The methane footprint of nations: Evidence from global panel data*

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Abstract

We develop a unique global dataset on methane inventories derived from production, final production, and consumption for 1997–2011. Anthropogenic emissions are quantitatively important for global warming and have increased about 25% from 1997–2011. The bulk of emissions produced is attributable to developing economies, though a considerable amount is exported to high income countries, which are net-importers of methane. Traded emissions have gained in importance with respect to total produced emissions and have increased from 18.5% to 22.9% between 1997 and 2011. Methane efficiency has improved very little during this period and realized efficiency gains differ considerably across country-groups and economic sectors, which indicates different abatement potentials.

Keywords: Economic growth, methane emissions, MRIO analysis, production-based inventories, methane footprint, income-elasticity, threshold estimation, sectoral analysis.

JEL-codes: F18, F64, O44, Q54, Q56.

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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 warming induced by long-lived GHGs since pre-industrial times, making it the second largest contributor to climate radiative forcing after Carbon Dioxide (CO_2; EPA, 2012). Methane has significant warming potential, notably in the beginning of its atmospheric life, and there is evidence of a strong and mostly coincident linkage between methane emissions and global temperature trends (Estrada et al., 2013).

Atmospheric methane concentrations result from a mix of natural and anthropogenic sources.[1] 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 have started to rise again (Kirschke et al., 2013). Estrada et al. (2013) identify two main causes of the slow-down in warming since the mid-1990s, which highlight the impact of human behavior in global warming. The first is the reduction in chlorofluorocarbon (CFC) emissions as a result of the Montreal Protocol (1989). The second is lower anthropogenic methane emissions, possibly caused by a decrease in microbial sources resulting from the use of chemical fertilizers and more efficient water use for rice production in Asia.

Despite its importance, methane has neither been a primary focus in recent economic and political debate on greenhouse gas regulation, nor has it been among the main targets of environmental policies. National methane regulations exist in some countries, but international cooperation in the reduction of methane is largely missing. While the Kyoto Protocol (1997) was meant to limit emissions of CO_2 and five other GHGs including methane (measured in CO_2 equivalents), binding emission reduction targets are small and confined to Annex I members of the protocol[2] (i.e. developed economies), providing substantial room for emission leakage. Furthermore, the protocol has not introduced mechanisms to change the behavior of the countries bound by emission targets of its Annex I (Barret, 2008), while the enforcement of compliance with these targets has also been problematic

[1] Kirschke et al. (2013) group sources of CH_4 emissions into two natural sources (natural wetland and other natural emissions) and three anthropogenic sources (agriculture and waste, fossil fuels, and biomass and biofuel burning). During the 2000-2009 period, natural wetland emissions and agriculture and waste emissions were the main sources of methane emissions, followed by anthropogenic fossil fuel emissions, other natural emissions, and emissions from biomass and biofuel burning.

[2] The Annex I countries were originally defined by the United Nations Framework Convention on Climate Change (UNFCCC). In the Kyoto Protocol emission targets for the Annex I countries were determined, with the exception of Turkey, and enshrined in the Annex B of the protocol. For the rest of the paper we stick to the term Annex I countries.

(see Nentjes and Klaassen, 2004, Hagem et al., 2005, Feaver and Durrant, 2008, Aichele and Felbermayr, 2012).

We develop a global panel dataset of national inventories of methane emissions embodied in standard (territorial) production, final production, and consumption activities. In the context of global supply chains and vertical specialization, the attribution of responsibilities in international environmental agreements and the determination of national policy targets and instruments must account for international linkages and potential for outsourcing. Our dataset takes into account cross-border linkages in production and provides valuable information about national (and sectoral) responsibility for emissions at three stages of the supply chain.

The dataset is built from underlying data covering 187 economies, grouped into 78 countries and regions and 57 sectors, for the years 1997, 2001, 2004, 2007, and 2011. Following the recent literature on international value chains, methane inventories are calculated based on multi-regional input-output (MRIO) analysis (Koopman et al., 2014; Fernández-Amador et al., 2017). This means that we extend territorial national production inventories, by tracing emissions embodied in intermediate input flows to compute emissions embodied in final production. We also map emissions embodied in trade flows of final goods and services in order to calculate final consumption emissions inventories.

Based on these comparable inventories, we identify four main stylized facts regarding methane emissions worldwide. First, methane mitigation is important for climate change control, especially in the short-term—anthropogenic methane emissions are equivalent to between 25% and 84% of the warming potential of CO_2 emissions from fossil fuel combustion, depending on whether we use a 100-year or a 20-year basis to compute the equivalence, and increased 25% during 1997–2011. Second, developing countries account for the largest part of anthropogenic CH_4 emissions. While high-income countries were able to reduce per-capita emissions between 1997 and 2011, the emissions from developing countries have increased despite considerable gains in CH_4 efficiency. Third, high income countries show net-imports of emissions embodied in goods and services, which are divided in intermediate and final products alike. Finally, there are important differences across sectors concerning the contributions of value added growth and methane efficiency gains, which are likely to affect transaction costs related to environmental regulation.

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 1997–2011. We conclude in Section 4.

2 Construction of national emission inventories

To construct the emission data, we first generate our national (standard, territorial) production-based emission inventories. For that purpose, we map methane emissions from several sources to the 57 sectors of the 78 regions covered.[3] These inventories constitute the standard measure of national CH_4 emissions relevant for multilateral agreements on emissions reduction such as the Kyoto Protocol. We then develop inventories of CH_4 emissions embodied in both final production and final consumption activities using MRIO techniques.

2.1 Construction of territorial production inventories

In order to create a consistent panel of sectoral methane emissions inventories for the years 1997, 2001, 2004, 2007 and 2011, we modify and extend the methodology developed by the Global Trade Analysis Project (GTAP) to elaborate the methane data provided by the different *non-CO_2 Emissions database* releases (see Rose and Lee, 2008, Rose et al., 2010, Ahmed et al., 2014, Irfanoglu and van der Mensbrugghe, 2015).[4] Unfortunately, the GTAP CH_4 emissions data cannot be used in a panel framework, since the sources of raw data and/or the methodology for data construction differ across releases.[5]

Therefore, we construct our territorial production inventories maintaining the sectoral disaggregation and countries present in GTAP data to ensure consistency over time. For the years 2001, 2004, 2007 and 2011, we match methane emission categories from the FAOSTAT (2014) and EDGAR (2011) databases directly to the 57 sectors where possible, using the concordance tables provided by Irfanoglu and van der Mensbrugghe (2015).[6]

[3] An overview of the regions and sectors covered is available in Table A.1 and A.2, respectively, in Appendix A. We maintained the highest degree of sectoral and regional disaggregation in order to minimize aggregation bias, while keeping consistency over time. Therefore, we were able to compute inventories at 57 sectors, which is equal to GTAP sectoral disaggregation, and 78 regions (66 countries and 12 regions) which is the minimum regional disaggregation of the raw data used (of GTAP release for 1997).

[4] These releases include methane emissions, among other GHGs, for the years 2001, 2004, 2007 and 2011, disaggregated to 57 economic sectors. We extend the time dimension backwards to 1997.

