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Horizon 2020 Societal challenge 5:
Climate action, environment, resource efficiency and raw materials

VERIFY

Observation-based system for monitoring and verification of greenhouse gases

GA number 776810, RIA

Deliverable number (relative in WP)	**D5.2**
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Responsible	Han Dolman
Contributor(s):	A.M. Roxana Petrescu, Han Dolman, Adrian Leip, Philippe Ciais, Efisio Solazzo, Gert-Jan Nabuurs, Giacomo Grassi, Peter Bergamaschi, Glen Peters, Greet Janssens-Maenhout, Robbie Andrew, Johannes Winkler, Gema Carmona-Garcia, Roberto Pilli, Emanuele Lugato and Mart-Jan Schelaas.
Internal reviewer:	/

DATA USE AND UPDATES: This data was collected with the greatest care but its occasionally prone to error due to various data corrections and updates. If you are using this data please make sure you are having the last available version and do not hesitate to contact us (corresponding author A.M.R. Petrescu, a.m.r.petrescu@vu.nl)

1. Changes with respect to the DoA

None.

2. Dissemination and uptake

(Who will/could use this deliverable, within the project or outside the project?)

This deliverable is intended to be public and used by all WPs of the VERIFY project.

3. Short Summary of results (<250 words)

Assessing the full greenhouse gas balance of EU countries and ecosystems: a first look at different emission estimates and their uncertainties

European greenhouse gas (GHG) emission reduction policies require accurate and robust estimates of anthropogenic emissions. Internationally recognized methods are needed to produce, and regularly update, these emission estimates, following TACCC (transparency, accuracy, comparability, consistency, completeness) UNFCCC requirements. New research is required to more accurately quantify carbon stocks and fluxes of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The development and improvement of methodologies for a GHG verification system will address its applicability in Europe, and, whenever needed, the upscaling from Europe to other GHG emitting countries and regions, through international cooperation mechanisms promoted by the WMO, the IPCC and the UNFCCC in the context of the Paris Agreement on Climate.

The EU funded project VERIFY aims to develop a framework for the synthesis of different data streams to produce harmonized European country-scale GHG budgets, with uncertainties and to provide scientific and observation-based evidence on the estimates. By reconciliation of data from different sources (e.g. bottom-up, top-down, regional emission estimates and national emission inventory reports) we aim to reduce overall uncertainty and identify and categorize key differences that are related to specific methods.

This first report is intended as a ‘proof of concept’, and our preliminary analysis is based on total EU28 and sector totals from UNFCCC and EDGAR with a focus on a) Agriculture (UNFCCC, CAPRI, EDGAR, FAO, GAINS) and b) LULUCF biogenic fluxes - carbon stocks and sinks (UNFCCC, EFISCEN, CBM and TRENDY.v6). We analyzed as well inverse C fluxes from four inversions of the global carbon project (GCP) and N_2O fluxes from the InGOS project. Together with CH_4 fluxes from GCP we also mention the CH_4 fluxes from natural wetlands. For the sector totals, we find a relatively good match between UNFCCC and the other sources with differences pertaining mostly to sectoral aggregation and/or expert judgment emission factors (EFs). We find large differences in the LULUCF carbon stocks and fluxes when comparing modelled results to UNFCCC reports. Differences in method (Tier 1 or Tier 2) and model set-up, might be the underlying cause of these discrepancies.

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4. Evidence of accomplishment

(report, manuscript, web-link, other)

The report itself constitutes the evidence of accomplishment. For future updates, please check the project space under: https://projectsworkspace.eu/sites/VERIFY/SitePages/WP5.aspx

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Version	Date	Description	Author (Organisation)
V0	10/2018	Creation/Writting	STICHTING VU
V1	14/11/2018	Formatting/Delivery	STICHTING VU
V2	30/11/2018	Formatting/Delivery on the Participant Portal	CEA/LSCE

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1. Introduction

Atmospheric measurements indicate that GHG concentrations have increased since pre-industrial times by 40% for carbon dioxide CO_2, 150% for methane (CH_4) and by 20% for nitrous oxide (N_2O) since 1980 (Tian et., al 2016).The increase of CO_2 and CH_4 is caused by fossil fuel combustion and land use change.

Fossil fuel emissions increased with 62% in 2016 compared to 1990 (Le Quéré et al., 2017) Rates of land use change CO_2 emissions, appear to have slightly declined in the past decade (Friedlingstein et al., 2010).

According to its last submission to the United Nations Framework Convention on Climate Change (UNFCCC), the European Union (EU) emitted 0.9 Pg C yr^{-1} of CO_2 from fossil fuel burning and cement production in 2014, about 9%-10% of the global total (confirmed by EDGARv4.2FT2014, see Olivier et al., 2016). In the UNFCCC reports, land cover change and forest management led to a net sink of about 0.1 Pg C yr^{-1}, about 10% of EU emissions. In contrast, the REgional Carbon Cycle Assessment and Processes (RECCAP) synthesis of research results from the Global Carbon Project (GCP) estimated a sink two times larger (Luyssaert et al. 2012).

After CO_2, atmospheric CH_4 is the second most impactful anthropogenic greenhouse gas in terms of radiative forcing. The fraction of atmospheric CH_4 reached 1810 ppb in 2012 and was 2.5 times larger than in 1750 (Saunois et al., 2016). The primary anthropogenic CH_4 emissions are leaks from natural gas extraction and distribution, the oil industry and coal extraction, livestock and rice paddies, landfills and biomass burning (Denman et al., 2007). Natural emissions of CH_4 are dominated by wetlands and lakes, with smaller contributions from geological natural venting, wildfires, and termites. Although global emissions of CH_4 are estimated to be around 550 Tg CH_4 yr^{-1} (30% of total global emissions) (Kirschke et al., 2013), they are only 4% of the global CO_2 anthropogenic emissions in units of carbon mass flux, but atmospheric CH_4 has contributed 20% (~0.48 Wm^{-2}) to the additional radiative forcing accumulated in the lower atmosphere since 1750 (Ciais et al., 2013). In the European Union (EU) CH_4 emissions account for 11 % of total EU GHG emissions in 2016 and decreased by 37 % since 1990 to 457 Mt CO_2 equivalents in 2016 (Figure 2.5). The two largest key sources are enteric fermentation and anaerobic waste. They account for 53 % of CH_4 emissions in 2016. (Annual European Union greenhouse gas inventory 1990–2016 and inventory report 2018: https://www.eea.europa.eu//publications/european-union-greenhouse-gas-inventory-2018).

Figure 1. Illustration of the main land surface sources and sinks for CO_2, CH_4 and N_2O GHG for Europe (VERIFY, Proposal-SEP-210406802.pdf).

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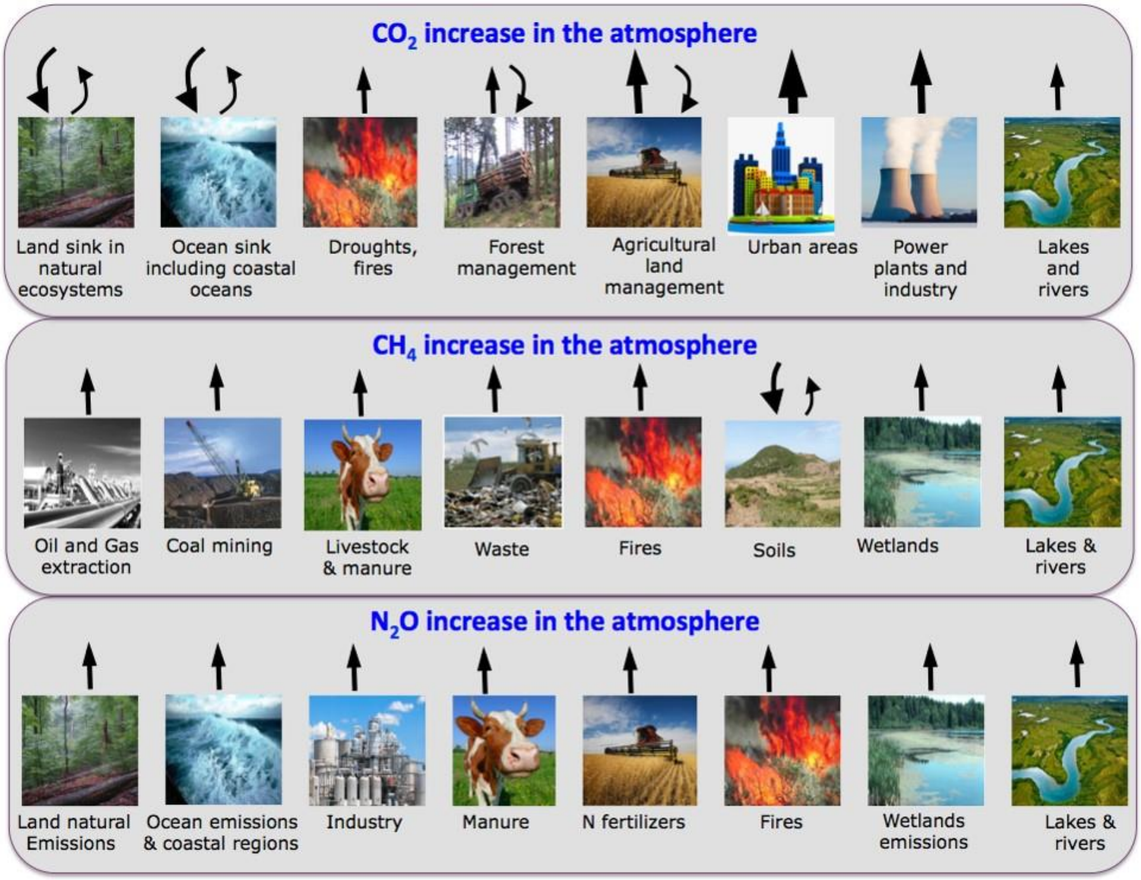

The third most important greenhouse gas in terms of radiative forcing is N_2O. Global N_2O emissions are ~17 Tg N yr^{-1} (Thompson et al. 2014a) of which the contribution of Europe, mainly from agriculture, is 1.3 Tg N yr^{-1}. Agriculture (and associated management practices) dominates the emissions of both CH_4 and N_2O and is therefore a priority sector for mitigation of CH_4 and N_2O emissions. These European totals should not mask that EU countries have very different contributions of CO_2, CH_4 and N_2O emissions and CO_2 sinks (Schulze et al. 2009).

