



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

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25 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.

35 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 (CO₂), 257 % for methane (CH₄) and 122 % for nitrous oxide (N₂O) (WMO 2019). The rise of CO₂ levels is caused primarily by fossil fuel combustion, with substantial contributions from land use change. Increases in emissions of CH₄ 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 N₂O 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).



80 According to 2018 NGHGI estimates, the European Union (EU28) emitted 3.9 Gt CO₂e in 2016 (incl. LULUCF) and 4.2 Gt CO₂e (excl. LULUCF) (the GWP100 metrics is here used to compare different gases in CO₂ equivalents (CO₂e)). 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
 85 (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 to NGHGI 2018 data, total anthropogenic emission of GHGs (Mt CO₂e) in the EU28 (Fig. 1) decreased by 24 % from 1990 to 2016 (UNFCCC, 2018). CO₂ emissions (incl. LULUCF) account for 81 % of the total EU28 emissions (Mt CO₂e) in 2016, and declined 24 % since 1990, accounting for 71 % of the total reduction in
 90 GHG emissions. CH₄ emissions account for 10 % of and N₂O 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
 95 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
 100 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).

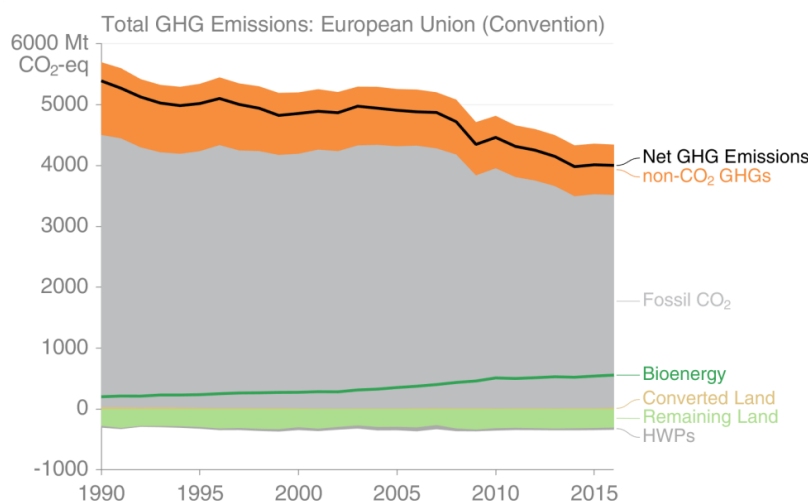


Figure 1: Total reported EU28 GHG emissions according to UNFCCC NGHGI 2018.



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Emissions from FOLU (i.e. LULUCF in this study) represented in 2016 a sink of about 300 Mt CO₂, 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.

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For CH₄, 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 CH₄ emissions in 2016 (EEA, 2018), that is 11 % of total EU28 GHG emissions (Mt CO₂e) in 2016. From 1990 to 2016, the total CH₄ emissions from EU28 decreased by 31 % (554 Mt CO₂e). The top five EU28 emitters of CH₄ are France (13 %), Germany (12 %), UK (12 %), Poland (11 %) and Italy (10 %) that account for 56 % of total EU28 CH₄ emissions (excl. LULUCF sector).

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For N₂O, 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 N₂O emissions in 2016, that is 5 % of total EU28 GHG emissions (Mt CO₂e) in 2016. From 1990-2016, the total N₂O emissions decreased by 35 % (251 Mt CO₂e). The top five EU28 emitters of N₂O are France (18 %), Germany (16 %), UK (9 %), Poland (8 %) and Italy (8 %) that account for 59 % of the total N₂O EU28 emissions (excl. LULUCF sector).

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Zooming on recent trends, non-CO₂ 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 N₂O which have offset the declining CH₄ emissions. The continued CH₄ 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).

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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-CO₂ 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’.

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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 CH₄ 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 CO₂, CH₄ and N₂O. The units are based on the metric tonne (t) [1kt = 10³ g; 1Mt = 10¹²g] for individual gases and [Mt=10¹² g; 1Tg=10¹²g] for CO₂ 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)



<i>References</i>	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
<i>N₂O</i>	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)	
<i>References</i>	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-CO₂ GHG emissions (IPCC SRCCL 2019; FAO 2015). The two major gases emitted by the agricultural sector are CH₄ and N₂O. 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 CO₂ equivalents (year 2016, UNFCCC 2018). In 2016, CH₄ from agricultural activities accounted for 53 % of total EU28 CH₄ emissions, while N₂O accounted for 65 % of N₂O emissions respectively. The preponderant share of agriculture in total anthropogenic non-CO₂ emissions also applies globally (IPCC SRCCL 2019).

Regarding the forestry sub-sector of AFOLU, LULUCF, the major GHG gas is CO₂. According to NGHGI 2018 data, in 2016, the total EU28 LULUCF sector was a net CO₂ sink of 314 Mt CO₂. 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



180 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 CH₄ and N₂O emissions

185 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-](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)
 190 [meetings/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories-](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)
[annex-i-parties/national-inventory-submissions-2018](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 CH₄ emissions and CH₄ and N₂O 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
 195 the section of the NIR in the documentation box of the corresponding sectoral background data tables.

Further in this section, we present estimates of CH₄ and N₂O 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 CO₂ emissions from agriculture, these are allocated to
 the liming and urea application, IPCC sectors 3G and 3H respectively. In terms of CO₂ they only represent <5 %
 200 of the total GHG emissions from agriculture, therefore are not included in this study.

CH₄

According to UNFCCC NGHGI data, in 2016 agricultural activities accounted for 53 % of the total CH₄
 205 emissions in EU28. At EU28 level (Fig. 2), we found that the total agriculture CH₄ 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
 210 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 CH₄ on the EU28
 level, are CH₄ emissions from enteric fermentation, CH₄ 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.

220 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).

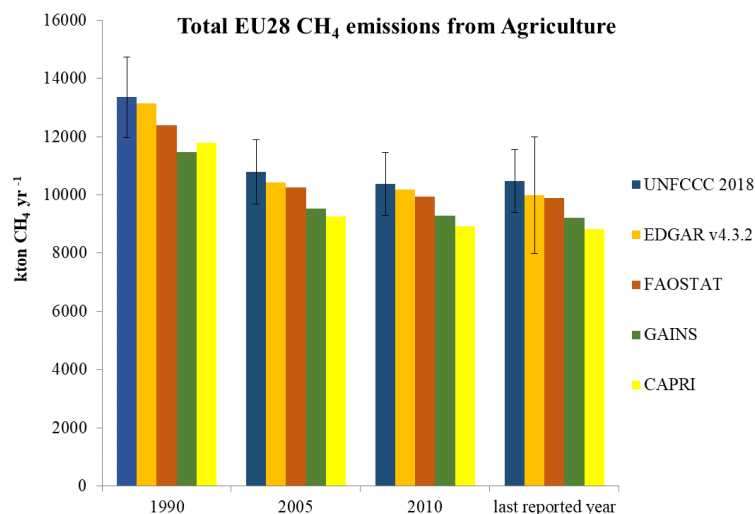


Figure 2. Total EU28 Agriculture CH_4 emissions from five data sources, UNFCCC 2018 communications, EDGAR, 225 FAOSTAT, CAPRI and GAINS. The relative error on the UNFCCC value, computed with the 95% confidence interval method, is 10 %. It represents the GHGI 2018 uncertainty for the agriculture data 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



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.

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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 disseminated 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).

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To better understand the differences between emissions in EU28 we plotted in Figure 3 the CH₄ emission percent difference between 2005 and 1990, and between last reported year, 2010 and 2005. We observe that for the 2005-1990 change there is a major reduction in CH₄ 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 CH₄ reduction is smaller but still consistent between all data sources.

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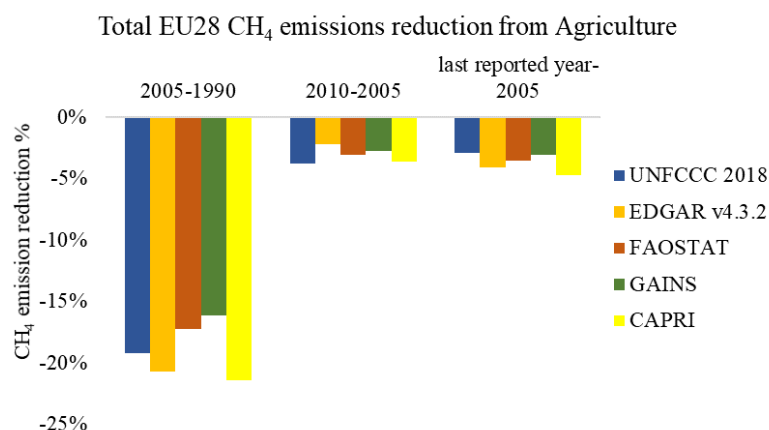


Figure 3: Change of EU28 total agricultural CH₄ emissions between different years. Last reported year in this study refers to 2016 (UNFCCC and FAOSTAT), 2012 (EDGAR), 2015 (GAINS) and 2013 (CAPRI).

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We could therefore conclude that all inventory-based data sources are consistent with each other for capturing recent CH₄ 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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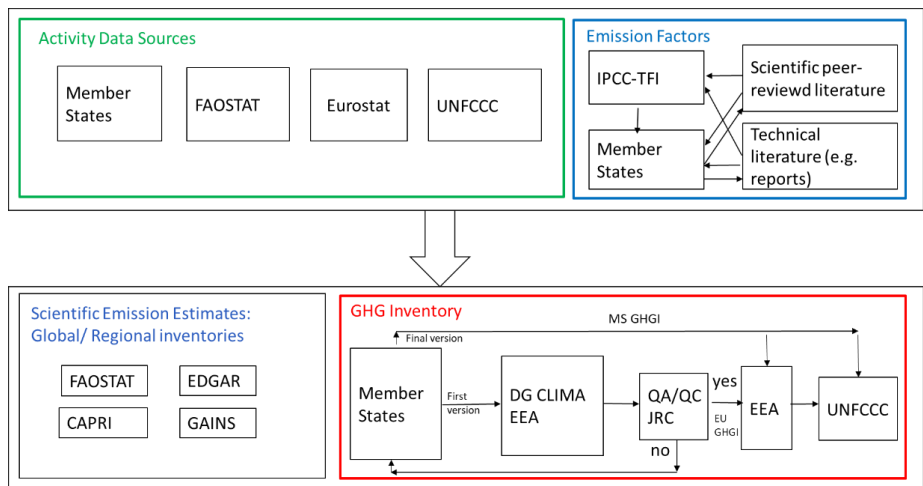


Figure 4: Example of flow of AD, EFs and emission estimates in EU based on IPCC regulations.

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From the detailed analysis of CH₄ emissions split into sectoral information (Figure 5) (all country data and figures are provided in the excel spreadsheets “Figures5,8_AppendixD_CH₄_N₂O_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 very high CH₄ 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 CH₄ emissions. UNFCCC uncertainties for CH₄ emissions are between 10-50 % but can be larger for some countries and sectors, e.g. Romania reporting a 500 % uncertainty for emissions from rice cultivation.

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To exemplify the shares of CH₄ emission from agriculture, in Figure 5 we present the total sub-sectoral CH₄ emissions for three example countries.