[5] The 2001 release was constructed in cooperation between GTAP and the US Environmental Protection Agency, resulting in a highly disaggregated database of GHG emissions linked to economic activity (see Rose et al., 2007, Rose and Lee, 2008); this undertaking has not been repeated since then. Thus, GTAP applied growth rates of detailed GHG emission categories provided by the EDGAR (2011, non-agricultural activities) and FAOSTAT (2014, agricultural activities) datasets on their 2001 data to extrapolate it to 2004 and 2007 (Ahmed et al., 2014). The only exceptions were the GTAP sectors "mineral production", "manufactures n.e.c". and "paper products and publishing". For these sectors no EDGAR data was available. Ahmed et al. (2014) thus extrapolate 2001 GTAP data of these sectors using an output growth approach. For the 2011 release GTAP changed methodology again and matched EDGAR (2011) and FAOSTAT (2014) data directly to sectors.

[6] As noted by Kirschke et al. (2013), depending on the methodology used to measure atmospheric methane emissions, anthropogenic emissions dominate natural emissions (top-down methods) or are of a com-

All categories in the FAO and many in the EDGAR databases can be directly matched to a single sector, resulting in a direct match of about 75% of global methane emissions. We allocate the remaining 25%, which are EDGAR (2011) emission categories that can be matched to more than one sector, to our 57 sectors by using sector shares of emissions provided by GTAP. To be as precise as possible, we additionally incorporate GTAP information on whether emissions are caused by usage of endowments by industries, output and input usage of industries, or input usage of households, to the mapping process.[7] Finally, as the most recent methane emissions data provided by EDGAR is from 2010, we follow Irfanoglu and van der Mensbrugghe (2015) and extrapolate EDGAR data to 2011 by using average growth rates of CH_4 in the EDGAR categories between 2007 and 2010.

Additionally, we extend our dataset back to 1997. As for the other years we match FAO and EDGAR CH_4 emissions data directly to sectors where possible. For the remaining sectors we apply moving averages on the GTAP data from 2001–2011 to derive estimates for 1997. We then allocate the EDGAR emission categories among sectors using those shares.

This procedure results in a dataset of territorial CH_4 emissions for the years 1997, 2001, 2004, 2007 and 2011 disaggregated to 57 economic sectors. This inventory refers to emissions originated within national boundaries. We further aggregate sectoral emissions to national emissions, resulting in a balanced panel dataset of 390 observations, which correspond to national production (territorial based) CH_4 inventories.[8] Territorial emission inventories constitute the standard measure of national emissions relevant for multilateral agreements on emissions reduction such as the Kyoto Protocol.

In a next step we combine territorial sectoral emissions data with input-output and trade data provided by GTAP to calculate comparable final production and consumption based CH_4 inventories (i.e. CH_4 footprints). Final production inventories collect all emissions embodied in intermediate inputs used in the production of final goods and assign them to the country and sector that produces the final good (supply-side of final products). Consumption-based inventories, by contrast, reflect the demand-side for final products

parable size, though slightly below them (bottom-up estimates). Nevertheless, there is uncertainty associated to these measurements; for example, Schwietzke et al. (2016) report that the estimated contribution of total fuel methane emissions (defined as fossil fuel industry plus natural geological seepage) has been estimated between 15 and 22% of total methane emissions. However, the authors provided evidence based on a new isotope records database that (i) total fuel methane emissions may be 60 to 110% larger than current estimates; (ii) emissions from the fossil fuel industry may be 20 to 60% larger than in current inventories; and (iii) natural gas production emissions may have declined from 8 to 2% during 1985–2013.

[7] A detailed description on how the emissions categories of FAO and EDGAR are matched to the sectors in the GTAP database is given in Table A.3 in the Appendix.

[8] We aggregate our data to the 66 countries and 12 regions present in the year 1997 to remain consistent over time.

and allocate emissions embodied in the consumption of products from specific sectors to the country in which consumption takes place.

2.2 From territorial emissions to final production and consumption inventories

To construct the footprint measures for national CH_4 emissions, we implement MRIO techniques. We first combine input-output and trade data sourced from GTAP to construct a global intermediate input requirements matrix. Next, we create an environmentally extended MRIO table by scaling the global requirements matrix to CH_4 emissions and calculate the environmentally extended Leontief-inverse matrix, which collects the direct and indirect CH_4 requirements for a given unit of output for each sector in each region. We finally derive the final production and consumption based national inventories.

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 its dimension s is the number of sectors defined in the economy (57 in our case). We define the exporter region as r and the importer region as p, such that $r, p \subseteq [1, n]$, where n stands for 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 is equal to the intermediates required as inputs from all sectors in all regions plus final demands from all regions. That is,

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

where $(x_1, x_2, x_3, \ldots, x_n)'$ is the companion vector of sectoral gross output for all the n regions. Each A_{rp} is the $s \times s$ matrix of trade in intermediates from region r to region p (which refers to domestic flows wherever $r = p$). We follow input–output conventions and define flows across rows as sales and flows down the columns as expenditures. 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 unit of output, where $k, j \subseteq [1, s]$. We calculate the MRIO tables for each year from input–output, trade, and demand data provided by the GTAP database following Peters et al. (2011).[9] The matrix with elements A_{rp}, which we cast A, is the MRIO matrix that collects all the intermediate input requirements of all sectors in all regions. It is of dimension $(n \cdot s) \times (n \cdot s)$.

Each element y_{pr} in the last matrix (which we name Y) appearing on the right-hand side of equation (1) denotes the final demand in region p for products from region r, being $y_{pr} = (y_{pr,1}, y_{pr,2}, \ldots, y_{pr,s})'$ a column vector of dimension s where each element $y_{pr,z}$ is the final demand in region p for products from sector z in region r. The vector l is an all-ones column vector of dimension n. The product of the matrix of final demands and the vector l, Yl, results in the column vector of total final demands y.

To take into account the indirect flows of CH_4 emissions through global supply chains, we first solve the expression above, $x = Ax + y$, for the companion vector of gross outputs, such that $x = (I - A)^{-1}y$. The matrix $(I - A)^{-1}$ is the Leontief-inverse matrix, where I is the identity matrix. The Leontief-inverse 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), generated by one unit of output. Denoting its sub-matrices as $(I - A)^{-1}_{rp}$, each element $(i - a)^{-1}_{kj}$ in $(I - A)^{-1}_{rp}$ contains the direct and indirect inputs needed from sector k in country r to produce one unit of output in sector j in country p.

Finally, we compute the final (embodied) production and final consumption emissions inventories at a national level. We can define the flux of CH_4 emissions embodied in final production of region r, $f^o_r = (f^o_{r1}, f^o_{r2}, \ldots, f^o_{rn})$, where the components of f^o_r (i.e., $f^o_{r1}, \ldots, f^o_{rn}$) show the final production of the region r using intermediates from regions 1 to n embodied in final production of region r. We also define the flux of CH_4 emissions embodied in final consumption of region r, $f^c_r = (f^c_{1r}, f^c_{2r}, \ldots, f^c_{nr})$, where the components of f^c_r (i.e., $f^c_{1r}, \ldots, f^c_{nr}$) show the final consumption of the region r of intermediates from regions 1 to n embodied in final demand of region r. Therefore,

$$f^o_r = E\,(I - A)^{-1}\,o_r \ , \tag{2}$$

$$f^c_r = E\,(I - A)^{-1}\,c_r \ , \tag{3}$$

[9] Kanemoto et al. (2012) discuss several methods to compute methane 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.