Overall, although Europe is a net source of GHGs to the atmosphere, European ecosystems range from being a net source of CO_2 eq (using the CO_2 equivalency of CH_4 and N_2O on a time horizon of 100 years) based on bottom-up land observations (Luyssaert et al. 2012), to a net sink of CO_2 based on atmospheric CO_2 observations and inverse modelling (top-down). This shows the importance of reducing the uncertainties in GHG emissions and the land CO_2 sink and the need to reconcile and integrate approaches into a joint bottom-up and top-down framework for the GHG balance of Europe. This report lays the groundwork to bring together the different datasets for a more thorough analysis and use in the future of the differences in the estimates.

1.1. The international reporting context

Emission reduction programs are developed in support of international agreements, such as the UNFCCC. Yet, anthropogenic emissions of CO_2 and CH_4 estimated from inventories are generally

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no validated by independent observations. The ability of nations, provinces, and local municipalities to implement policies that reduce emissions or create sinks of CO_2 and CH_4 (de Richter and Caillol, 2011; Kucharczyk, 2011; Stolaroff et al., 2012) will partly depend upon their ability to measure progress and evaluate the effectiveness of national and sub-national actions. Uncertainties in inventories, and our ability to verify them, need to be reduced to support effective policies. To date, efforts to monitor and report emissions of CO_2 and CH_4 have been based mostly on limited large-scale, subsampled land use observations, self-reported data on land and energy use, and extrapolated emission factor measurements. These data have uncertainties that limit their ability to support greenhouse management strategies (Schulze et al., 2009).

The climate, environmental and policy communities are challenged to provide the needed framework making use of the Measuring, Reporting, and Verifying (MRV) mechanism to monitor the effectiveness of GHG emission reductions after the Paris Agreement in a transparent way. The UNFCCC reporting guidelines on national inventories, established under the principles of Transparency, Accuracy, Completeness, Comparability, Consistency, need extension. A key priority is to facilitate the global stocktake process of the UNFCCC, which creates a political momentum for enhancing the Nationally Determined Contributions under the Paris Agreement. The purpose of the global stocktake is to assess the collective progress towards achieving the near- and long-term objectives of the Agreement, considering mitigation, adaptation and the means of implementation. Current UNFCCC procedures do not incorporate independent large-scale observation-derived GHG budgets, but few countries (e.g. Switzerland and UK and Australia) are already using atmospheric GHG measurements as an additional consistency check of their national declarations.

A key feature after the transparency framework of the Paris Agreement is that non-Annex 1 (mainly developing) countries are engaged to provide regular updates of their declarations to UNFCCC. Many of these countries are facing challenges to improve inventories and reduce uncertainties of their GHG statistical accounting systems, which calls for robust and transparent approaches that can be applied to different situations.

1.2. The aim

This report represents a 'proof of concept' and a first compilation of pre-VERIFY data at the country level in an effort towards an operational system with yearly automatic updates as needed for the UNFCCC. It stands as a collection of products already published delivered by VERIFY partners. The data should form the basis for the analysis of the total uncertainties and aims in presenting the reader with existent data sources and their GHG estimates and uncertainties, highlighting the differences and inconsistencies between emissions. Except for UNFCCC, which has an established consistent way in calculating and submitting emissions with uncertainties, there is a scarce availability of uncertainties from the other sources. Therefore, we mainly calculated the overall uncertainty as represented by the 95% confidence interval between sources not taking into account the UNFCCC estimate and considering it as policy base estimate.

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The VERIFY estimates of GHG emissions and sinks are designed to deliver new information as an aid for decision-making by policy-makers at the national and European levels, and by regional authorities in Europe and other regions, and to actively contribute to the international effort on GHG monitoring. These GHG budgets estimates will be updated each year during the project for an effective comparison with national inventories, as well as with detailed regional inventories in selected areas. Specific attention will be given to the assessment of uncertainties for both inventory-based estimates and observation-based estimates produced by the project and the reconciliation of both approaches.

2. Data sources

The VERIFY project relies on observational data-streams to quantify GHG fluxes: 1) bottom-up activity data (AD) (e.g. fuel use and emission factors) and ecosystem measurements (bottom-up models) and 2) atmospheric GHG concentrations from satellites and ground-based networks (top-down atmospheric inversion models). For CO_2, a specific effort is made to separate fossil fuel emissions from ecosystems fluxes (typically using C-14). For CH_4 and N_2O, we separate agricultural from fossil fuel and industrial emissions. Finally, trends in the budgets of the three GHGs are analyzed in the context of NDC targets.

The purpose of this first report is the reconciliation of differences between bottom-up and top-down emission estimates, providing an assessment of persistent differences and their potential causes making use of pre-VERIFY data (Table 1).

Table 1: Data sources for the three main GHG available as pre-VERIFY data

CH_4	N_2O	C (NBP)
UNFCCC	UNFCCC	UNFCCC
FAO	FAO	CBM
EDGAR v4.3.2	EDGAR	EFISCEN
CAPRI	CAPRI	TRENDY.v6v6
GAINS	GAINS	
Inverse CH4 emissions from ensemble (Bergamaschi et al., 2018)	Inverse N2O emissions from InGOS	Inverse C emissions from GCP
Natural wetlands (Poulter et al. 2017)	Direct soil emissions of N_2O -N (Lugato et al., 2017)	Soil eroded C (Lugato et al., 2016)

For CH_4 and N_2O we choose as base year 1990 and further looked at 2000, 2010 and 2012. The reason for choosing 2012 as final reporting year was to keep consistent with the last year of the Kyoto Protocol first period (and also of EDGARv4.3.2).

The emissions for these three gases pertain to the following activities:

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CH_4: AGRICULTURE: Enteric fermentation (ENT), Manure management (MAN), Rice cultivation (RIC), Agricultural field burning.
INVERSIONS (EU28 totals), natural emissions from wetlands (GCP 11 models)

N_2O: AGRICULTURE: Manure management, direct soil emissions, grazing, indirect emissions
INVERSIONS (EU28 total).

Carbon (NBP)

For carbon we analysed the data for 2000, 2005, 2010 and 2015 (2012 for CBM (Pilli et al., 2017)).

- UNFCCC vs. EFISCEN vs. CBM – forest remaining forest (EU28)
- UNFCCC vs 8 DGVMs from TRENDY.v6– all land uses EU28
- 4 Inversion GCP models vs. UNFCCC and TRENDY.v6

For CH_4 and N_2O we analyzed as well country specific examples such Germany (DEU), France (FRA), UK+Ireland (UK+IRL), BENELUX, Czech Republic+Slovakia (CZE+SVK) and Poland (POL) while for NBP Forest Land remaining Forest Land (FL-FL) we focused on Germany (DEU), Poland (POL), Greece (GRC), Italy (ITA), The Netherlands (NDL) and Sweden (SWE).

The pre-VEIRIFY data consists of GHG emissions and uncertainties reported under the UNFCCC 2018 country submissions and data sources such FAO, EDGAR and bottom-up and top-down approaches.

The VERIFY WPs involved in this report are:

Work packages	Partners and data activities
WP1	UNFCCC country submissions and uncertainties
WP3	(JRC) Soil eroded C (Lugato et al., 2016) and direct soil emissions of N_2O -N (Lugato et al., 2017) (IIASA) GAINS – CH_4 and N_2O emissions from all sectors
WP4	(JRC) EDGAR - EU total and sectoral $CH_4$and N_2O emissions with uncertainties
	(JRC) CAPRI - CH_4 and N_2O emissions from agriculture
	(JRC) CBM - C dynamics: NBP
	(WUR) EFISCEN – Forest NBP
	(JRC) Inverse CH_4 emissions from ensemble, Bergamaschi et al., 2018
	(JRC) Inverse N_2O emissions from InGOS, JRC Reports Bergamaschi et al., 2018
WP7	(GCP) Inverse net CO_2 fluxes from GCP and CH_4 from natural wetlands

3. Results

3.1. Bottom-up activity data and uncertainties

3.1.1. Anthropogenic CH_4 and N_2O

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The intensity of European ecosystem management, superimposed on regional climate patterns, nitrogen deposition and rising CO_2, control the GHG fluxes. In VERIFY, we use complementary data-driven and process-based ecosystem models to combine flux tower measurements with inventories of soil carbon and forest biomass carbon stocks, and space-borne observations of vegetation cover, phenology, and biomass.

A special effort in this report will be to assess the effect of changes in management intensity on GHG budgets, such as the strong decrease of livestock number in Europe since 1990 impacting grassland GHG fluxes, reduced nitrogen deposition and fertilizer applications to croplands, and changes in forest harvest.

a) CH_4

Our results show that, at European level, the total EU28 CH_4 emissions are consistent in trends among sources. For the sector totals our first investigations show a relatively good match between UNFCCC and EDGAR with differences pertaining mostly to sectoral aggregation in EDGAR and expert judgment of emission factors.

