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European anthropogenic AFOLU emissions and their uncertainties: a review and benchmark data

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Abstract

Emission of greenhouse gases (GHG) and removals from land, including both anthropogenic and natural fluxes, require reliable quantification, along with estimates of their inherent uncertainties, in order to support credible mitigation action under the Paris Agreement. This study provides a state-of-the-art scientific overview of bottom-up anthropogenic emissions data from agriculture, forestry and other land use (AFOLU) in Europe. The data integrates recent AFOLU emission inventories with ecosystem data and land carbon models, covering the European Union (EU28) and summarizes GHG emissions and removals over the period 1990-2016, of relevance for UNFCCC. This compilation of bottom-up estimates of the AFOLU GHG emissions of European national greenhouse gas inventories (NGHGI) with those of land carbon models and observation-based estimates of large-scale GHG fluxes, aims at improving the overall estimates of the GHG balance in Europe with respect to land GHG emissions and removals. Particular effort is devoted to the estimation of uncertainty, its propagation and role in the comparison of different estimates. While NGHGI data for EU28 provides consistent quantification of uncertainty following the established IPCC guidelines, uncertainty in the estimates produced with other methods will need to account for both within model uncertainty and the spread from different model results. At EU28 level, the largest inconsistencies between estimates are mainly due to different sources of data related to human activity which result in emissions or removals taking place during a given period of time (IPCC 2006) referred here as activity data (AD) and methodologies (Tiers) used for calculating emissions/removals from AFOLU sectors. The referenced datasets related to figures are visualised at http://doi.org/doi:10.5281/zenodo.3460311, Petrescu et al., 2019.

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1. Introduction

The atmospheric concentrations of the main greenhouse gases (GHG) have increased significantly since pre-industrial times (pre-1750), by 46 % for carbon dioxide (CO_2), 257 % for methane (CH_4) and 122 % for nitrous oxide (N_2O) (WMO 2019). The rise of CO_2 levels is caused primarily by fossil fuel combustion, with substantial contributions from land use change. Increases in emissions of CH_4 are mainly driven by agriculture and by fossil fuel extraction activities, while increases in natural emissions post-2006 cannot be ruled out (e.g. Worden et al., 2017). Increases in N_2O emissions are largely due to anthropogenic activities, mainly in relation to the application of nitrogen (N) fertilizers in agriculture (FAO 2015; IPCC SRCCL 2019). Globally, fossil fuel emissions grew at a rate of 1.5 % yr^{-1} for the decade 2008–2017 and account for 87 % of the anthropogenic sources in the total carbon budget (Le Quéré et al., 2018). In contrast, global emissions from land-use change were estimated from bookkeeping models and land carbon models (DGVMs) to be approximately stable in the same period, albeit with large uncertainties (Le Quéré et al., 2018). Emissions from land management changes were not estimated in the global budget from Le Quéré et al. 2018.

National greenhouse gas inventories (NGHGI) are prepared and reported by countries based on IPCC Guidelines using national data and different calculation methods (Tiers) for well-defined sectors. The IPCC tiers represent the level of sophistication used to estimate emissions, with Tier 1 based on default assumptions, Tier 2 similar to Tier 1 but based on country specific parameters, and Tier 3 based on the most detailed process-level estimates (i.e. models).

European countries are expected in the future to monitor their GHG emissions reductions following the IPCC methodological Guidelines (IPCC 2006 Guidelines, complemented by the IPCC 2019 Refinement) and the newly approved UNFCCC transparency framework (UNFCCC, 2018), including the reporting principles of Transparency, Accuracy, Completeness, Comparability, Consistency (TACCC). Furthermore, the IPCC 2019 Refinement has updated guidance on the possible and voluntary use of atmospheric data for independent verification of GHG inventories. So far, only few countries (e.g. Switzerland, UK and Australia) are already using atmospheric GHG measurements, on a voluntary basis, as an additional consistency check of their national inventories. Annex I countries (including the EU) submit annually complete inventories of GHG emissions from the 1990 base year until the current year-2, and these inventories are all reviewed to ensure TACCC. This allows for most of these Annex I countries to track progress towards their reduction targets committed for the Kyoto Protocol (UNFCCC, 1997) and now for the Paris Agreement (PA).

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According to 2018 NGHGI estimates, the European Union (EU28) emitted 3.9 Gt CO_2e in 2016 (incl. LULUCF) and 4.2 Gt CO_2e (excl. LULUCF) (the GWP100 metrics is here used to compare different gases in CO_2 equivalents (CO_2e)). These anthropogenic emissions, incl. LULUCF, represent about 8 % of the global total. This number is consistent with the EDGAR v4.3.2FT2017 inventory (Olivier and Peters, 2018) using IEA (2017) and BP (2018) data for energy sectors and EDGARv4.3.2 (Janssens-Maenhout et al., 2019) and FAOSTAT 2018 for other (mainly agricultural) sectors. A few large economies accounted for the largest share of EU28 emissions, with UK and Germany representing 33 % of the total EU28 emissions.

According NGHGI 2018 data, total anthropogenic emission of GHGs (Mt CO_2e) in the EU28 (Fig. 1) decreased by 24 % from 1990 to 2016 (UNFCCC, 2018). CO_2 emissions (incl. LULUCF) account for 81 % of the total EU28 emissions (Mt CO_2e) in 2016, and declined 24 % since 1990, accounting for 71 % of the total reduction in GHG emissions. CH_4 emissions account for 10 % of and N_2O for 19 total % GHG emissions, both gases recording a reduction of 37 % from 1990 levels. These reductions were due to both European and country specific policies on agriculture and environment implemented in the early 1990s (e.g., the nitrogen directive which limited the amount of N use in agriculture with repercussions to both fertilizer use and livestock numbers) and energy policies in the 2000s, (e.g. the EU Emissions Trading System (ETS), and support for renewable energy and energy efficiency). The specific policies triggered lower levels of mining activities, smaller livestock numbers, as well as lower emissions from managed waste disposal on land and from agricultural soils. Specific historical structural changes in the economy linked to the collapse of eastern European economies in early 1990's, the discovery and development of large natural gas sources in the North Sea, and more recently the economic recession in 2009-2012, contributed as well to these diminishing trends (Karstensen et al 2018). A few large, populous countries account for the largest share of EU28 emissions (UK and Germany combined represent 33 % of the total) while the reduction of total emissions in 2016 compared to 1990 is led by UK (38 %), Germany (24 %), Spain (23 %), Italy (15 %), Poland (18 %) and France (11 %) (Olivier and Peters, 2018).

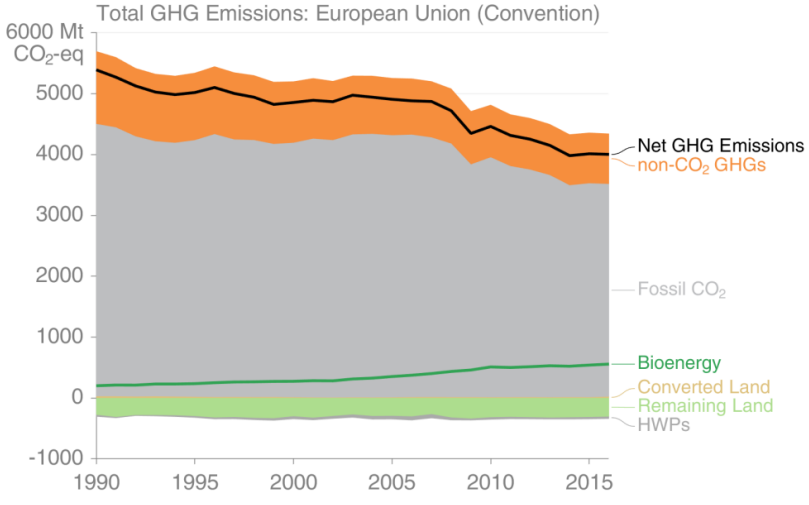

Figure 1: Total reported EU28 GHG emissions according to UNFCCC NGHGI 2018.

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Emissions from FOLU (i.e. LULUCF in this study) represented in 2016 a sink of about 300 Mt CO_2, and this sink has increased 15 % from 1990 to 2016. Bioenergy emissions are reported as a memo in the energy sector, as the emissions are captured in the forestry and land-use sector. The memo implies that bioenergy is carbon neutral in the energy sector but to compensate, the emissions are captured as a harvest (stock change) in the LULUCF sector.

For CH_4, the two largest anthropogenic sources in EU28 are agriculture (e.g. emissions from enteric fermentation) and waste (e.g. anaerobic waste) sectors. These two sources accounted for 53 % of total CH_4 emissions in 2016 (EEA, 2018), that is 11 % of total EU28 GHG emissions (Mt CO_2e) in 2016. From 1990 to 2016, the total CH_4 emissions from EU28 decreased by 31 % (554 Mt CO_2e). The top five EU28 emitters of CH_4 are France (13 %), Germany (12 %), UK (12 %), Poland (11 %) and Italy (10 %) that account for 56 % of total EU28 CH_4 emissions (excl. LULUCF sector).

For N_2O, the largest EU28 sources are agriculture and the industrial processes and product use (IPPU) sectors, while the AFOLU sub-sectors that cover carbon stocks in agriculture and forests is a small source. Agriculture contributes emissions largely from the use of fertilizers in agricultural soils, while industrial production of nitric and adipic acid dominates IPPU-related emissions. These sources accounted for 85 % of N_2O emissions in 2016, that is 5 % of total EU28 GHG emissions (Mt CO_2e) in 2016. From 1990-2016, the total N_2O emissions decreased by 35 % (251 Mt CO_2e). The top five EU28 emitters of N_2O are France (18 %), Germany (16 %), UK (9 %), Poland (8 %) and Italy (8 %) that account for 59 % of the total N_2O EU28 emissions (excl. LULUCF sector).

Zooming on recent trends, non-CO_2 emissions show a very small decrease (- 0.4 %) from 2004 to 2014 and an increase (+0.8 %) from 2015 to 2017 (Olivier and Peters, 2018). This recent growth is principally determined by the increase of N_2O which have offset the declining CH_4 emissions. The continued CH_4 emissions decrease is mainly due to shifts in the fossil fuel production from coal to natural gas in Germany, Italy and the Netherlands (BP, 2018).

The main objective of the present study is to present a synthesis of AFOLU GHG emission estimates from bottom-up approaches that can serve as a benchmark for future assessments, important during the reconciliation process with top-down GHG emissions. We use existing officially reported data from NGHGI submitted under the UNFCCC as well as other emission estimates based on research data, from global emissions datasets to detailed biogeochemical models. A synthesis of available top-down non-CO_2 estimates has already been undertaken by Bergamaschi et al. (2015) and will not be discussed further here. The bottom-up approaches considered, although based on independent efforts form those in the NGHGI, have some level of redundancy among them and the inventories, since they use similar activity data (AD) and largely apply the current IPCC (2006) methodology, albeit using different 'Tiers'.

Independent bottom-up estimates are valuable to compare with estimates officially reported to the UNFCCC and may identify differences that need closer investigation. The uncertainties presented in this paper are taken from the UNFCCC NGHGI 2018 submissions. For the global emissions dataset EDGAR uncertainties are only calculated for the year 2012 as described in the Appendix B. We evaluate the reason for differences in emissions by carefully comparing the estimates, quantifying uncertainties and detecting discrepancies. We compare the inconsistencies (defined by differences between estimates) to the uncertainties (error associated to each estimate) and identify those

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sectors that would yield most benefit from improvements. Uncertainties from the other datasets and models were not yet available. We include natural CH_4 emissions from wetlands, whose accounting will become mandatory from 2026 under the new EU LULUCF Regulation, (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.156.01.0001.01.ENG&toc=OJ:L:2018:156:FULL).

2. Compilation of AFOLU emission estimates

We collected available data of AFOLU emissions and removals (Table 1) between 1990 and 2016 that have been documented in peer reviewed literature. NGHGI and other data sources for AFOLU emissions or component fluxes as well as methodologies are described in Appendix B. For all three GHGs, total emissions from Agriculture and LULUCF for EU28 are presented in Appendix Table A2. Whenever necessary we provide details on individual countries separating CO_2, CH_4 and N_2O. The units are based on the metric tonne (t) [1kt = 10^9 g; 1Mt = 10^{12}g] for individual gases and [Mt =10^{12} g; 1Tg=10^{12}g] for CO_2 and carbon (C) from AFOLU sectors. We rely on observational data-streams to quantify GHG fluxes from bottom-up models together with country specific inventory from NGHGI official statistics (UNFCCC), global inventory datasets (EDGAR), global statistics (FAOSTAT) and global land GHG biogeochemical models used for research assessments (e.g. DGVMs TRENDY-GCP, bookkeeping models).

Table 1: Summary of AFOLU data sources for the three main GHG available and their references. In bold is highlighted the last reported year for each underlying database used in this study.

Gas	*Official and other estimates* **(global datasets, models used for research)**						
CO_2	UNFCCC 2018 (1990-**2016**)	CBM (2000-**2015**)	EFISCEN (1995-**2015**)	FAOSTAT (1990-**2016**)	TRENDY.v6 (1990-**2016**)	Bookkeeping model H&N (1990-**2015**)	Bookkeeping model BLUE (1990-**2017**)
References	2006 IPCC guidelines and CRFs	Pilli et al., 2016b, 2017	Petz et al., 2016	Tubiello et al. (2013) FAO, 2015 Federici et al., 2015 Tubiello, 2019	GCP 2018 (Le Quéré et al., 2018)	Houghton and Nassikas (2017)	Hansis et al., 2015 as updated for Le Quéré et al., 2018
CH_4	UNFCCC 2018 (1990-**2016**)	EDGAR v4.3.2 (1990-**2012**)	EDGAR FT2017 (1990-**2016**)	CAPRI v. Star 2.3 (1990-**2013**)	FAOSTAT (1990-**2016**)	GAINS scenario "ECLIPSE v6" (1990-**2015**)	Natural (wetlands) CH_4 emission model ensemble GCP 2018 (1990-**2017**)

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References	2006 IPCC guidelines and CRFs	Janssens-Maenhout et al., 2019 Crippa et al., 2019	Olivier and Peters, 2018	Britz and Witzke, 2014 Weiss and Leip, 2012	Tubiello et al. 2013 FAO, 2015 Federici et al., 2015 Tubiello, 2019	Höglund-Isaksson, L. 2012 Höglund-Isaksson, L. 2017 Gomez-Sanabria, A. et al., 2018	Poulter et al. 2017 GCP, 2018
N_2O	UNFCCC 2018 (1990-**2016**)	EDGAR v4.3.2 (1990-**2012**)	EDGAR FT2017 (1990-**2016**)	CAPRI v. Star 2.3 (1990-**2013**)	FAOSTAT (1990-**2016**)	GAINS (1990-**2015**)	
References	2006 IPCC guidelines and CRFs	Janssens-Maenhout et al., 2019 Crippa et al., 2019	Olivier and Peters, 2018	Britz and Witzke, 2014 Weiss and Leip, 2012	Tubiello et al. 2013 FAO, 2015 Federici et al., 2015 Tubiello, 2019	Winiwarter et al., 2018	

As an overview of potential uncertainty sources, Appendix Tables A1a and A1b present the use of emission factor data (EF), activity data (AD) and uncertainty estimation methods used for all agriculture and forestry data sources used in this study. The referenced data used for figures are available for download at http://doi.org/doi:10.5281/zenodo.3460311 (Petrescu et al., 2019).