In expressions (2) and (3), the Leontief-inverse matrix is rescaled by the diagonal matrix E of dimension $(n \cdot s) \times (n \cdot s)$ of regional emission-intensities. For that purpose, we define the vector of sectoral emission-intensities in region i as $e_i = (e_{i,1}, e_{i,2}, \ldots, e_{i,s})$ such that each element is calculated as the ratio of CH_4 emissions per gross output of the corresponding sector $(x_{i,s})$. The vector of elements of the main diagonal of E, $e = (e_1, e_2, \ldots, e_n)$, stacks all the n regional emission-intensities e_i. Thus, the term $E\,(I - A)^{-1}$ is the matrix of total (direct and indirect) embodied methane intensities of each sector in each region; it is of dimension $(n \cdot s) \times (n \cdot s)$. The vectors o_r and c_r are the column-vectors of final production from region r, $o'_r = (y'_{r1},\ y'_{r2},\ y'_{r3},\ \ldots,\ y'_{rn})$, and final consumption of region r, $c'_r = (y'_{1r},\ y'_{2r},\ y'_{3r},\ \ldots,\ y'_{nr})$. Both have dimension $(n \cdot s)$.[10]

Expression (2) describes the flux of emissions embodied in final production of region r. Methane emissions are a function of the bundle of intermediates from all sectors and regions that are used in the supply chain, determined by the Leonfief inverse, $(I - A)^{-1}$, and the methane intensities, collected in E. As mentioned above, the components of f^o_r (i.e., $f^o_{r1}, \ldots, f^o_{rn}$) show the final production of the region r using intermediates from regions 1 to n embodied in final production of region r. Furthermore, the sum of the components of f^o_r across providers of intermediates, $\phi^o_r = \sum_p f^o_{rp}$, shows the total (direct and indirect) CH_4 emissions embodied in final production of region r. We can finally define a vector of components ϕ^o_r, where $r \subseteq [1, n]$, which constitutes our national final (embodied) production emissions inventories.

Analogously, equation (3) describes the flux of emissions embodied in final consumption of region r. Methane emissions are a function of the bundle of final goods (incorporating intermediates) from all sectors and regions that are embodied in final demand of region r, determined by the Leontief-inverse, $(I - A)^{-1}$, and the methane intensities, collected in E. As mentioned above, the components of f^c_r (i.e., $f^c_{1r}, \ldots, f^c_{nr}$) show the final consumption of the region r of intermediates from regions 1 to n embodied in final demand of region r. Furthermore, the sum of the elements of f^c_r across providers of final goods, $\phi^c_r = \sum_p f^o_{pr}$, shows the total (direct and indirect) CH_4 emissions embodied in final consumption of region r. We can also define a vector of components ϕ^c_r, where $r \subseteq [1, n]$, which constitutes our national consumption emissions inventories.

[10] y_{rp} in o_r denotes exports of final production from region r to region p, while y_{pr} in c_r denotes imports of final demand by region r of production from region p. y_{rr} denotes domestic final demand. As mentioned above, both y_{rp} and y_{pr} are row vectors of dimension s.

3 Stylized facts of national emission inventories

3.1 Global sources of methane and national emission inventories

Table 1 presents the total amount of anthropogenic methane emissions released during the period 1997–2011 in warming potential equivalent to CO_2 emissions from fossil fuel combustion, computed by Fernández-Amador et al. (2016), using two alternative time frames. Although methane has a relatively short atmospheric life-time, 12.4 years, its global warming potential is 72 times that of CO_2 (by equivalent mass) over a 20-year period and 21 times over a 100-year time frame, respectively (IPCC, 2007). The table indicates that although anthropogenic methane emissions are equivalent to 25% of CO_2 emissions on a 100-year basis, they are only somewhat lower (84%) than the warming potential of CO_2 emissions over a 20-year period. In addition, global methane emissions increased by 25% between 1997 and 2011. In this sense, methane mitigation is important for climate change control, especially in the short-term.[11]

	CH_4 (CO_2e, 100y)		**CH_4** (CO_2e, 20y)		**CO_2**
	Mt	% of CO_2	Mt	% of CO_2	Mt
1997	5862.41	25.82	20099.68	88.54	22701.79
2001	5999.47	26.02	20569.60	89.22	23054.30
2004	6410.75	24.28	21979.73	83.25	26403.22
2007	6800.65	23.35	23316.50	80.07	29121.03
2011	7313.50	23.61	25074.85	80.96	30971.11

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 21 and 72, respectively (IPCC, 2007). CO_2 data are available from Fernández-Amador et al. (2016).

Figure 1 shows the contribution of the 57 sectors to global methane emissions embodied in territorial production (upper graph) and final production and consumption patterns (lower graph) as calculated in our database. Production-based emissions are concentrated in relatively few sectors, which correspond to very heterogeneous economic processes such as livestock breeding (34.7%), drilling and transportation of fossil fuels (25.1%), public administration (19.9%, which is mainly waste management), and rice cultivation (7.8%). Footprint-based emissions, by contrast, are spread across sectors more evenly as a result of domestic and international inter-sectoral supply-chain relations. Particularly, much of the methane produced by rice cultivation and livestock breeding is used in food processing sectors, while emissions from fossil fuel drilling are mainly used by industrial activities and transportation services.

[11] Methane also contributes to thermal expansion of the ocean over much longer time scales than its atmospheric life-time (Zickfeld et al., 2017).