The main differences in total EU28 CH_4 emissions are coming from the Energy Industries sector 1A where we notice that UNFCCC emissions are almost double than EDGAR. Contrary, for fugitive emissions from solid fuels, oil and gas sector 1B1 and 1B2 and Wastewater sector 5, EDGAR has double higher emissions compared to UNFCCC (Figure 2). The general trend for 1990-2012 is descending but the differences remain mostly constant.

Figure 2. Total sectoral CH_4 emissions from EDGAR and UNFCCC. The uncertainties are reported to UNFCCC in 2018 together with the country submissions. EDGAR uncertainties were only calculated for 2012 as lognormal distribution function.

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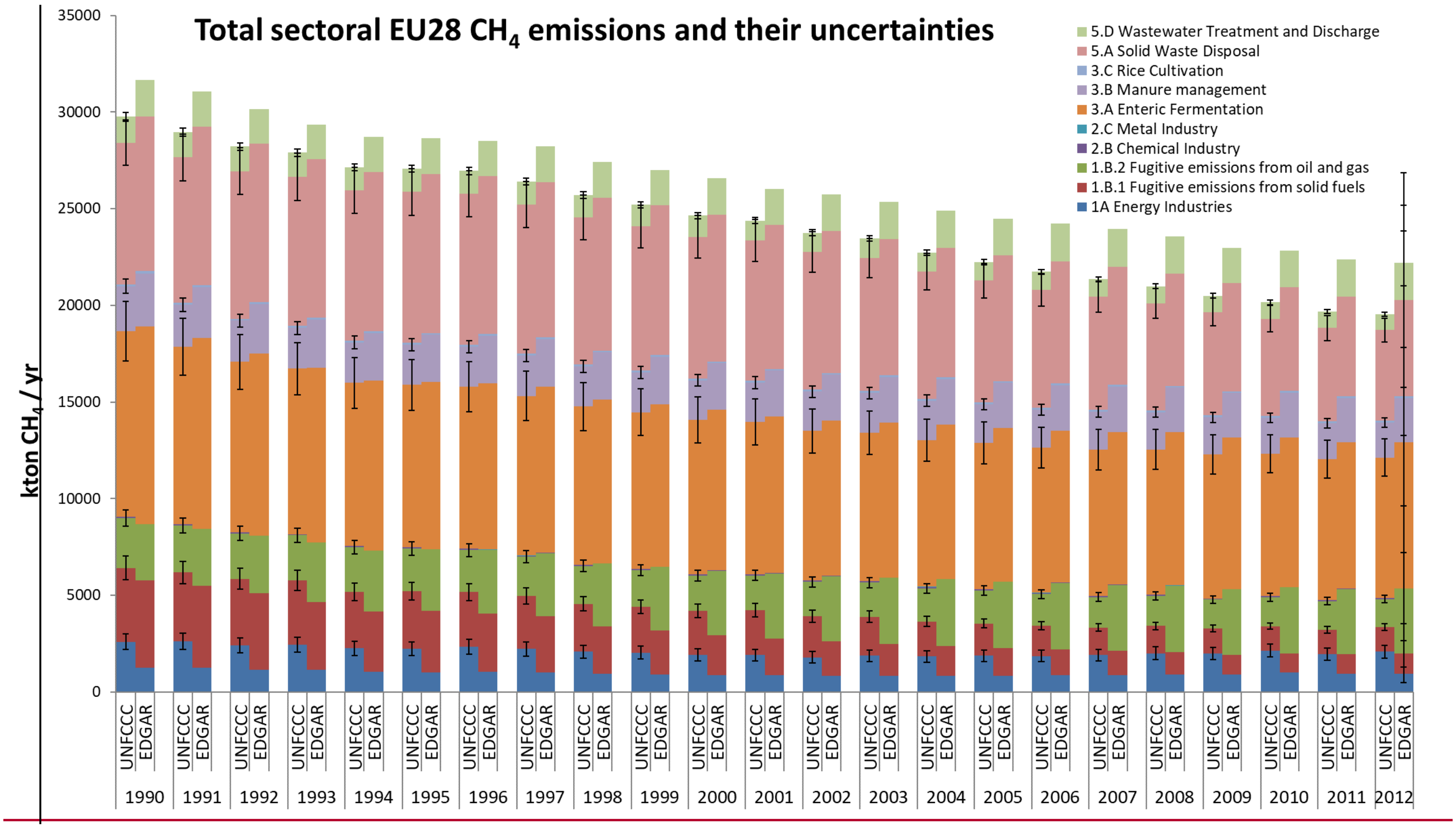
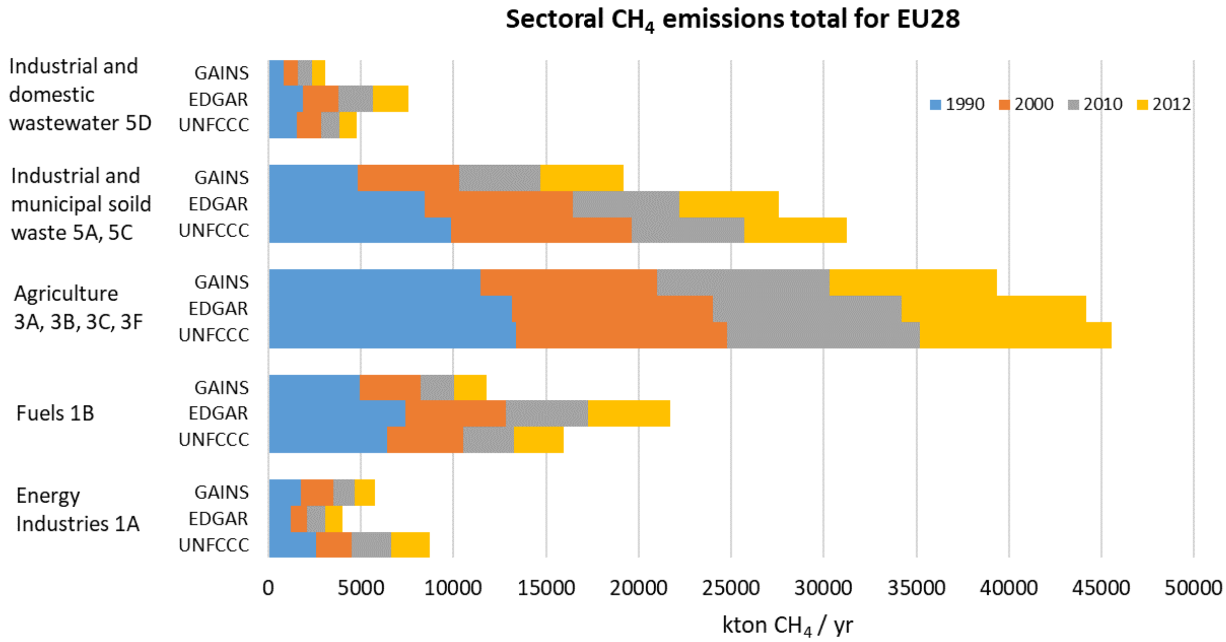


In Figure 3 we added next to UNFCCC and EDGAR estimates, data from GAINS model. Except for Energy Industries, for all other sources GAINS underestimates the emissions. GAINS however applies a consistent methodology across all countries. A possible explanation of differences in historical waste emissions could be that GAINS uses a simplified version instead of a full FOD (First-Order-Decay) method. The simplification means that due to lack of data before 1970, GAINS accounts for emissions from biodegradable waste landfilled from 1970 onwards and assume no emissions from waste landfilled before 1970 while IPCC recommends to go 50 years back in time (hence to 1940 if estimating emissions for 1990) (L. Hoglund, pers. comm. And methodology available in Hoglund-Isaksson et al., 2012).

Figure 3: Total EU28 CH_4 emissions as reported by countries to UNFCCC and compared to EDGAR (JRC) and GAINS model (IIASA). We did not present the uncertainties because of different way of aggregation of sectors compared to Figure 2 and 4.



In more detail, Figure 4 shows UNFCCC versus EGDAR emissions and their uncertainties for 2012.

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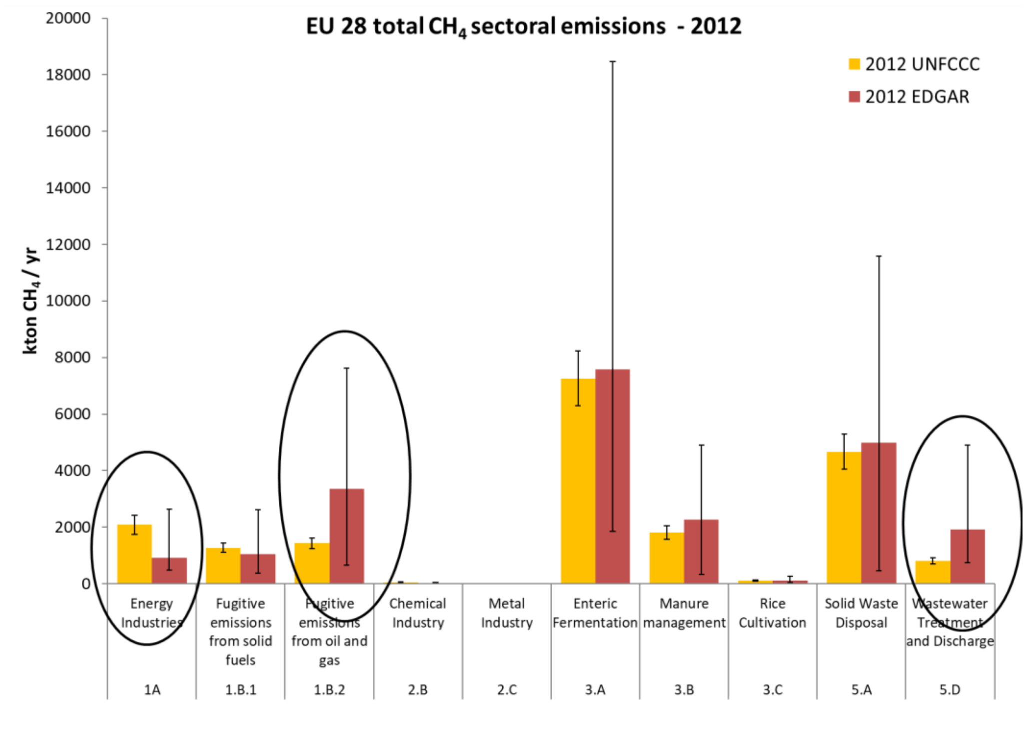
Figure 4. 2012 split in sectoral CH_4 emissions for EDGAR and UNFCCC. The circles are highlighting the sectors with highest differences. UNFCCC error bars represent the uncertainties reported by the countries in 2018 submissions and EDGAR error bars represent the minimum and maximum uncertainty calculated as lognormal distribution value.