3. Emission estimates

As part of the AFOLU sectors, agricultural activities play a significant role in non-CO_2 GHG emissions (IPCC SRCCL 2019; FAO 2015). The two major gases emitted by the agricultural sector are CH_4 and N_2O. According to the 2018 UNFCCC NGHGI data updated up to the year 2016, agriculture contributes as much as 11 % from the total EU28 GHG emissions expressed in CO_2 equivalents (year 2016, UNFCCC 2018). In 2016, CH_4 from agricultural activities accounted for 53 % of total EU28 CH_4 emissions, while N_2O accounted for 65 % of N_2O emissions respectively. The preponderant share of agriculture in total anthropogenic non-CO_2 emissions also applies globally (IPCC SRCCL 2019).

Regarding the forestry sub-sector of AFOLU, LULUCF, the major GHG gas is CO_2. According to NGHGI 2018 data, in 2016, the total EU28 LULUCF sector was a net CO_2 sink of 314 Mt CO_2. To note that in general the reported values for GHG emissions do not include the flux estimates from LULUCF which are usually accounted for separately, because they are inherently very uncertain and show large inter-annual variations as a result of inter-annual

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variability in climatic conditions, and (in part as a consequence of this variability) in natural disturbances (Kurz et al., 2010, Olivier et al., 2017).

3.1. Agriculture CH_4 and N_2O emissions

At EU28 level, GHG emission reporting is mandatory for all countries and is done under the consistent framework of UNFCCC. Every year in May all EU parties report to the convention their National Inventory Report (NIR) and provide data using Common Reporting Format (CRF) tables. The NIRs contain detailed descriptive and numerical information on all emission sources and the CRF tables contain all GHG emissions and removals, implied EFs and AD for the whole time series 1990 to two years before the submission year (https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories-annex-i-parties/national-inventory-submissions-2018). It is important to note that the 2006 IPCC Guidelines used for this process do not provide methodologies for the calculation of CH_4 emissions and CH_4 and N_2O removals from agricultural soils and field burning of agricultural residues. Parties that have estimated such emissions should provide, in the NIR, additional information (AD and EF) used to derive these estimates and include a reference to the section of the NIR in the documentation box of the corresponding sectoral background data tables.

Further in this section, we present estimates of CH_4 and N_2O agriculture fluxes during the period from 1990 up to the last available year reported by each of the data sources. The detailed values for the last available year are shown in Appendix A, Table A2. Regarding the CO_2 emissions from agriculture, these are allocated to the liming and urea application, IPCC sectors 3G and 3H respectively. In terms of CO_2 they only represent <5 % of the total GHG emissions from agriculture, therefore are not included in this study.

CH_4

According to UNFCCC NGHGI data, in 2016 agricultural activities accounted for 53 % of the total CH_4 emissions in EU28. At EU28 level (Fig. 2), we found that the total agriculture CH_4 emissions are consistent in trends and values among sources. For the agriculture sector totals our results show a relatively good match between UNFCCC and the four other data sources, with the lowest estimate (CAPRI) within 15 % of the UNFCCC value. The differences pertain mostly to Tier use (e.g. CAPRI) and expert judgment on the choice of EFs (e.g. EDGARv4.3.2.). Considering that the 2016 UNFCCC total agriculture reported uncertainty is 10 %, we acknowledge this relative difference of up to 15 % to be important in the emissions reconciliation process. In Table 2 we present the allocation of emissions by sub-sector following the IPCC 2006 classification. Key categories, investigated in this study for CH_4 on the EU28 level, are CH_4 emissions from enteric fermentation, CH_4 emissions from manure management, rice cultivation and agricultural residues.

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Table 2: Agricultural CH_4 emissions - allocation of emissions in different sectors by different data sources used in this study.

Data source/sectors	UNFCCC 2018	EDGAR v4.3.2	CAPRI	GAINS*	FAOSTAT
3 - Agriculture	Enteric fermentation Manure management Rice Cultivation Field Burning of Agricultural Residues	Enteric fermentation Manure management Rice cultivation Agricultural waste burning	Enteric Fermentation Manure management Rice cultivation	Enteric fermentation and manure management* Beef_cattle Dairy_cows Sheep_Goats_etc Pigs Poultry Rice_cultivation Agr_waste_burning	Enteric fermentation Manure management Rice cultivation Field Burning of Agricultural Residues

**GAINS does not separate between CH_4 emissions from enteric fermentation and manure management.*

As a consequence of the similar trends and distribution of emissions to sectors presented in Table 2, we notice a small but consistent variability of total emissions between the five data sources (Fig. 2).

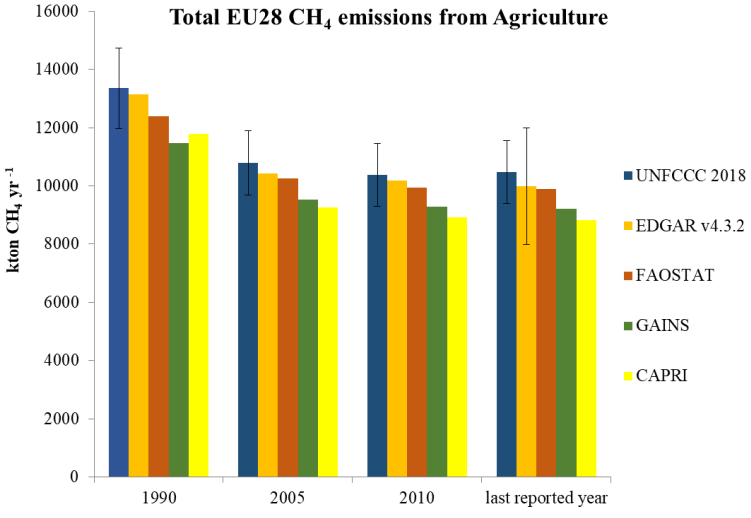

Figure 2. Total EU28 Agriculture CH_4 emissions from five data sources, UNFCCC 2018 communications, EDGAR, FAOSTAT, CAPRI and GAINS. The relative error on the UNFCCC value, computed with the 95% confidence interval method, is 10 %. It represents the GHGI 2018 uncertainty for the agriculture data reported to UNFCCC. Uncertainty for EDGAR v4.3.2 was calculated for 2012 and is 20 %; it represents the 95 % confidence interval of a lognormal

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distribution. Last reported year in this study refers to 2016 (UNFCCC and FAOSTAT), 2012 (EDGAR), 2015 (GAINS) and 2013 (CAPRI). The positive values represent a source.

One possible cause for the similarity lays in the fact that almost all sources use EFs from the same IPCC guidelines (2006). In EU28, AD are produced by four main sources and further dissiminated to the end users (see Fig. 4) and this can be subject to a certain amount of commonalities. Therefore, excluding AD and EFs, we might conclude that differences shown in Figure 2 are mainly due to the choice of the Tier method for calculating emissions (e.g. in CAPRI as shown in Appendix A, Table A1a).

To better understand the differences between emissions in EU28 we plotted in Figure 3 the CH_4 emission percent difference between 2005 and 1990, and between last reported year, 2010 and 2005. We obeserve that for the 2005-1990 change there is a major reduction in CH_4 emissions for all data sources due to the implementation in the 1990s of European and country specific emission reduction policies on agriculture and environment, and socio-economic changes in the sector resulting overall into lower agricultural livestock, lower emissions from managed waste disposal on land and from agricultural soils. For the other two periods considered, the relative agricultural CH_4 reduction is smaller but still consistent between all data sources.

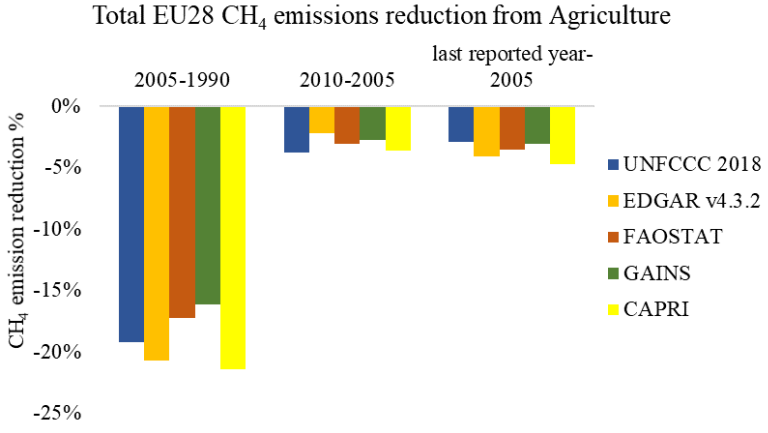

Figure 3: Change of EU28 total agricultural CH_4 emissions between different years. Last reported year in this study refers to 2016 (UNFCCC and FAOSTAT), 2012 (EDGAR), 2015 (GAINS) and 2013 (CAPRI).

We could therefore conclude that all inventory-based data sources are consistent with each other for capturing recent CH_4 emissions reductions, or that they are not independent because they use similar methodology with different versions of the same AD (Fig. 4) which is mostly the case for the EU28 countries. The AD follows also a different course than the emissions data (see Fig. 4). The AD used is highly uncertain due to the collection process from surveys and different national reporting systems. FAOSTAT statistics use a relative value of 20 % uncertainty that is within the range for the confidence interval that IPCC (2006) suggests.

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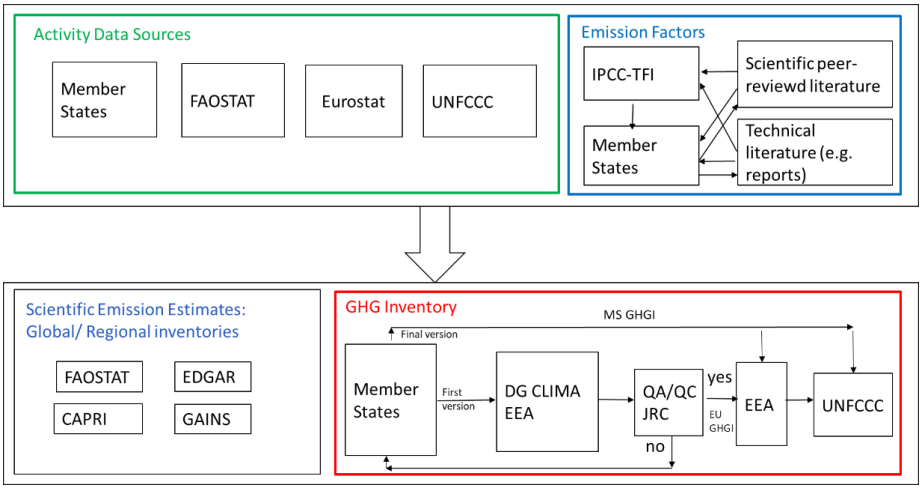

Figure 4: Example of flow of AD, EFs and emission estimates in EU based on IPCC regulations.

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From the detailed analysis of CH_4 emissions split into sectoral information (Figure 5) (all country data and figures are provided in the excel spreadsheets "Figures5,8_AppendixD_CH_4_N_2O_per_country" downloadable at http://doi.org/doi:10.5281/zenodo.3460311), for the former Eastern European communist centralized economy block (Latvia, Lithuania, Estonia (ex USSR), Czech Republic, Poland, Romania and Hungary, East Germany) we notice
260 very high CH_4 emissions for 1990 which afterwards show a constant decreasing trend. This is best explained by the dissolution of the Soviet Union (1989–1991) and the consequent structural changes. The worst match between data sources in EU28 is found for Malta, Cyprus and Croatia but their emissions represent in the UNFCCC reporting less than 1 % of the total EU28 agricultural CH_4 emissions. UNFCCC uncertainties for CH_4 emissions are between 10-50 % but can be larger for some countries and sectors, e.g. Romania reporting a 500 % uncertainty for emissions from
265 rice cultivation.

To exemplify the shares of CH_4 emission from agriculture, in Figure 5 we present the total sub-sectoral CH_4 emissions for three example countries.

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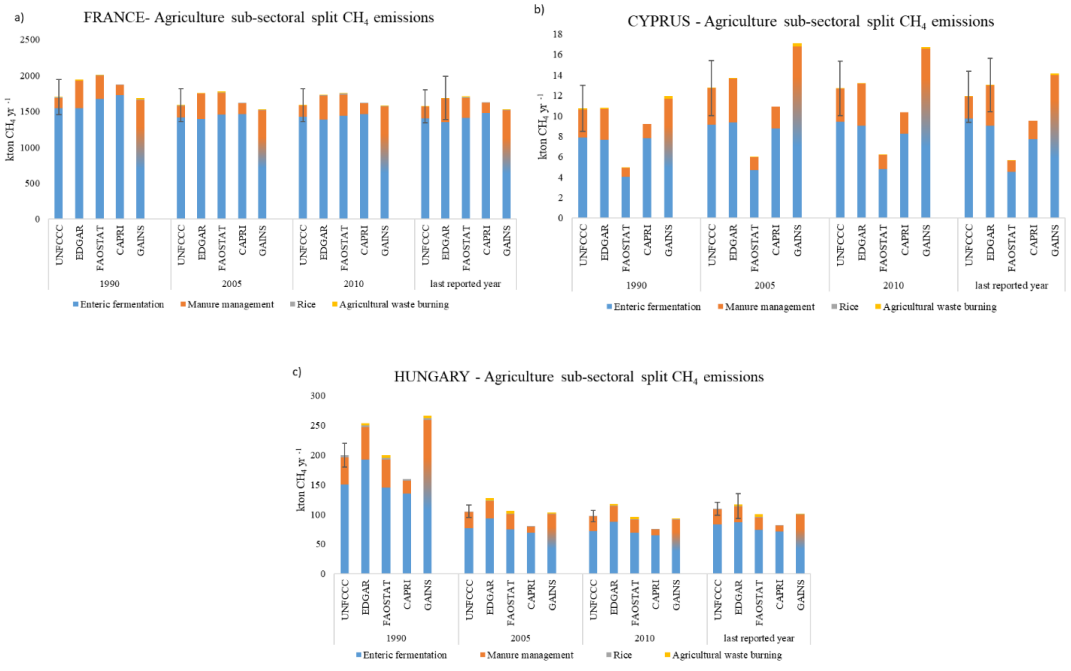

Figure 5: CH_4 emission from five data sources (UNFCCC NGHGI 2018, EDGAR v4.3.2., FAOSTAT, CAPRI and GAINS) split into main activities: enteric fermentation for ruminant livestock (blue) and manure management (orange). GAINS gradient (orange-blue) represent the total emissions from enteric fermentation and manure management. Rice cultivation and agricultural field burning banned since 2000 are very small and hardly distinguishable in the plots; a) *very good consistency of the different data sources for France b) poor consistency for Cyprus; c) high 1990 CH_4 emissions for Hungary (former Eastern European Block). The relative error on the UNFCCC values are computed with the method described in Appendix C based on the NGHGI 2018 uncertainties for the agriculture CH_4 data reported to UNFCCC. Uncertainty for EDGAR v4.3.2 was calculated for 2012 and represents the 95 % confidence interval of a lognormal distribution as discribed in Appendix B. The positive values represent a source. Last reported year in this study refers to 2016 (UNFCCC and FAOSTAT), 2012 (EDGAR), 2015 (GAINS) and 2013 (CAPRI).*

The highest share is attributed to enteric fermentation which for almost all countries count as ~80 % of total agricultural CH_4 emissions. We notice that a very good consistency between emission estimates are found in Figure 5a for France while, on contrary a worse consistency is presented in Figure 5b for Cyprus, which might not report AD to FAOSTAT from its entire territory. Figure 5c exemplifies the high 1990 CH_4 emissions for Hungary in the former Eastern European Block and the lower subsequent estimates, mainly caused by political and economic changes after the dissolution of the Soviet Union (1989–1991). Note that some Eastern European countries, i.e. Romania and Bulgaria, used different base years for Kyoto, as statistical data were considered problematic for 1990.