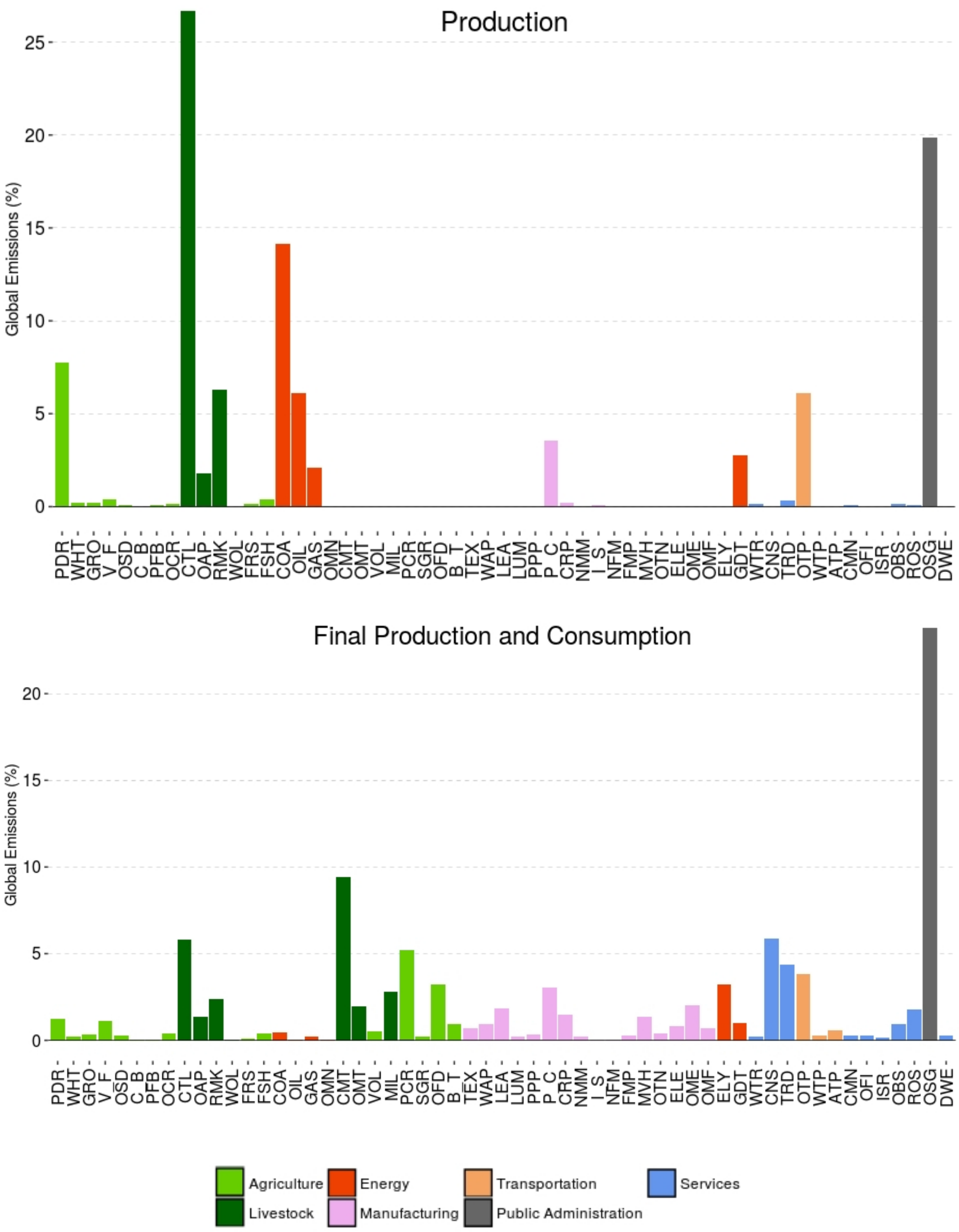

Figure 1: Sector shares of global CH_4 emissions, three inventories (average 1997–2011). The barplots show CH_4 emissions associated with production (upper plot) and consumption and final production (lower plot) in each of the 57 sectors as share of global methane emissions. On a global level methane emissions associated with final production and final consumption are equal. For a definition of sector-abbreviations and for the assignment of each sector to the broad sectors represented by the different colors, see Table A.2 in Appendix A.

	production		final prod.		consumption		CH₄ pc*		CH₄ per VA*	
			Total CH_4*				CH_4 pc*		CH_4 per VA*	
	production		final prod.		consumption		prod.	cons.	prod.	cons.
	(Mt)	(shr.)	(Mt)	(shr.)	(Mt)	(shr.)	(t per capita)		(kg/USD)	
1997										
High Income	1496.75	25.53	1882.10	32.10	2009.19	34.27	1.52	2.04	0.07	0.10
Australia	117.30	2.00	86.90	1.48	71.41	1.22	6.35	3.86	0.33	0.20
EU 15	471.63	8.04	659.80	11.25	712.22	12.15	1.27	1.92	0.07	0.10
EEU	156.15	2.66	160.88	2.74	155.46	2.65	1.46	1.45	0.56	0.50
USA	571.54	9.75	657.94	11.22	714.18	12.18	2.16	2.70	0.07	0.09
Upper Middle	2433.79	41.52	2174.01	37.08	2092.06	35.69	1.10	0.94	0.62	0.53
Brazil	289.14	4.93	301.21	5.14	301.16	5.14	1.79	1.86	0.39	0.40
Russia	444.11	7.58	332.37	5.67	334.54	5.71	3.02	2.28	1.16	0.88
China	868.77	14.82	799.34	13.64	731.02	12.47	0.71	0.60	1.23	1.03
Mexico	94.60	1.61	94.47	1.61	94.08	1.60	1.00	0.99	0.27	0.28
Middle East	200.17	3.41	138.32	2.36	142.80	2.44	1.27	0.91	0.44	0.31
Lower Middle	1812.98	30.93	1689.48	28.82	1647.58	28.10	0.76	0.69	1.27	1.11
Former SU	211.47	3.61	187.60	3.20	170.80	2.91	1.53	1.24	1.93	1.50
India	552.82	9.43	550.69	9.39	540.87	9.23	0.58	0.56	1.57	1.51
Indonesia	153.50	2.62	141.32	2.41	143.01	2.44	0.76	0.71	0.79	0.74
RSA	112.63	1.92	112.02	1.91	109.89	1.87	0.64	0.63	1.85	1.70
SSA	362.86	6.19	316.47	5.40	309.12	5.27	0.90	0.77	2.43	2.02
Low Income	118.89	2.03	116.81	1.99	113.58	1.94	0.57	0.54	1.75	1.58
2011										
High Income	1330.18	18.19	1862.66	25.47	1971.02	26.95	1.23	1.83	0.05	0.08
Australia	152.85	2.09	96.35	1.32	83.18	1.14	6.84	3.72	0.26	0.14
EU 15	377.51	5.16	641.30	8.77	678.23	9.27	0.94	1.69	0.05	0.09
EEU	134.10	1.83	151.88	2.08	149.93	2.05	1.32	1.47	0.28	0.28
USA	486.94	6.66	619.17	8.47	681.79	9.32	1.56	2.19	0.05	0.07
Upper Middle	3453.37	47.22	3122.14	42.69	3036.25	41.52	1.36	1.20	0.44	0.38
Brazil	407.19	5.57	394.44	5.39	387.11	5.29	2.07	1.97	0.40	0.37
Russia	549.30	7.51	368.27	5.04	372.21	5.09	3.84	2.60	1.04	0.66
China	1451.27	19.84	1426.06	19.50	1308.10	17.89	1.08	0.97	0.51	0.45
Mexico	108.54	1.48	107.26	1.47	109.31	1.49	0.91	0.92	0.18	0.18
Middle East	335.29	4.58	220.58	3.02	256.35	3.51	1.52	1.16	0.35	0.29
Lower Middle	2360.64	32.28	2167.21	29.63	2147.30	29.36	0.77	0.70	0.85	0.73
Former SU	256.67	3.51	201.26	2.75	196.90	2.69	1.84	1.41	1.18	0.91
India	658.59	9.01	666.90	9.12	643.27	8.80	0.54	0.53	0.63	0.59
Indonesia	210.47	2.88	185.24	2.53	190.92	2.61	0.86	0.78	0.67	0.58
RSA	172.96	2.36	174.46	2.39	172.70	2.36	0.74	0.74	1.45	1.26
SSA	489.26	6.69	429.97	5.88	444.12	6.07	0.83	0.76	1.72	1.40
Low Income	169.31	2.32	161.49	2.21	158.93	2.17	0.59	0.55	1.37	1.28

Table 2: Main indicators for CH_4 inventories: 1997 and 2011. Selected regions. Note: *Data is reported as CO_2 equivalents with respect to global warming potential for a 100 year time frame. pc stands for per capita, VA stands for value added, Mt stands for megatons, shr. for world shares, t for ton, kg for kilogram. EEU stands for Eastern European Union members joining the Union in 2004 and 2007, including the upper-middle income countries Bulgaria and Romania; for the group totals these countries are assigned to their respective income group. RSA stands for the Rest of South Asia area, SSA for the Rest of Sub-Saharan Africa region. For details on the countries covered in these regions see Table A.1 in Appendix A.