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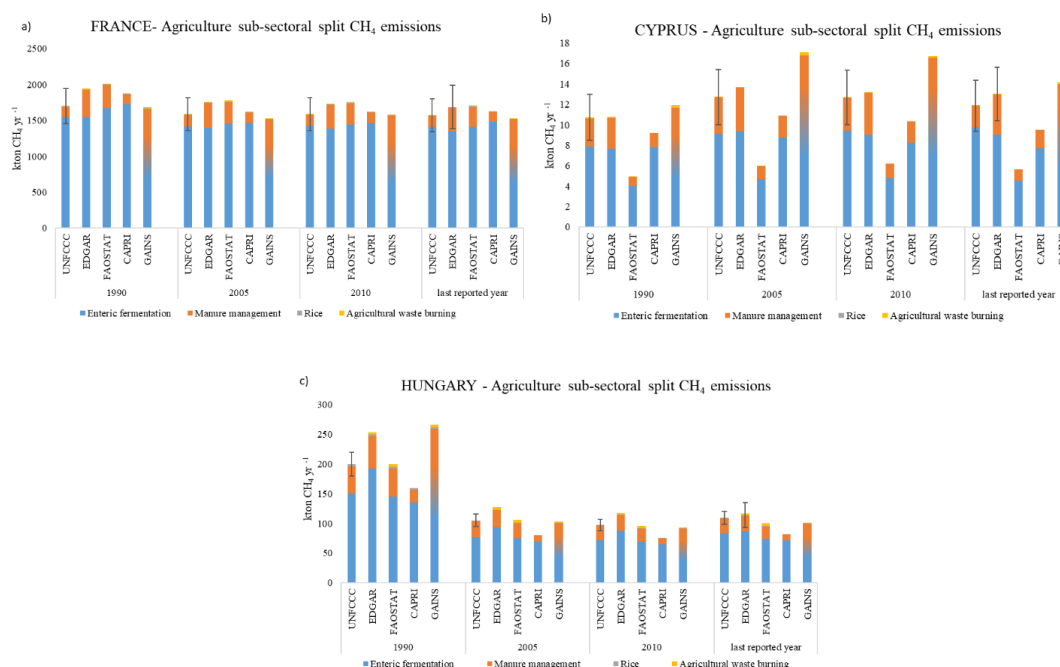


Figure 5: CH_4 emission from five data sources (UNFCCC NGHGI 2018, EDGAR v4.3.2., FAOSTAT, CAPRI and GAINS) split into main activities: enteric fermentation for ruminant livestock (blue) and manure management (orange). GAINS gradient (orange-blue) represent the total emissions from enteric fermentation 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 described 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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N_2O

According to UNFCCC NGHGI data, in 2016 agricultural activities accounted for 78 % of the total N_2O 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.

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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_2 OMAN – 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_2 OAPP – manure application on soils N_2 OSYN – synthetic fertilizer application N_2 OHIS – histosols N_2 OCRO – 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_2 OGRA - grazing	3.D.a.3 - grazing	3.D.1.3 -Urine and Dung Deposited by Grazing Animals



Indirect N₂O emissions	3.B.2.5. – Indirect N ₂ O Emissions from manure management 3.D.2 Indirect emissions from soils	4.D.3 – Indirect N ₂ O from agriculture	N ₂ OLEA – leaching N ₂ OAMM – ammonia volatilization N ₂ ODEP – atmospheric deposition (no IPCC)	3.D.b.1 – atmospheric deposition 3.D.b.2 – leaching	3.B.2.5 Indirect N ₂ O emissions 3.D.2 – Indirect N ₂ O 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 CH₄ emissions, N₂O 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 CH₄, CAPRI has the lowest estimate but well within the uncertainty interval.

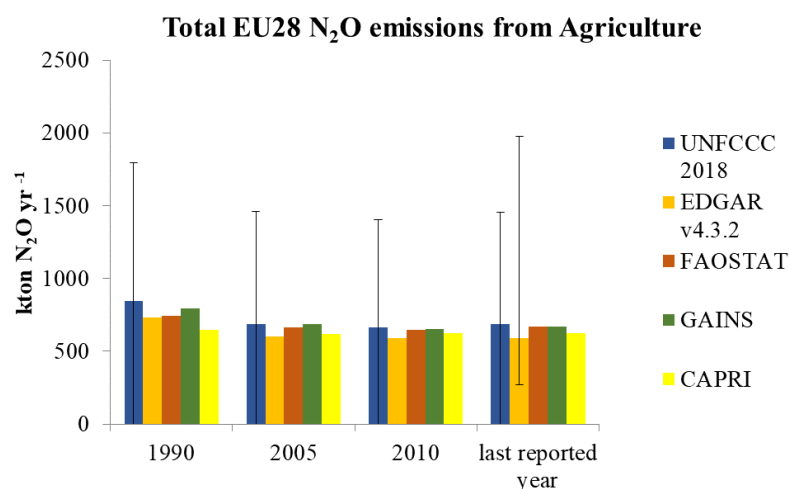


Figure 6: Total EU28 Agriculture N₂O emissions from five data sources, UNFCCC NGHGI 2018, EDGAR v4.3.2., FAOSTAT, CAPRI and GAINS. The relative error on the UNFCCC value, computed with the 95% confidence interval method, is 106 %. It represents the GHGI 2018 uncertainty for the EU28 total N₂O agriculture 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.



In Figure 7 we present the N₂O emission difference between 2005 and 1990, and between the last reported year, 2010 and 2005. We observe that for the 2005-1990 there is a major reduction in N₂O emissions for all data sources for the same reasons stated for CH₄ but the spread between different reduction estimates is much larger than for CH₄. 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).

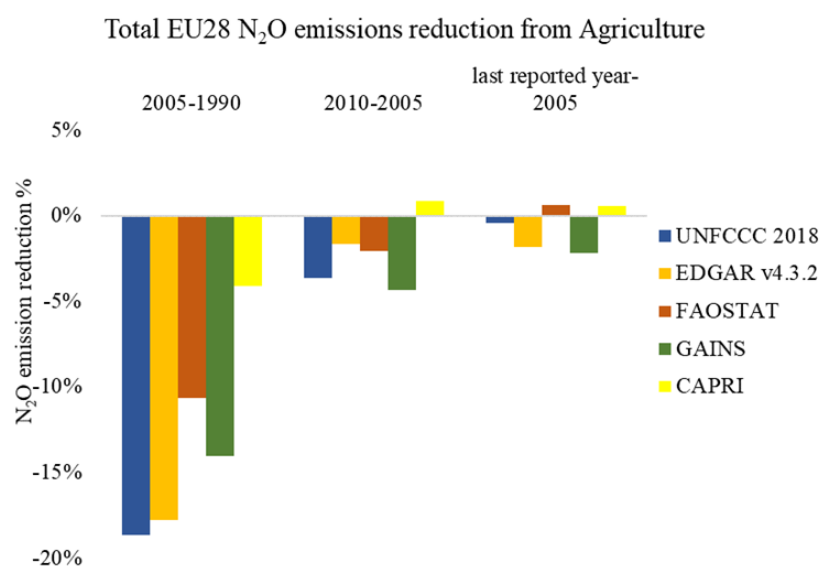


Figure 7: Change of EU28 total agricultural N₂O emissions between different years. Last reported year in this study refers to 2016 (UNFCCC and FAOSTAT), 2012 (EDGAR), 2015 (GAINS) and 2013 (CAPRI).

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Nevertheless, despite inconsistent sign of N₂O emission changes between datasets, the spread between absolute values of N₂O emission changes is smaller for recent periods than for the period 1990-2005. For both CAPRI and FAOSTAT, the increase in N₂O 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.

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The two most important sources for N₂O emissions from agriculture pertain to direct (synthetic fertilizer, manure application to soils, histosols, crop residues and biological nitrogen fixation) and indirect (ammonia volatilization, leaching and atmospheric deposition) emissions. We exemplify this in Figure 8 where we present the N₂O 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_CH₄_N₂O_per_country” downloadable at <http://doi.org/doi:10.5281/zenodo.3460311>) (e.g. former USSR countries i.e. Latvia, Lithuania, Estonia and former Eastern European Block i.e. Romania, Hungary, Slovakia, Bulgaria) higher N₂O 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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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 N₂O emissions. In general, the uncertainties reported by UNFCCC for total N₂O 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 N₂O emissions from manure management, while Greece reports a very small uncertainty of less than 2 % for N₂O emissions from agricultural soils.

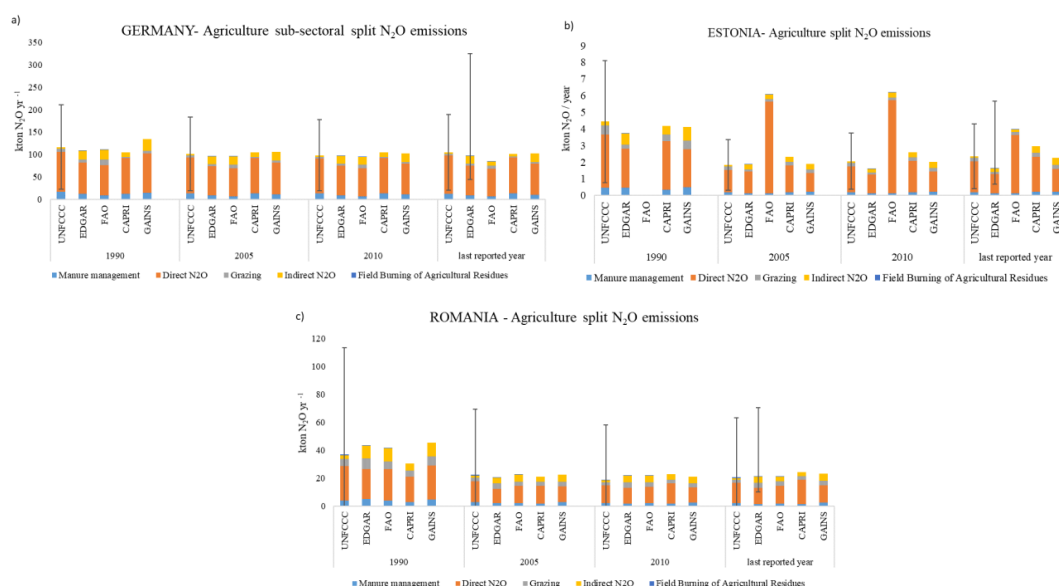


Figure 8: N₂O emission from Agriculture split into main activities: manure management, direct emissions, grazing, indirect emissions and field burning of agricultural residues; a) very good consistency for Germany b) poor consistency for Estonia; c) high 1990 N₂O emissions for Romania (former Eastern 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 N₂O 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 described 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 N₂OSYN – synthetic fertilizer application - does not have a correspondent in GAINS activities. The leaching, ammonia and atmospheric deposition N₂O emissions in CAPRI do not have a clear



correspondent sub-activity in UNFCCC, while in FAOSTAT those N₂O emissions are reported under other categories: manure left on pasture and manure applied to soils.

375 For N₂O emissions, uncertainties are mostly in the range of 100 % or more. The countries reporting the highest N₂O 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 N₂O emissions for Romania
 380 (former Eastern European Block) and is due to irregularities in reporting during the dissolution of the Soviet Union (1989–1991).

3.2. Natural CH₄ emissions

385 In recent assessments of the global CH₄ budget (Saunois et al., 2019), covering the period 2008-2017, CH₄ emissions from top-down and bottom-up sources are estimated to be 178 Tg CH₄ yr⁻¹ (range 155-200) and 149 Tg CH₄ yr⁻¹ (range 102-182), respectively (Saunois et al., 2019).

In the EU28, natural emissions of CH₄ are represented by wetlands and are not yet fully accounted for and reported under NGHGI. According NGHGI 2019, between 2008 and 2017, the natural CH₄ emissions in the EU28
 390 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 CH₄. The only countries in EU28 reporting CH₄ from wetlands were Denmark, Finland, Germany, Ireland, Latvia and Sweden.

Wetlands are sinks for CO₂ and sources of CH₄. Their net GHG emissions therefore depends on the relative
 395 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 CH₄ 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 CH₄, 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),
 400 due to the GWP100 of CH₄ and the generally opposite directions of CO₂ and CH₄ 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
 405 reaching the EU climate targets.