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300

N_2O

According to UNFCCC NGHGI data, in 2016 agricultural activities accounted for 78 % of the total N2O emissions in EU28. For the agriculture sector, key categories on the EU28 level are N_2O emissions from manure management, direct N_2O emissions from agricultural soils and indirect N_2O emissions from agricultural soils. In Table 3 we present the allocation of emissions by subsector following the IPCC classification and we notice that each data source has its own particular way of grouping emissions.

305

Table 3: Agricultural N_2O emissions - Allocation of emissions in different sectors by different data sources

Emission sources/Data providers	**UNFCCC 2018**	**EDGAR v4.3.2**	**CAPRI**	**GAINS**	**FAOSTAT**
Direct N_2O emissions from manure management	3.B.2 – manure management	4B – manure management	N_2OMAN – manure management	3B – manure management	3.B.2 – farming (N_2O and NMVOC emissions)
Direct N_2O emissions	3.D.1.1 and 3.D.1.2 – direct N_2O emissions from managed soils 3.D.1.4 Crop residues 3.D.1.6 Cultivation of organic soils	4.D.1 – direct soil emissions	N_2OAPP – manure application on soils N_2OSYN – synthetic fertilizer application N_2OHIS - histosols N_2OCRO – crop residues	3.D.a.1 - Soil: Inorganic fertilizer and crop residues 3.D.a.2 - organic fertilizer 3.D.a.6 - histosols	3.D.1.1 - Inorganic N Fertilizers 3.D.1.2 - Organic N Fertilizers 3.D.1.4 – crop residues 3.D.1.6 – cultivation of organic soils
Direct and indirect N_2O emissions from grazing animals	3.D.1.3 – Urine and Dung Deposited by Grazing Animals	4.D.2 - Manure in pasture/range/paddock	N_2OGRA - grazing	3.D.a.3 - grazing	3.D.1.3 -Urine and Dung Deposited by Grazing Animals

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Indirect N_2O emissions	3.B.2.5. – Indirect N_2O Emissions from manure management 3.D.2 Indirect emissions from soils	4.D.3 – Indirect N_2O from agriculture	N_2OLEA - leaching N_2OAMM – ammonia volatilization N_2ODEP – atmospheric deposition (no IPCC)	3.D.b.1 - atmospheric deposition 3.D.b.2 - leaching	3.B.2.5 Indirect N_2O emissions 3.D.2 - Indirect N_2O Emissions From Managed Soils (atmospheric deposition and N leaching to the soils)
Field burning of agricultural residues	3F - Field Burning of Agricultural Residues	4F – agricultural waste burning	-	-	3F - Field Burning of Agricultural Residues

Similar to CH_4 emissions, N_2O emissions show very good consistency between the five data sources for total EU28 emissions (Fig. 6). We note as well that uncertainties of UNFCCC and EDGAR are large but have similar magnitudes. Similar to CH_4, CAPRI has the lowest estimate but well within the uncertainty interval.

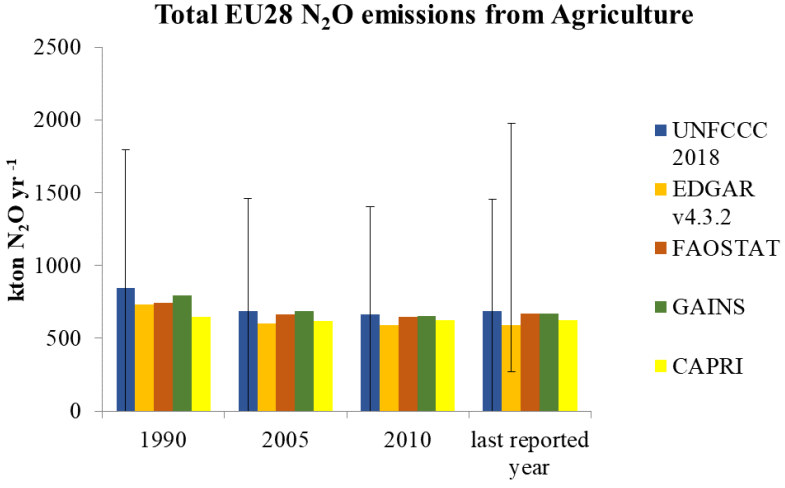

Figure 6: Total EU28 Agriculture N_2O emissions from five data sources, UNFCCC NGHGI 2018, EDGAR v4.3.2., FAOSTAT, CAPRI and GAINS. The relative error on the UNFCCC value, computed with the 95% confidence interval method, is 106 %. It represents the GHGI 2018 uncertainty for the EU28 total N_2O agriculture data reported to UNFCCC.. EDGAR uncertainty is only calculated for the last available year, 2012. Last reported year in this study refers to 2016 (UNFCCC and FAOSTAT), 2012 (EDGAR), 2015 (GAINS) and 2013 (CAPRI). The positive values represent a source.

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In Figure 7 we present the N_2O emission difference between 2005 and 1990, and between the last reported year, 2010 and 2005. We obeserve that for the 2005-1990 there is a major reduction in N_2O emissions for all data sources for the same reasons stated for CH_4 but the spread between different reduction estimates is much larger then for CH_4. We do not see the same agreement for the reduction between 2005 and 2010 (i.e. CAPRI shows a small increase and other datasets a net decrease) and between 2005 and last reported year (i.e. FAOSTAT and CAPRI show small increases).

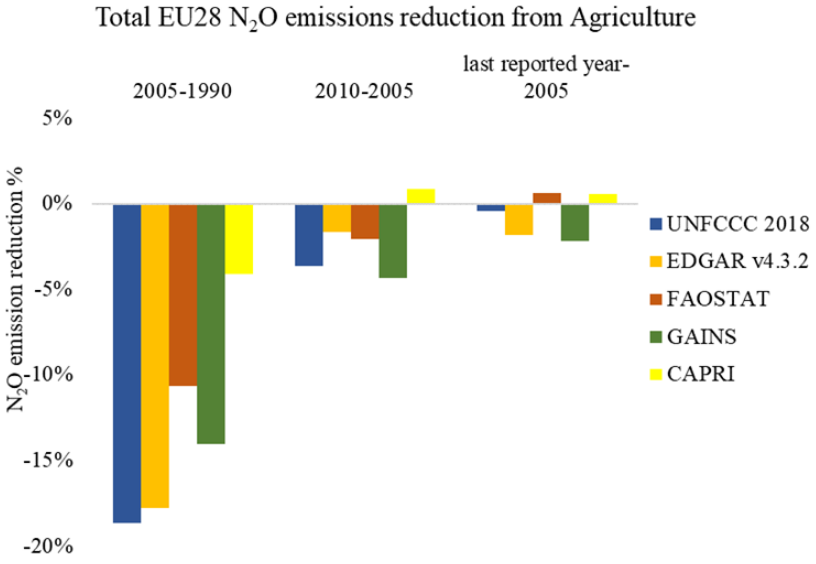

Figure 7: Change of EU28 total agricultural N_2O emissions between different years. Last reported year in this study refers to 2016 (UNFCCC and FAOSTAT), 2012 (EDGAR), 2015 (GAINS) and 2013 (CAPRI).

Nevertheless, despite inconsistent sign of N_2O emission changes between datasets, the spread between absolute values of N_2O emission changes is smaller for recent periods than for the period 1990-2005. For both CAPRI and FAOSTAT, the increase in N_2O emissions, well represented by the positive changes seen in Figure 7, can be explained by changes in AD from synthetic fertilizers and correlated increment of crop residues.

The two most important sources for N_2O emissions from agriculture pertain to direct (synthetic fertilizer, manure application to soils, histosols, crop residues and biological nitrogen fixation) and indirect (ammonia vollatilization, leaching and atmopsheric deposition) emissions. We exemplify this in Figure 8 where we present the N_2O split in sub-activities.

We notice for the Eastern European former communist centralized economy block ((all country data and figures are provided in the excel spreadsheets "Figures5,8_AppendixD_CH_4_N_2O_per_country" downloadable at http://doi.org/doi:10.5281/zenodo.3460311) (e.g. former USSR countries i.e. Latvia, Lithuania, Estonia and former Easter European Block i.e. Romania, Hungary, Slovakia, Bulgaria) higher N_2O emissions for 1990 which afterwards show a constant decreasing trend. This is again best explained by the economic transition in 1989–1991 and

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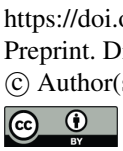

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consequent impacts on the agriculture sector. The poorest consistency between data sources in EU28 is seen for Belgium, Estonia, Lithuania, Latvia and Luxembourg (http://doi.org/doi:10.5281/zenodo.3460311) and count for as much as 4.5 % of total EU28 N_2O emissions. In general, the uncertainties reported by UNFCCC for total N_2O emissions from the agriculture sector are very high and have a range between 22 % (Malta) and 207 % (Romania). For sub-activities extreme uncertainties are reported by Denmark and Bulgaria as 300 % for N_2O emissions from manure management, while Greece reports a very small uncertainty of less than 2 % for N_2O emissions from agricultural soils.

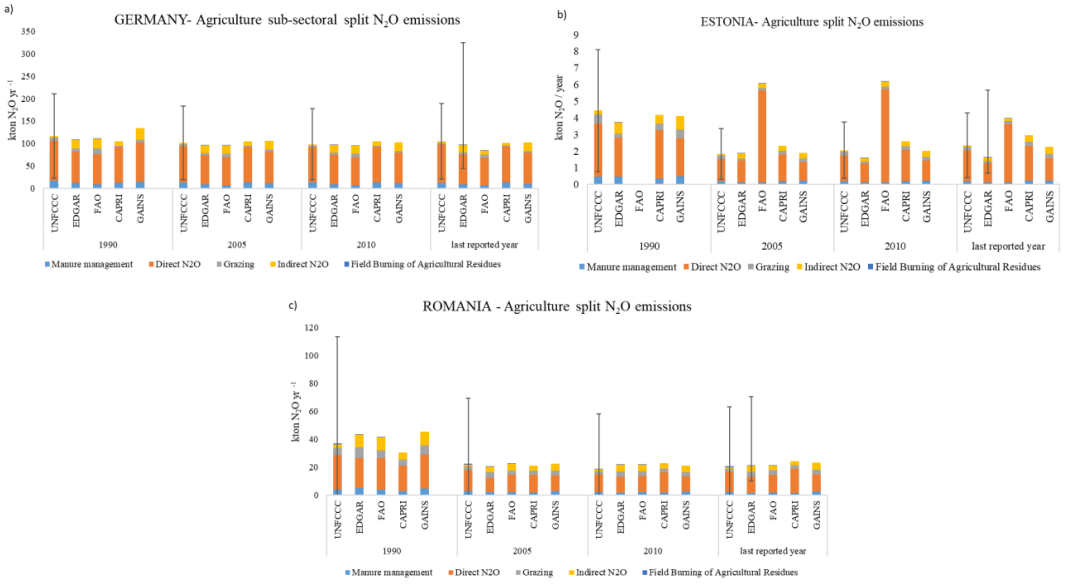

Figure 8: N_2O emission from Agriculture split into main activities: manure management, direct emissions, grazing, indirect emissions and field burning of agricultural residues; a) *very good consistency for Germany b) poor consistency for Estonia; c) high 1990 N_2O emissions for Romania (former Eastern European Block). The relative error on the UNFCCC values are computed with the method described in Appendix C based on the NGHGI 2018 uncertainties for the agriculture N_2O data reported to UNFCCC. Uncertainty for EDGAR v4.3.2 was calculated for 2012 and represents the 95 % confidence interval of a lognormal distribution as discribed in Appendix B. The positive values represent a source. Last reported year in this study refers to 2016 (UNFCCC and FAOSTAT), 2012 (EDGAR), 2015 (GAINS) and 2013 (CAPRI).*

EDGAR is using data from FAOSTAT thus, for the majority of countries (figures found at DOI: link as described in Appendix D), we observe similar estimates between these two sources (e.g. France, Italy, Poland). A reason for discrepancies may be attributed to the different way the data sources allocate their emissions to sub-activities (Table 3). For example, CAPRI N_2OSYN – synthetic fertilizer application - does not have a correspondent in GAINS activities. The leaching, ammonia and atmospheric deposition N_2O emissions in CAPRI do not have a clear

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correspondent sub-activity in UNFCCC, while in FAOSTAT those N_2O emissions are reported under other categories: manure left on pasture and manure applied to soils.

For N_2O emissions, uncertainties are mostly in the range of 100 % or more. The countries reporting the highest N_2O uncertainties are Buglaria, Denmark, Estonia and Cyprus, which, for manure management and agricultural soils, count as much as 200 % to 300 %. We notice that a very good match between emission estimates is found in Figure 8a for Germany while on contrary a worse match is presented in Figure 8b for Estonia with no FAO data available in 1990 (only for former USSR). Figure 8c exemplifies the high 1990 N_2O emissions for Romania (former Eastern European Block) and is due to irregularities in reporting during the dissolution of the Soviet Union (1989–1991).

3.2. Natural CH_4 emissions

In recent assessments of the global CH_4 budget (Saunois et al., 2019), covering the period 2008-2017, CH_4 emissions from top-down and bottom-up sources are estimated to be 178 Tg CH_4 yr^{-1} (range 155-200) and 149 Tg CH_4 yr^{-1} (range 102-182), respectively (Saunois et al., 2019).

In the EU28, natural emissions of CH_4 are represented by wetlands and are not yet fully accounted for and reported under NGHGI. According NGHGI 2019, between 2008 and 2017, the natural CH_4 emissions in the EU28 reported under LULUCF (CRF table 4(II) accessible for each EU28 country at: https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories-annex-i-parties/submissions/national-inventory-submissions-2018), summed up to 0.1 Tg CH_4. The only countries in EU28 reporting CH_4 from wetlands were Denmark, Finland, Germany, Ireland, Latvia and Sweden.

Wetlands are sinks for CO_2 and sources of CH_4. Their net GHG emissions therefore depends on the relative sign and magnitude of the land–atmosphere exchange of these two major GHGs. Undisturbed wetlands are estimated have a great carbon sequestration potential because near water-logged conditions reduce or inhibit microbial respiration, but CH_4 production may partially or completely counteract carbon uptake (Petrescu et al., 2015). The net GHG balance of natural wetlands is thus uncertain. Natural emission of CH_4, in particular wetlands and inland waters and their net GHG balance, are the most important source of uncertainty in the methane budget (Saunois et al, 2019), due to the GWP100 of CH_4 and the generally opposite directions of CO_2 and CH_4 fluxes.

Under the new EU LULUCF Regulation, article 7 (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.156.01.0001.01.ENG&toc=OJ:L:2018:156:FULL) the accounting of natural wetland emissions will become mandatory from 2026 onwards, i.e. the reported numbers will be compared to numbers already reported under category 4(II) wetlands between 2005-2009 and the net difference will count towards reaching the EU climate targets.

Since CH_4 emissions are highly variable in time and space as a function of climate and disturbances, it makes EF-based methods impractical and national budget estimates difficult, making it challenging to accurately estimate CH_4 emissions in NGHGI. There is also a risk of double counting with emissions from inland waters as discussed e.g. by Saunois et al. 2019 for the global CH_4 budget. The sum of all natural sources of CH_4 as inferred by different models

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may be too large by about 30 % compared to the constraint provided global inversions. The spread of wetland emissions from process-based wetland emission models used in the global CH_4 budget (Poulter et al., 2017) forced by the same variable flooded area dataset, is 30 % (80 Tg CH_4 yr^{-1}) globally (given their estimated emissions of 177–284 Tg CH_4 yr^{-1} using bottom-up modeling approaches) and up to 70 % for EU28 calculated based on the model-to-model variability and even larger at national scale. In absence of any better information, we used in this study the results of these ensemble models (see Appendix B) to provide a first estimate of this source.