Table 2 reports a summary of the three CH_4 inventories for the most important producers and consumers of methane emissions, which taken together represent roughly 80% of produced emissions between 1997 and 2011, and for the four income groups as defined by the World Bank. The first six columns report total CH_4 emissions in megatons (Mt) of

CO_2 equivalents and as world shares for each emission inventory.[12] The last four columns summarize CH_4 emissions per capita (in tons) and per value added (as kg per USD) for production- and consumption-based inventories.[13]

The bulk of anthropogenic methane emissions is concentrated in developing economies, especially in the upper and lower-middle income groups. Together, these groups accounted for 72% of produced and 64% of consumed CH_4 in 1997.[14] The dynamics of emissions between 1997 and 2011 were very different for developed and developing economies. Emissions in developing countries grew considerably for all three methane inventories, especially in upper-middle income countries, which include the BRIC countries Brazil, Russia and China, and in low-income countries. For the high income group, by contrast, CH_4 emissions derived from production declined by 11% between 1997 and 2011; the decline was less pronounced for emissions embodied in final production and consumption.

High-income countries show, on average, the highest level of methane emissions per person, followed by upper-middle and lower-middle income countries. In high-income countries, per capita emissions consumed are larger than per capita CH_4 embodied in production, reflecting the fact that they are net importers of emissions. By contrast, for the other income categories the opposite is true. During 1997–2011, emissions per capita grew most strongly in upper-middle income countries, whereas they increased only slightly in the lower-middle and low-income groups and even experienced a decrease in the high-income countries. Large producers of fossil fuels show rather high per capita emissions compared to the other countries in their respective income groups and are usually also net exporters of emissions, as the production-based per capita inventories considerably exceed the consumption-based ones.

High-income economies show by far the highest methane efficiency per unit of value added, followed by upper-middle and lower-middle income countries; low-income economies are particularly methane intensive. Yet, the methane efficiency of high-income countries is higher for production than for consumption inventories whereas the opposite is the case in the other income groups. Between 1997 and 2011, improvements in methane efficiency were especially important in the lower- and upper-middle income countries, which were able to reduce the methane content of value added by about one third. The high- and low-income groups showed only slightly lower improvements in the methane content of

[12] CO_2 equivalents of methane are based on a global warming potential (GWP) over 100 years; this equivalence is commonly used in the literature.

[13] Pollution intensity (efficiency) is often measured in pollution per GDP. We opt for a value added based measure in order to align the definition of the economic aggregate and the flux of methane emissions derived from it.

[14] This contrasts with data for CO_2 releases from fossil fuel combustion, where most of the emissions are released by developed economies (see Fernández-Amador et al., 2016).

value added from production and comparably smaller improvements in the CH_4 efficiency embodied in consumption.

3.2 Decomposition of changes in methane emissions

Figure 2 decomposes the growth rate of total emissions between 1997 and 2011 (marked by the black dots) from the three emission inventories and for the four income groups into changes in methane intensity (dark bar), changes in value added per capita (light bar), and population growth (white bar). In general, the expansion of value added per capita and population growth have increased emissions, whereas efficiency gains had the opposite effect. Only in high-income countries, the rather moderate growth rates of population and value added did not outweigh efficiency improvements and, as a result, total emissions decreased during 1997–2011. In the other income groups, the expansion of value added per capita and population surpassed efficiency gains and yielded increasing methane releases.

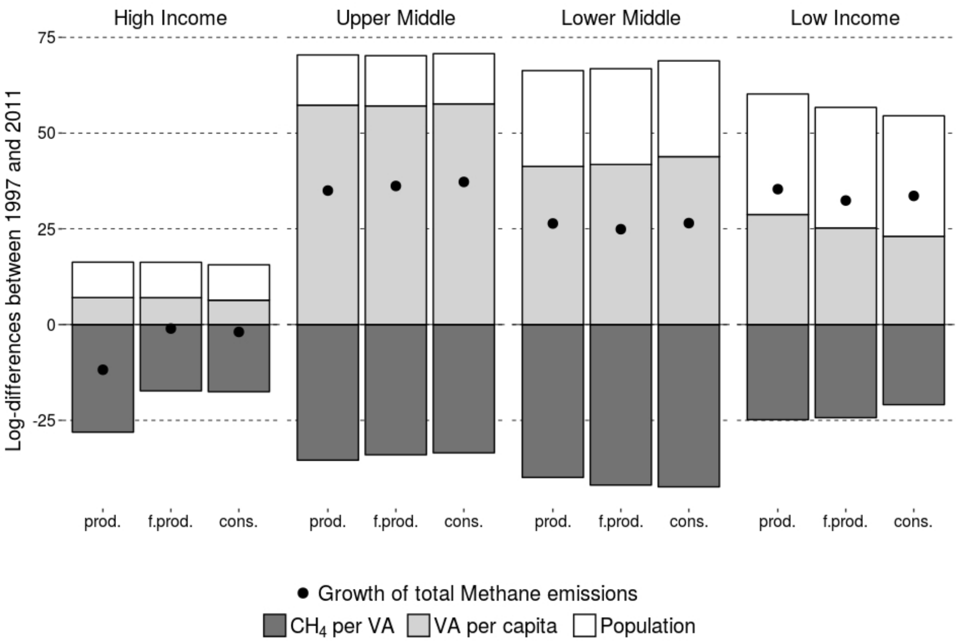

Figure 2: Change in components of the Kaya-identity (1997–2011). Note: The barplots show the log-differences of the components of the Kaya-identity between 1997 and 2011 for the four World Bank income groups. The Kaya identity decomposes total CH_4 emissions into CH_4 per value added, value added per capita, and population, according to the formula $CH_4 = \frac{CH_4}{VA} \cdot \frac{VA}{pop} \cdot pop$. The data is presented 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.