Since CH₄ 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 CH₄ 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 CH₄ budget. The sum of all natural sources of CH₄ as inferred by different models



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 CH₄ budget (Poulter et al., 2017) forced by the same variable flooded area dataset, is 30 % (80 Tg CH₄ yr⁻¹) globally (given their estimated emissions of 177–284 Tg CH₄ 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.

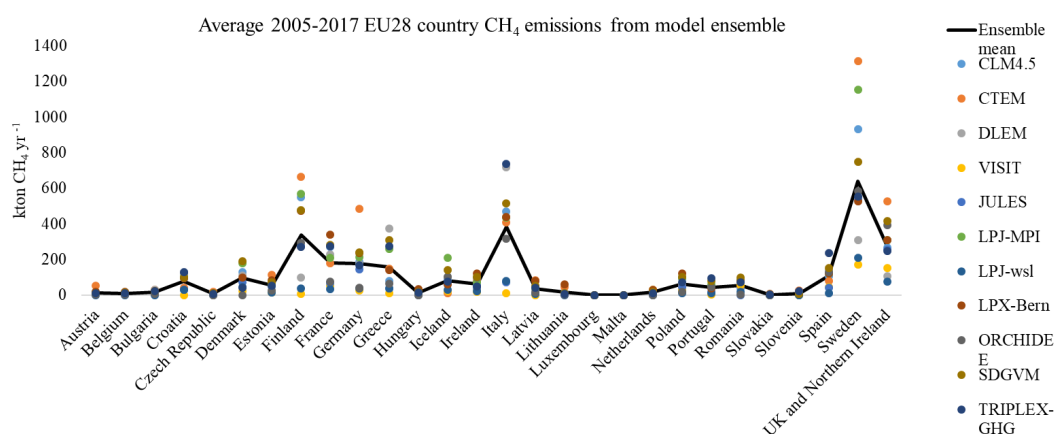


Figure 9. Distribution of CH₄ emissions from undisturbed natural wetlands for all the countries of EU28 as simulated by an ensemble of 11 global emission models averaged between 2005-2017 (Poulter et al., 2017). The positive values represent a source.

According to Poulter et al. (2017), between 2005-2017, the total wetland CH₄ emissions in EU28 averaged 3 Tg CH₄ 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 CH₄ emissions. For the same period, GHGI 2019 reports an average of 10.34 kton CH₄, 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 CH₄ 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 CH₄ model to provide to GHGI a very detailed list of estimates for all CH₄ sub-activities.

3.3. Forestry and Other Land Uses

Forestry and Other Land Uses (FOLU) chapter includes in this analysis CO₂ 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



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 2°C 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 CO₂ 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 CO₂ 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.



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

<i>LULUCF data sources</i>	<i>Short description</i>	<i>References</i>
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



	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 CO₂ emissions/removals from Forest Land (FL) (in UNFCCC GHGI 2018, IPCC sector 4A) includes net
 480 CO₂ 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
 CO₂ net sink) simulated with CBM and EFISCEN models with UNFCCC and FAOSTAT data consisting of net carbon
 485 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 CO₂ 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,
 490 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



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 CO₂ 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.

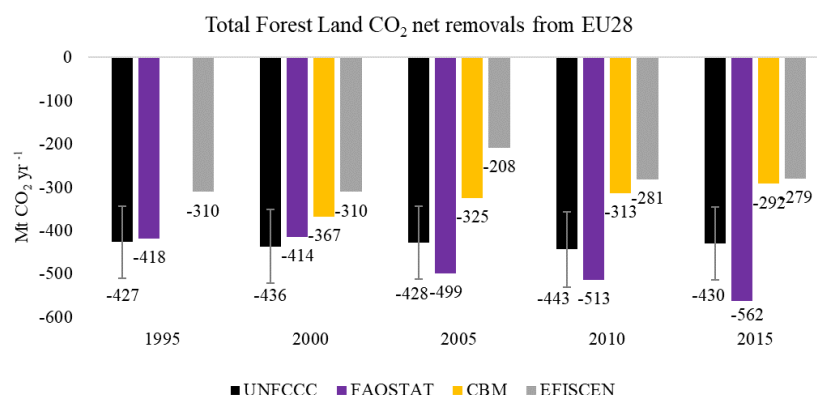


Figure 10: Total EU28 single year values of CO₂ net removals from FL as reported by UNFCCC, CBM, EFISCEN and FAOSTAT. Negative numbers denote net CO₂ uptake. EFISCEN data 1995-2000 is based on Karjalainen et al., 2003 estimates. CBM does not report data for 1995. The relative error on the UNFCCC value, 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 CO₂ 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 NGHGI specifically report emissions and removals, and are formally reviewed annually, while FAO-FRA reports are not primarily for reporting CO₂ emissions and removals, and are not formally reviewed (Grassi et al., 2017).



520 Cropland and Grassland soil Carbon

Cropland and Grassland (CL and GL) (in UNFCCC GHGI 2018, IPCC sector 4B and 4C, respectively) include CO₂ 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
 525 change. In FAOSTAT GHG emissions in the domain “Cropland” and “Grassland” are currently limited to the CO₂ 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
 530 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
 535 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
 540 all grassland from wild lands to recreational areas as well as agricultural and silvo-pastoral 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
 545 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).

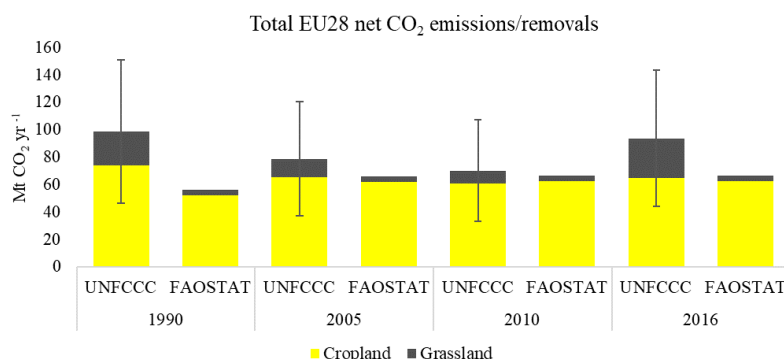


Figure 11: Total EU28 net CO₂ emissions/removals from FAOSTAT and UNFCCC 2018 country submission estimates of Cropland and Grassland for 1990, 2015, 2010 and 2016. The relative error on the UNFCCC value, computed with the 95 % confidence interval method, is 53 %. It represents the NGHGI 2018 uncertainty for the CL and GL data pool reported to UNFCCC.

From Figure 11 we see that in the EU28 croplands and grasslands are CO₂ sources to the atmosphere in the UNFCCC and FAOSTAT databases. Cropland CO₂ 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

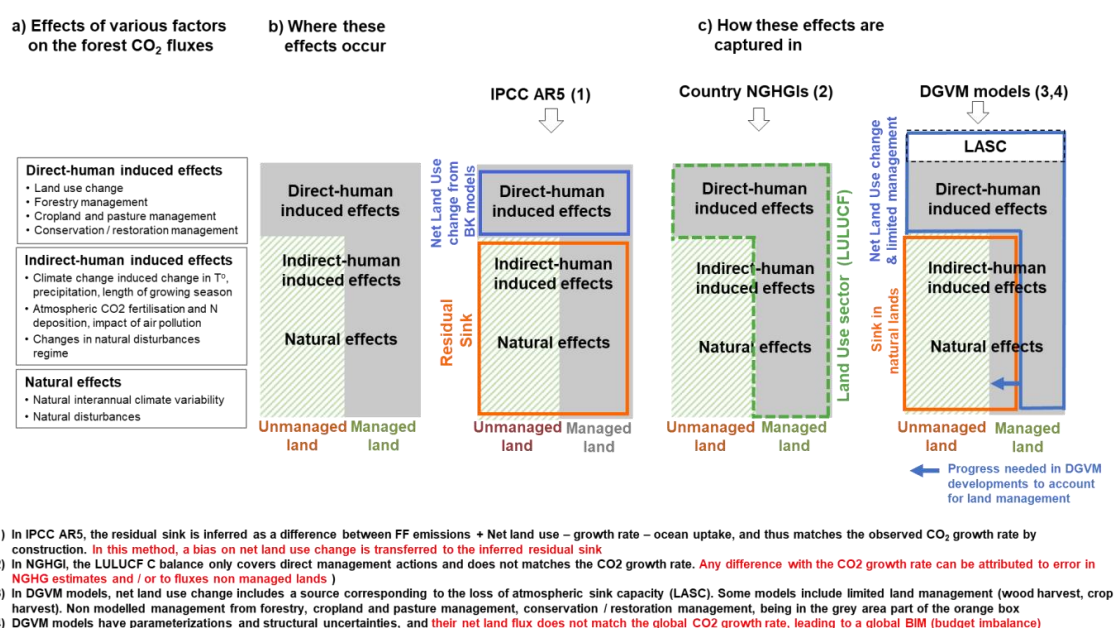
Land-related carbon emissions can also be estimated by global models such as DGVMs - TRENDY v6 ensemble and bookkeeping models (BLUE and H&N). In this section we compare these global model results with data from FAOSTAT and UNFCCC. There is significant uncertainty in both the underlying datasets of land 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,



that is, the sink that favorable environmental changes, in particular CO₂ 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.

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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).



585 **Figure 12:** Summary of the main conceptual differences in defining the “anthropogenic land CO₂ flux” between IPCC and countries’ GHG inventories (NGHGs). 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 GHGs 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, CO₂ 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*.

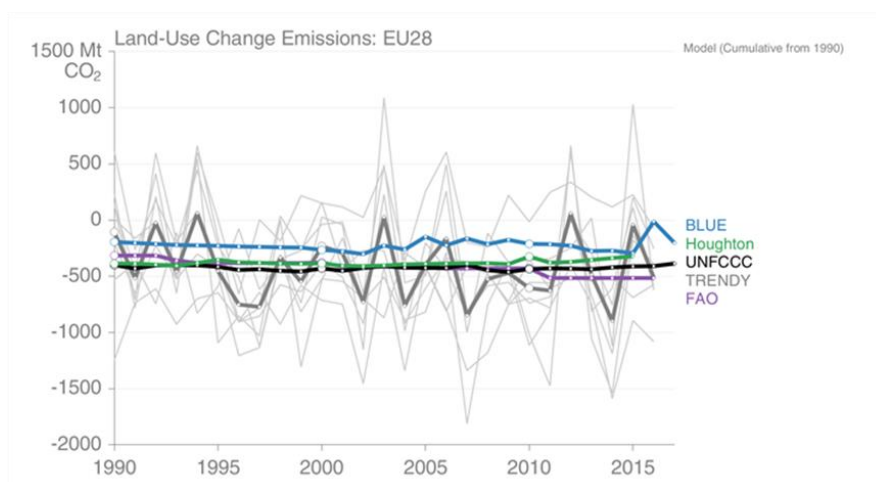
National Greenhouse Gas Inventories (NGHGI) use the notion of “managed land” as a proxy for direct “anthropogenic” emissions, hence in practice include most or all (depending on the specific method) indirect emissions into their anthropogenic estimates. In addition, the area considered “managed” by countries 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 CO₂ 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 (Hurt 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.



635 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.



640 *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.*

645 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.

655



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. CH₄ 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 N₂O emissions have very large uncertainties (>100 %) owing to the heterogeneity of sources and uncertainty in emission factors for the main N₂O 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 N₂O emissions must rely on the adoption of existing technologies. Currently available technology could reduce global N₂O 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 N₂O 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 CH₄ 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. CH₄ and N₂O 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



695 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 N₂O emissions from agricultural soils (3.D.2), while there are
 no countries using only high tiers in direct N₂O 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 N₂O
 700 emissions from manure management and direct and indirect emissions together with CH₄ 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).