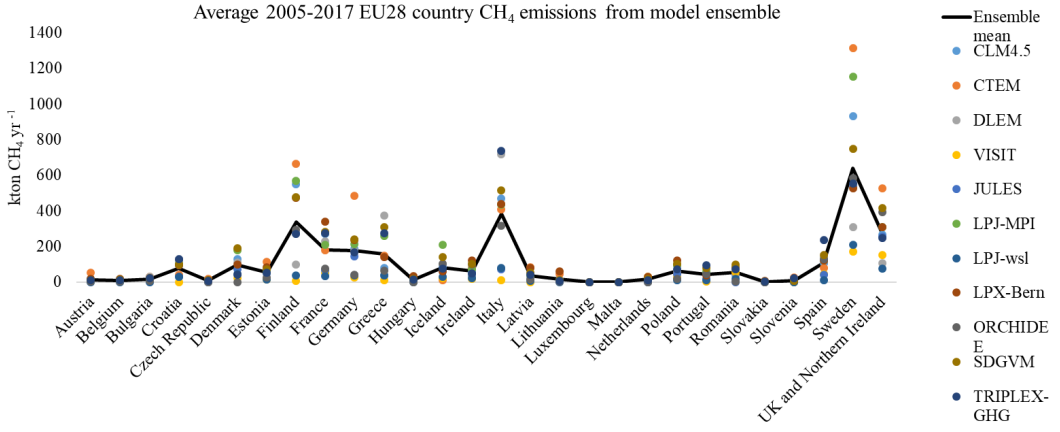

Figure 9. Distribution of CH_4 emissions from undisturbed natural wetlands for all the countries of EU28 as simulated by an ensemble of 11 global emission models averaged between 2005-2017 (Poulter et al., 2017). The positive values represent a source.

According to Poulter et al. (2017), between 2005-2017, the total wetland CH_4 emissions in EU28 averaged 3 Tg CH_4 with an uncertainty (1-sigma spread) of 70%, with seven countries having the highest emissions (Fig. 9). Finland, Italy, Sweden, UK, France, Greece and Germany, accounted for 75% of total EU28 wetland CH_4 emissions. For the same period, GHGI 2019 reports an average of 10.34 kton CH_4, a highly underestimated value compared to the modelled results, due to non-reporting and accounting under NGHGI.

Given this current gap between modelled and GHGI reported data on CH_4 emission from wetlands in EU28, we stress the need of investing in better modelling methodologies for emission calculation and verification. Out of all EU28 countries, for the purpose of reporting, only Finland developed its own biogeochemical CH_4 model to provide to GHGI a very detailed list of estimates for all CH_4 sub-activities.

3.3. Forestry and Other Land Uses

Forestry and Other Land Uses (FOLU) chapter includes in this analysis CO_2 emissions/removals from forests and soil organic carbon (SOC) changes from grasslands and croplands. We will refer throughout this study to FOLU as Land Use, Land Use Change and Forestry (LULUCF). A comprehensive assessment of the overall carbon stocks and fluxes of forests, croplands and grasslands is required to complement the analyses of climate change impacts on

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forest productivity and composition (Lindner et al., 2015). Several studies analyzed the European forest carbon budget from different perspectives and over several time periods (Kauppi et al., 1992; Karjalainen et al., 2003), using GHG budgets from fluxes, inventories and inversions (Lyussaert et al,, 2012), flux towers (Valentini et al., 2000), forest inventories (Liski et al., 2000, Pilli et al., 2017) and IPCC guidelines (Federici et al., 2015).

Achieving the well-below 2ºC temperature goal of the PA requires forest-based mitigation (Grassi et al., 2018, Nabuurs et al. 2017). Currently, the EU28 forests act as a sink and forest management will continue to be the main driver affecting the productivity of European forests for the next decades (Koehl et al., 2010). Forest management, however, can enhance (Schlamadinger et al., 1996) or weaken (Searchinger et al., 2018) this sink. Forest management not only influences the sink strength, it also changes forest composition and structure, which affects the exchange of energy with the atmosphere (Naudts et al., 2016), therefore the potential of mitigating climate change (Luyssaert et al., 2018; Grassi et al., 2019).

We compared CO_2 net emissions/removals from the LULUCF sector reported by UNFCCC NGHGI 2018 to those included in FAOSTAT and to the carbon balance here termed as the Net Biome Production (NBP) from different models (Table 4). The categories presented in this study are forest land, cropland and grassland. We present separate the results from forest land and land use because, some models (e.g. CBM and EFISCEN) use a different definition of forest land than the Dynamic Global Vegetation Models (DGVMs) ensemble TRENDY (Sitch et al., 2008, Le Quéré et al., 2009) or bookkeeping models (Houghton & Nassikas 2017, Hansis et al., 2015).

To better illustrate differences between estimates we exemplify how four of the data sources interpret and calculate the NBP:

- UNFCCC NBP definition depends on the method used by each country;
- CBM calculates NBP as the total ecosystem and stock change the difference between net ecosystem production (NEP) and the direct losses due to harvest and natural disturbances (e.g., fires) (Pilli et al., 2017, Kurz et al., 2009). Adding to the NBP the total changes in the harvested wood product (HWP) carbon stock, CBM estimates the net sector exchange (NSE) (Karjalainen et al., 2003, Pilli et al., 2017);
- EFISCEN's NBP is derived from total tree gross growth minus soil losses, minus (density related) mortality minus harvest. Natural disturbances tend to occur relatively little in Europe and, if are happening, are included in regular harvest, therefore EFISCEN does not consider them in addition for the NBP calculation;
- DGVMs calculate NBP as the net flux between land and atmosphere defined as photosynthesis minus the sum of plant respiration and soil heterotrophic respiration, carbon emissions from fire (some models and CO_2 emissions from harvested wood products) and harvest. Land use change emissions are calculated as the imbalance between photosynthesis and respiration over land areas that followed a transition. Positive flux is into the land. NBP should be equal to changes in total carbon reservoirs. The net land use change flux is derived by differencing the NBP of a simulation with and without land use change.

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475 *Table 4: Model description and their references therein.*

LULUCF data sources	*Short description*	*References*
UNFCCC CRF tables	Reported by Annex I (essentially developed) countries following the IPCC methodological guidelines (IPCC, 2006).	IPCC, 2006
FAOSTAT	Tracks net carbon stock change in the living biomass pool (aboveground and belowground) associated with forests and net forest conversion to other land uses, using country specific emission factors (carbon densities) reported from countries to FAO following the IPCC stock difference method (IPCC, 2006) with FAOSTAT and FRA activity data from countries. It also contains estimates of CO_2 emissions from drained organic soils in cropland and grasslands; as well as non-CO_2 emissions from biomass fires other than agriculture and CO_2 and non-CO_2 emissions from fires on organic soils.	FAO, 2014 Federici et al., 2015 Tubiello, 2019
CBM	An inventory-based, yield-data driven model that simulates the stand- and landscape-level forest carbon dynamics of living biomass, dead organic matter and soil, including natural and anthropogenic disturbances.	Kurz et al., 2009 Pilli et al., 2016b Pilli et al., 2017
EFISCEN	Empirical forest scenario simulator. It uses national forest inventory data as a main source of input. Includes a detailed dynamic growth module, while natural mortality and	Verkerk et al., 2016 Nabuurs et al., 2018

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	harvesting are included as fixed regimes, depending on the region.	
BLUE	A half degree grid bookkeeping model that tracks individual histories of successive LULCC events in each grid cell. Estimates for peat burning and peat drainage are included.	Hansis et al., 2015 Le Quéré et al., 2018
H&N	A country-level bookkeeping model, that tracks land use and land cover (croplands, pastures, plantations, industrial wood harvest, and fuelwood harvest) in four carbon pools (living aboveground and belowground biomass; dead biomass; harvested wood products; and soil organic carbon).	Houghton & Nassikas, 2017
DGVMs (TRENDY v6)	The DGVM results presented in the Global Carbon Project (GCP) with variations in the land surface coverage of each model.	Le Quéré et al., 2018 Arneth et al., 2017

Forest Land

Net CO_2 emissions/removals from Forest Land (FL) (in UNFCCC GHGI 2018, IPCC sector 4A) includes net CO_2 emissions/removals from forest land remaining forest land and conversions to forests, i.e. it includes effects from both environmental changes and from land management and land use change as long as they occur on forest land declared as managed. According to IPCC guidelines, to become accountable in the GHGI under forest land remaining forest land, a land must be a forest for at least 20 years. Over FL we compare modelled NBP estimates (presented as CO_2 net sink) simulated with CBM and EFISCEN models with UNFCCC and FAOSTAT data consisting of net carbon stock change in the living biomass pool (aboveground and belowground biomass) associated with forest and net forest conversion including deforestation.

Figure 10 presents the total net CO_2 sink estimates simulated with CBM and EFISCEN models (described in Table 4 and Appendix B), FAOSTAT and countries official reporting done under UNFCCC. The sign convention denotes the negative numbers as being a sink. The results show that the differences between models are systematic, with EFISCEN and CBM showing systematically lower sinks than UNFCCC, while FAOSTAT has systematically higher sinks which are increasing with time. The similarities between the two models lie in the fact that both EFISCEN

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and CBM models use national forest inventory (NFI) data as main source of input to describe the current structure and composition of European forest. However, CBM and EFISCEN make different assumptions about allometry, wood density or carbon content of trees. The difference between all estimates and FAOSTAT may lie in the fact that FAOSTAT uses as input into the stock change calculations directly the carbon stocks and area data computed by countries and submitted through the FAO Global Forest Resource Assessments (FRA) (http://www.FAOSTAT.org/forestry/fra/en/), rather than employing models to estimate them. Further, FAOSTAT numbers include af/reforestation, while the others datasets not, resulting in an even bigger sink if af/reforestation is removed.

Since the UNFCCC GHGI uncertainty of CO_2 estimates for FL at EU28 level, computed with the 95 % confidence interval method (IPCC, 2006) is 19.6 % (the uncertainty increases to 25–50 % when analyzed at country level (EU NIR 2014)), and given the fact that both CBM and EFISCEN use different methodologies to estimate emissions/removals (Pilli et al., 2016b, Petz et al., 2016) than those used by the NGHGI, we consider the match between the two models and the EU GHGI to be satisfactory.

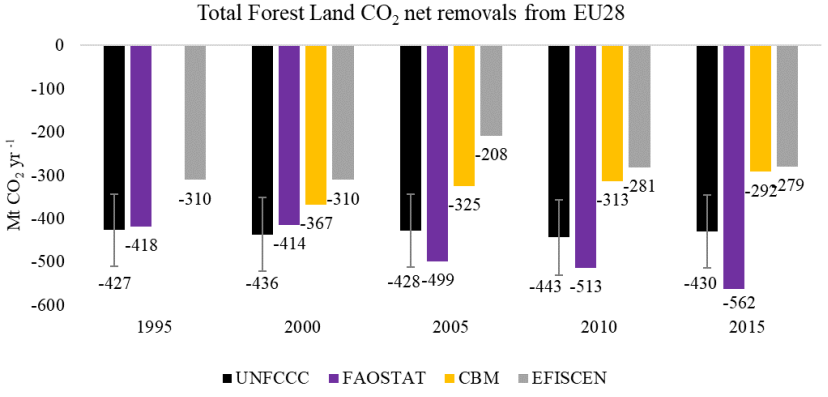

Figure 10: Total EU28 single year values of CO_2 net removals from FL as reported by UNFCCC, CBM, EFISCEN and FAOSTAT. Negative numbers denote net CO_2 uptake. EFISCEN data 1995-2000 is based on Karjalainen et al., 2003 estimates. CBM does not report data for 1995. The relative error on the UNFCCC value, computed with the 95% confidence interval method, is 19.6 %. It represents the GHGI 2018 uncertainty for the FL data pool reported to UNFCCC.

In 2015, most of the differences between FAOSTAT estimates and UNFCCC country data were generated by few countries: for Finland there is a disagreement from neutrality (due to extrapolation of previous data) in FAOSTAT to a large sink of 38 Mt CO_2 yr^{-1} reported to UNFCCC. For Romania and Latvia we find that the FAOSTAT sink is a factor 7 larger than the reported UNFCCC, and for Denmark we find a sink according to FAOSTAT estimates and a source reported to UNFCCC. When comparing NGHGI and FAO-FRA data, it should be considered that NGHGIs specifically report emissions and removals, and are formally reviewed annually, while FAO-FRA reports are not primarily for reporting CO_2 emissions and removals, and are not formally reviewed (Grassi et al., 2017).

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Cropland and Grassland soil Carbon

Cropland and Grassland (CL and GL) (in UNFCCC GHGI 2018, IPCC sector 4B and 4C, respectively) include CO_2 emissions/removals from soil organic carbon (SOC) under 'remaining' and 'conversion' categories. Similar as for FL, fluxes include effects from both environmental changes and from land management and land use change. In FAOSTAT GHG emissions in the domain "Cropland" and "Grassland" are currently limited to the CO_2 emissions from cropland/grassland organic soils associated with carbon losses from drained histosols under cropland/grassland. This can be one of the reasons for differences between estimates reported by the two sources (Fig. 11).

Cropland definition in IPCC includes arable and tillage land, and agro-forestry systems where vegetation falls below the threshold used for the forest land category, consistent with the selection of national definitions (IPCC glossary). According to EUROSTAT, the term 'crop' within cropland covers a very broad range of cultivated plants. In 2015 more than one fifth (22 %) of the EU28's area was covered by cropland (EUROSTAT, updated in 2019). Denmark (51 %) and Hungary (44 %) had the highest proportion of their area covered by cropland in 2015. For the vast majority of the EU Member States (MS), cropland accounted for between 15 % and 35 % of the total area, this share falling to 10–15 % in Latvia, Estonia and Portugal, while the lowest proportions were registered in Slovenia (9 %), Finland (6 %), Ireland (6 %) and Sweden (4 %). In absolute terms, France, Germany, Spain and Poland had the biggest areas of cropland in 2015.

Grassland definition in IPCC includes rangelands and pasture land that is not considered as cropland, as well as systems with vegetation that fall below the threshold used in the forest land category.. This category also includes all grassland from wild lands to recreational areas as well as agricultural and silvo-pastural systems, subdivided into managed and unmanaged, consistent with national definitions. Grasslands tend to be concentrated in regions with less favorable conditions for growing crops or where forests have been cut down. In 2015 just above one fifth of the EU28's (21 %) was covered by grassland. Some of these are found in northern Europe (for example, most of Finland and Sweden), while others are in the far south, for example, the south of Spain. Ireland was the only EU Member State with more than half of its land area as grassland in 2015 (56 %) of the total area. At the other end of the scale, grassland covered less than 6 % of the land in Finland and Sweden (EUROSTAT: https://ec.europa.eu/eurostat/statistics-explained/index.php/Land_cover_statistics).