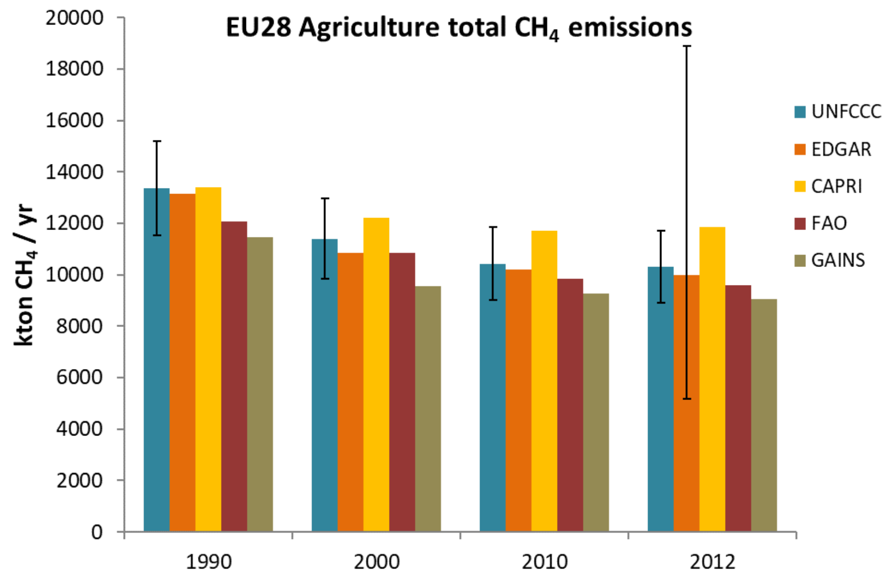


While in 1990 EDGAR underestimates solid fuel emissions sector 1B1 with more than double (Figure 2), the two have converged by 2012 (Figure 4). The main differences remain for the Energy Industries 1A sector where we notice that UNFCCC emissions are almost double than EDGAR and contrary the Wastewater sector 5 where EDGAR has double higher emissions compared to UNFCCC (Figure 3). The large difference between 1B and 1A for EDGAR versus the others remain with the allocation of distribution losses (for EDGAR under 1B, but these could be also under transformation losses of 1A).

Having a closer look at the Agricultural sector we observe that CAPRI and GAINS are the extremes in terms of estimates while the other three sources show similar emissions. To also note that CAPRI data does not include emissions from agricultural waste burning but those represent only less than 1% of the total CH_4 emissions from agriculture. Between 1990 and 2012 the trend in emissions for all sources is descending. The error bar on UNFCCC estimates accounts for 13.65%, 13.67%, 13.51% and 13.56% for 1990, 2000, 2010 and 2012 respectivelly and were calculated based on the uncertainty percentages for CH_4 from the Agricultural sector submitted in 2018.
According to Leip et al., 2010 under UNFCCC reporting several countries use the same uncertainty value for the activity data (AD) of CH_4 emissions from enteric fermentation and manure

management. While CAPRI uses Tier 2 for cattle and Tier 1 for swine, poultry, sheep and goat for the calculation of CH_4 emissions this may be a plausible cause of the differences between CAPRI and the other emissions.

Figure 5. Total EU28 Agriculture CH_4 emissions from five data sources, UNFCCC, EDGAR, FAO, CAPRI and GAINS. The error bars on UNFCCC estimates account for 13.65%, 13.67%, 13.51% and 13.56% for 1990, 2000, 2010 and 2012 respectivelly and were calculated based on the uncertainty percentages for CH_4 from the Agricultural sector submitted in 2018. EDGAR uncertainty was only calculated for 2012 and represents the minimum and maximum uncertainty value calculated as lognormal distribution.



When split into sub-sectoral totals we notice (Figure 6) that in relative terms the difference comes from the Rice Cultivation estimates with FAO a factor two higher estimates compared to UNFCCC and EDGAR. In absolute terms these emissions are negligible as the contribution to the total emissions from agriculture are very small. CAPRI model is not represented in the figure because it does not simulate emissions from agricutural waste burning.

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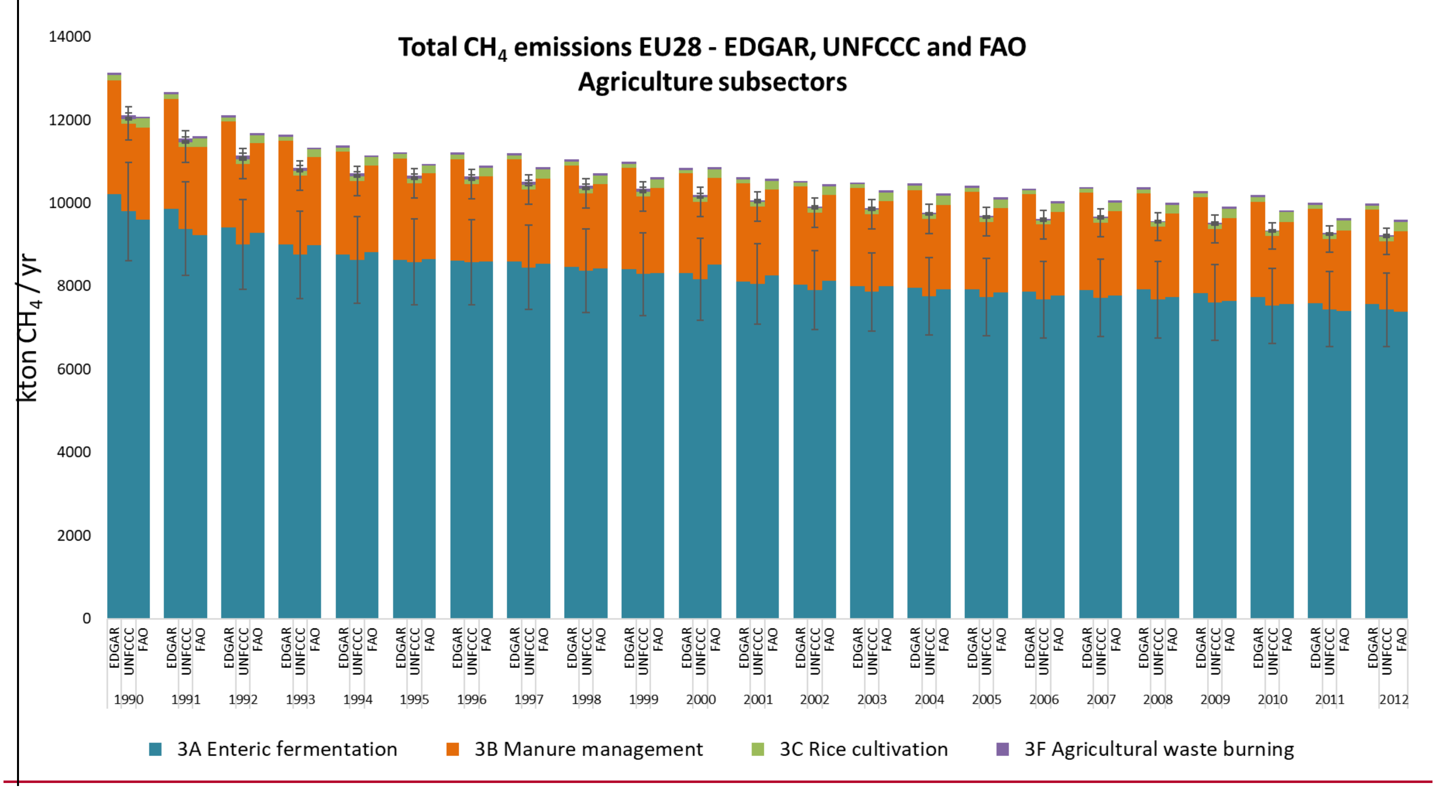
Figure 6. Total EU28 CH_4 emissions for agriulture sector split into the main four sub-sectors. We do not present EDGAR uncertainties because we do not have it calculated for all years (only 2012) and 3F sub-sector.



We calculated the 95% confidence interval of the range between the three data sources EDGAR, CAPRI and GAINS) relative to the total EU28 agricultural emissions presented in Figure 5. For this calculation we did not include UNFCCC considering it as the baseline for our estimates and we did not inlcude FAO because their estimates are based on data (EFs) from UNFCCC. The UNFCCC error bar represents the total EU28 uncertainty estimates in percentages for the Agriculture sector received from the 2018 country submissions. We notice that there is the slight increase in uncertainty band towards 2012 compared to 1990 which is entirely triggered by the CAPRI model which appears to overestimate and diverge from the other sources over time.

Based on this confidence analysis the two models are at the high confidence +5% and low confidence -5% of the interval while EDGAR and FAO are closely following the UNFCCC trend as both are based on the UNFCCC data. Methodologies are as well different, CAPRI and GAINS using mostly higher tiers while EDGAR and FAO a Tier 1. The reason for which in the ninties EDGAR/ UNFCCC estimates are much closer to CAPRI than now (2012) is due to the use of averaged EFs coming from CAPRI results.