705 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 N₂O 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).

710 4.2. Forestry and Other Land Uses

For the LULUCF sector, methods for the estimation of GHGs and CO₂ 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
 715 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-
 720 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).

725 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 CO₂ 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
 730 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



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 CO₂ yr⁻¹ in global anthropogenic net land-use emissions (Grassi et al., 2018a, IPCC 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 CO₂ 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 CO₂ 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.

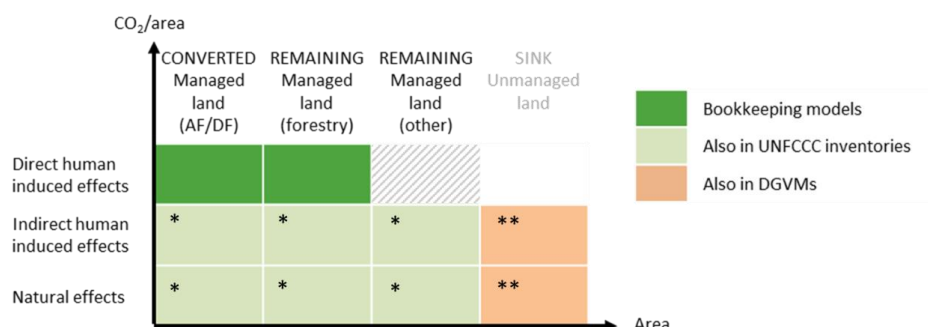


Figure 14: A conceptual extension of Figure 12 to disaggregate the managed land into three different components, showing how they map to components reported in the UNFCCC inventories. The converted land is equivalent to afforestation (AF) plus deforestation (DF). Remaining land is split into forestry 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/CO₂ 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 CH₄ and N₂O 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.



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 CH₄ from
 agriculture 10-20 % difference). We stress the need of looking as well on the LULUCF CO₂ 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 CO₂ 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 CO₂, CH₄ and N₂O 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 CH₄ and N₂O 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; Saunio 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).

820



825 6. Appendices

Appendix A

Methodology tables

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

<i>CH₄/N₂O emission calculation</i>	<i>AD/Tier</i>	<i>EFs/Tier</i>	<i>Uncertainty assessment method</i>
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.



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

<i>CO₂/NBP</i>	<i>AD/Tier</i>	<i>EFs/Tier</i>	<i>Uncertainty assessment method</i>
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).

<i>Gases</i>	<i>EU28</i>	<i>Year</i>	<i>Total EU28 Agriculture estimates for last available year kton CH₄, N₂O yr⁻¹</i>				
CH₄			<i>Enteric Fermentation</i>	<i>Manure management</i>	<i>Rice Cultivation</i>	<i>Agricultural Waste Burning</i>	<i>Total</i>



	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			<i>Manure management</i>	<i>Direct N₂O emissions</i>	<i>Grazing</i>	<i>Indirect N₂O emissions</i>	<i>Agricultural Waste Burning</i>	<i>Total</i>
	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

840

Appendix B

Data source description

UNFCCC

845 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
 850 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
 855 (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
 860 24 members of the Paris Agreement decided on the Modalities, Guidelines and Procedures of the reporting under the



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.

865 Under the convention Annex I parties are requested since 2015, following decision 24/CP.19¹, 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
 870 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
 875 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
 880 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:

- 885 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 CO₂ emissions were reported under Agriculture, from 2015 the CO₂ emissions from urea and lime application were reallocated from LULUCF to Agriculture.



For this study an analysis of the reported uncertainties under the NGHGI for CO₂, CH₄ and N₂O has been performed for 26 EU countries⁴. 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 CO₂, CH₄ and N₂O 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. N₂O 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 COP19⁵, 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>



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
 915 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
 920 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
 925 EDGAR FT2017 provide global, country-level and gridded annual emissions of CO₂, CH₄ and N₂O (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
 930 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 CO₂ Human Emissions (CHE). The agriculture component of EDGAR comprises the agricultural soils (crops that are not rice) (N₂O), application of urea and agricultural lime (N₂O), enteric fermentation (CH₄), rice cultivation (CH₄), manure management (CH₄, N₂O), fertilizer use (synthetic and manure) (N₂O), agricultural waste burning (in field)
 935 (CH₄, N₂O) 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 CH₄
 940 and N₂O 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 CO₂ emissions were reported under Agriculture, from 2015 the CO₂ emissions from urea and lime application were reallocated from LULUCF to Agriculture.



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 CH₄ and N₂O are fully correlated, thus the uncertainty of the sum is the sum of the

uncertainties;

- When dealing with CO₂, 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 CH₄ and N₂O. 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	20	30
		D		50
		CS		20
Manure management	MNM	I	20	30
		D		30



		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 ₂ O emission from managed soils	I D CS	20	70 (65 for pasture) 200 70
	Indirect N ₂ O managed soils	I D CS	50	70 200 70
	Indirect N ₂ O 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).



980 CAPRI

CAPRI is an economic, partial equilibrium model for the agricultural sector, focused on the EU (Britz and Witzke, 2014⁸; Weiss and Leip, 2012⁹). 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 985 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 CH₄ and N₂O 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 990 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, CO₂, CH₄ 995 and N₂O 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 1000 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 CO₂ and CO₂e (from CH₄ and N₂O), 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 1005 categories: cropland, forest land, and grassland, collectively called emissions/removals from the LULUCF sector. LULUCF emissions consist of CO₂ (carbon dioxide), CH₄ (methane) and N₂O (nitrous oxide) associated with land management activities. CO₂ 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. CH₄ and N₂O, and additional CO₂ emissions are estimated for fires and drainage of organic soils. The FAOSTAT emissions database is 1010 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 CO₂e from CH₄ and N₂O, net emissions/removals as Gg CO₂ and Gg CO₂e, 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>



1015

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



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://dgvn.ceh.ac.uk/index.html>. DGVM models are forced by historical agricultural land cover change, climate change and CO₂ 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 CO₂, nitrogen deposition and other environmental factors). Carbon



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 CH₄ 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 et al., 2012), LPJ-wsl (Hodson et al., 2011), LPX-Bern (Spahni et al., 2011), ORCHIDEE (Ringer 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 CO₂. 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.



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	CH ₄	237,955502	0,24758837	0,00
4 A	CH ₄	40,1929129	1,06066017	0,00
4 A	CO ₂	-30251,343	0,24758837	0,00
4 A	CO ₂	-5829,38043	1,06066017	0,00
4 A	N ₂ O	0,8914493	0,24758837	0,00
4 A	N ₂ O	0,15057789	1,06066017	0,00
4 B	CH ₄	2,05470896	1,06066017	0,00
4 B	CO ₂	1917,59719	1,06066017	0,00
4 B	CO ₂	541,959929	1,06066017	0,00
4 B	N ₂ O	0,76975268	1,06066017	0,00
4 B	N ₂ O	26,874189	1,06066017	0,00
Total emissions of all sectors		397935,125		

2. To calculate the contribution to variance for the sector 4A CO₂, 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, CO₂)
- (2) $((-30251,343 * 0,24758837)^2 + (-5829,38 * 1,06066017)^2) / (-36080,72)^2 = 0,0724584$ (intermediate step for calculating the Combined Uncertainty)
- (3) $\text{SQRT}(0,0724584) = 26,918 \%$ (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	CO ₂	-36080,7234	0,26918099	0,001



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.

1135 The results of the Uncertainty Analysis show a clear trend of the main uncertainties and gases across the analyzed 26 EU MS.

Appendix D

1140 Country specific emissions

Detailed agriculture CH₄ and N₂O 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_CH₄_N₂O_per_country” excel document.

1145 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
 1150 subject to future updates and it refers only to this version of the manuscript.

Acronyms and abbreviations

AD Activity data

1155 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

1160 CH₄ Methane

CO₂ Carbon dioxide

COP Conference of the Parties

CRF Common Reporting Format

DG CLIMA Directorate General CLIMA (European Commission)

1165 DGVMs (TRENDY) Dynamic global vegetation models



- EDGAR Emission Database for Global Atmospheric Research
- EEA European Environmental Agency
- EF Emission factor
- EFISCEN European Forest Information SCENario Model
- 1170 ESA CCI European Space Agency Climate Change Initiative
- ETS Emissions Trading System
- EU28 European Union
- EUROSTAT European Statistical Office
- FADN Farm Accountancy Data Network
- 1175 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
- 1180 GCP Global Carbon Project
- GHG Greenhouse Gases
- GMB Global Methane Budget
- H2020 Horizon 2020
- IEA International Energy Agency
- 1185 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
- 1190 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
- 1195 N₂O Nitrous oxide
- NBP Net Biome Productivity
- NBS National Bureau of Statistics of China



NDCs - Nationally Determined Contributions

NEP Net Ecosystem production

1200 NFI National forest inventory

NGHGI National Greenhouse Gas Inventory

NIRs National Inventory Reports

NPP Net Primary Production

NUTS2 Nomenclature of territorial units for statistics

1205 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

1210 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

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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 CH₄ and N₂O 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.

1225

Competing interests

The authors declare that they have no conflict of interest.

1230



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References

Alkama, R. & Cescatti, A.: Biophysical climate impacts of recent changes in global forest cover, *Science* 351, 600–604, 2016.

Arneth, A., Sitch, S., Pongratz, J., Stocker, B.D., Ciais, P., Poulter, B., Bayer, A.D., Bondeau, A., Calle, L., Chini, L.P., Gasser, T., Fader, M., Friedlingstein, P., Kato, E., Li, W., Lindeskog, M., Nabel, J.E.M.S., Pugh, T.A.M., Robertson, E., Viovy, N., Yue, C., Zaehle, S.: Historical carbon dioxide emissions caused by land-use changes are possibly larger than assumed, *Nature Geosci.* 10 (2), 79–84, 2017.

Bergamaschi, P., Houweling, S., Segers, a., Krol, M., Frankenberg, C., Scheepmaker, R. a., Dlugokencky, E., Wofsy, S. C., Kort, E. a., Sweeney, C., Schuck, T., Brenninkmeijer, C., Chen, H., Beck, V. and Gerbig, C.: Atmospheric CH₄ in the first decade of the 21st century: Inverse modeling analysis using SCIAMACHY satellite retrievals and NOAA surface measurements, *J. Geophys. Res. Atmos.*, 118(13), 7350–7369, doi:10.1002/jgrd.50480, 2013.

Bergamaschi, P., Corazza, M., Karstens, U., Athanassiadou, M., Thompson, R. L., Pison, I., Manning, A. J., Bousquet, P., Segers, A., Vermeulen, A. T., Janssens-Maenhout, G., Schmidt, M., Ramonet, M., Meinhardt, F., Aalto, T., Haszpra, L., Moncrieff, J., Popa, M. E., Lowry, D., Steinbacher, M., Jordan, A., O'Doherty, S., Piacentino, S., and Dlugokencky, E.: Top-down estimates of European CH₄ and N₂O emissions based on four different inverse models, *Atmos. Chem. Phys.*, 15, 715–736, https://doi.org/10.5194/acp-15-715-2015, 2015.

Berger, J., Günther, D., & Hain, B.: Das Übereinkommen von Paris - ein wichtiger Wegweiser für eine lebenswerte Zukunft und einen Politikwandel in Deutschland. *Zeitschrift für Umweltpolitik & Umweltrecht / Journal of Environment Law and Policy*, 39 (Sonderausgabe zur Pariser UN-Klimakonferenz), 4–12, 2016.

Bond, T. C., Streets, D. G., Yarber, K. F., Nelson, S. M., Woo, J.-H., and Klimont, Z.: A technology-based global inventory of black and organic carbon emissions from combustion, *J. Geophys. Res.*, 109, D14203, doi:10.1029/2003JD003697, 2004.

