016) are caused by the combustion of fossil fuels, and the usage of these fuels is well documented (see e.g. information from the International Energy Agency, IEA). Additionally, the carbon content of different fossil fuels is well known and it can be assumed that all carbon is released due to combustion as discussed in Fernández-Amador et al. (2016). This makes large differences in databases on CO_2 less likely than in the case of methane. Furthermore, in the GTAP data many European high income countries, such as the United Kingdom, Germany, France and Italy, show decreasing CH_4 emission between 2001 and 2007, which then increase again in 2011. Since this pattern does not occur in our data, we are skeptical of comparing GTAP data over time.

	all years	2001	2004	2007	2011
No. Sectors:	57	57	57	57	57
No. Countries:	78	78	78	78	78
Avg. Difference:	27.57%	24.78%	26.38%	31.09%	28.02%
Median Difference:	18.95%	17.58%	18.61%	19.73%	20.43%
Stdv. Difference:	25.25%	24.18%	24.29%	29.94%	21.93%
Min.:	0.14%	0.26%	0.19%	0.14%	1.18%
Min. (Country):	Portugal	R. o. Andean Pact	Spain	Portugal	Colombia
Max.:	130.29%	103.36%	108.71%	130.29%	110.5%
Max. (Country):	Singapore	R. o. EFTA	R. o. EFTA	Singapore	Latvia

Table F.2: Comparison with GTAP CH_4 emissions by country. In Table F.2 we compare the differences between GTAP's non-CO_2 emissions database releases for the years that data is available with our own calculations at the regional level. For this we aggregated both databases in each year first to the 78 countries and regions as defined in the main text. For each of those 78 regions in each year we calculate the difference, δ_t^r, between both databases as $\delta_t^r{=}(|e_t^{g,r}{-}e_t^{o,r}|{*}2)/(e_t^{g,r}{+}e_t^{o,r})$, denoting emissions of region r in year t in GTAP by $e_t^{r,g}$ and our own regional emissions as $e_t^{o,r}$. The global warming potential in both databases applied is 28, which is the same as used in the main text.

Finally, in our third comparison we analyze the differences of global CH_4 emissions between the databases on the sectoral level. The upper panel in Figure F.1 uses sectoral emission data from GTAP to show the contribution of the 57 sectors to total emissions (averaged between 2001 and 2011), whereas the lower panel is based on the data we developed (for the corresponding period). As it can be seen from comparing the two panels, despite the differences found on the country level, the pattern of sectoral CH_4 emissions is rather similar in both databases.

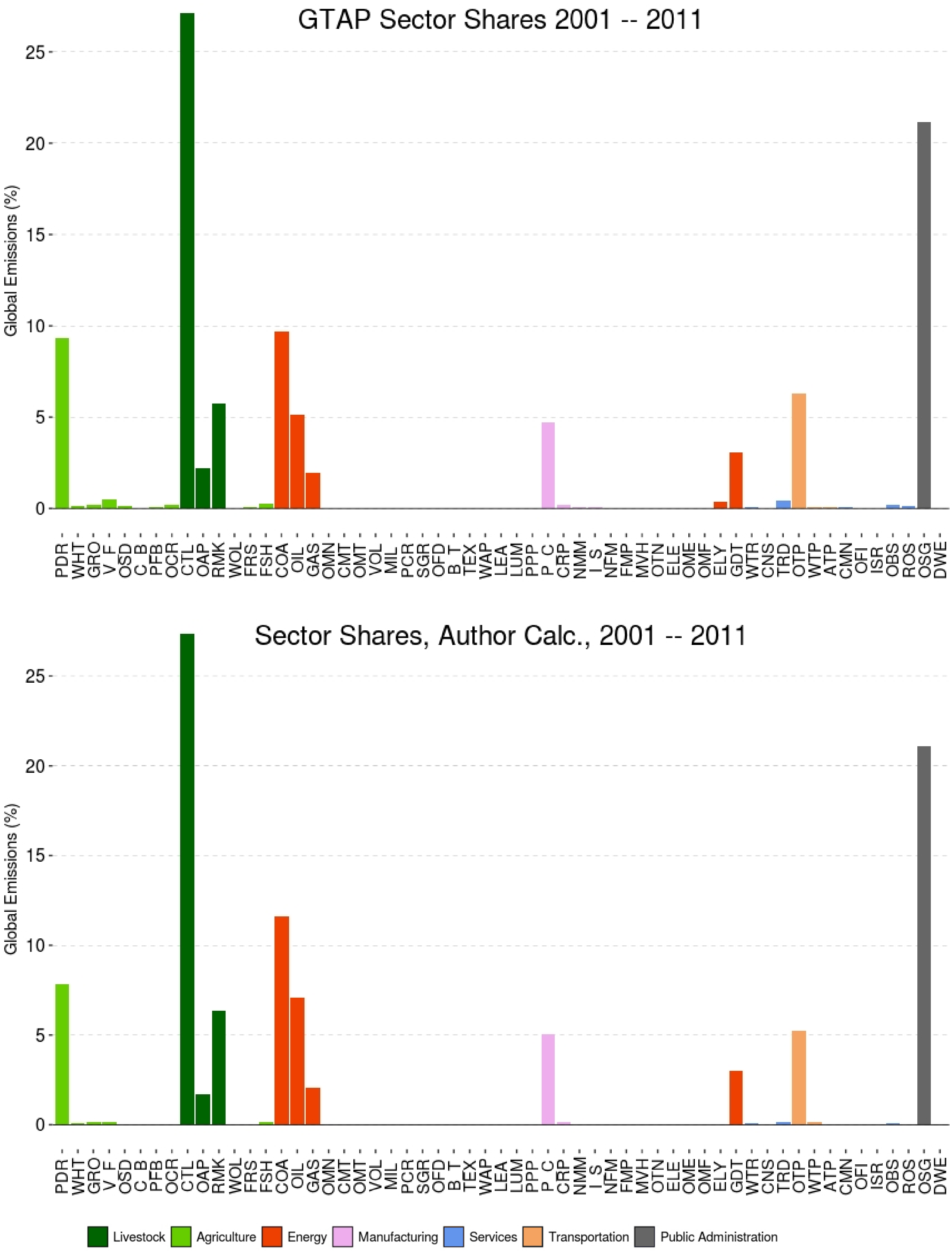

Figure F.1: Sector shares of global CH_4 emissions (average 2001–2011). The barplots show CH_4 emissions associated with production in each of the 57 sectors as shares of global methane emissions. This data is alternatively showen for the average of the releases of the GTAP non-CO_2 emissions databases in 2001 – 2011 (upper plot) and our own data for the same time period (lower plot). 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.