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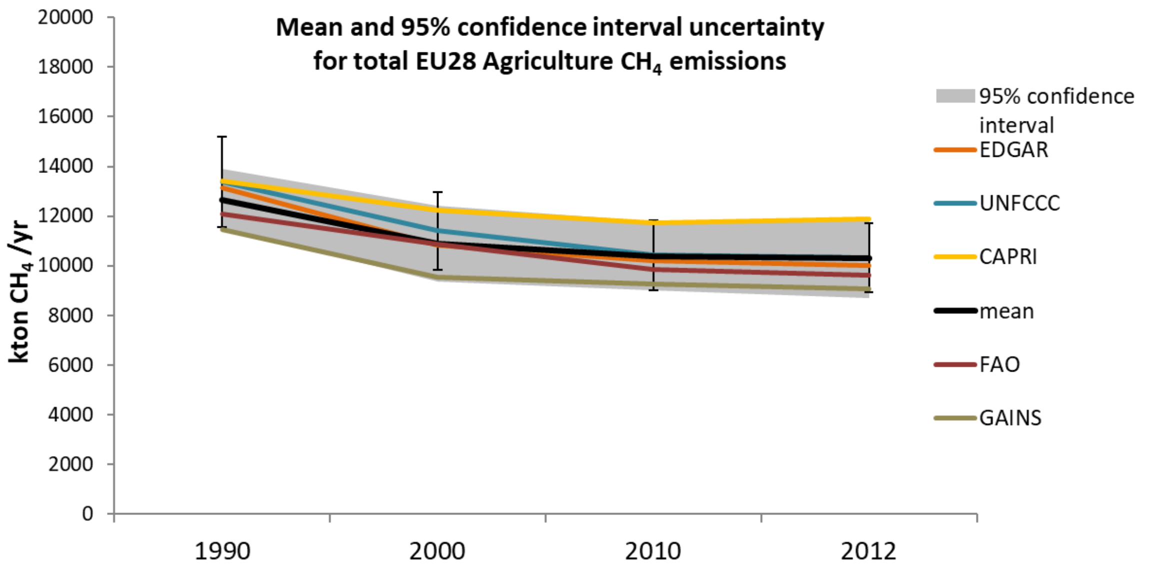
Figure 7. Mean and 95% confidence interval uncertainty in Agriculture total CH_4 emissions for the three data sources EDGAR, CAPRI and GAINS. The error bars on UNFCCC estimates account for 13.65%, 13.67%, 13.51% and 13.56% for 1990, 2000, 2010 and 2012 respectivelly and were calculated based on the uncertainty percetages for CH_4 from the Agricultural sector submitted in 2018.



b) N_2O

Inventory estimates of N_2O emissions have very large uncertainties (>100%) owing to the heterogeneity of sources and uncertainty in emission factors for the main N_2O sources, in particular, agriculture. Since agricultural soil and manure management emissions vary strongly from site to site depending on e.g. soil properties and background emissions, management and meteorology, it is extremely challenging to determine accurate mean emission factors (JRC InGOS report, https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/atmospheric-monitoring-and-inverse-modelling-verification-greenhouse-gas-inventories).

Our N_2O results show that, at European level, the total EU28 N_2O emissions are much higher for UNFCCC then for all other sources (Figure 8). When split in sub-activities we see that differences pertain mostly to the Energy industry sector 1A (similar to CH_4) where the trend and difference between 1990 and 2012 seems to remain constant. Another interesting trend is seen for the Production of chemical sector 2B where in 1990 EDGAR was underestimating the emissions while in 2012 it reversed to overestimation.

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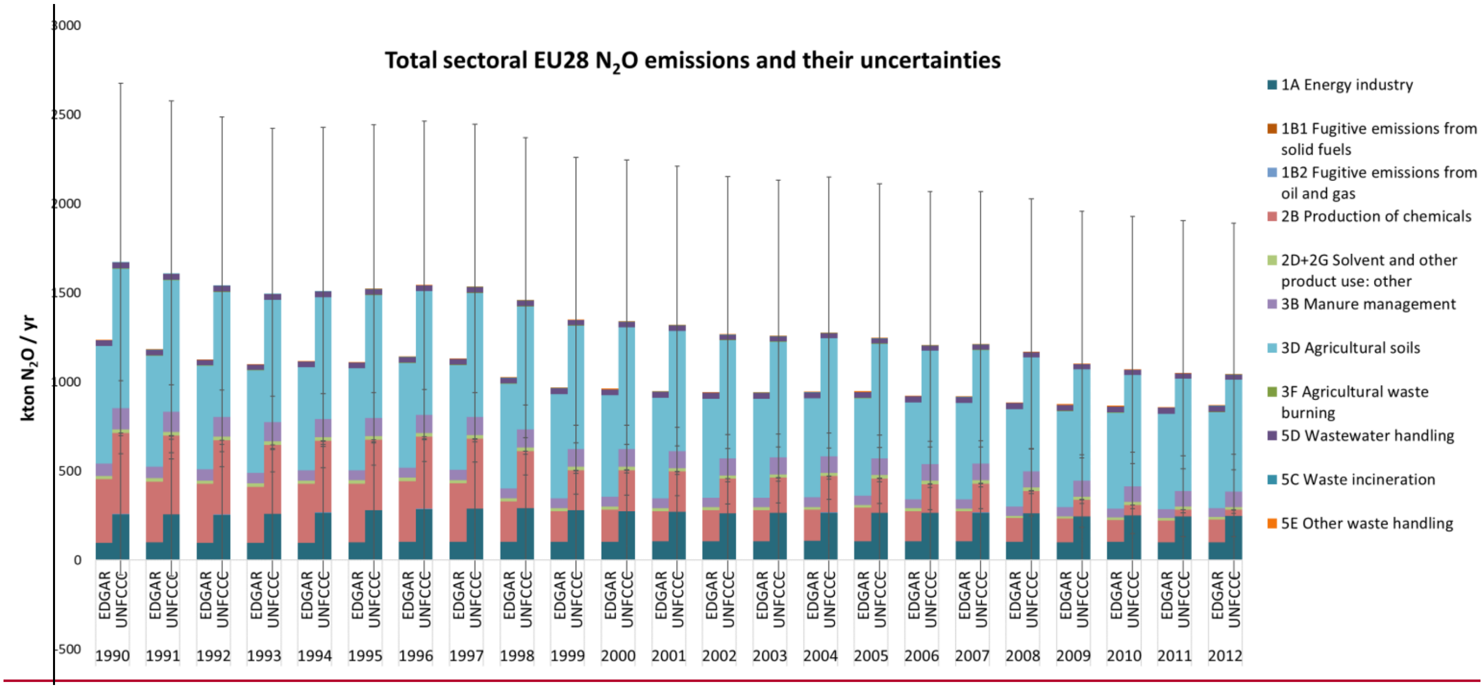
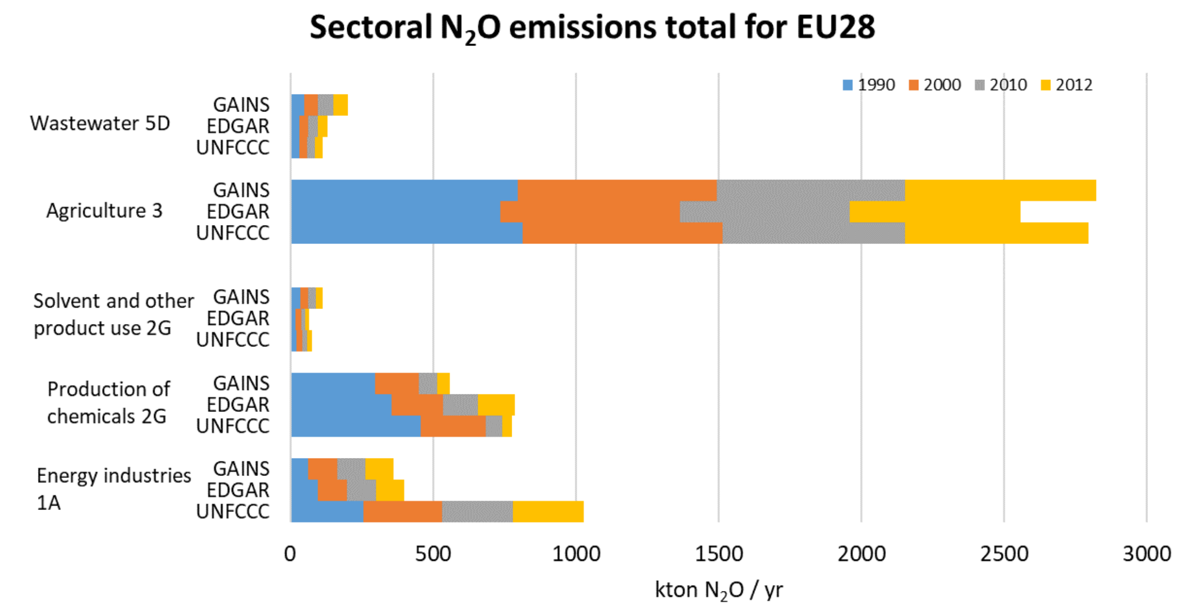
Figure 8. Total EU28 sectoral emissions of N_2O for UNFCCC and EDGAR. The uncertainties bars belong to the UNFCCC 2018 national submissions.



In Figure 9 we added next to UNFCCC and EDGAR estimates, data from GAINS model. We notice that except for the Energy Industries sector and Production of chemicals where UNFCCC emissions are higher, all three data sources agree.