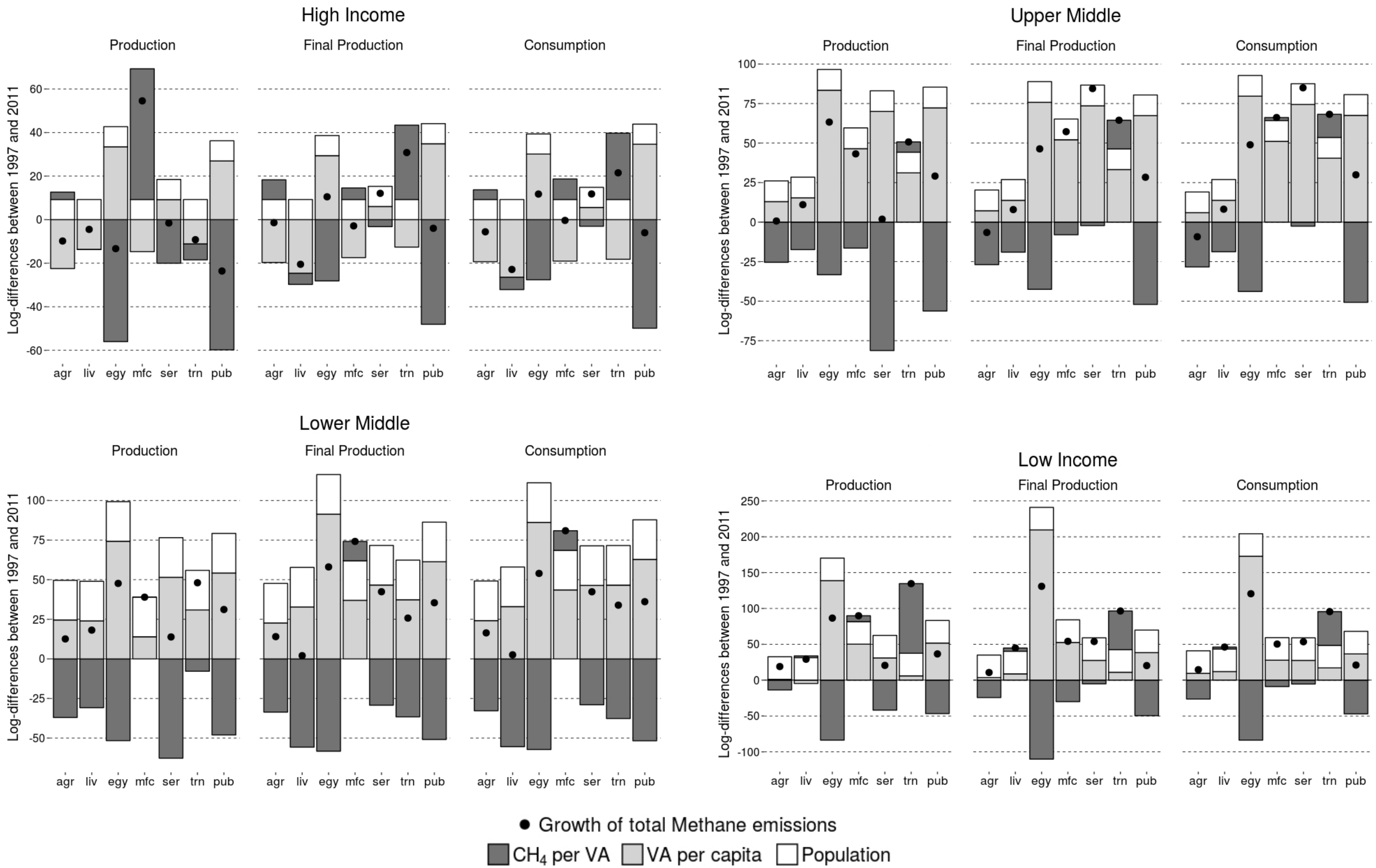

Figure 3: Change in components of the Kaya-identity (1997 – 2011, sectors). Note: The barplots show the log-differences of the components of the Kaya-identity between 1997 and 2011 for seven sectors of the four World Bank income groups. The Kaya identity decomposes sectoral CH_4 emissions into CH_4 per 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. The data is presented 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.

Figure 3 shows the decomposition of emissions growth at the sectoral level and reveals that the aggregate pattern shown in Figure 2 hides important sector-specific characteristics.[15] Although efficiency gains were important on the aggregate level, they were not realized to the same extent in every economic sector. This points towards different potential for emission abatement in different sectors. Improvements in efficiency were particularly limited in the manufacturing and transport sectors, which even experienced an increase in the CH_4 intensity of value added in most income groups. Also the primary sectors have shown lower mitigation potential as compared to other sectors; the livestock sector in low-income countries and the agriculture sector in high-income economies were characterized by a slight decline in methane efficiency. In all income groups the largest efficiency gains took place in the energy, services, and public administration sectors.

The economy-wide changes in value-added per capita are also to a large extent influenced by sectoral shifts of production and consumption patterns. The energy and the public administration sectors (the latter includes landfills and sewage treatment) experienced a strong growth during 1997–2011 in all income groups. In low-income countries also the manufacturing sector expanded considerably, whereas for the other income groups the service sector was among the sectors that grew more strongly. In high-income countries, the primary, manufacturing, and transport sectors even decreased their shares in value added. These patterns are consistent with the structural shifts usually associated with economic development (Kuznets, 1973, Herrendorf et al., 2013) and highlight the importance of analyzing emissions at the sectoral level.

3.3 Methane embodied in international trade

Table 3 describes the flows of methane emissions embodied in international trade. It reports the CH_4 content of exports and imports scaled to production-based emissions, net-exports of emissions embodied in intermediates and total trade, indicators for emission leakage, and measures of methane intensity of international trade.

As a result of intensifying globalization, the ratio of traded to total methane emissions increased from 18.5% to 22.9% between 1997 and 2011, particularly in high-income countries. The group of high-income countries traded embodied emissions more intensively than their less developed counterparts. This is largely driven by the CH_4 content of imports, since the share of exported methane emissions scaled to total production-based emissions is relatively low in most regions.[16] With the exception of fuel exporters such as

[15] For the sectoral analysis we aggregate the 57 sectors in our dataset to seven 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.

[16] Exceptions are large fossil fuel exporters, such as Australia, Russia, and the Middle East.

	Embodied CH_4*				CH_4 leakage*		CH_4 per VA*	
	exports	imports	BEETI	BEETT	prod.	imports	exports	imports
	(shares of prod. emissions)				(shares of)		(kg/USD)	
1997								
High Income	18.21	52.43	-25.75	-34.24	32.91	62.76	0.10	0.31
Australia	48.40	9.27	25.92	39.13	5.95	64.20	0.99	0.19
EU 15	8.40	59.41	-39.90	-51.01	35.59	59.90	0.05	0.38
EEU	22.87	22.43	-3.03	0.44	9.56	42.60	0.49	0.35
USA	11.63	36.59	-15.12	-24.96	25.50	69.70	0.09	0.27
Upper Middle	22.13	8.10	10.67	14.04	5.23	64.60	0.72	0.25
Brazil	3.18	7.34	-4.17	-4.16	5.51	75.08	0.18	0.30
Russia	32.04	7.37	25.16	24.67	5.54	75.10	2.10	0.49
China	19.12	3.26	7.99	15.86	1.86	56.93	1.12	0.19
Mexico	12.83	12.28	0.14	0.55	4.07	33.17	0.16	0.16
Middle East	45.92	17.26	30.90	28.66	9.17	53.12	0.68	0.25
Lower Middle	14.60	5.48	6.81	9.12	2.74	49.97	1.06	0.33
Former SU	29.40	10.17	11.29	19.23	0.63	6.15	2.57	0.76
India	4.58	2.42	0.39	2.16	1.87	77.17	0.75	0.33
Indonesia	15.08	8.24	7.94	6.83	4.52	54.81	0.53	0.29
RSA	6.36	3.92	0.54	2.44	3.03	77.14	0.90	0.38
SSA	16.82	2.27	12.78	14.81	1.55	68.26	1.73	0.21
Low Income	8.22	3.75	1.75	4.47	3.03	80.88	1.22	0.37
2011								
High Income	23.03	71.36	-40.03	-48.18	46.78	65.56	0.08	0.27
Australia	60.57	14.99	36.97	45.58	11.29	75.33	0.83	0.20
EU 15	11.94	91.59	-69.88	-79.66	57.81	63.12	0.04	0.32
EEU	23.50	35.31	-13.26	-11.81	16.01	45.34	0.23	0.24
USA	13.46	53.48	-27.16	-40.02	39.44	73.75	0.07	0.25
Upper Middle	25.87	13.74	9.59	12.08	9.94	72.37	0.49	0.25
Brazil	12.66	7.73	3.13	4.93	5.74	74.24	0.48	0.23
Russia	40.29	8.05	32.96	32.24	6.03	74.93	1.73	0.27
China	19.49	9.63	1.74	9.86	6.64	68.99	0.49	0.21
Mexico	19.77	20.47	1.19	-0.70	10.25	50.05	0.17	0.17
Middle East	53.06	29.52	34.21	23.54	21.72	73.58	0.44	0.31
Lower Middle	19.15	10.11	8.19	9.04	7.41	73.28	0.76	0.31
Former SU	32.55	9.27	21.59	23.29	4.19	45.23	1.13	0.32
India	11.86	9.53	-1.26	2.33	7.48	78.55	0.51	0.30
Indonesia	22.76	13.47	11.99	9.29	10.05	74.57	0.72	0.34
RSA	6.98	6.83	-0.87	0.15	5.79	84.70	0.90	0.38
SSA	16.60	7.37	12.12	9.23	6.04	82.00	1.09	0.33
Low Income	13.03	6.91	4.62	6.13	6.22	90.04	0.84	0.44

Table 3: CH_4 emissions embodied in trade: 1997 and 2011. 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. BEETI and BEETT stand for net balance of emissions embodied in trade in intermediates and total trade, respectively. EEU stands for Eastern European Union members joining the Union in 2004 and 2007. The region includes the upper middle income countries Bulgaria and Romania. For the development group aggregates these countries were assigned to the upper middle income group, however. 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.