Bousquet, P., Ciais, P., Miller, J. B., Dlugokencky, E. J., Hauglustaine, D. A., Prigent, C., Van der Werf, G. R., Peylin, P., Brunke, E.-G., Carouge, C., Langenfelds, R. L., Lathière, J., Papa, F., Ramonet, M., Schmidt, M., Steele, L. P., Tyler, S. C., and White, J.: Contribution of anthropogenic and natural sources to atmospheric methane variability, *Nature*, 443, 439–443, https://doi.org/10.1038/nature05132, 2006.



- BP: BP Statistical Review of World Energy 2018, downloaded in 2019 from <https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2018-full-report.pdf>, 2018.
- 1275 Britz, W. and Witzke, P.: CAPRI model documentation 2014, available for download at: https://www.capri-model.org/docs/capri_documentation.pdf, 2014.
- Carlson, D. and Oda, T.: Editorial: Data publication – ESSD goals, practices and recommendations, *Earth Syst. Sci. Data*, 10, 2275–2278, <https://doi.org/10.5194/essd-10-2275-2018>, 2018.
- 1280 Clark, D. B., Mercado, L. M., Sitch, S., Jones, C. D., Gedney, N., Best, M. J., Pryor, M., Rooney, G. G., Essery, R. L. H., Blyth, E., Boucher, O., Harding, R. J., Huntingford, C., and Cox, P. M.: The Joint UK Land Environment Simulator (JULES), model description – Part 2: Carbon fluxes and vegetation dynamics, *Geosci. Model Dev.*, 4, 701–722, <https://doi.org/10.5194/gmd-4-701-2011>, 2011.
- Crippa, M., Janssens-Maenhout, G., Guizzardi, D., Van Dingenen, R., Dentener, F.: Contribution and uncertainty of sectoral and regional emissions to regional and global PM_{2.5} health impacts, *Atmos. Chem. Phys.*, 19 pp. 5165–5186, <https://doi.org/10.5194/acp-19-5165-2019>, 2019.
- 1285 European Commission 28/11/2018 - COM (2018) 773 - A Clean Planet for all - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy, 2018 <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52018DC0773&from=EN>, 2018.
- EEA 2018, Annual European Union greenhouse gas inventory 1990–2016 and inventory report 2018: <https://www.eea.europa.eu/publications/european-union-greenhouse-gas-inventory-2018>, 2018.
- 1290 EDGAR report http://edgar.jrc.ec.europa.eu/news_docs/jrc-2016-trends-in-global-co2-emissions-2016-report-103425.pdf, 2016.
- Effort Sharing Decision (ESD) No 406/2009/EC: https://data.europa.eu/euodp/en/data/dataset/data_esd_2009.
- 1295 Eggleston, H. S., Buendia, L., Miwa, K., Ngara, T. and Tanabe, K.: IPCC Guidelines for National Greenhouse Gas Inventories. Prepared by the National Greenhouse Gas Inventories Programme, vol. 4. IGES, Japan, 2006.
- den Elzen, M., Roelfsema, M., van Soest, H. (PBL Netherlands Environmental Assessment Agency); Forsell, N., Turkovska, O. (IIASA): Greenhouse gas mitigation scenarios for major emitting countries – Analysis of current climate policies and mitigation pledges (Update November 2016) NewClimate Institute <https://core.ac.uk/download/pdf/79433352.pdf>, 2016.
- 1300 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)
- EUROSTAT: https://ec.europa.eu/eurostat/statistics-explained/index.php/Land_cover_statistics
- 1305 FAO: The State of Food and Agriculture: Social protection and agriculture: breaking the cycle of rural poverty, 2015, Rome, Italy: <http://www.fao.org/3/a-i4910e.pdf>, 2015.
- FAOSTAT, data downloaded from <http://www.fao.org/faostat/en/#data>, 2018.
- Federici, S., Tubiello, F. N., Salvatore, M., Jacobs, H., and Schmidhuber, J.: New estimates of CO₂ forest emissions and removals: 1990–2015, *Forest Ecol. Manage.*, 352, 89–98, 2015.
- 1310 Frey, C.: Evaluation of an approximate analytical procedure for calculating uncertainty in the Greenhouse gas version of the multi scale motor vehicle and equipment emission system (order 3A-0419-NATX), 2003.
- Gasser, T. and Ciais, P.: A theoretical framework for the net land to-atmosphere CO₂ flux and its implications in the definition of “emissions from land-use change”, *Earth Syst. Dynam.*, 4, 171–186, doi:10.5194/esd-4-171-2013, 2013.



- Global Carbon Project, <http://www.globalcarbonproject.org/methanebudget/13/hl-compact.htm>
- 1315 Global Forest Resource Assessments (FRA) (<http://www.FAOSTAT.org/forestry/fra/en/>).
<https://unfccc.int/process/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories/submissions-of-annual-greenhouse-gas-inventories-for-2017/submissions-of-annual-ghg-inventories-2014>, 2014.
- 1320 Gomez-Sanabria, A., L. Höglund-Isaksson, P. Rafaj, W. Schöpp: Carbon in global waste and wastewater flows - its potential as energy source under alternative future waste management regimes, *Advances in Geosciences* 45:105–113, <https://doi.org/10.5194/adgeo-45-105-2018>, 2018.
- Grassi, G., House, J., Dentener, F., Federici, S., den Elzen & Penman, J.: The key role of forests in meeting climate targets requires science for credible mitigation, *Nature Climate Change* 7, 220–226, 2017.
- 1325 Grassi, G., House, J., Kurz, W. A., Cescatti, A., Houghton, R. A., Peters, G. P., Sanz, M. J., Viñas, R. A., Alkama, R., Arneth, A., Bondeau, A., Dentener, F., Fader, M., Federici, S., Friedlingstein, P., Jain, A. K., Kato, E., Koven, C. D., Lee, D., Nabel, J. E. M. S., Nassikas, A. A., Perugini, L., Rossi, S., Sitch, S., Viovy, N., Wiltshire, A. and Zaehle, S.: Reconciling global-model estimates and country reporting of anthropogenic forest CO₂ sinks, *Nat. Clim. Chang.*, 8(10), 914–920, doi:10.1038/s41558-018-0283-x, 2018a.
- 1330 Grassi, G., Pilli, R., House, J., Federici, S., & Kurz, W. A.: Science-based approach for credible accounting of mitigation in managed forests, *Carbon balance and management*, 13(1), 8, 2018b.
- Grassi, G., Cescatti, A., Matthews, R., Duveiller, G., Amia, A., Federici, S., House, J., de Noblet-Ducoudré, N., Pilli, R. & Vizzarri, M.: On the realistic contribution of European forests to reach climate objectives, *Carbon Balance and Management* volume 14, Article number: 8, 2019.
- 1335 Hansis, E., Davis, S. J. and Pongratz, J.: Relevance of methodological choices for accounting of land use change carbon fluxes, *Global Biogeochem. Cycles*, 29(8), 1230–1246, doi:10.1002/2014GB004997, 2015.
- Hayman, G. D., O'Connor, F. M., Dalvi, M., Clark, D. B., Gedney, N., Huntingford, C., Prigent, C., Buchwitz, M., Schneising, O., Burrows, J. P., Wilson, C., Richards, N., and Chipperfield, M.: Comparison of the HadGEM2 climate-chemistry model against in situ and SCIAMACHY atmospheric methane data, *Atmos. Chem. Phys.*, 14, 13257–13280, <https://doi.org/10.5194/acp-14-13257-2014>, 2014.
- 1340 Hirsch, A. I., A. M. Michalak, L. M. Bruhwiler, W. Peters, E. J. Dlugokencky, and P. P. Tans, Inverse modeling estimates of the global nitrous oxide surface flux from 1998–2001, *Global Biogeochem. Cycles*, 20, GB1008, doi:10.1029/2004GB002443, doi:doi:10.1029/2004GB002443, 2006.
- Hodson, E. L., B. Poulter, N. E. Zimmermann, C. Prigent, and J. O. Kaplan (2011), The El Niño–Southern Oscillation and wetland methane interannual variability: Wetland methane emissions and ENSO, *Geophys. Res. Lett.*, 38, L08810, doi:10.1029/2011GL046861.
- 1345 Hopcroft, P. O., Valdes, P. J., and Beerling, D. J.: Simulating idealized Dansgaard-Oeschger events and their potential impacts on the global methane cycle, *Quat. Sci. Rev.*, 30, 3258–3268, 2011.
- 1350 Houghton, R.A., Hobbie, J.E., Melillo, J.M., Moore, B., Peterson, B.J., Shaver, G.R., and Woodwell, G.M.: Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: A net release of CO₂ to the atmosphere, *Ecological Monographs*, 53:235–262, 1983.
- Houghton, R.A.: Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850–2000, *Tellus* 55B(2):378–390, 2003.
- 1355 Houghton, R. A., House, J. I., Pongratz, J., van der Werf, G. R., DeFries, R. S., Hansen, M. C., Le Quéré, C., and Ramankutty, N.: Carbon emissions from land use and land-cover change, *Biogeosciences*, 9, 5125–5142, <https://doi.org/10.5194/bg-9-5125-2012>, 2012.



- 1360 Houghton, R. A. and Nassikas, A. A.: Global and regional fluxes of carbon from land use and land cover change 1850–2015, *Global Biogeochem. Cycles*, 31(3), 456–472, doi:10.1002/2016GB005546, 2017.
- Höglund-Isaksson, L.: Global anthropogenic methane emissions 2005–2030: Technical mitigation potentials and costs, *Atmos. Chem. Phys.*, 12(19), 9079–9096, doi:10.5194/acp-12-9079-2012, 2012.
- Höglund-Isaksson, L.: Bottom-up simulations of methane and ethane emissions from global oil and gas systems, *Environmental Research Letters* 12(2), 2017.
- 1365 Huang, J., A. Golombek, R. Prinn, R. Weiss, P. Fraser, P. Simmonds, E. J. Dlugokencky, B. Hall, J. Elkins, P. Steele, R. Langenfelds, P. Krummel, G. Dutton, and L. Porter, Estimation of regional emissions of nitrous oxide from 1997 to 2005 using multinetwerk measurements, a chemical transport model, and an inverse method, *J. Geophys. Res. Atmos.*, 113(D17), doi:10.1029/2007jd009381, 2008.
- 1370 Hurtt, G. C., Chini, L. P., Frolking, S., Betts, R. A., Feddema, J., Fischer, G., Fisk, J. P., Hibbard, K., Houghton, R. A., Janetos, A., Jones, C. D., Kindermann, G., Kinoshita, T., Klein Goldewijk, K., Riahi, K., Shevliakova, E., Smith, S., Stehfest, E., Thomson, A., Thornton, P., van Vuuren, D. P., and Wang, Y. P.: Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands, *Climatic Change*, 109, 117–161, <https://doi.org/10.1007/s10584-011-0153-2>, 2011.
- 1375 Hurtt, G., Chini, L., Sahajpa, R., and Frolking, S.: Harmonization of global land-use change and management for the period 850–2100, *Geosci. Model Dev. Discuss.*, in preparation, 2018.
- IEA World Energy Balances 2017, OECD Publishing, Paris, https://doi.org/10.1787/world_energy_bal-2017-en, 2017.
- 1380 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme. IGES, Japan, <https://www.ipcc-nggip.iges.or.jp/public/2006gl/>, 2006.
- IPCC 2006, Chapter 3, Uncertainties: https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/1_Volume1/V1_3_Ch3_Uncertainties.pdf
- IPCC 2006, Chapter 3, equation 3.4: https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/1_Volume1/V1_3_Ch3_Uncertainties.pdf
- 1385 IPCC 2006, Chapter 3, equation 3.7: https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/1_Volume1/V1_3_Ch3_Uncertainties.pdf
- 1390 IPCC 2007: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., Miller, H. L.: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge univ. Press, Cambridge, UK, 2007.
- IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Cambridge University Press, United Kingdom and New York, NY, USA, 2011.
- 1395 IPCC Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp, 2014.
- 1400 IPCC Summary for Policymakers. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. World Meteorological Organization, Geneva, Switzerland, 32 pp, 2018.