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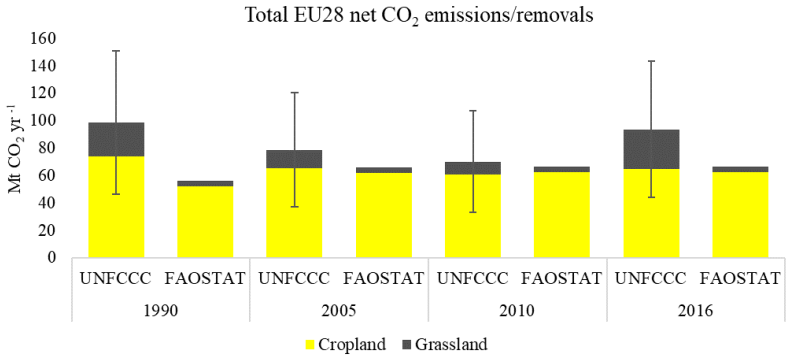

Figure 11: Total EU28 net CO_2 emissions/removals from FAOSTAT and UNFCCC 2018 country submission estimates of Cropland and Grassland for 1990, 2015, 2010 and 2016. The relative error on the UNFCCC value, computed with the 95 % confidence interval method, is 53 %. It represents the NGHGI 2018 uncertainty for the CL and GL data pool reported to UNFCCC.

From Figure 11 we see that in the EU28 croplands and grasslands are CO_2 sources to the atmosphere in the UNFCCC and FAOSTAT databases. Cropland CO_2 emissions are rather stable with time and are in good agreement between FAOSTAT and UNFCCC, except in 1990. Grassland emissions reported by countries to UNFCCC are higher than the FAOSTAT and show an abrupt increase in 2016 compared to the previous years.

Climate change and climate effects on soil temperature and moisture are key drivers in the 21st century increase of soil decomposition and decrease of the soil carbon stock (Smith et al., 2005). Avoiding soil carbon losses or restoring stocks requires practices that increase C input in excess of losses from erosion and decomposition, such as diminished grazing intensity for grasslands, higher return of residues or reduced tillage for croplands, and manure additions for both. Further change in land use and management will also affect the soil carbon stock of European cropland and grasslands (Smith et al., 2005).

Land-related emissions from global models

Land-related carbon emissions can also be estimated by global models such as DGVMs - TRENDY v6 ensemble and bookkeeping models (BLUE and H&N). In this section we compare these global model results with data from FAOSTAT and UNFCCC. There is significant uncertainty in both the underlying datasets of land use changes, the coverage of different land use change practices, and the calculation of carbon fluxes (see below). In addition, marked differences in definitions must also be considered to compare independent estimates. Bookkeeping models give net emissions from land use change including immediate emissions during land conversion, legacy emissions from slash and soil carbon after land use change, regrowth of secondary forest after abandonment, and emissions from harvested wood products when they decay. DGVMs estimate net land use emission as the difference between a run with and a run without land use change, and their estimate includes the loss of atmospheric sink capacity,

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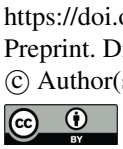

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that is, the sink that favorable environmental changes, in particular CO_2 fertilization. This sink created over forest land in the simulation without land use change is "lost" in the simulation with land use change because agricultural land lacks the woody material and thus has a higher carbon turnover (Gasser et al., 2013, Pongratz et al., 2014). This different definition from bookkeeping models historically implies higher carbon emissions from DGVMs, even if all post-conversion carbon stocks changes were the same in DGVMs and bookkeeping models.

The key difference between DGVMs and bookkeeping models, on the one hand, and FAO and UNFCCC methodology, on the other, is that the latter are based on the managed land proxy (Grassi et al., 2018a) (Fig. 12).

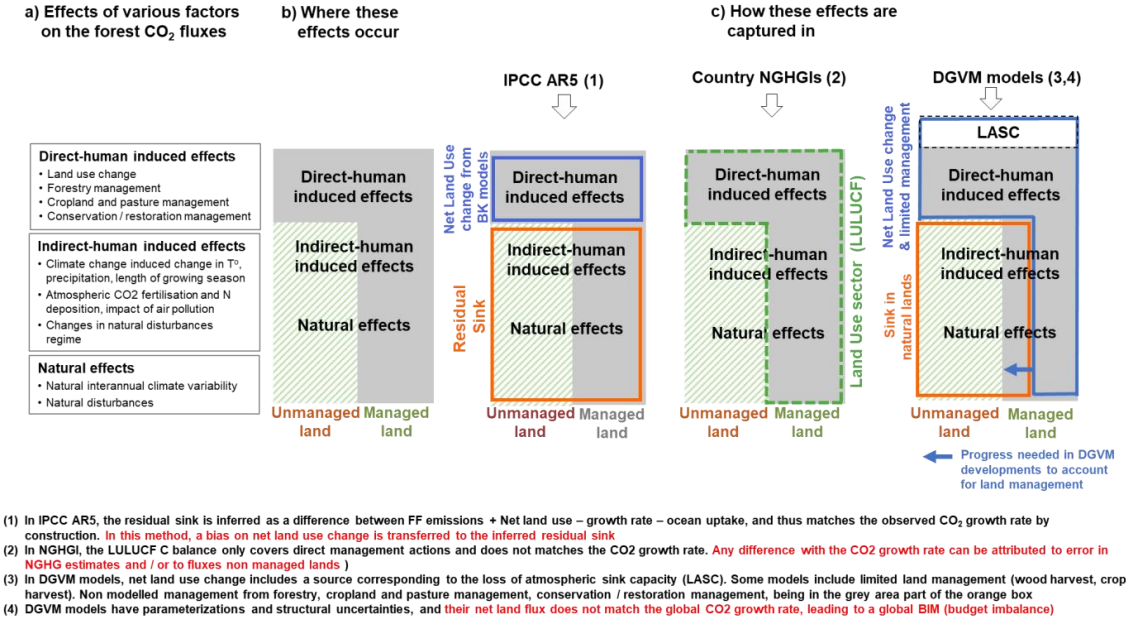

Figure 12: Summary of the main conceptual differences in defining the "anthropogenic land CO_2 flux" between IPCC and countries' GHG inventories (NGHGIs). a) Effects of key processes on the land flux as defined by IPCC; b) Where these effects occur (in unmanaged/primary lands vs. managed/secondary lands); c) How these effects are captured: in the IPCC 5th Assessment Report (AR5) the anthropogenic "net land use" from Grassi et al., 2018a (solid blue line, including only direct human-induced effects), and the non-anthropogenic "residual sink" (solid red line, calculated by difference from the other terms in the GCP); countries' anthropogenic land flux from GHGIs reported to UNFCCC (under the LULUCF sector, green dashed line), which in most cases includes direct and indirect human-induced and natural effects in an area of "managed" land that is broader than the one considered by Grassi et al., 2018a. (Figure adapted from Fig. 3 in Grassi et al., 2018a).

Land fluxes can be differentiated into three processes: 1) Direct anthropogenic effects (land-use and land use change, e.g., harvest, other management, deforestation), 2) Indirect anthropogenic effects (e.g., changes induced by climate change, CO_2 fertilization), and 3) Natural effects (i.e., that would happen without human caused climate

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change, such as natural disturbances). The IPCC guidelines use a so-called land use proxy to estimate only "direct anthropogenic effects" that happen on managed land, hence how managed land is defined makes a big difference to reported emissions. In other words, following IPCC guidelines attributes all fluxes (including natural ones) on managed lands towards human activity.

In general, across all methods, managed land is defined as "land where human interventions and practices have been applied to perform production, ecological or social functions" (IPCC, 2006) but, models and inventories approach this issue differently:

Biogeochemical Models. *Bookkeeping approaches* only estimate direct anthropogenic effects. *DGVMs* also consider fluxes linked to indirect effects and natural processes. In the GCP (Le Quéré et al., 2018b, Friedlingstein et al., 2019), the fluxes associated to the direct anthropogenic effects are estimated with *Bookkeeping models*, while the remaining "land sink" (including all indirect and natural effects) are estimated by DGVMs.

National Greenhouse Gas Inventories (NGHGI) use the notion of "managed land" as a proxy for direct "anthropogenic" emissions, hence in practice include most or all (depending on the specific method) indirect emissions into their anthropogenic estimates. In addition, the area considered "managed" by countries is typically much greater than the area used by biophysical models to simulate the direct anthropogenic effects, as it includes areas that are not actively managed (for instance, forest parks or forest seldomly harvested) (Grassi et al. 2018a).

The differences between biogeochemical models and NGHGI of around 4-5Gt CO_2 yr^{-1} globally is to a large part attributable to the accounting of indirect effects on managed land towards AFOLU emissions for NGHGI (Grassi et al., 2018a, IPCC SRCCL). The differences at the EU28 level are much smaller, because nearly all forest land is managed in the EU.

Independent estimates of the land-related flux for the EU28 are presented in Figure 13. The data behind the three main estimates, bookkeeping models, NGHGI and FAOSTAT represent the total net land use emissions/removal from forest, cropland and grassland, including conversions to and from one category to another. Next to them, we plotted each of the net land use change flux (in grey) (difference of simulation with and without land use change) from eight of the DGVMs TRENDYv6 with their mean, as they mostly simulate the indirect and natural sink considered unmanaged. FAOSTAT includes emissions from peatland drainage and fires, and from biomass fires (not considered herein). It does not include however other carbon stock changes in cropland and grassland. We excluded from UNFCCC estimate the Wetlands remaining Wetlands and Settlements remaining Settlements, biomass burning and drainage. The UNFCCC NGHGI and Houghton's estimates are similar because the managed areas for EU28 are similar in both estimates (Grassi et al., 2018a). Differences between the two bookkeeping models, BLUE and H&N, relate to the different forcing applied by each of the models and differences in biome types. The forcing used by H&N is based directly on FAOSTAT/FRA agricultural and wood harvest data, while BLUE uses LUH2 (Hurtt et al., 2011, 2018). LUH2 is based on HYDE3.2 (Klein Goldewijk et al., 2017a, b), which provides annual, half-degree, fractional data on cropland and pasture based on FAOSTAT, but overlays subgrid-scale transitions between all land use types and wood harvesting. H&N allocates pasture expansion preferentially on natural grasslands, while all available vegetation types of a gridcell are assigned proportionally to agricultural expansion in BLUE. Carbon densities and regrowth and decay curves are structurally similar, but differ in detail.

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The EU28 has a very small area of unmanaged land and this denotes that most of the LULUCF emissions in the EU28 are from direct effects in the forestry sector (including agricultural expansion/abandonment). According to FAOSTAT and UNFCCC NGHGI, the net forest conversion is relatively small in the EU so the simulations include mostly managed net area.

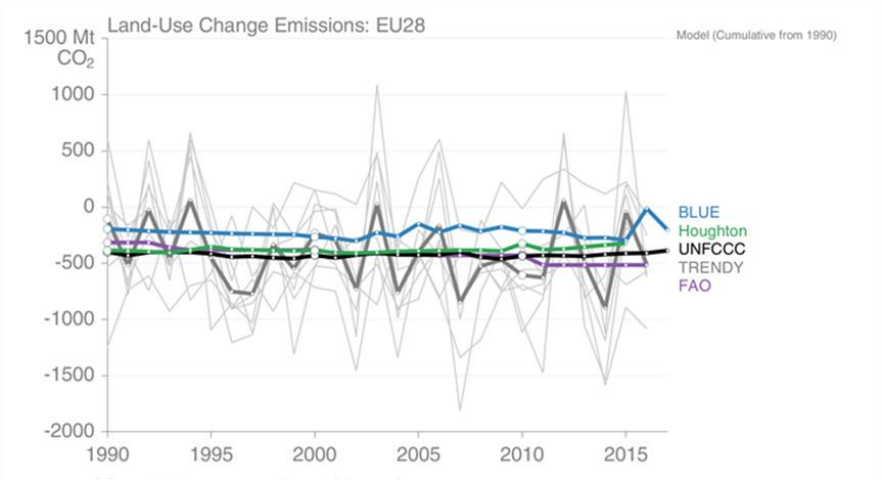

Figure 13: A comparison of different estimates of the land-use change flux in the EU28 from five data available sources: BLUE, H&N, UNFCCC, DGVMs (TRENDY v6) and FAOSTAT. The grey lines represent the individual model data for eight DGVMs. The UNFCCC estimate includes the following categories: Forest Land, Cropland, Grassland net and with conversions and Wetlands, Settlements and Other land only conversions. The negative values represent a sink, while the positive a source.

DGVMs differ strongly in their estimate of the net land use change flux due to different comprehensiveness of including land use practices such as wood harvesting, shifting cultivation, or fire management (LeQuéré et al., 2018), different land use change datasets (HYDE3.2 or LUH2) and their implementation, apart from general model differences of how photosynthesis, respiration and natural disturbances are simulated. Most striking in comparison to the other, more empirical, approaches is the large inter-annual variability, related to the climate dependency of vegetation processes. Though DGVMs are conceptually similar to GHGIs in simulating all indirect and direct fluxes on a given area, differencing of the simulations with and without land use change leaves only the land-use related effects to be attributed to the net land use change flux (see Fig. 12). DGVMs are thus closer to the bookkeeping definition of LULUCF emissions, apart from differing assumptions on environmental changes (constant in bookkeeping, historical in TRENDY) and the loss of additional sink capacity included in DGVMs.

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4. Discussion

4.1 Agricultural emissions

At European level the largest inconsistencies between estimates from AFOLU emission sources/sinks were found to be mainly caused by the use of different methodologies, including use of different AD and/or Tier level. When looking at final emission estimates, inconsistencies in methodology and Tier application in calculating emissions give as much as 10-20 % variation across estimates (e.g. CH_4 from agriculture),. Higher tiers require more detailed AD for calculating emissions/removals from AFOLU sectors.

Within the UNFCCC practice, for agriculture, each country uses its own country specific method which takes considers specific national circumstances (as long as they are in accordance with the 2006 IPCC Guidelines) as well as IPCC default values, which are usually more conservative. The EU GHG inventory underlies the assumption that the individual use of national country specific methods leads to more accurate GHG estimates than the implementation of a single EU wide approach (UNFCCC, 2018b). The Tier level a country applies depends on the national circumstances, which explains the variability of uncertainties among the sector itself as well as among EU countries. For example, inventory estimates of N_2O emissions have very large uncertainties (>100 %) owing to the heterogeneity of sources and uncertainty in emission factors for the main N_2O sources, in particular, agriculture. Since agricultural soil and manure management emissions vary strongly from site to site depending on e.g. soil properties and background emissions, management and meteorology, it is extremely challenging to determine accurate mean emission factors (JRC InGOS report, https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/atmospheric-monitoring-and-inverse-modelling-verification-greenhouse-gas-inventories). Winiwarter et al., 2018 stated that under current technologies, agricultural emissions have a large potential to abatement and, in the short term, reductions of N_2O emissions must rely on the adoption of existing technologies. Currently available technology could reduce global N_2O emissions by about 26 % below the baseline projection in 2030 (Winiwarter et al 2018). The most applicable pathways to enhance emission reductions are: the refinements of existing options (use of fertilizers), increasing the efficiency of measures (N use efficiency), changing human diets (lower consumption of animal protein). Oenema et al., (2013) estimate a total reduction potential for N_2O emissions from agriculture including human diet changes of up to 60 % in 2050, adding about half to the reductions available from technical measures alone (41 % reductions). According Höglund-Isaksson et al., 2012 and the scenario work based on GAINS model, technical mitigation potential for the agriculture sector in 2030 can only reach 8% due to mitigation opportunities which are found limited and often costly both from social and private interest rates (Höglund-Isaksson et al., 2012.).