Australia, the CH_4 content of imports is rather large in the group of high-income countries, as exemplified by the EU-15 and the USA, where imported emissions amounted to 92% and 53% of production-based emissions in 2011.

The higher CH_4 content of imports relative to exports in high-income countries again confirms that they are net-importers of methane. Their trade balance of emissions embodied in trade in intermediates (BEETI) and in total trade (BEETT), scaled to production-based emissions, is typically negative. This imbalance grew between 1997 and 2011, with a growing reliance of high-income countries on net-imports of CH_4, mirrored by increased net-exports in middle- and low-income countries. Also shown by BEETI and BEETT, traded methane emissions are embodied in traded intermediates and final goods alike.[17]

The net-importation of methane in high-income countries, many of which are bound by emission targets specified in the Annex I of the Kyoto Protocol, points towards potential for methane leakage. Emissions embodied in imports from non-Annex I countries scaled to emissions from territorial production are the largest in the group of high-income countries, particularly in the EU-15 and USA, whereas they are below the high-income average in Australia and EEU. In middle- and low-income countries this indicator is typically much lower, though during 1997–2011 it doubled in the upper-middle and low-income groups and increased by a factor of 2.7 in the lower-middle income group, reflecting the growing importance of trade among developing countries. The importance of developing economies in methane embodied in trade flows appears even clearer when we look at emissions embodied in imports from non-Annex I members as a share of total imported emissions. This other indicator of methane leakage is rather high in all income groups and has been growing over the period considered.

In terms of methane intensity, imports of high-income countries are, on average, more intensive in CH_4 content per unit of value added than exports. For the other income groups the opposite applies, with a notable difference in the low-income group. A comparison of these figures to the CH_4 intensities reported in Table 2 reveals that exports of the high- and upper-middle income groups are typically more CH_4 intensive than their national production, whereas the CH_4 intensity of imports is higher than the one of consumption in the high-income group. For the lower-middle and low-income groups, trade flows show larger methane efficiency than production and consumption aggregates; that is, the aggregate of domestic emissions (produced and consumed in the territory) is less environmentally efficient than the sectors oriented to trade. Finally, we observe a general decrease in the CH_4 intensity of trade over time, reflecting gains in methane efficiency that were also visible from Table 2.

[17] This contrasts with CO_2 emissions, which are mainly embodied in trade in intermediates, because of their origin in energy usage (see Fernández-Amador et al., 2016).

4 Conclusions

We put forward a global panel dataset of national inventories of methane emissions embodied in territorial production, final production, and consumption activities. Our dataset reveals several stylized facts of anthropogenic methane emissions. Global methane emissions are quantitatively important. They are equivalent to between 25% and 84% of CO_2 emissions from fossil fuel combustion, depending on the time frame used to compute the equivalence, and have increased about 25% during 1997–2011. The bulk of emissions is attributable to developing countries, but still high-income countries have been net-importers of emissions. Economic growth and expanding population have been responsible for the increase in emissions from developing countries, whereas methane efficiency gains only partially counteracted these effects.

International, coordinated action on climate change mainly concerns the determination of property rights on responsibilities for damage, and costs and rents from policies. There are transaction costs that increase the costs or decrease the probability of reaching an agreement for multilateral cooperation (Libecap, 2014). Atmospheric methane emissions are an important global pollutant which shows negative (global) externalities and poses several challenges to coordinated action to mitigate or abate it. Effective international cooperation to mitigate global negative externalities, such as methane emissions, will take place when transaction costs are overcome. In this sense, the information contained in our dataset contributes to reduce transaction costs associated with scientific uncertainty regarding the causes of global methane pollution at a regional level and transaction costs associated with enforcement of policies. Therefore, it can be valuable for the design and enforcement of policy instruments, and for evaluation of potential inter-sectoral and international spillovers of the environmental policies applied.

The rapid increase that methane emissions have recently experienced, together with their high warming potential, highlight the necessity to start a strong policy strategy to mitigate and abate atmospheric concentrations of methane. The carbon-based climate change paradigm has been connected to the responsibility for CO_2 concentrations which have been reached after decades or centuries of emissions. Given the strong warming potential of methane in the beginning of its atmospheric life, increasing methane emissions may change this paradigm, making global warming more dependent on current rather than past patterns of pollution. This calls for efficient mechanisms to attribute the responsibility for emissions to all economies, regardless of whether they are responsible for past levels of methane concentrations.

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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 Equador
Central America, Caribbean	Anguila, Antigua & Barbados, Aruba, Bahamas, Barbados Belize, Cayman Islands, Costa Rica, Cuba, Dominica, Dominican Republic, El Salvador, Grenada, Guatemala, Haiti, Honduras, Jamaica, Netherlands Antilles, Nicaragua, Panama, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Trinidad and Tobago and Virgin Islands (GB)
Rest of EFTA	Iceland, Liechtenstein and Norway
Rest of Former Soviet Union	Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyszstan, Moldova, Tajikistan, Turkmenistan, Ukraine, and Uzbekistan
Middle East	Bahrain, Iran (Islamic Republic of), Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syrian Arab Rep., United Arab Emirates and Yemen
Rest of North Africa	Algeria, Egypt, Libyan Arab Jamahiriya and Tunisia
Other Southern Africa	Angola and Mauritius
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, Cote d'Ivoire, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Liberia, Magagascar, Mali, Mauritania, Mayotte, Niger, Nigeria, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, Sudan, Togo and Congo (DPR)
Rest of World	Afghanistan, Albania, Andorra, Bermuda, Bosnia and Herzegowina, Brunei, Cambodia, Faroe Islands, Fiji, French Polynesia, Gibraltar, Greenland, Guadeloupe, Kiribati, Lao (PDR), Macau, Macedonia (former Yugoslav Republic of), Marshall Islands, Micronesia, Monaco, Mongolia, Myanmar, Nauru, New Caledonia, Korea (DPR), Papua New Guinea, San Marino, Solomon Islands, Tonga, Tuvalu, Vanuatu, Western Samoa, Rest of former Yugoslavia

Table A.1: Countries and GTAP composite regions in the database. Note: Computations were performed using the regional aggregation of GTAP 5. Countries which show up in later GTAP databases but not in GTAP 5 were assigned to the Rest of World composite region. Those countries are too small to change results, however. 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 Fortuna, for example). The only notable exceptions are Timor-Leste and Greenland.