- 1405 IPCC SRCCL 2019 Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (SRCCL). IPCC (Report). August <https://www.ipcc.ch/report/srccl/>, 2019.
- IPCC 2019 Refinement <https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/>, 2019.
- 1410 Ito, A. and Inatomi, M.: Use of a process-based model for assessing the methane budgets of global terrestrial ecosystems and evaluation of uncertainty, *Biogeosciences*, 9, 759–773, <https://doi.org/10.5194/bg-9-759-2012>, 2012.
- Jain, A. K., Meiyappan, P., Song, Y., and House, J. I.: CO₂ Emissions from Land-Use Change Affected More by Nitrogen Cycle, than by the Choice of Land Cover Data, *Glob. Change Biol.*, 9, 2893–2906, 2013.
- Houghton, R. A. and Nassikas, A. A.: Global and regional fluxes of carbon from land use and land cover change 1850–2015, *Global Biogeochem. Cy.*, 31, 456–472, <https://doi.org/10.1002/2016GB005546>, 2017.
- 1415 Janssens-Maenhout, G., Crippa, M., Guizzardi, D., Muntean, M., Schaaf, E., Dentener, F., Bergamaschi, P., Pagliari, V., Olivier, J. G. J., Peters, J. A. H. W., van Aardenne, J. A., Monni, S., Doering, U., Petrescu, A. M. R., Solazzo, E., and Oreggioni, G. D.: EDGAR v4.3.2 Global Atlas of the three major greenhouse gas emissions for the period 1970–2012, *Earth Syst. Sci. Data*, 11, 959–1002, <https://doi.org/10.5194/essd-11-959-2019>, 2019.
- 1420 Jonsson, R., Blujdea, V. N., Fiorese, G., Pilli, R., Rinaldi, F., Baranzelli, C., & Camia, A.: Outlook of the European forest-based sector: forest growth, harvest demand, wood-product markets, and forest carbon dynamics implications, *iForest-Biogeosciences and Forestry*, 11(2), 315, <https://doi.org/10.3832/ifer2636-011>, 2018.
- 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>, 2018.
- 1425 Karjalainen, T., Pussinen, A., Liski, J., Nabuurs, G.-N., Eggers, T., Lapveteläinen, T., and Kaipainen, T.: Scenario analysis of the impacts of forest management and climate change on the European forest sector carbon budget, *Forest Policy Econ.*, 5, 141–155, doi:10.1016/S1389-9341(03)00021-2, 2003.
- Karstensen, J., Peters, G. P., & Andrew, R. M.: Trends of the EU's territorial and consumption-based emissions from 1990 to 2016. *Climatic Change*, 151, 131–142. doi: 10.1007/s10584-018-2296-x, 2018.
- 1430 Kauppi, P. E., Mielikäinen, K., and Kuusela, K.: Biomass and carbon budget of European forests, 1971 to 1990, *Science*, 70–74, doi:10.1126/science.256.5053.70, 1992.
- Klein Goldewijk, K., Beusen, A., Doelman, J., and Stehfest, E.: An- thropogenic land use estimates for the Holocene – HYDE 3.2, *Earth Syst. Sci. Data*, 9, 927–953, <https://doi.org/10.5194/essd-9-927-2017>, 2017a.
- Klein Goldewijk, K., Dekker, S. C., and van Zanden, J. L.: Per- capita estimations of long-term historical land use and the con- sequences for global change research, *J. Land Use Sci.*, 12, 313–337, 2017b.
- 1435 Kleinen, T., Brovkin, V., and Schuldt, R. J.: A dynamic model of wetland extent and peat accumulation: results for the Holocene, *Biogeosciences*, 9, 235–248, <https://doi.org/10.5194/bg-9-235-2012>, 2012.
- Koehl, M., Hildebrandt, R., Olschofsky, K., Koehler, R., Roetzer, T., Mette, T., Pretzsch, H., Koethke, M., Dieter, M., Abiy, M., Makeschin, F., and Kenter, B.: Combating the effects of climatic change on forests by mitigation strategies, *Carbon Balance and Management*, 5, 8, doi:10.1186/1750-0680-5-8, 2010.
- 1440 Krinner, G., Viovy, N., de Noblet, N., Ogée, J., Friedlingstein, P., Ciais, P., Sitch, S., Polcher, J., and Prentice, I. C.: A dynamic global vegetation model for studies of the coupled atmosphere-biosphere system, *Global Biogeochem. Cy.*, 19, 1–33, <https://doi.org/10.1029/2003GB002199>, 2005.
- Kurz, W.A., Dymond, C.C., White, T.M., Stinson, G., Shaw, C.H., Rampley, G.J., Smyth, C., Simpson, B.N., Neilson, E.T., Trofymow, J.A., Metsaranta, J., Apps, M.J.: CBM-CFS3: a model of carbon-dy-namics in forestry and land-use



- 1445 change implementing IPCC standards. *Ecological Modelling*, 220, 480–504, doi: 10.1016/j.ecolmodel.2008.10.018, 2009.
- Kurz, W.A.: Large inter-annual variations in carbon emissions and removals, Pages 41–48 Invited Background Paper in H.S. Eggleston, N. Srivastava, K. Tanabe, and J. Baasansuren, editors. IPCC 2010, Revisiting the Use of Managed Land as a Proxy for Estimating National Anthropogenic Emissions and Removals, May 5–7, 2009, INPE, São José dos Campos, Brazil. IGES, Hayama, Japan, 2010.
- 1450 Le Quéré, C., Raupach, M. R., Canadell, J. G., Marland, G., Bopp, L., Ciais, P., Conway, T. J., Doney, S. C., Feely, R. A., Foster, P., Friedlingstein, P., Gurney, K., Houghton, R. A., House, J. I., Huntingford, C., Levy, P. E., Lomas, M. R., Majkut, J., Metzl, N., Ometto, J. P., Peters, G. P., Prentice, I. C., Randerson, J. T., Running, S. W., Sarmiento, J. L., Schuster, U., Sitch, S., Takahashi, T., Viovy, N., van der Werf, G. R., and Woodward, F. I.: Trends in the sources and sinks of carbon dioxide, *Nat. Geosci.*, 2, 831–836, 2009.
- 1455 Le Quéré, C., Andrew, R. M., Friedlingstein, P., Sitch, S., Pongratz, J., Manning, A. C., Korsbakken, J. I., Peters, G. P., Canadell, J. G., Jackson, R. B., Boden, T. A., Tans, P. P., Andrews, O. D., Arora, V. K., Bakker, D. C. E., Barbero, L., Becker, M., Betts, R. A., Bopp, L., Chevallier, F., Chini, L. P., Ciais, P., Cosca, C. E., Cross, J., Currie, K., Gasser, T., Harris, I., Hauck, J., Haverd, V., Houghton, R. A., Hunt, C. W., Hurtt, G., Ilyina, T., Jain, A. K., Kato, E., Kautz, M., Keeling, R. F., Klein Goldewijk, K., Körtzinger, A., Landschützer, P., Lefèvre, N., Lenton, A., Lienert, S., Lima, I., Lombardozzi, D., Metzl, N., Millero, F., Monteiro, P. M. S., Munro, D. R., Nabel, J. E. M. S., Nakaoka, S., Nojiri, Y., Padin, X. A., Peregon, A., Pfeil, B., Pierrot, D., Poulter, B., Rehder, G., Reimer, J., Rödenbeck, C., Schwinger, J., Séférian, R., Skjelvan, I., Stocker, B. D., Tian, H., Tilbrook, B., Tubiello, F. N., van der Laan-Luijkx, I. T., van der Werf, G. R., van Heuven, S., Viovy, N., Vuichard, N., Walker, A. P., Watson, A. J., Wiltshire, A. J., Zaehle, S. and Zhu, D.: Global Carbon Budget 2017, *Earth Syst. Sci. Data*, 10(1), 405–448, doi:10.5194/essd-10-405-2018, 2018.
- 1460 Lienert, S. and Joos, F.: A Bayesian ensemble data assimilation to constrain model parameters and land-use carbon emissions, *Biogeosciences*, 15, 2909–2930, https://doi.org/10.5194/bg-152909-2018, 2018.
- Lindner, M., Fitzgerald, J. B., Zimmermann, N. E., Reyer, C., Delzon, S., van der Maaten, E., Schelhaas, M.-J., Lasch, P., Eggers, J., van der Maaten-Theunissen, M., Suckow, F., Psomas, A., Poulter, B., and Hanewinkel, M.: Climate change and European forests: What do we know, what are the uncertainties, and what are the implications for forest management? *J. Environ. Manage.*, 146, 69–83, doi:10.1016/j.jenvman.2014.07.030, 2015.
- 1470 Liski, J., Karjalainen, T., Pussinen, A., Nabuurs, G.-J., and Kauppi, P.: Trees as carbon sinks and sources in the European Union, *Environ. Sci. Policy*, 3, 91–97, doi:10.1016/S1462-9011(00)00020-4, 2000.
- Luyssaert, S. M., et al.: Land management and land-cover change have impacts of similar magnitude on surface temperature. *Nature Climate Change* 4:389–393, 2014.
- 1475 Luyssaert, S., Marie, G., Valade, A., Chen, Y. Y., Njakou Djomo, S., Ryder, J., Otto, J., Naudts, K., Lansø, A. S., Ghattas, J. and McGrath, M. J.: Trade-offs in using European forests to meet climate objectives, *Nature*, 562(7726), 259–262, doi:10.1038/s41586-018-0577-1, 2018.
- 1480 Mikaloff Fletcher, S. E., Tans, P. P., Bruhwiler, L. M., Miller, J. B., and Heimann, M.: CH₄ sources estimated from atmospheric observations of CH₄ and its ¹³C/¹²C isotopic ratios: 1. Inverse modelling of source processes, *Global Biogeochem. Cy.*, 18, GB4004, https://doi.org/10.1029/2004GB002223, 2004a.
- Mikaloff Fletcher, S. E., Tans, P. P., Bruhwiler, L. M., Miller, J. B., and Heimann, M.: CH₄ sources estimated from atmospheric observations of CH₄ and its ¹³C/¹²C isotopic ratios: 2. Inverse modelling of CH₄ fluxes from geographical regions, *Global Biogeochem. Cy.*, 18, GB4005, https://doi.org/10.1029/2004GB002224, 2004b.
- 1485 Nabuurs, G. J., Delacote, P., Ellison, D., Hanewinkel, M., Hetemäki, L., Lindner, M. and Ollikainen, M.: By 2050 the mitigation effects of EU forests could nearly double through climate smart forestry, *Forests*, 8(12), doi:10.3390/f8120484, 2017.
- Nabuurs, G. J., Arets, E. J. M. M. and Schelhaas, M. J.: Understanding the implications of the EU-LULUCF regulation for the wood supply from EU forests to the EU 07 Agricultural and Veterinary Sciences 0705 Forestry Sciences