Concerning the IPCC calculation of CH_4 emissions from enteric fermentation, depending on the type of animal, the situation within the EU28 varies from country to country. For cattle (IPCC sector 3.A.1) emissions are calculated with very sophisticated methods, with only Cyprus using partially Tier 1. For the enteric fermentation of sheep (3.A.2), the situation is more divided with 13 countries using Tier 1 methods and 15 using higher tiers (including those with higher emissions). For other cattle (3.A.4), only three countries (Romania, France and Portugal) are using higher tiers, with all the others combining different methods. CH_4 and N_2O emissions from manure management (3.B.1 and 3.B.2) it is even more mixed, with Germany, Denmark, Finland, France, Croatia and Romania using exclusively

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higher tiers in both categories. For the calculation of emissions from soils, the share of high tiers is very low; only Denmark and Sweden use solely higher tiers in indirect N_2O emissions from agricultural soils (3.D.2), while there are no countries using only high tiers in direct N_2O emissions (3.D.1), but only some combining high with low tier methods (UNFCCC, 2018b). All these differences in calculating emissions produce evidently higher uncertainties in the results. For the UNFCCC, throughout the variability of the analyzed national GHG inventories, it turned out that N_2O emissions from manure management and direct and indirect emissions together with CH_4 emissions from rice cultivation have the largest uncertainties. When we aggregated UNFCCC uncertainties at country level (using the methodology described in Appendix C), we also noticed the fact that not all countries report sub-sectoral uncertainties (e.g. Greece for grazing) and some countries (Sweden, Poland, Croatia and Czech Republic) had no uncertainty analysis performed for all sub-activities due to lack of data (e.g. confidential data).

There is as well the need to define a common methodology for overall uncertainty calculation while checking for consistency in the way uncertainties are calculated for different data sources and the way data is aggregated for different sectors. We noticed that for agricultural N_2O emissions the split in sub-activities is not always consistent with IPCC sectors and this leaves room to differences when aggregating the results (Table 3).

4.2. Forestry and Other Land Uses

For the LULUCF sector, methods for the estimation of GHGs and CO_2 fluxes differ enormously among countries and land use categories. Within the UNFCCC practice, each country uses its own country specific method which considers specific national circumstances (as long as they are in accordance with the 2006 IPCC GLs), as well as IPCC default values, which result in higher uncertainties. When we analyze the estimates from multiple sources (inventories and models) we observe that, published estimates contain two main sources of uncertainties: a) differences due to input data and structural/parametric uncertainty of models (Houghton et al., 2012); b) differences in definition (Pongratz et al., 2014; Grassi et al., 2018b). These differences result from choices in the simulation setup, and are partly predetermined (for b) in particular) by the type of model used: bookkeeping models, DGVMs, or inventory-based – and whether fluxes are attributed to LULUCF emissions due to the cause or place of occurrence (indirect fluxes on managed land included in GHGIs and FAOSTAT). Differences in definitions and methodology calculation of estimates across model types is crucial and may lead to model-to-model variability. In Figure 13 the variability between the mean of the DGVMs ranges between 44 % in 1996 and 186 % in 2016 (distance between interquartile range and median across models for each year).

Depending on the degree of independence between assumptions, variability can become a reliable proxy for structural uncertainty when more accurate estimates are lacking (Solazzo et al., 2017). In general the definition of NBP denotes the net gain or loss of carbon from a region. NBP is equal to the Net Ecosystem Production (NEP) minus the carbon lost due to a disturbance (e.g., a forest fire, freshwater CO_2 emissions or a forest harvest) taking into account as well the net C balance of harvested products (described by the IPCC 2006 Guidelines) and C emitted by inland waters. In the context of land use change, the last GCP 2018 (Le Quéré et al., 2018) highlighted harvest as one of the main uncertainties. Only to exemplify, according Nabuurs et al. (2018) the uncertainty affecting all studies is that EU

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harvesting levels are rather uncertain. According to the FAOSTAT report 2015 most European countries have a solid forest inventory but there is still large uncertainty over harvesting levels. For many countries the statistics from FAOSTAT have shortcomings such as: very large differences between reported periods, data corrected in later versions, unreported (harvest) removals (Nabuurs et al., 2018).

Checking collective progress towards meeting the goals of the PA will be done by the PA's global stocktake. At present, there is a discrepancy of about 4 Gt CO_2 yr^{-1} in global anthropogenic net land-use emissions (Grassi et al., 2018a, IPCCC SRCCL) between DGVM models reflected in IPCC assessment reports and aggregated national UNFCCC GHG inventories. Grassi et al., 2018a shows that about 3.2 Gt CO_2 yr^{-1} can be explained by conceptual differences in anthropogenic forest sink estimation, related to the representation of environmental change impacts and the areas considered as managed. In order to limit temperature increase to 1.5°C and keep it below 2°C, net-zero CO_2 emissions at global level need to be achieved around 2050 and neutrality for all other GHGs somewhat later in the century. At this point, any remaining GHG emissions in certain sectors need to be compensated for by absorption in other sectors, with a specific role for the land use sector, agriculture and forests (DG CLIMA Report, 2018).

It is important to distinguish between reporting and accounting in the GHG inventory context, as not all reported emissions account towards emission reduction efforts (Grassi et al., 2018b). Reporting refers to the inclusion of estimates of anthropogenic GHG fluxes in NIRs, following the methodological guidance provided by the IPCC. The NIR should, in principle, aim to reflect "what the atmosphere sees" (Peters et al., 2009) in managed lands, within the limits given by the method used and the data available. In the context of mitigation targets (e.g. the PA), accounting refers to the comparison of emissions and removals with the target and quantifies progress toward the target. For the LULUCF sector, specific accounting rules are used to filter reported flux estimates with the aim to better quantify the results of mitigation actions (Grassi et al., 2018b). The UNFCCC reporting principles allocate emissions to the territorial location (national boundaries) at the time that they occur (Peters et al., 2009).

The different definitions and concepts used by the global models and inventory communities mean that the land fluxes cannot necessarily be consistently compared. The framework developed by Grassi et al. (2018a) and shown in Figure 12 can be generalized to make a more direct comparison. Figure 14 disaggregates managed forest land into components that are reported in the UNFCCC CRFs: converted land (e.g., land changing from cropland to forest land), HWPs, and the remaining land (e.g., forest land remaining forest land) is split into land that is "production" (forestry) or land that is used for "ecological or social functions", based on the definitions of managed land. Unmanaged land cannot have direct human induced effects.

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*Figure 14: A conceptual extension of Figure 12 to disaggregate the managed land into three different components, showing how they map to components reported in the UNFCCC inventories. The converted land is equivalent to afforestation (AF) plus deforestation (DF). Remaining land is split into forestry and other (ecological and social functions) and the sink (S) belongs to unmanaged land. Bookkeeping models (Hansis et al., 2015; Houghton & Nassikas, 2017) include only the dark green components (direct managed land) but do account for transition between cropland and pasture, for example, and related C fluxes (dashed component); they do not account for land management *changes* (increasing tillage, introducing irrigation etc.). CRFs include all green components (direct, indirect, natural on managed land), and DGVMs include all components but only in the S3 run (the "historical run" with climate/CO_2 and land use changes. The net land use change flux is derived from S3 minus S2 which means all direct effects, but also the difference of indirect and of natural effects between managed land and its potential vegetation coverage. *difference between fluxes on managed land vs potential vegetation coverage, **cancels by subtracting simulations with and without land use change.*

Overall, our results suggest that most of the LULUCF emissions in the EU28 are from direct effects in the managed forest sector, including age-legacy effects (forest expansion and regrowth after WWII), with small net emissions from land conversion as they are largely compensated by deforestation (from CRFs). With appropriate data and models, it is theoretically possible to expand and enumerate the estimates more accurately.

5. Conclusions

There are many independent estimates of GHG emissions, but adequate understanding of their differences (either qualitatively or quantitatively) is lacking. For CH_4 and N_2O the main differences between countries reports and models are the use of tiers and methodologies (for both emissions and uncertainty calculation). Countries reporting to UNFCCC use an inconsistent mix of tiers depending on the animal type and activity following the approach described by the 2006 IPCC Guidelines, while models run with more accurate data being able to disaggregate better the activities. One detected similarity between all sources is the use of EFs, as almost all sources make use of the IPCC defaults. AD is as well somehow shared, coming mostly from the MS, FAOSTAT, Eurostat or UNFCCC, with the flow between these four sources not totally understood.

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790 At EU28 level, countries are generally doing well in reporting their total GHG emissions but there is large room for improvement mainly when looking at differences between UNFCCC Tier use and models (e.g. for CH_4 from agriculture 10-20 % difference). We stress the need of looking as well on the LULUCF CO_2 estimates, where a quantification of differences between net emission estimates (inventories, models etc.) caused by inconsistencies in methodology and/or Tier application in the EU28 is not yet available. More data is needed to account for and reduce
795 these differences. Narrowing down the analysis to sensitive parameters (e.g. AD) which may trigger the differences (e.g. Appendix A, Table A1) also requires more information on uncertainties.

As previously discussed, it is of great importance to better distinguish between direct and indirect effects on land use emissions especially for the purpose of reconciling land-related emissions from global datasets and NGHGI. Currently our comparisons give significant uncertainty, mostly related to coverage of different land use practices and
800 the differences in definitions (Fig. 12).

It is also important to recognize that just because independent inventories agree well for a sector, does not necessarily mean that the estimate is better in the sense that it is closer to real emissions. The reason for agreement across inventories may simply be that the different inventories used the same methodology and data sources. In recent years there has been increased attention to the quantitative differences between land-based CO_2 emissions, with a
805 much better understanding between inventories and estimates from the scientific community. However, there remain gaps in our understanding of differences between FAOSTAT and UNFCCC and between different DGVMs and bookkeeping models. One explanation can be linked to the fact that models use different methods to estimate emissions/removal then countries use in reporting to UNFCCC.

The current atmospheric GHG network is coordinated by the Integrated Carbon Observation System (ICOS)
810 infrastructure at the European level. Within the future UNFCCC reporting framework, we argue that countries should use, whenever possible, global inversions to provide additional constraints for the verification and reconciliation purposes. Within the VERIFY project framework, we will use in a following study, inversions based on better, higher resolution, transport models to assimilate the precise ICOS GHG concentration data complemented by satellite retrievals of column CO_2, CH_4 and N_2O concentrations. The main challenge for the inversion community remains the
815 separation of natural and anthropogenic part of the total emission column. For the moment, global inverse models are widely used to estimate emissions of CH_4 and N_2O at global/continental scale, using mainly high-accuracy surface measurements at remote stations (e.g. Bergamaschi et al., 2013; Bousquet et al.,2006; Mikaloff Fletcher et al., 2004a, b; Saunois et al., 2016, Hirsch et al., 2006; Huang et al., 2008; Saikawa et al., 2014; Thompson et al., 2014b; Wells et al., 2018, InGOS JRC report, 2018).

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6. Appendices

Appendix A

Methodology tables

Table A1a: Agriculture source specific activity data (AD), emission factors (EF) and uncertainty methodology

CH_4/N_2O emission calculation	*AD/Tier*	*EFs/Tier*	*Uncertainty assessment method*
UNFCCC	Country-specific information consistent with the IPCC Guidelines	IPCC guidelines / Country specific information for higher Tiers	IPCC guidelines (https://www.ipcc-nggip.iges.or.jp/public/2006gl/) for calculating the uncertainty of emissions based on the uncertainty of AD and EF, two different approaches: 1. Error propagation, 2. Monte Carlo Simulation
EDGAR	IEA, FAOSTAT, USGS, WSA, IFA, NBS of China Tier 2 (but when info is failing, Tier 1)	Mainly derived from IPCC defaults (Tier1). Depending upon availability of more refined estimates, country specific EF are adopted (Tier 2 and Tier 3)	IPCC guidelines for emission factor and activity data uncertainty; assumptions for the propagation of the uncertainty when aggregating emission from several sources and/or countries.
CAPRI	Farm and market balances, economic parameters, crop areas, livestock population and yields from EUROSTAT, parameters for input-demand functions at regional level from FADN (EC), data on trade between world regions from FAOSTAT, policy variables from OECD.	IPCC 2006: Tier 2 for emissions from enteric fermentation of cattle and from manure management of cattle. Tier 1 for all other livestock types and emission categories. N-flows through agricultural systems (including N excretion) calculated endogenously.	N/A
GAINS	Livestock numbers by animal type (FAOSTAT, 2010; EUROSTAT, 2009; UNFCCC, 2010) Growth in livestock numbers from FAOSTAT (2003), CAPRI model (2009) Rice cultivation Land area for rice cultivation (FAOSTAT, 2010) Projections for EU are taken from the CAPRI Model	Country-specific information and: Livestock - Implied EFs reported to UNFCCC and IPCC Tier 1 (2006, Vol.4, Ch. 10) default factors Rice cultivation - IPCC Tier 1–2 (2006, Vol. 4, p. 5.49 Agricultural waste burning - IPCC Tier 1 (2006, Vol. 5, p. 5.20	IPCC (2006, Vol.4, p.10.33) uncertainty range
FAOSTAT	FAOSTAT Crop and Livestock Production domains; FAOSTAT Land Use Domain; Harmonized world soil; ESA CCI; MODIS 6 Burned area products	IPCC guidelines	IPCC (2006, Vol.4, p.10.33) - confidential Uncertainties in estimates of GHG emissions are due to uncertainties in emission factors and activity data. They may be related to, inter alia, natural variability, partitioning fractions, lack of spatial or temporal coverage, or spatial aggregation.

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835 *Table A1b: LULUCF source specific activity data (AD), emission factors (EF) and uncertainty information.*

CO_2/NBP	*AD/Tier*	*EFs/Tier*	*Uncertainty assessment method*
UNFCCC	Country-specific information consistent with the IPCC Guidelines	IPCC guidelines / Country specific information for higher Tiers	IPCC guidelines for calculating the uncertainty of emissions based on the uncertainty of AD and EF, two different approaches: 1. Error propagation, 2. Monte Carlo Simulation
CBM	national forest inventory data, Tier 2	EFs directly calculated by model, based on specific parameters (i.e., turnover and decay rates) defined by the user	N/A used from IPCC
EFISCEN	national forest inventory data, Tier 3	emission factor is calculated from net balance of growth minus harvest	Sensitivity analysis on EFISCEN V3 in Schelhaas et al. 2007. (the manual) . Total sensitivity is caused by esp. young forest growth, width of volume classes, age of felling and few more. Scenario uncertainty comes on top of this when projecting in future.
FAOSTAT	The FAOSTAT emissions database is computed following Tier 1 IPCC 2006 Guidelines for National GHG Inventories (http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html).	The FAOSTAT emissions database is computed following Tier 1 IPCC 2006 Guidelines for National GHG Inventories (http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html).	N/A
DGVMs (TRENDYv6)	Can be considered as Tier 3 although the models have never been used for any reporting	Can be considered as Tier 3. Cover only LCC emissions for CO_2	Model specific
Bookkeeping models (H&N and BLUE)	Simple assumptions about C-stock densities (per biome or per biome/country) based on literature	Transient change in C-stocks following a given transition (time dependent EF after an land use transition)	There is no uncertainty estimate per model

*Table A2: Total EU28 agriculture estimates in kton gas per year reported by the five data sources for last available year (**in bold**).*

Gases	*EU28*	*Year*	*Total EU28 Agriculture estimates for last available year kton CH_4, N_2O yr-1*				
CH_4			*Enteric Fermentation*	*Manure management*	*Rice Cultivation*	*Agricultural Waste Burning*	*Total*

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	UNFCCC 2018	1990-**2016**	8513	1832	105	25	10475	
	EDGAR v4.3.2	1990-**2012**	7576	2263	103	48	9990	
	FAOSTAT	1990-**2016**	7630	1987	221	53	9893	
	GAINS	1990-**2013**	9007		97	105	9208	
	CAPRI	1990-**2015**	7470	1269	86	-	8825	
N2O			*Manure management*	*Direct N2O emissions*	*Grazing*	*Indirect N2O emissions*	*Agricultural Waste Burning*	*Total*
	UNFCCC 2018	1990-**2016**	87	393	70	134	0.76	685
	EDGAR v4.3.2	1990-**2012**	49	346	82	110	1.23	588
	FAOSTAT	1990-**2016**	73	381	94	117	1.4	667
	GAINS	1990-**2013**	67	392	76	135	-	670
	CAPRI	1990-**2015**	71	412	79	61	-	623

Appendix B
Data source description

UNFCCC

In order to monitor and evaluate the progress towards the targets of the UN Framework Convention on climate Change (UNFCCC), the UNFCCC committed in articles 4 and 12 countries to provide a national inventory of anthropogenic emissions by sources and removals by sinks of all greenhouse gases not controlled by the Montreal Protocol using comparable methodologies. The Conference of Parties (COP) at its fifth session decided on these reporting guidelines (decision 3/CP.5), which were revised and complemented at COP 8, COP 11 and finally at COP 19.