Final Dem. Sector	GTAP Sectors
Agriculture (agr.)	Paddy rice (pdr); Wheat (wht); Cereal grains nec (gro); Vegetables, fruit, nuts (v_f); Oil seeds (ost); 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 (v_f); 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 GTAP sectors into final demand sectors. Note: Original 57 sectors from GTAP database were 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[a]
		FAO CH_4 categories matched directly to a single GTAP sector:					
Rice Cultivation	n.a.	pdr	8.25	8.06	7.51	7.28	7.10
Burning Crops Residues	n.a.		0.32	0.30	0.29	0.28	0.28
of which:							
Maize		gro	0.14	0.13	0.13	0.13	0.13
Paddy Rice		pdr	0.08	0.08	0.07	0.07	0.07
Sugar Cane		c_b	0.01	0.01	0.01	0.01	0.01
Wheat		wht	0.09	0.08	0.08	0.07	0.07
Burning Savanna	n.a.	ctl	1.63	2.03	1.69	1.57	1.67
Enteric Fermentation	n.a.		31.36	30.78	30.10	29.50	27.85
of which:							
Cattle, dairy		rmk	5.93	5.70	5.53	5.39	5.24
Cattle, non-dairy[b]		ctl	25.08	24.73	24.24	23.78	22.29
Swines		oap	0.35	0.35	0.33	0.33	0.32
Manure Management	n.a.		3.15	3.07	2.95	2.89	2.74
of which:							
Cattle, dairy		rmk	0.75	0.70	0.66	0.63	0.59
Cattle, non-dairy[b]		ctl	1.08	1.04	1.00	0.98	0.92
Poultry/Swines[c]		oap	1.33	1.33	1.29	1.27	1.22
		EDGAR CH_4 categories matched directly to a single GTAP sector:					
Coal Mining	1B1	coa	11.65	11.73	13.83	15.35	17.23
Other - Chemicals	2B	crp	0.04	0.04	0.05	0.05	0.06
Landfilling	6A	osg	9.57	9.23	9.01	8.89	8.53
Wastewater Treatment	6B	osg	9.39	9.90	9.77	9.50	9.22
		EDGAR CH_4 categories matched to more than one GTAP sector:					
Combustion[d]	1A1 - 1A4		4.90	4.45	4.22	4.09	4.22
of which:							
Energy Industries	1A1	coa, oil, gas, p_c, ely, gdt	0.09	0.08	0.09	0.10	0.10
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, cns	0.14	0.37	0.35	0.35	0.34
Transport Sectors	1A3	otp, wtp, atp	0.27	0.01	0.01	0.01	0.01
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	4.41	3.99	3.77	3.64	3.77
Oil and Gas Fugitives[e]	1B2	oil, gas, p_c, gdt, otp	19.73	20.37	20.54	20.56	21.09
Other - Metals[f]	2C	i_s, nfm	0.02	0.02	0.03	0.02	0.02

Table A.3: CH_4 Emissions from FAO and EDGAR categories (percentage of total annual emissions). Note: [a] EDGAR data for 2011 is extrapoleted. [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 and steel production as well as other metals.

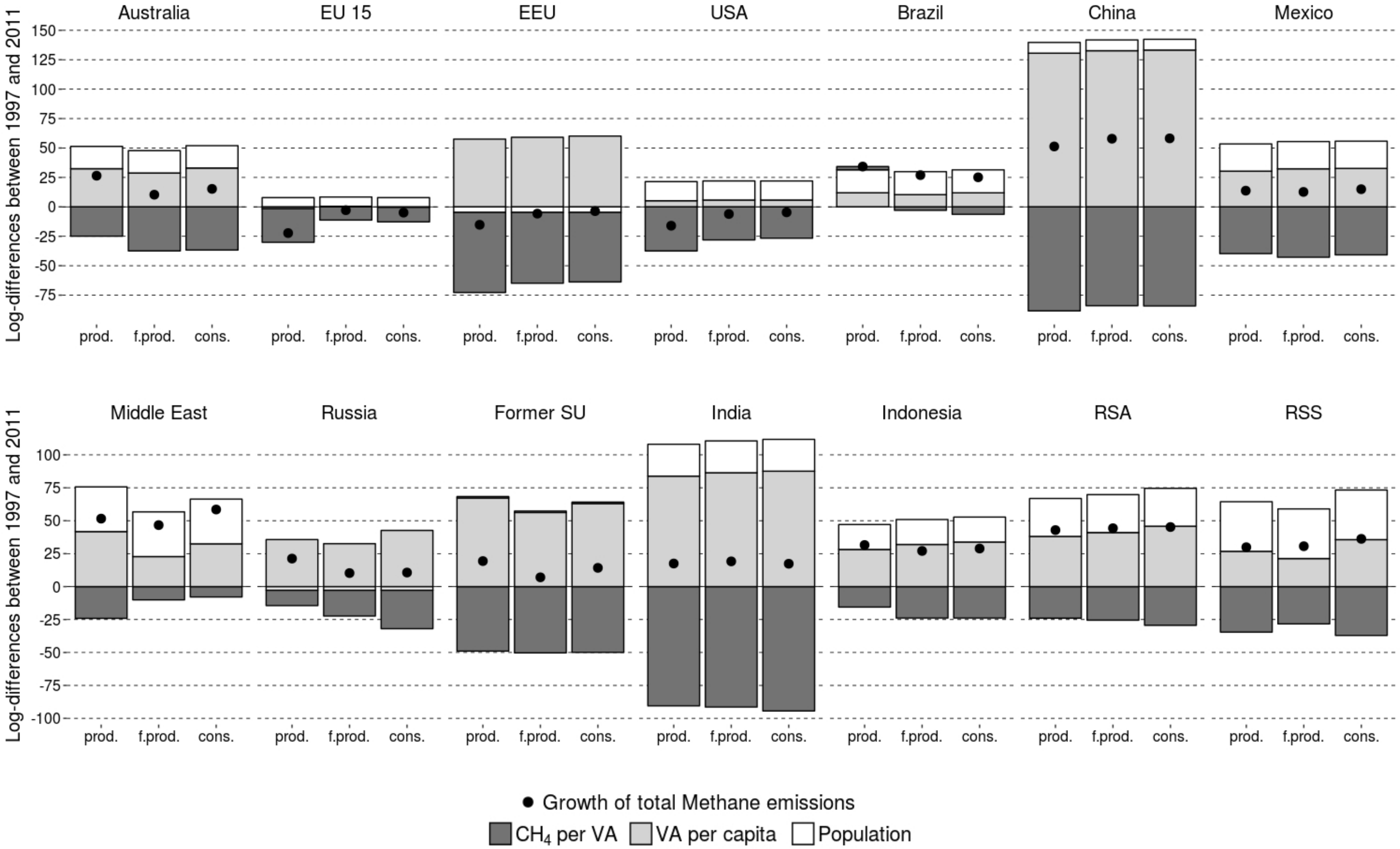

Figure A.1: Change in components of the Kaya-identity (1997 - 2011, selected regions). Note: The barplots show the log-differences of the components of the Kaya-identity between 1997 and 2011 for the 14 most important producers of CH_4 emissions. The Kaya identity decomposes total CH_4 emissions into CH_4 per value added, value added per capita, and population, according to the formula $CH_4 = \frac{CH_4}{VA} \cdot \frac{VA}{pop} \cdot pop$. The data is presented for the three inventories in our dataset: standard production, final production and consumption. Additionally we show the growth rate of total emissions per country (in log-differences), marked as black dot.