Figure 9: Total EU28 N_2O emissions as reported by countries to UNFCCC and compared to EDGAR and GAINS model (IIASA). We did not present the uncertainties because of different way of aggregation of sectors compared to Figure 8.



Having a closer look at the Agriculture sector (Figure 10) we notice that all data sources are having similar estimates and with EDGAR and CAPRI having a slight increase in the emisions towards 2012. The error bar on UNFCCC estimates accounts for all gases 45.4% and was calculated for the total EU28 unceratinty estimates in the Agriculture sector (2018 country submissions). We observed that between 1990 and 2012 the trend for almost all sources is descending, except for CAPRI which has a constant trend in emissions.

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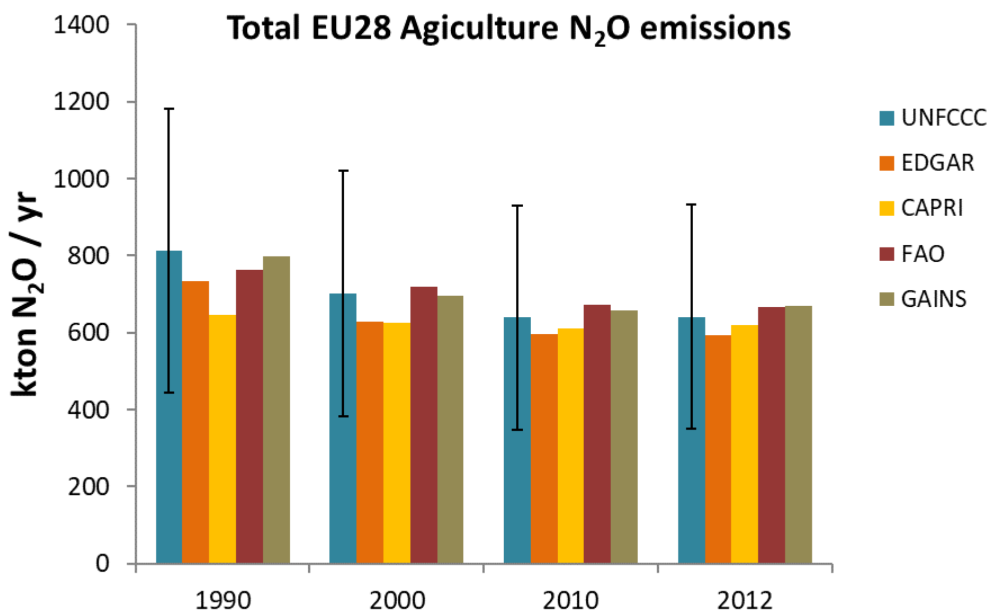
Figure 10: Total EU28 agriculture N_2O emissions from UNFCCC with uncertainty (blu), EDGAR (orange) CAPRI (yellow), FAO (red) and GAINS (brown). GAINS data for 2012 was not available therefore we used the data for 2015. The error bar on UNFCCC represent the 45.4% uncertainty estimate for the Agriculture sector, 2018 country submissions.



The differences are better seen when we zoom into the sub-sectoral totals. From Figure 11 we understand that the higher CAPRI and UNFCCC emissions are triggered by the direct and indirect N_2O soil emissions. We also notice that differences and trends remain for all sources constant over time. The similar estimates of EDGAR and FAO are due to the fact that EDGAR is using the activity data from FAO. The differences between FAO and the other sources appear to be due to the Tier 1 approach on which FAO is entirely based on.

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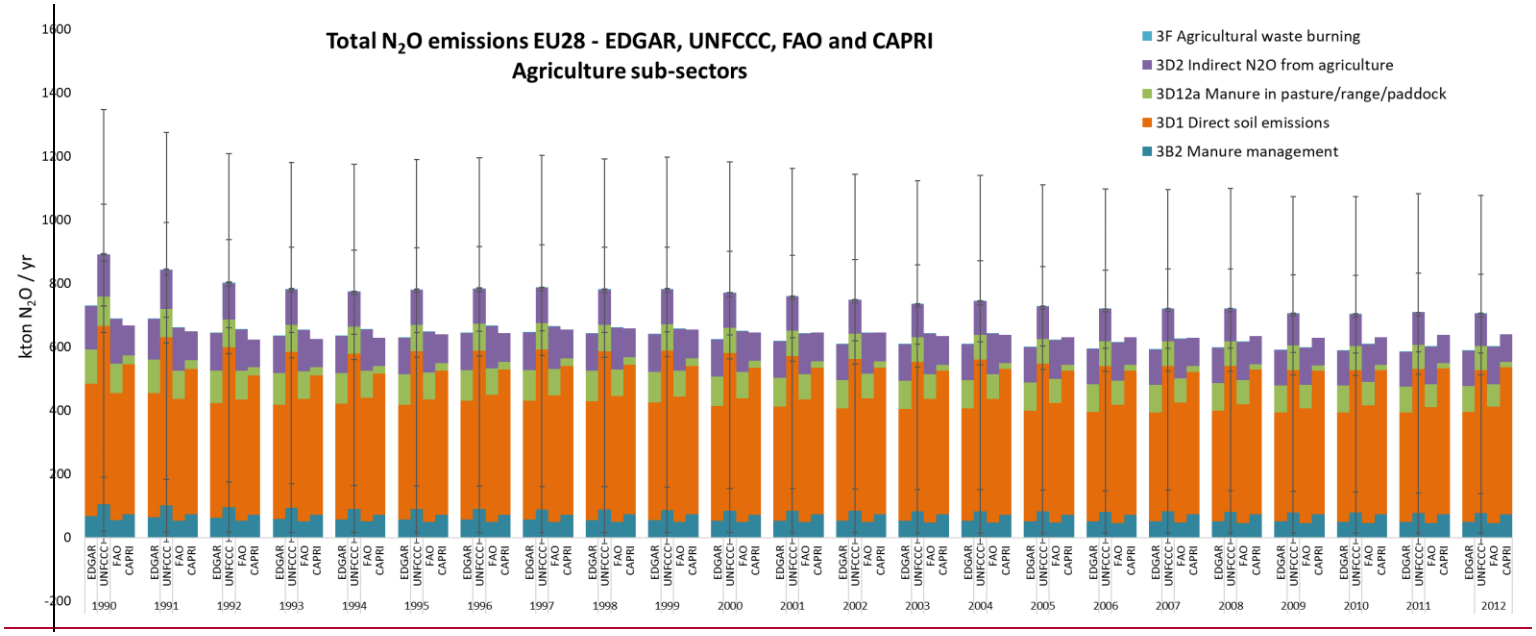
Figure 11. Total EU28 N_2O emissions for Agriculture sector split into the main five sub-sectors. We do not present EDGAR uncertainties because we do not have it calculated yet for N_2O.



Looking at the 95% confidence interval relative to the total emissions in Figure 12, we observe that the emissions together with the uncertainty band is having a decreasing trend towards 2012 with GAINS having the highest estimates. At the lowest -5% confidence is EDGAR. FAO and EDGAR are based on the UNFCCC data and therefore FAO was not taken into account for this analysis.

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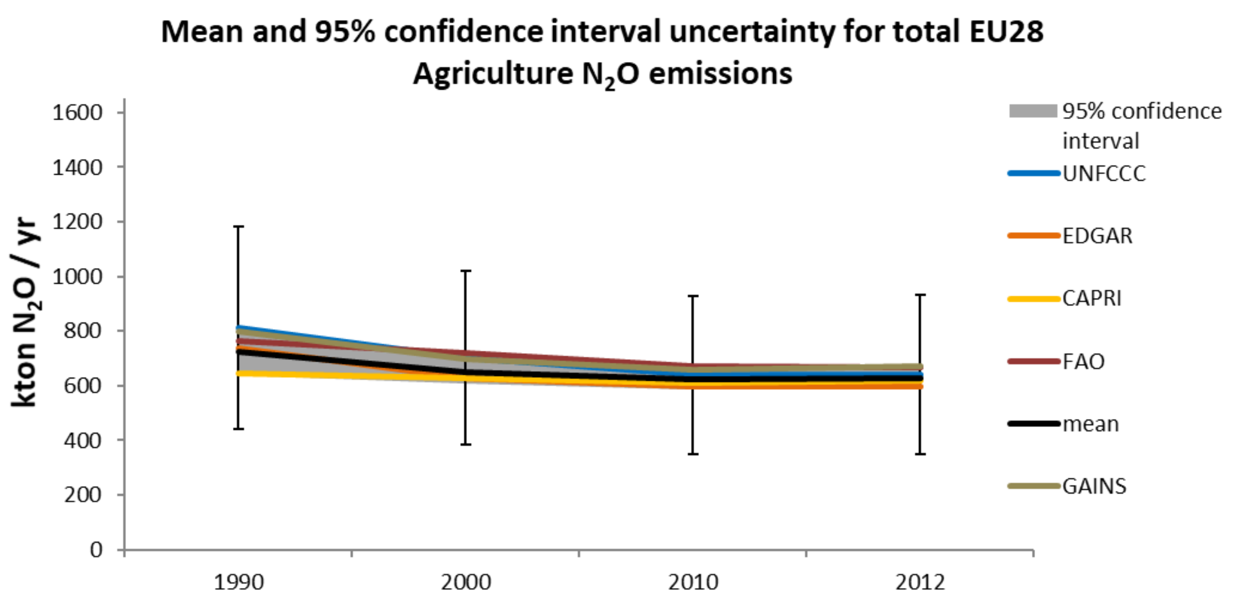
Figure 12. Mean and 95% confidence interval uncertainty in Agriculture total N_2O emissions calculated for the three main data sources, EDGAR, CAPRI and GAINS. The error bar on UNFCCC represent the uncertainty estimate for the EU28 Agriculture sector, calculated based on 81.4% uncertainty from manure management and 121.6% uncertainty for agricultural soils, from 2018 country submissions. We considered 0% the uncertainty from grazing and indirect emissions.