- 1490 Georgii Alexandrov, Carbon Balance Manag., 13(1), doi:10.1186/s13021-018-0107-3, 2018.
 Naudts, K., Chen, Y., McGrath, M.J., Ryder, J., Valade, A., Otto, J., Luyssaert, S.: Europe's forest management did not mitigate climate warming, Science, 351, pp. 597-600, [10.1126/science.aad7270](https://doi.org/10.1126/science.aad7270), 2016.
 NGHGI (<http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html>)
- 1495 Oenema, O. et al.: Reducing N₂O emissions from agricultural sources Drawing Down N₂O to Protect Climate and the Ozone Layer. A UNEP Synthesis Report ed J Alcamo, S A Leonard, A R Ravishankara and M A Sutton (Nairobi: United Nations Environment Programme) ch 4 pp 17–25, 2013.
 Olivier, J.G.J., Berdowski, J.J.M., Peters, J.A.H.W., Bakker, J., Visschedijk, A.J.H. and Bloos, J.P.J.: Applications of EDGAR. Including a description of EDGAR 3.2: reference database with trend data for 1970–1995. RIVM, Bilthoven RIVM report 773301001/NRP report 410200051, Downloaded from <http://www.rivm.nl/bibliotheek/rapporten/410200051.html>, 2002.
 Olivier, J.G.J., Janssens-Maenhout, G., Muntean, M. and Peters, J.A.H.W.: Trends in global CO₂ emissions; 2016 Report, The Hague: PBL Netherlands Environmental Assessment Agency; Ispra: European Commission, Joint Research Centre, 2016.
- 1505 Olivier, J.G.J., Schure, K.M and Peters, J.A.H.W.: Trends in global CO₂ and total greenhouse gas emissions: 2017 report. PBL Netherlands Environmental Assessment Agency, The Hague., https://www.pbl.nl/sites/default/files/downloads/pbl-2017-trends-in-global-co2-and-total-greenhouse-gas-emissions-2017-report_2674_0.pdf, 2017.
- 1510 Olivier, J.G.J. and Peters, J.A.H.W.: Trends in global CO₂ and total greenhouse gas emissions: 2018 report. PBL Netherlands Environmental Assessment Agency, The Hague., https://www.pbl.nl/sites/default/files/cms/publicaties/pbl-2018-trends-in-global-co2-and-total-greenhouse-gas-emissions-2018-report_3125.pdf, 2018.
- 1515 Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J.G., Ciais, P., Jackson, R.B., Pacala, S.W., McGuire, A.D., Piao, S., Rautiainen, A., Sitch, S., Hayes, D.: A Large and Persistent Carbon Sink in the World's Forests, Science 333 (6045), 988-993, 2011.
 Peters, G. P., Marland, G., Hertwich, E. G., Saikku, L., Rautiainen, A., and Kauppi, P. E.: Trade, Transport, and Sinks Extend the Carbon Dioxide Responsibility of Countries, Climatic Change, 97, 379–388, 2009.
 Petrescu, A. M. R., Lohila, A., Tuovinen, J.-P., Baldocchi, D. D., Desai, A. R., Roulet, N. T., Vesala, T., Dolman, A. J., Oechel, W. C., Marcolla, B., Friborg, T., Rinne, J., Matthes, J. H., Merbold, L., Meijide, A., Kiely, G., Sottocornola, M., Sachs, T., Zona, D., Varlagin, A., Lai, D. Y. F., Veenendaal, E., Parmentier, F.-J. W., Skiba, U., Lund, M., Hensen, A., van Huissteden, J., Flanagan, L. B., Shurpali, N. J., Grünwald, T., Humphreys, E. R., Jackowicz-Korczyński, M., Aurela, M. A., Laurila, T., Grüning, C., Corradi, C. A. R., Pongratz, J., Reick, C. H., Houghton, R. A. and House, J. I.: Terminology as a key uncertainty in net land use and land cover change carbon flux estimates, Earth Syst. Dyn., 5(1), 177–195, doi:10.5194/esd-5-177-2014, 2014.
- 1525 Petrescu, A. M. R., Dolman, A. J., Peters, G. P., Janssens-Maenhout, G., Ciais, P., Tubiello, F. N., Grassi, G., Nabuurs, G.-J., Leip, A., Carmona-Garcia, G., Winiwarter, W., Höglund-Isaksson, L., Günther, D., Solazzo, E., Kiesow, A., Bastos, A., Pongratz, J., Conchedda, G., Pilli, R., Nabel, J., Andrew, R. M., and Schelhaas, M.-J.: European anthropogenic AFOLU emissions and their uncertainties: a review and benchmark data, version 1, Zenodo, <http://doi.org/doi:10.5281/zenodo.3460311>, 2019.
- 1530 Petz, K., Schulp, C. J.E., H. van der Zanden, E., Veerkamp, C., Schelhaas, M.-J., Nabuurs, G.-J., Hengeveld, G.: Indicators and modelling of land use, land management and ecosystem services. Methodological documentation Nature Outlook. PBL Netherlands Environmental Assessment Agency. PBL publication number: 2386, 2016.
 Pielke Sr. R. A., G. Marland, R. A. Betts, T. N. Chase, J. L. Eastman, J. O. Niles, D. D. Niyogi, S. W. Running: The influence of land-use change and landscape dynamics on the climate system: Relevance to climate-change policy



- 1535 beyond the radiative effect of greenhouse gases. *Philos. Trans. A Math. Phys. Eng. Sci.* 360, 1705–1719. doi:10.1098/rsta.2002.1027 pmid:12460493, 2002.
- Pielke R. A., Pitman A., Niyogi D., Mahmood R., McAlpine C., Hossain F., Goldewijk K. K., Nair U., Betts R., Fall S., Reichstein M., Kabat P., de Noblet N.: Land use/land cover changes and climate: Modeling analysis and observational evidence, *WIREs Clim. Change* 2, 828, 2011.
- 1540 Pilli, R., Grassi, G., Kurz, W.A., Moris, J.V., Viñas, R.A.: Modelling forest carbon stock changes as affected by harvest and natural disturbances. II. EU-level analysis including land-use changes, *Carbon Balance and Management*, 11(20), doi: 10.1186/s13021-016-0059-4, 2016b.
- 1545 Pilli, R., Grassi, G., Kurz, W. A., Fiorese, G. and Cescatti, A.: The European forest sector: Past and future carbon budget and fluxes under different management scenarios, *Biogeosciences*, 14(9), 2387–2405, doi:10.5194/bg-14-2387-2017, 2017.
- Pongratz, J., Reick, C. H., Raddatz, T., and Claussen, M.: Effects of anthropogenic land cover change on the carbon cycle of the last millennium, *Global Biogeochem. Cy.*, 23, GB4001, doi:10.1029/2009GB003488, 2009.
- 1550 Pongratz, J., Reick, C.H., Houghton, R.A., House, J.I.: Terminology as a key uncertainty in net land use and land cover change carbon flux estimates, *Earth Syst. Dynam.*, 5 (1), 177–195, 2014.
- Poulter, B., Bousquet, P., Canadell, J. G., Ciais, P., Peregon, A., Saunio, M., Arora, V. K., Beerling, D. J., Brovkin, V., Jones, C. D., Joos, F., Gedney, N., Ito, A., Kleinen, T., Koven, C. D., McDonald, K., Melton, J. R., Peng, C., Peng, S., Prigent, C., Schroeder, R., Riley, W. J., Saito, M., Spahni, R., Tian, H., Taylor, L., Viovy, N., Wilton, D., Wiltshire, A., Xu, X., Zhang, B., Zhang, Z. and Zhu, Q.: Global wetland contribution to 2000–2012 atmospheric methane growth rate dynamics, *Environ. Res. Lett.*, 12(9), doi:10.1088/1748-9326/aa8391, 2017.
- 1555 Reick, C. H., Raddatz, T., Brovkin, V. and Gayler, V.: Representation of natural and anthropogenic land cover change in MPI-ESM, *J. Adv. Model. Earth Syst.*, 5, 459–482, doi:https://doi.org/10.1002/jame.20022, 2013.
- 1560 Regulation (EU) No 525/2013 of the European Parliament and of the Council of 21 May 2013 on a mechanism for monitoring and reporting greenhouse gas emissions and for reporting other information at national and Union level relevant to climate change and repealing Decision No 280/2004/EC: <https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1417431825480&uri=CELEX:32013R0525>, 2013.
- 1565 Riley, W. J., Subin, Z. M., Lawrence, D. M., Swenson, S. C., Torn, M. S., Meng, L., Mahowald, N. M., and Hess, P.: Barriers to predicting changes in global terrestrial methane fluxes: analyses using CLM4Me, a methane biogeochemistry model integrated in CESM, *Biogeosciences*, 8, 1925–1953, <https://doi.org/10.5194/bg-8-1925-2011>, 2011.
- 1570 Ringeval, B., de Noblet-Ducoudré, N., Ciais, P., Bousquet, P., Prigent, C., Papa, F. and Rossow, W. B.: An attempt to quantify the impact of changes in wetland extent on methane emissions on the seasonal and interannual time scales, *Global Biogeochem. Cycles*, 24, GB2003, doi:10.1029/2008GB003354, 2010.
- Rypdal, K., & Winiwarter, W.: Uncertainties in greenhouse gas emission inventories — evaluation, comparability and implications, *Environmental Science & Policy*, 4(2), 107–116, doi:https://doi.org/10.1016/S1462-9011(00)00113-1, 2001.
- 1575 Saikawa, E., R. G. Prinn, E. Dlugokencky, K. Ishijima, G. S. Dutton, B. D. Hall, R. Langenfelds, Y. Tohjima, T. Machida, M. Manizza, M. Rigby, S. O'Doherty, P. K. Patra, C. M. Harth, R. F. Weiss, P. B. Krummel, M. van der Schoot, P. J. Fraser, L. P. Steele, S. Aoki, T. Nakazawa, and J. W. Elkins, Global and regional emissions estimates for N₂O, *Atmos. Chem. Phys.*, 14(9), 4617–4641, doi:10.5194/acp-14-4617-2014, 2014.
- 1580 Sallnäs, O. : A matrix model of the Swedish forest. *Studia Forestalia Suecica* 183, 23, 1990.
- Saunio, M., Bousquet, P., Poulter, B., Peregon, A., Ciais, P., Canadell, J. G., Dlugokencky, E. J., Etiope, G.,