However, these requirements only commit developed country parties listed in the Annex I of the UNFCCC. This is explained by the fact that in the 1990s, when the Convention's and the Kyoto Protocol's reporting system was developed and adopted, there was a clear division of the regional distribution of GHG emissions. In industrialized countries, most GHG emissions were released, while in developing and emerging countries, emissions were low (Berger et al., 2016). Therefore, the Convention based on the principle of common but differentiated responsibilities. Developing countries are neither requested to mitigate GHG emissions nor to provide detailed information on national GHG emissions on an annual basis.

This changed with the Enhanced Transparency Framework of the Paris Agreement in 2015. Art 13 of the Paris Agreement commit all countries inter alia to report on their annual GHG emissions on a national level. At COP 24 members of the Paris Agreement decided on the Modalities, Guidelines and Procedures of the reporting under the

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Paris Agreement. Regarding reporting of GHG emissions all countries shall provide inventories of emissions by sources and removals by sinks in their biennial transparency report from 2024 onwards using the same guidelines comparable with the recent ones for Annex I parties, but giving some degree of flexibilities for countries which need it in the light of their capacities.

Under the convention Annex I parties are requested since 2015, following decision 24/CP19[1], to report GHG inventories (GHGI) following the Revised UNFCCC Reporting Guidelines for Greenhouse Gas Inventories of Parties in Annex I to the Convention (UNFCCC, 2013), here after UNFCCC Reporting Guidelines. These guidelines request Annex I country parties to use the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Eggleston et al., 2006) and the GWP100 values of the IPCC 4th Assessment Report (IPCCC, 2007) for the calculation of emissions, to report emission using the spreadsheets with the Common Reporting Format (CRF), which keeps within the AFOLU sectors Agriculture and LULUCF distinguished[2,3]. EU Members states are committed separately under the EU Effort Sharing Decision (ESD) (2009) to the reporting scheme at the European level following the same guidelines.

GHG emissions have to be reported in time series from 1990 up to two years before the due date of the reporting. The reporting is strictly source category based and is divided into the following main sectors: Energy (CRF 1), Industrial processes and product use (CRF 2), Agriculture (CRF 3), Land use, land-use change and forestry (LULUCF) (CRF 4) and Waste (CRF 5). For each sector, the UNFCCC reporting guidelines provide a detailed catalog of source categories reflecting a comprehensive inventory of all sources and sinks of the above mentioned gases within an economy.

Chapter 3 of *2006 IPCC Guidelines for National Greenhouse Gas Inventories* on the mandatory Uncertainty Assessment uses two main statistical concepts – the probability density function (PDF) and confidence limits, where the probability density function describes the range and relative likelihood of possible values and the confidence limits give the range (confidence interval) within which the underlying value of an uncertain quantity is thought to lie for a specified probability.

According Chapter 3 there are two ways uncertainties can be calculated:

a) Where uncertain quantities are to be combined by multiplication, the standard deviation of the sum will be the square root of the sum of the squares of the standard deviations of the quantities that are added.

b) Where uncertain quantities are to be combined by addition or subtraction, the standard deviation of the sum will be the square root of the sum of the squares of the standard deviations of the quantities that are added.

[1] https://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf#page=2

[2] This represents a distinction between then UNFCCC Annex I reporting guidelines as determined in negotiation between parties and the UNFCCC, and the IPCC Reporting Guidelines. The UNFCCC Secretariat developed new tables for AFOLU in 2010 (https://unfccc.int/sites/default/files/set_2_afolu_final.pdf) but these were not introduced to reporting requirements.

[3] Whereas before 2015 no CO_2 emissions were reported under Agriculture, from 2015 the CO_2 emissions from urea and lime application were reallocated from LULUCF to Agriculture.

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For this study an analysis of the reported uncertainties under the NGHGI for CO_2, CH_4 and N_2O has been performed for 26 EU countries[4]. The analysis has not been performed for Sweden and Czech Republic due to lack of data (e.g. confidential data). To identify the main uncertainties, the Approach 1: propagation of error, has been applied to each country's uncertainty assessment under the NGHGI.

Since the EU MS report all on different subsectors, the uncertainties have been aggregated to the subsectors per gas that all countries have in common, see the following table B1:

Table B1: Aggregation of sub-sectors for the uncertainty analysis.

Energy Sector (CRF 1A)	1A1, 1A2, 1A3, 1A4, 1A5
Fugitive Emissions Sector (CRF 1B)	1B1, 1B2
IPPU Sector (CRF 2)	2A, 2B, 2C, 2D, 2E, 2F, 2G, 2H
Agriculture Sector (CRF 3)	3A, 3B, 3C, 3D, 3E, 3F, 3G, 3H
LULUCF Sector (CRF 4)	4A, 4B, 4C, 4D, 4E, 4F, 4G, 4H
Waste Sector (CRF 5)	5A, 5B, 5C, 5D, 5E

Generally, for almost all countries, the uncertainties for CO_2, CH_4 and N_2O in the agriculture sector, LULUCF sector are rather high and variable compared to the other sectors. For the EU as a whole, the level uncertainties vary by sector; for the agriculture sector it is 45.4%, and for the LULUCF sector it is 33% (UNFCCC, 2018b). This is because of the inherently different aspects of these sectors due to their dependencies on a number of variable factors and parameters, which make it harder to measure greenhouse gases accurately. For example, Rypdal & Winiwarter (2001) claim that it is the incomplete understanding of soils that is the largest contribution to national uncertainty assessments, which can be confirmed with the uncertainty analysis. N_2O emissions in soil are affected by microbiological activity and processes, the natural variation in soil conditions and the impacts of inter-annual variation in climate on the emissions, making it difficult to measure. Other important contributions to the overall uncertainty are uncertainties about the amount of solid waste (organic material that decomposes to produce methane) that is deposited and the extent of land use change.

Since the 2015, following decisions of COP19[5],inventories of Annex I need to be reported annually by 15th April following the 2006 IPCC Guidelines (Eggleston et al., 2006), using the spreadsheets with the Common Reporting

[4] All MS analyzed in this study have performed their uncertainty assessment using the approach 1, i.e. the methodology of propagation of error.

[5] https://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf#page=2

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Format (CRF), using the GWP100 of AR4 and following the new structure for sectoral specifications but keeping within the AFOLU sector Agriculture and LULUCF distinguished[6,7].

The Revised UNFCCC Reporting Guidelines for Greenhouse Gas Inventories of Parties in Annex I to the Convention (UNFCCC, 2013), here after UNFCC Reporting Guidelines, define what and how to report GHG emission by source and removals by sinks in order to comply with requirements. However, these requirements only commit developed country parties listed in the Annex I of the UNFCCC. This is explained by the fact that in the 1990s, when the Convention's and the Kyoto Protocol's reporting system was developed and adopted, there was a clear division of the regional distribution of GHG emissions. In industrialized countries, most GHG emissions were released, while in developing and emerging countries, emissions were low (Berger et al., 2016). Therefore, the Convention also includes the principle of common but differentiated responsibilities. Developing countries are not requested to provide detailed information on national GHG emissions.

EDGAR

The Emissions Database for Global Atmospheric Research (EDGAR) with versions EDGARv4.3.2. and EDGAR FT2017 provide global, country-level and gridded annual emissions of CO_2, CH_4 and N_2O (as well as of other species, not discussed here), used by policy makers and the IPCC (AR5).

EDGAR is developed and maintained by the Joint Research Centre of the European Commission, with continued inputs by PBL. The version v4.3.2 released in 2017, (Janssens-Maenhout et al., 2019) provides 0.1° gridded emissions from 1970 to 2012. The 'Fast Track' (FT) version produced every year using a variant method provides time series updates making use of latest available information on major sources (energy statistics of IEA and BP).

The EDGAR v4.3.2FT2015 has been producing 2015 grid maps at 0.1°x0.1° resolution for the H2020 project CO_2 Human Emissions (CHE). The agriculture component of EDGAR comprises the agricultural soils (crops that are not rice) (N_2O), application of urea and agricultural lime (N_2O), enteric fermentation (CH_4), rice cultivation (CH_4), manure management (CH_4, N_2O), fertilizer use (synthetic and manure) (N_2O), agricultural waste burning (in field) (CH_4, N_2O) and is based on agricultural statistics and commodity statistics for some products (e.g. lime). Although agricultural field burning is included, other large-scale biomass burning from Savannah and forests and carbon stock changes due to land use activities are not included in EDGAR (Janssens-Maenhout et al., 2019). Details on EDGAR methodology for emissions calculations and uncertainties is referenced in Table A1.1a Recently, EDGAR v4.3.2FT2015 has been updated to EDGAR v5/v4.3.2FT2017 (Olivier and Peters, 2018) which includes national CH_4 and N_2O emissions up to 2017.

EDGAR uses emission factors (EFs) and activity data (AD) to estimate emissions. Both EFs and AD are uncertain to some degree, and when combined their uncertainties need to be combined too. To estimate EDGAR's

[6] This represents a distinction between then UNFCCC Annex I reporting guidelines as determined in negotiation between parties and the UNFCCC, and the IPCC Reporting Guidelines. The UNFCCC Secretariat developed new tables for AFOLU in 2010 (https://unfccc.int/sites/default/files/set_2_afolu_final.pdf) but these were not introduced to reporting requirements.

[7] Whereas before 2015 no CO_2 emissions were reported under Agriculture, from 2015 the CO_2 emissions from urea and lime application were reallocated from LULUCF to Agriculture.

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uncertainties (stemming from lack of knowledge of the true value of the EF and AD), the methodology devised by IPCC (2006, Chapter 3) is adopted, that is the sum of squares of the uncertainty of the EF and AD (uncertainty of the product of two variables). When aggregating the emissions from subcategories, or different sources, or countries the covariance of the respective probability distribution enter into play.

The assumptions introduced by, e.g. Bond et al, (2004), Bergamaschi et al, (2015), Olivier et al., (2002) hold:

- Uncertainties of different source categories are uncorrelated;
- Subsectors for CH_4 and N_2O are fully correlated, thus the uncertainty of the sum is the sum of the uncertainties;
- When dealing with CO_2, full correlation is assumed for subsets sharing the same emission factors (typically fuel-dependent);
- Aggregated emissions from same categories but different countries assumes full correlation, unless the emission factor is country-specific, or derived from higher tiers (i.e. not default EF defined by IPCC).

In addition, the following assumption is adopted:

- When uncertainty is defined within a range (e.g. for the energy sector, IPCC recommend that the methane emission factors are treated with an uncertainty ranging from 50% to 150%), the upper bound of the range is assigned to developing countries, whilst the lower bound to developed countries. Uncertainty of country or process-specific EF is not propagated (no correlation).

Although assuming full correlation when aggregating emissions is quite conservative (overestimating the uncertainty introduced by emission factors), this approach is intended to balance for other sources of uncertainty that are not taken into account, such as covariance among activity data (deemed negligible), uncertainty of technologies factors (no information available as to how these factors are uncertain, as for example on the different rice cultivar practices), and uncertainty due to the 'fast track', i.e. applying trends to estimate latest year's emissions.

The EFs and AD uncertainties are reported in Table B2.

Table B2. Uncertainty assigned to activity data (AD) and emission factors (EF) for CH_4 and N_2O. The table is mostly derived by IPCC guidelines (IPCC, 2006) for Tier 1 emission factors, complemented with estimates by Olivier et al, (2002) and expert judgement.

Source category	**EDGAR code**		**Uncertainty components**	
			u_{AD} (%)	u_{EF} (%)
CH4				
Enteric fermentation	ENF	I D CS	20	30 50 20
Manure management	MNM	I D	20	30 30

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		CS		20
Rice cultivation	AGS.RIC	I D	5 10	[-38;+69] on default emission factors plus uncertainty on scaling factors for water regimes: IRR: [-20; 26]; UPL: 0%; RNF and DWE: [-22; +26]
Biomass burning of crops	AWB.CRP	I D CS	5 10 5	50 150 50
N2O				
			Uncertainty components	
Manure management	MNM	I D CS	20	50 100 50
Synthetic Fertilizers; Animal Manure Applied to Soils; Crop Residue; Pasture	Direct N_2O emission from managed soils	I D CS	20	70 (65 for pasture) 200 70
	Indirect N_2O managed soils	I D CS	50	70 200 70
	Indirect N_2O manure management	I D CS	50	75 150 75

I: industrialised (developed) countries

D: developing countries

CS: country specific

975 A log-normal probability distribution function is assumed to avoid negative values, and uncertainties are reported as 95 % confidence interval according to IPCC (2006, chapter 3, equation 3.7). For emission uncertainty in the range 50 % to 230% a correction factor is adopted as suggested by Frey et al (2003) and IPCC (2006, chapter 3, equation 3.4).

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CAPRI

CAPRI is an economic, partial equilibrium model for the agricultural sector, focused on the EU (Britz and Witzke, 2014[8]; Weiss and Leip, 2012[9]). CAPRI stands for 'Common Agricultural Policy Regionalised Impact analysis', and the name hints at the main objective of the system: assessing the effect of CAP policy instruments not only at the EU or Member State level but at sub-national level. The model is calibrated for the base year (currently 2012) and then baseline projections are built, allowing the ex-ante evaluation of agricultural policies and trade policies on production, income, markets, trade and the environment.

Among other environmental indicators, CAPRI simulates CH_4 and N_2O emissions from agricultural production activities (enteric fermentation, manure management, rice cultivation, agricultural soils). Activity data is mainly based on FAOSTAT and EUROSTAT statistics and estimation of emissions follows IPCC 2006 methodologies, with a higher or lower level of detail depending on the importance of the emission source. Details on CAPRI methodology for emissions calculations is referenced in Table A1a.

FAOSTAT

FAOSTAT: Statistics Division of the Food and Agricultural Organisation of the United Nations, CO_2, CH_4 and N_2O emissions from agriculture and LULUCF statistics till 2017, available at: http://www.FAOSTAT.org/FAOSTAT/en/#home. The FAOSTAT emissions database is computed following Tier 1 IPCC 2006 Guidelines for National GHG Inventories (http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html). Country reports to FAO on crops, livestock and agriculture use of fertilizers are the source of activity data. Forest data are those reported to FAO within the FRA process. Geospatial data are the source of AD for the estimates from cultivation of organic soils, biomass and peat fires. GHG emissions are provided by country, regions and special groups, with global coverage, relative to the period 1961-present (with annual updates) and with projections for 2030 and 2050, expressed as Gg CO_2 and CO_2e (from CH_4 and N_2O), by underlying agricultural emission sub-domain and by aggregate (agriculture total, agriculture total plus energy, agricultural soils). Similarly, Land Use Total contains all GHG emissions and removals produced in the different Land Use sub-domains, representing the three IPCC Land Use categories: cropland, forest land, and grassland, collectively called emissions/removals from the LULUCF sector. LULUCF emissions consist of CO_2 (carbon dioxide), CH_4 (methane) and N_2O (nitrous oxide) associated with land management activities. CO_2 emissions/removals are derived from estimated net carbon stock changes in above and below-ground biomass pools of forest land, including forest land converted to other land uses. CH_4 and N_2O, and additional CO_2 emissions are estimated for fires and drainage of organic soils. The FAOSTAT emissions database is computed following Tier 1 IPCC 2006 Guidelines for National GHG Inventories (http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html). GHG emissions are provided as by country, regions and special groups, with global coverage, relative to the period 1990-most recent available year (with annual updates), expressed as Gg CO_2e from CH_4 and N_2O, net emissions/removals as Gg CO_2 and Gg CO_2e, by underlying land use emission sub-domain and by aggregate (land use total).