Currently within UNFCCC reporting system parties report their uncertainties which are calculated based on Tier 1 approach as described in the 2006 IPCC guidelines (https://www.ipcc-nggip.iges.or.jp/public/2006gl/). IPCC Guidelines (2006) suggest that moving from Tier 1 to higher Tiers may lead to a 10–20% decrease in the uncertainty of national emission factors associated to the physical processes involved. It should however be highlighted that complex, landscape dynamic models typically used in Tier 2–3 assessments also carry uncertainties (e.g. related to spatial and temporal aggregation schemes, applicability ranges, etc.) (Tubiello et al., 2013).

3.1.2. Natural CH_4 emissions

After CO_2, CH_4 is the second most important well-mixed greenhouse gas contributing to human-induced climate change. For the decade of 2000-2009, global emissions of methane averaged 548 (526-569) Tg CH_4 per year as estimated from atmospheric inversions (top-down approach) (Saunois et al., 2016). The global CH_4 sink is 540 (514–560) Tg CH_4 per year. The source–sink mismatch reflects, and is consistent with, the observed average imbalance in the atmosphere of 6 Tg CH_4 per year (the CH_4 growth rate). The sum of all sources as estimated from inventories and modeling (bottom-up approaches) is 678 (542-852) Tg CH_4, 20% higher than estimated from the top-down approach and reflecting the compounded uncertainties of the multiple CH_4 sources (Poulter et al., 2017).

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Wetlands are unique ecosystems because they are in general sinks for carbon dioxide and sources of methane. Their climate footprint therefore depends on the relative sign and magnitude of the land–atmosphere exchange of these two major greenhouse gases. This controversial climate footprint of wetlands is due to the difference in atmospheric lifetimes and the generally opposite directions of CO_2 and CH_4 exchanges, which leads to an uncertain sign of the net radiative budget. Wetlands in fact have a great potential to preserve the carbon sequestration capacity because near water-logged conditions reduce or inhibit microbial respiration, promoting meanwhile CH_4 production that may partially or completely counteract carbon uptake (Petrescu et al., 2015).

Natural emissions of CH_4 are 347 (238-484) Tg CH_4 for the decade of 2000-2009 and are dominated by emissions from wetlands (51-82%) (Global Carbon Project, http://www.globalcarbonproject.org/methanebudget/13/hl-compact.htm).

Scientific breakthroughs are needed to more accurately estimate methane emissions, particularly with a changing climate. First, annual to decadal CH_4 emissions from natural wetlands and other inland water systems are highly uncertain. The sum of all natural methane sources as inferred by process-based bottom up modelling is too large by about 30% compared to the constraint provided by methane atmospheric mixing ratios (Saunois et al., 2017). Second, the partitioning of CH_4 emissions and sinks by region and process needs to be better constrained by atmospheric observations and process-based models (Poulter et al., 2017).

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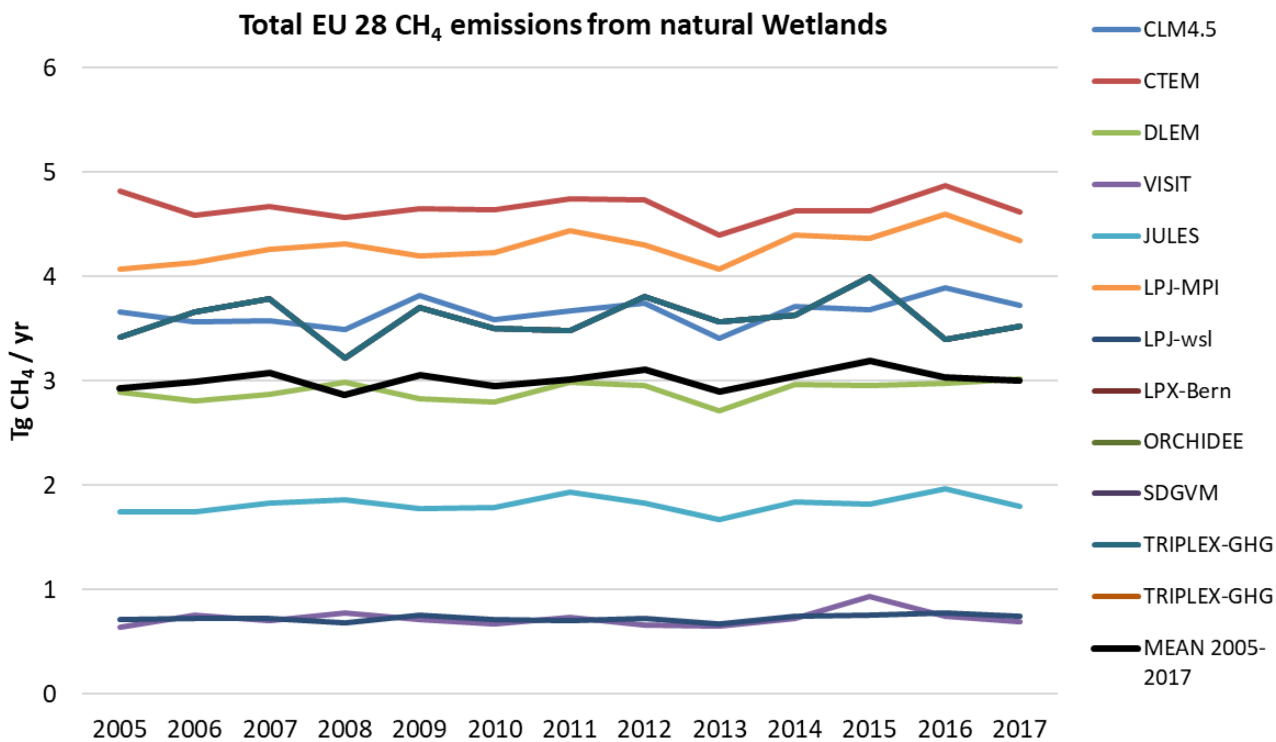
Figure 13: Average EU28 CH_4 emissions from natural wetlands for 2006-2012 with black line representing the mean of the 11 models (submitted to GCP 2018).



At European level the countries having the highest emissions (Figure 14) are Finland, Italy, Sweden, UK and Germany. For the moment the reporting of wetland emissions is since 2013 (ref. IPCC GL on wetland, as complement to IPCC 2006 GL) recommended under UNFCCC. From 2026 onwards, the accounting will become mandatory 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), i.e. the reported numbers will be compared to numbers in 2005-2009 and the difference (net-net) will count toward reaching the EU climate targets (G. Grassi, pers. comm).

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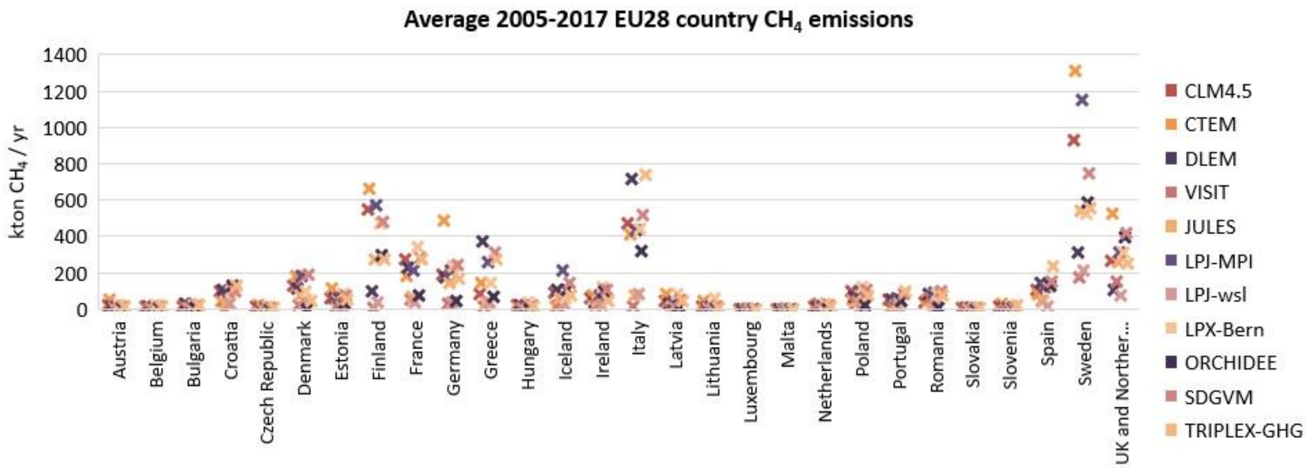
Figure 14. Distribution of natural CH_4 emissions from wetlands for all EU countries as simulated by model ensemble, average between 2005 and 2017 (submitted to GCP 2018).



3.1.3. Carbon emissions from the LULUCF sector

Achieving the 2°C temperature goal of the Paris Agreement requires forest-based mitigation (Grassi et al., 2018). In Europe forests act as a sink and forest management and its long tradition 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, which has put it on the political agenda as a mechanism for mitigating climate change (UN, Kyoto Protocol, 1998). Forest management not only influences the sink strength, it also changes forest structure, which affects the exchange of energy and water vapor with the overlying atmosphere (Naudts, et al 2016), therefore the potential of mitigating climate change involves accounting for the effects from both biogeochemical changes (greenhouse gas emissions) and biophysical changes (water and energy fluxes) (Luyssaert et al., 2014; Pielke et al., 2002, 2011).

A comprehensive assessment of the overall carbon stocks and fluxes of managed forests 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 different time periods (Kauppi et al., 1992; Karjalainen et al., 2003), using different approaches such as process-based ecosystem models (i.e.,Valentini et al.,2000) or estimates based on forest inventories(Liski et al., 2000) (Pilli et al., 2017).