- 1585 Bastviken, D., Houweling, S., Janssens-Maenhout, G., Tubiello, F. N., Castaldi, S., Jackson, R. B., Alexe, M., Arora, V. K., Beerling, D. J., Bergamaschi, P., Blake, D. R., Brailsford, G., Brovkin, V., Bruhwiler, L., Crevoisier, C., Crill, P., Covey, K., Curry, C., Frankenberg, C., Gedney, N., Höglund-Isaksson, L., Ishizawa, M., Ito, A., Joos, F., Kim, H. S., Kleinen, T., Krummel, P., Lamarque, J. F., Langenfelds, R., Locatelli, R., Machida, T., Maksyutov, S., McDonald, K. C., Marshall, J., Melton, J. R., Morino, I., Naik, V., O'Doherty, S., Parmentier, F. J. W., Patra, P. K., Peng, C., Peng, S., Peters, G. P., Pison, I., Prigent, C., Prinn, R., Ramonet, M., Riley, W. J., Saito, M., Santini, M., Schroeder, R., Simpson, I. J., Spahni, R., Steele, P., Takizawa, A., Thornton, B. F., Tian, H., Tohjima, Y., Viovy, N., Voulgarakis, A., Van Weele, M., Van Der Werf, G. R., Weiss, R., Wiedinmyer, C., Wilton, D. J., Wiltshire, A., Worthy, D., Wunch, D., Xu, X., Yoshida, Y., Zhang, B., Zhang, Z. and Zhu, Q.: The global methane budget 2000-2012, *Earth Syst. Sci. Data*, 8(2), 697–751, doi:10.5194/essd-8-697-2016, 2016a.
- 1590 Saunio, M., Jackson, R. B., Bousquet, P., Poulter, B. and Canadell, J. G.: The growing role of methane in anthropogenic climate change, *Environ. Res. Lett.*, 11(12), doi:10.1088/1748-9326/11/12/120207, 2016b.
- 1595 Saunio, M., Stavert, A. R., Poulter, B., Bousquet, P., Canadell, J. G., Jackson, R. B., Raymond, P. A., Dlugokencky, E. J., Houweling, S., Patra, P. K., Ciais, P., Arora, V. K., Bastviken, D., Bergamaschi, P., Blake, D. R., Brailsford, G., Bruhwiler, L., Carlson, K. M., Carrol, M., Castaldi, S., Chandra, N., Crevoisier, C., Crill, P. M., Covey, K., Curry, C. L., Etiope, G., Frankenberg, C., Gedney, N., Hegglin, M. I., Höglund-Isakson, L., Hugelius, G., Ishizawa, M., Ito, A., Janssens-Maenhout, G., Jensen, K. M., Joos, F., Kleinen, T., Krummel, P. B., Langenfelds, R. L., Laruelle, G. G., Liu, L., Machida, T., Maksyutov, S., McDonald, K. C., McNorton, J., Miller, P. A., Melton, J. R., Morino, I., Müller, J., Murgia-Flores, F., Naik, V., Niwa, Y., Noce, S., O'Doherty, S., Parker, R. J., Peng, C., Peng, S., Peters, G. P., Prigent, C., Prinn, R., Ramonet, M., Regnier, P., Riley, W. J., Rosentretter, J. A., Segers, A., Simpson, I. J., Shi, H., Smith, S. J., Steele, P. L., Thornton, B. F., Tian, H., Tohjima, Y., Tubiello, F. N., Tsuruta, A., Viovy, N., Voulgarakis, A., Weber, T. S., van Weele, M., van der Werf, G. R., Weiss, R. F., Worthy, D., Wunch, D., Yin, Y., Yoshida, Y., Zhang, W., Zhang, Z., Zhao, Y., Zheng, B., Zhu, Q., Zhu, Q., and Zhuang, Q.: The Global Methane Budget 2000–2017, *Earth Syst. Sci. Data Discuss.*, <https://doi.org/10.5194/essd-2019-128>, in review, 2019.
- 1600 Schlamadinger, B. and Marland, G.: The role of forest and bioenergy strategies in the global carbon cycle, *Biomass and Bioenergy* 10:275–300, 1996.
- 1610 Schelhaas, M.J., Eggers, J., Lindner, M. et al. : Model documentation for the European Forest Information Scenario model (EFISCEN 3.1). Wageningen, Alterra, Alterra report 1559, EFI Technical Report 26, Joensuu, Finland, 2007.
- Schrier-Uijl, A. P., Christensen, T. R., Tamstorf, M. P., Mastepanov, M., Martikainen, P. J., Verma, S. B., Bernhofer, C. and Cescatti, A.: The uncertain climate footprint of wetlands under human pressure, *Proc. Natl. Acad. Sci.*, doi:10.1073/pnas.1416267112, 2015.
- 1615 Searchinger, T.D., Wiersma, S., Beringer, T., & Dumas, P.: Assessing the efficiency of land use changes for mitigating climate change, *Nature*, 564, 249–253. doi: 10.1038/s41586-018-0757-z, 2018.
- Sitch S, et al.: Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic vegetation model. *Global Change Biology*, 9, 161-185, 2003.
- 1620 Sitch, S., Huntingford, C., Gedney, N., Levy, P. E., Lomas, M., Piao, S. L., Betts, R., Ciais, P., Cox, P., Friedlingstein, P., Jones, C. D., Prentice, J. C. and Woodward, F. I: Evaluation of the terrestrial carbon cycle, future plant geography and climate-carbon cycle feedbacks using five Dynamic Global Vegetation Models (DGVMs), *Global Change Biol.*, 14, 2015–2039, 2008.
- 1625 Smith, J.U., Smith, P., Wattenbach, M., Zaehle, S., Hiederer, R., Jones, R.J.A., Montanarella, L., Rounsevell, M.D.A., Reginster, I., Ewert, F.: Projected changes in mineral soil carbon of European croplands and grasslands, 1990–2080, *Glob. Change Biol.*, 11, pp. 2141-2152, 2005.
- 1630 Solazzo, E., Riccio, A., Van Dingenen, R., Valentini, L., Galmarini, S.: Evaluation and uncertainty estimation of the impact of air quality modelling on crop yields and premature deaths using a multi-model ensemble, *Science of the Total Environment*, 633, pp. 1437-1452, doi: 10.1016/j.scitotenv.2018.03.317, 2018.



- Spahni, R., Wania, R., Neef, L., van Weele, M., Pison, I., Bousquet, P., Frankenberg, C., Foster, P. N., Joos, F., Prentice, I. C., and van Velthoven, P.: Constraining global methane emissions and uptake by ecosystems, *Biogeosciences*, 8, 1643–1665, <https://doi.org/10.5194/bg-8-1643-2011>, 2011.
- 1635 Tian, H., Xu, X., Liu, M., Ren, W., Zhang, C., Chen, G., and Lu, C.: Spatial and temporal patterns of CH₄ and N₂O fluxes in terrestrial ecosystems of North America during 1979–2008: application of a global biogeochemistry model, *Biogeosciences*, 7, 2673–2694, <https://doi.org/10.5194/bg-7-2673-2010>, 2010.
- 1640 Tian, H., Lu, C., Ciais, P., Michalak, A. M., Canadell, J. G., Saikawa, E., Huntzinger, D. N., Gurney, K. R., Sitch, S., Zhang, B., Yang, J., Bousquet, P., Bruhwiler, L., Chen, G., Dlugokencky, E., Friedlingstein, P., Melillo, J., Pan, S., Poulter, B., Prinn, R., Saunio, M., Schwalm, C. R. and Wofsy, S. C.: The terrestrial biosphere as a net source of greenhouse gases to the atmosphere, *Nature*, 531(7593), 225–228, doi:10.1038/nature16946, 2016.
- 1645 Thompson, R. L., F. Chevallier, A. M. Crowell, G. Dutton, R. L. Langenfelds, R. G. Prinn, R. F. Weiss, Y. Tohjima, T. Nakazawa, P. B. Krummel, L. P. Steele, P. Fraser, S. O'Doherty, K. Ishijima, and S. Aoki, Nitrous oxide emissions 1999 to 2009 from a global atmospheric inversion, *Atmos. Chem. Phys.*, 14(4), 1801–1817, doi:10.5194/acp-14-1801-2014, 2014a.
- TRENDY-GCP <http://dgvm.ceh.ac.uk/node/9/index.html>
- Tubiello, F. N., Salvatore, M., Rossi, S., Ferrara, A., Fitton, N. and Smith, P.: The FAOSTAT database of greenhouse gas emissions from agriculture, *Environ. Res. Lett.*, 8(1), doi:10.1088/1748-9326/8/1/015009, 2013.
- 1650 Tubiello, F.N., Salvatore, M., C ndor Golec, R.D., Ferrara, A., Rossi, S., Biancalani, R., Federici, S., Jacobs, H., Flammini, A.: Agriculture, Forestry and Other Land Use Emissions by Sources and Removals by Sinks, 1990–2011 Analysis, FAO Statistics Division Working Paper Series ESS/14-02, 2014.
- Tubiello, F.N.: Greenhouse Gas Emissions Due to Agriculture, DOI: 10.1016/B978-0-08-100596-5.21996-3, 2019.
- 1655 UNFCCC Kyoto Climate Change Decision <https://unfccc.int/process-and-meetings/conferences/past-conferences/kyoto-climate-change-conference-december-1997/decisions-kyoto-climate-change-conference-december-1997>, 1997.
- 1660 UNFCCC Revision of the UNFCCC reporting guidelines on annual inventories for Parties included in Annex I to the Convention, Decision 24/CP.19, Annex I, Guidelines for the preparation of national communications by Parties included in Annex I to the Convention. Retrieved from <http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf#page=2>, 2013.
- UNFCCC CRFs downloaded from <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-2017>, 2017.
- UNEP The Emissions Gap Report 2018. United Nations Environment Programme, Nairobi, 2018
- 1665 UNFCCC National Inventory Submissions. Retrieved from <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>, 2018.
- 1670 Valentini, R., Matteucci, G., Dolman, A. J., Schulze, E. D., Rebmann, C., Moors, E. J., Granier, A., Gross, P., Jensen, N. O., Pilegaard, K., Lindroth, A., Grelle, A., Bernhofer, C., Grunwald, T., Aubinet, M., Ceulemans, R., Kowalski, A. S., Vesala, T., Rannik,  ., Berbigier, P., Loustau, D., Guomundsson J., Thorgeirsson, H., Ibrom, A., Morgenstern, K., Clement, R., Moncrieff, J., Montagnani, L., Minerbi, S., and Jarvis, P. G.: Respiration as the main determinant of carbon balance in European forests, *Nature*, 404, 861–865, doi:10.1038/35009084, 2000.
- VERIFY H2020 <https://verify.lscce.ipsl.fr/>



- 1675 Verkerk, P.J., Schelhaas, M.-J., Immonen, V., Hengeveld, G., Kiljunen, J., Lindner, M., Nabuurs, G.-J., Suominen, T., Zudin, S.: Manual for the European Forest Information Scenario model (EFISCEN 4.1). EFI Technical Report 99, European Forest Institute. 49 p., 2016.

Weiss, F. & Leip, A.: Greenhouse gas emissions from the EU livestock sector: A life cycle assessment carried out with the CAPRI model, *Agriculture, Ecosystems and Environment* 149, 124-134.
- 1680 WMO 2019, United in Science Report, https://public.wmo.int/en/resources/united_in_science, 2012.

Wells, K. C., Millet, D. B., Boussez, N., Henze, D. K., Griffis, T. J., Chaliyakunnel, S., Dlugokencky, E. J., Saikawa, E., Xiang, G., Prinn, R. G., O'Doherty, S., Young, D., Weiss, R. F., Dutton, G. S., Elkins, J. W., Krummel, P. B., Langenfelds, R., and Steele, L. P.: Top-down constraints on global N₂O emissions at optimal resolution: application of a new dimension reduction technique, *Atmos. Chem. Phys.*, 18(2), 735-756, 2018.
- 1685 Winiwarter, W., Höglund-Isaksson, L., Klimont, Z., Schöpp, W., Amann, M.: Technical opportunities to reduce global anthropogenic emissions of nitrous oxide, *Environmental Research Letters* 13, 014011, 2018.

Worden, J. R., Bloom, A. A., Pandey, S., Jiang, Z., Worden, H. M., Walker, T. W., et al.: Reduced biomass burning emissions reconcile conflicting estimates of the post-2006 atmospheric methane budget. *Nat. Comm.*, 8(1), 2227, doi.org/10.1038/s41467-017-02246-0, 2017.
- 1690 Zaehle, S., Ciais, P., Friend, A. D., and Prieur, V.: Carbon benefits of anthropogenic reactive nitrogen offset by nitrous oxide emissions, *Na. Geosci.*, 4, 601–605, <https://doi.org/10.1038/NGEO1207>, 2011.

Zeng, N.: Glacial-interglacial atmospheric CO₂ change - The glacial burial hypothesis, *Advances in Atmospheric Sciences*, 20(5), 677-673, 2003.
- 1695 Zeng, N., A. Mariotti, and P. Wetzol: Terrestrial mechanisms of interannual CO₂ variability, *Global Biogeochemical Cycles*, 2005.

Zhu, Q., Peng, C., Chen, H., Fang, X., Liu, J., Jiang, H., Yang, Y., and Yang, G.: Estimating global natural wetland methane emissions using process modelling: spatio-temporal patterns and contributions to atmospheric methane fluctuations, *Global Ecol. Biogeogr.*, 24, 959–972, 2015.
- 1700