[8] https://www.capri-model.org/docs/CAPRI_documentation.pdf

[9] https://www.sciencedirect.com/science/article/pii/S0167880911004415

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GAINS

The Greenhouse gas and Air pollution Interactions and Synergies (GAINS) model (http://gains.iiasa.ac.at/) provides a framework for assessing strategies that reduce future emissions of multiple air pollutants and greenhouse gases at least costs, and minimize their negative effects on human health, ecosystems and climate change. Although the focus of GAINS is more on future scenarios and air quality policies, GAINS estimates for its baseline historical emissions from 1990 to 2050 of 10 air pollutants and 6 GHGs for each country based on data from international energy and industrial statistics, emission inventories and on data supplied by countries themselves. It assesses emissions on a medium-term time horizon, with projections being specified in five-year intervals through the year 2050 (http://www.iiasa.ac.at/web/home/research/researchPrograms/air/GAINS.html). An important objective of the GAINS model is to use a consistent emission estimation methodology across all countries and sectors. Country- and sector/technology- specific emission factors are often derived in a consistent manner and are known to influence emissions, thereby producing emission estimates that are comparable across geographic and temporal scales and for which it is possible to explain deviations in emissions. By identifying the impact on emissions from implementation of various control technologies, the GAINS model can assess the expected impact on emissions from introducing additional control in the future.

CBM

The Carbon Budget Model developed by the Canadian Forest Service (CBM-CFS3), can simulate the historical and future stand- and landscape-level C dynamics under different scenarios of harvest and natural disturbances (fires, storms), according to the standards described by the IPCC (Kurz et al., 2009). Since 2009, the CBM has been tested and validated by the Joint Research Centre of the European Commission (JRC), and adapted to the European forests. It is currently applied to 26 EU MS, both at country and NUTS2 level (Pilli et al., 2016b).

Based on the model framework, each stand is described by area, age and land use classes and up to 10 classifiers based on administrative and ecological information and on silvicultural parameters (such as forest composition and management strategy). A set of yield tables define the merchantable volume production for each species while species-specific allometric equations convert merchantable volume production into aboveground biomass at stand-level. At the end of each year the model provides data on the net primary production (NPP), carbon stocks and fluxes, as the annual C transfers between pools and to the forest product sector.

The model can support policy anticipation, formulation and evaluation under the LULUCF sector, and it is used to estimate the current and future forest C dynamics, both as a verification tool (i.e. to compare the results with the estimates provided by other models) and to support the EU legislation on the LULUCF sector (Grassi et al., 2018a). In the biomass sector, the CBM can be used in combination with other models, to estimate the maximum wood potential and the forest C dynamic under different assumptions of harvest and land use change (Jonsson et al., 2018).

EFISCEN

The European Forest Information SCENario Model (EFISCEN) is a large-scale forest model that projects forest resource development on regional to European scale. The model uses national forest inventory data as a main

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source of input to describe the current structure and composition of European forest resources. The model projects the development of forest resources, based on scenarios for policy, management strategies and climate change impacts. With the help of biomass expansion factors, stem wood volume is converted into whole-tree biomass and subsequently to whole tree carbon stocks. Information on litter fall rates, felling residues and natural mortality is used as input into the soil module YASSO (Liski et al. 2005), which is dynamically linked to EFISCEN and delivers information on forest soil carbon stocks. The core of the EFISCEN model was developed by Prof. Ola Sallnäs at the Swedish Agricultural University (Sallnäs 1990). It has been applied to European countries in many studies since then, dealing with a diversity of forest resource and policy aspects. A detailed model description is given by Verkerk et al. (2016), with online information on availability and documentation of EFISCEN at http://efiscen.efi.int. The model and its source code are freely available, distributed under the GNU General Public License conditions (www.gnu.org/licenses/gpl-3.0.html).

DGVMs (TRENDY v6)

This study uses the ensemble of DGVMs TRENDY version 6 (v6) (Le Quéré et al., 2018) including the following models: ORCHIDEE (Krinner, G. et al. 2005), OCN (Zaehle, S. et al. 2011), JULES (Clark, D. B. et al. 2011), JSBACH (Reick, C. H. et al., 2013), VEGAS (Zeng, N., 2003, 2005), LPX-Bern (Lienert and Joos 2018), LPJ (Sitch, S. 2003), ISAM (Jain, A. K. et al., 2013). We make use of carbon trends in net land carbon exchange over Europe, during the period 1990-2016. Data available for download at http://dgvm.ceh.ac.uk/index.html. DGVM models are forced by historical agricultural land cover change, climate change and CO_2 since 1901. The models calculate forest area from agricultural land in different ways, thus have very different forest areas in EU. Models include biomass and soil C loss or gains associated with land cover change (diagnosed from factorial simulations) but they do not include a realistic representation of cropland management for Europe, nor of forestry and grassland management.

Bookkeeping models

The LULUCF chapter makes use of data from two bookkeeping models: **H&N** (Houghton & Nassikas, 2017) and BLUE (Hansis et al., 2015). Bookkeeping models (Houghton, 1983) calculate land-use change CO2 emissions and uptake fluxes for transitions between various natural vegetation types and agricultural lands (croplands and pastures). The original bookkeeping approach of Houghton (2003) keeps track of the carbon stored in vegetation and soils before and after the land-use change. Carbon gain or loss is based on response curves derived from literature. The response curves describe decay of vegetation and soil carbon, including transfer to product pools of different life-times, as well as carbon uptake due to regrowth of vegetation and consequent re-filling of soil carbon pools. Natural vegetation can generally be distinguished into primary and secondary land. For forests, a primary forest that is cleared cannot recover back to its original carbon density. Instead long- term degradation of primary forest is assumed and represented by lowered standing vegetation and soil carbon stocks in the secondary forests. Apart from land use transitions between different types of vegetation cover, forest management practices in the form of wood harvest volumes are included. Different from dynamic global vegetation models, bookkeeping models ignore changes in environmental conditions (climate, atmospheric CO_2, nitrogen deposition and other environmental factors). Carbon

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densities at a given point in time are only influenced by the land use history, but not by the preceding changes in the environmental state. Carbon densities are taken from observations in the literature and thus reflect environmental conditions of the last decades.

BLUE is spatially explicit at half-degree resolution, while H&N works on country level model by Houghton & Nassikas, 2017). See main text for further model difference, including land use change input.

Wetland emissions ensemble of models

This model ensemble simulates natural CH_4 emissions from wetlands and contains eleven biogeochemical models (CLM4.5 (Riley et al., 2011), CTEM, DLEM (Tian et al., 2010), VISIT (Ito and Inatomi 2012), JULES (Hayman et al., 2014), LPJ-MPI (Kleinen at al., 2012), LPJ-wsl (Hodson et al., 2011), LPX-Bern (Spahni et al., 2011), ORCHIDEE (Ringeval et al., 2010), SDGVM (Hopcroft et al., 2011), TRIPLEX-GHG (Zhu et al., 2015)). These models are referenced and can be found in Poulter et al., 2017 Supplementary Information: https://iopscience.iop.org/1748-9326/12/9/094013/media/ERL_12_9_094013_suppdata.pdf

Appendix C

Example of country specific uncertainty calculation for LULUCF sector 4

Table C1: Aggregation of IPCC sub-sectors for the uncertainty analysis

Energy Sector (CRF 1A)	1A1, 1A2, 1A3, 1A4, 1A5
Fugitive Emissions Sector (CRF 1B)	1B1, 1B2
IPPU Sector (CRF 2)	2A, 2B, 2C, 2D, 2E, 2F, 2G, 2H
Agriculture Sector (CRF 3)	3A, 3B, 3C, 3D, 3E, 3F, 3G, 3H
LULUCF Sector (CRF 4)	4A, 4B, 4C, 4D, 4E, 4F, 4G, 4H
Waste Sector (CRF 5)	5A, 5B, 5C, 5D, 5E

For a better understanding and overview of the single steps of the Uncertainty Analysis, an example calculation for Uncertainty Assessment is included, where the combined uncertainty and contribution to variance is calculated for 4A CO_2. The same was done for 4B, 4C etc.

1. Table C2 shows the subsectors 4A and 4B of one the EU28 MS Uncertainty Assessment for 2016.

Table C2: Calculation example of the uncertainty analysis; uncertainty assessment 2016.

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IPCC Code	Gas	Year *x* emissions or removals	Combined uncertainty	Contribution to Variance by Category in Year x
		Input data	$\frac{(G*D)^2}{(\sum D)^2}$	$\sqrt{E^2+F^2}$
		kt CO_2 equivalent	%	
4 A	CH4	237,955502	0,24758837	0,00
4 A	CH4	40,1939139	1,06066017	0,00
4 A	CO2	-30251,343	0,24758837	0,00
4 A	CO2	-5829,38043	1,06066017	0,00
4 A	N2O	0,8914493	0,24758837	0,00
4 A	N2O	0,15057789	1,06066017	0,00
4 B	CH4	2,05470896	1,06066017	0,00
4 B	CO2	1917,59719	1,06066017	0,00
4 B	CO2	541,959929	1,06066017	0,00
4 B	N2O	0,76975268	1,06066017	0,00
4 B	N2O	26,874189	1,06066017	0,00
Total emissions of all sectors		397935,125		

2. To calculate the contribution to variance for the sector 4A CO_2, the following steps have to be performed:
   (1) (-30251,343) + (-5829,38) = (- 36080,72) (building the sum of the emissions of year x for 4A, CO_2)
   (2) ((-30251,343 * 0,24758837)^2 + (-5829,38 * 1,06066017)^2) / (-36080,72)^2 = 0,0724584 (intermediate step for calculating the Combined Uncertainty)
   (3) SQRT(0,0724584) = 26,918 % (Combined Uncertainty)
   (4) ((-36080,7234* 26,918)^2) / 397935,125^2 = 0,001 (Contribution to Variance for year x)
3. Results can be found in table C3

Table C3: Calculation example of the uncertainty analysis; section from one of the MS of the EU28 uncertainty assessment 2016.

IPCC Code	Gas	Year *x* emissions or removals	Combined uncertainty	Contribution to Variance by Category in Year x
		Input data	$\frac{(G*D)^2}{(\sum D)^2}$	$\sqrt{E^2+F^2}$
		kt CO_2 equivalent	%	
4A	CO2	-36080,7234	0,26918099	0,001

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To check for correctness, the total uncertainty for the aggregated sectors can be calculated. If the total uncertainty for the aggregated sectors matches the total uncertainty of the uncertainty assessment, the calculated uncertainties for the subsectors are correct. This was the case for all calculations performed for this analysis.

The results of the Uncertainty Analysis show a clear trend of the main uncertainties and gases across the analyzed 26 EU MS.

Appendix D

Country specific emissions

Detailed agriculture CH_4 and N_2O emissions split in activities for all EU28 countries can be downloaded at the following link: http://doi.org/doi:10.5281/zenodo.3460311 and are found under the "Figures5,8_AppendixD_CH_4_N_2O_per_country" excel document.

Data availability

All raw data files reported in this work which were used for calculations and figures are available for public download at http://doi.org/10.5281/zenodo.3460311 (Petrescu et al., 2019).The data we submitted is reachable with one click (without the need for entering login and password), and a second click to download the data, consistent with the two-click access principle for data published in ESSD (Carlson and Oda, 2018). The data and the DOI number is subject to future updates and it refers only to this version of the manuscript.

Acronyms and abbreviations

AD Activity data

AFOLU Agriculture, Forestry and Other Land Use

AR Assessment Report

BP The British Petroleum Company

CAPRI Common Agricultural Policy Regionalised Impact analysis model

CBM Carbon Budget Model

CH_4 Methane

CO_2 Carbon dioxide

COP Conference of the Parties

CRF Common Reporting Format

DG CLIMA Directorate General CLIMA (European Commission)

DGVMs (TRENDY) Dynamic global vegetation models

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EDGAR Emission Database for Global Atmospheric Research

EEA European Environmental Agency

EF Emission factor

EFISCEN European Forest Information SCENario Model

ESA CCI European Space Agency Climate Change Initiative

ETS Emissions Trading System

EU28 European Union

EUROSTAT European Statistical Office

FADN Farm Accountancy Data Network

FAOSTAT Food and Agriculture Organization of the United Nations

FL Forest Land

FOLU Forestry and Other Land Use

FRA Global Forest Resources Assessment

GAINS Greenhouse gas and Air pollution Interactions and Synergies model

GCP Global Carbon Project

GHG Greenhouse Gases

GMB Global Methane Budget

H2020 Horizon 2020

IEA International Energy Agency

IFA International fertilizer industry organization

IPCC Intergovernmental Panel on Climate Change

IPCC GLs IPCC Guidelines

IPCC SRCCL IPCC Special Report on Climate Change and Land

IPPU Industrial processes and product use

JRC Joint Research Centre of the European Commission

KP Kyoto Protocol

LULUCF Land Use, Land Use Change and Forestry

MODIS Moderate resolution imaging spectroradiometer

MS Member States

N_2O Nitrous oxide

NBP Net Biome Productivity

NBS National Bureau of Statistics of China

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NDCs - Nationally Determined Contributions

NEP Net Ecosystem production

NFI National forest inventory

NGHGI National Greenhous Gas Inventory

NIRs National Inventory Reports

NPP Net Primary Production

NUTS2 Nomenclature of territorial units for statistics

PA Paris Agreement

PBL Planbureau voor de Leefomgeving (Netherlands Environmental Assessment Agency)

OECD The Organisation for Economic Co-operation and Development

TACCC Transparency, Accuracy, Completeness, Comparability, Consistency

UNEP United Nation Environment Programme

UNFCCC United Nations Framework Convention on Climate Change

USGS United States Geological Survey

VERIFY Verifying greenhouse gas emissions, EU H2020 project, grant agreement No 776810

WSA World steel association

WWII World War two

Author contributions

A.M.R.P and H.D. designed research and led the discussions, A.M.R.P. analyzed the data and wrote the initial version of the paper; G.P. provided the figures and initial text for the LULUCF chapter, A.M.R.P., P.C., H.D., G.P., G.G., G.J.M, F.N.T., W.W. made significant changes throughout all versions of the paper, G-J.N., A.L., G.C-G., L.H-J., E.S., R.P., A.K., A.B., J.P., G.C. and R.M.A. reviewed the initial versions of the paper and provided comments, suggestions and advice during the preparation of this manuscript., A.K. developed the methodology for the UNFCCC uncertainty calculation for each Member State, provided the information and contributed to the writing of Appendix C, E.S. developed the methodology for the EDGAR uncertainty calculation and provided the CH_4 and N_2O uncertainties, D.G. contributed to the writing of the UNFCCC description (Appendix B), R.M.A. provided the initial text for the UNFCCC and EDGAR descriptions (Appendix B), M-J.S. R.P., G.C-G., L.H-J., W.W., A.B., G.C, J.E.M.S.N. are data providers and advised during data analysis process.

Competing interests

The authors declare that they have no conflict of interest.

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