All Parties to the UNFCCC are required to report national GHGs of anthropogenic emissions and removals, with different obligations for developed and developing countries (Supplementary Section 1). Under UNFCCC methodologies countries have to report net CO_2 emissions/removals for total LULUCF (taking into account all land uses) as well as Forest land Remaining forest land. When comparisons are made with modelled estimates one should be careful if all sources/sinks are taken into account.

Collective progress is needed towards meeting the goals of the Paris Agreement's Global stocktake. At present, there is a discrepancy of about 4 Gt CO_2 yr^{-1} in global anthropogenic net land-use emissions (Grassi et al., 2018) between models reflected in IPCC assessment reports and aggregated national UNFCCC GHG inventories. Grassi et al., 2018 shows that about 3.2 Gt CO_2 yr^{-1} can be explained by conceptual differences in anthropogenic forest sink estimation, related to the representation of environmental change impacts and the areas considered as managed.

For this report we are using the carbon data from modelled estimates of Net Biome Production (NBP). In general the definition of NBP is straight forward and implies 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 or a forest harvest) taking into account as well the net C balance of harvested products and C emitted by inland waters. The last GCP 2017 carbon budget highlighted harvest as one of the main uncertainties in the context of land use change.

Published estimates contain two main sources of uncertainties: a) differences due to input data and processes included in models have been described and sometimes quantified and account for about 50 % uncertainty in land use and land cover change (LULCC) estimates (Houghton et al., 2012); b) terminological differences that result from differences in definition. These differences result from ad hoc choices in the simulation setup, but are partly predetermined by the type of model used. The main three model types are: the bookkeeping models, the dynamic global vegetation models (DGVMs) and Earth system models (ESMs) linked with process based vegetation models (Pongratz et al., 2014).

According different sources differences in estimates can appear from the way different sources interpret and calculate the NBP. In our case the four data sources have all different ways of calculating and defining NBP:
- UNFCCC NBP is = 'net change' in 'carbon stock change in living biomass'.
- CBM NBP is = the difference between NEP and the direct losses due to harvest and natural disturbances (e.g., fires)
- TRENDY.v6 NBP is = Net flux between land and atmosphere defined as photosynthesis MINUS the sum of plant and soil respiration, carbon fluxes from fire, harvest, grazing, land use change and any other C flux in/out of the ecosystem (e.g. DIC, DOC, VOCs,...). Positive flux is into the land. NBP should be equal to changes in total carbon reservoirs.
- EFISCEN NBP is derived from total tree gross growth minus soil losses, minus (density related) mortality minus harvest.

a) Forest land remaining forest land (FL-FL)

Due to the different definitions for FL-FL we can only compare the NBP estimates simulated with CBM and EFISCEN and plotted them next to UNFCCC data from Tab 4 Forest land remaining forest land - sink cell B9 –(Net CO_2 emissions/removals) and Area Table 4.1 cell B7.

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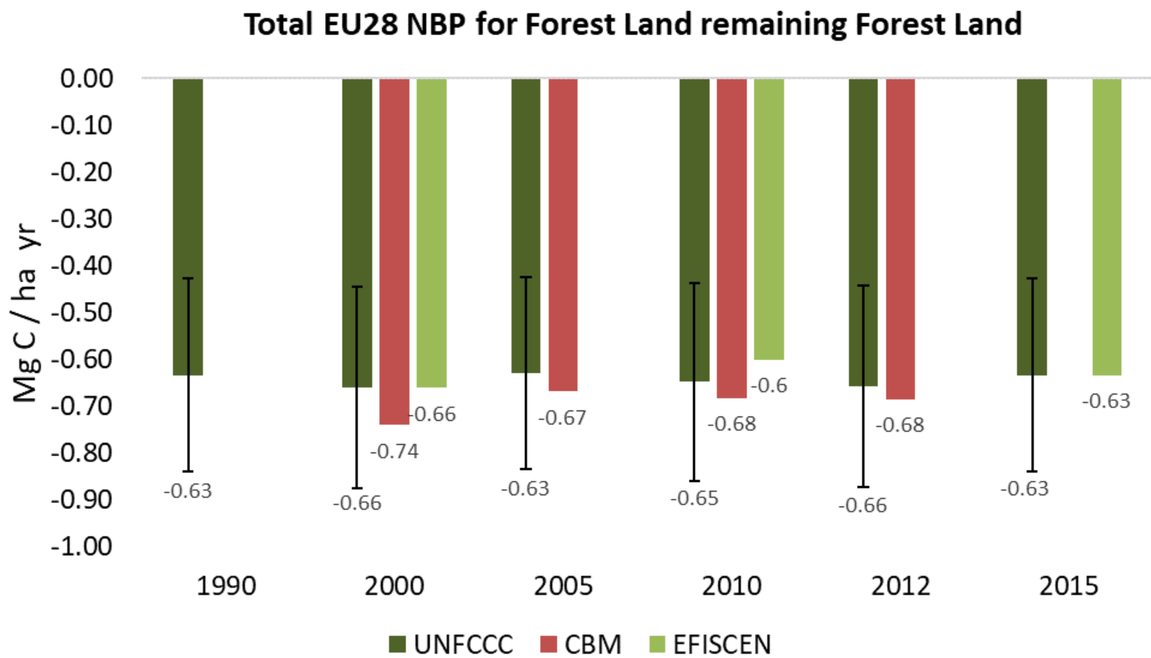
The error bar on UNFCCC value accounts for 32.6% and represent the total EU28 uncertainty on emissions for the LULUCF sector 4 from the 2018 country submissions. The estimates agree very well. One explanation for emissions similarities could be the fact that both models use forest inventory data as main source of input to describe the current structure and composition of European forest resources.

Figure 15: Total EU 28 NBP for FL-FL from CBM, EFISCEN and UNFCCC. Negative numbers denote land C uptake. EFISCEN data is only available for 2000, 2010 and 2015 while CBM data is available for 2000, 2005, 2010 and 2012.



b) All land uses

The second approach based on the NBP definitions is to compare estimates taking into account all land uses. For this purpose we can only use the TRENDY.v6 S3 ensemble simulations and UNFCCC data from Table 4 Total LULUCF– cell B7 (Net CO_2 emissions/removals) and the Area from Table 4.1 cell L17. There is a high variably between the eight DGVMs in all four years but most of them predict a net sink.

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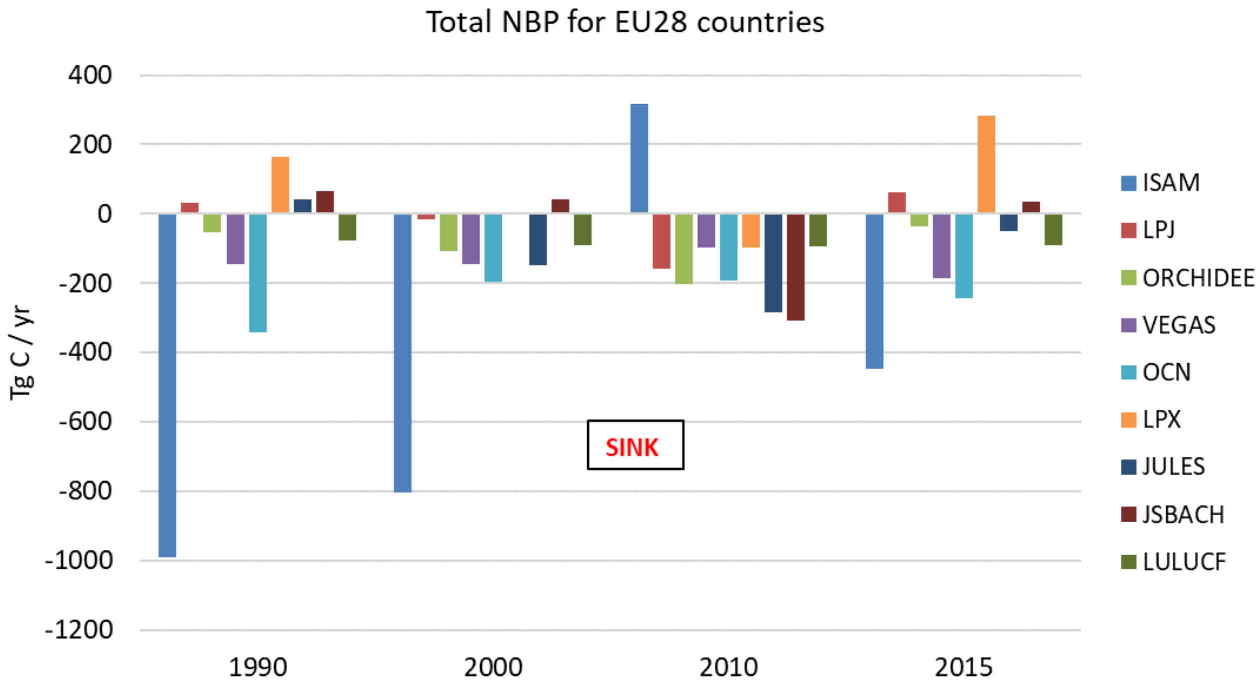
Figure 16: EU 28 total NBP from eight DGVMs from TRENDY.v6 compared to LULUCF country submissions from all land uses. Negative numbers denote land carbon uptake.



Below we calculated the 95% confidence interval for all models in the TRENDY.v6 ensemble and we added as dashed line the UNFCCC estimate together with error bar accounting for 32.6% uncertainty based on the total LULUCF sector as submitted in 2018. It is surprizing to see how the mean of these models agree with the UNFCCC values. This could be due to the fact that models have no forest demography and an overestimate of climate and CO_2 induced C sinks because of too high biomass turnover in the models (P. Ciais pers. comm).

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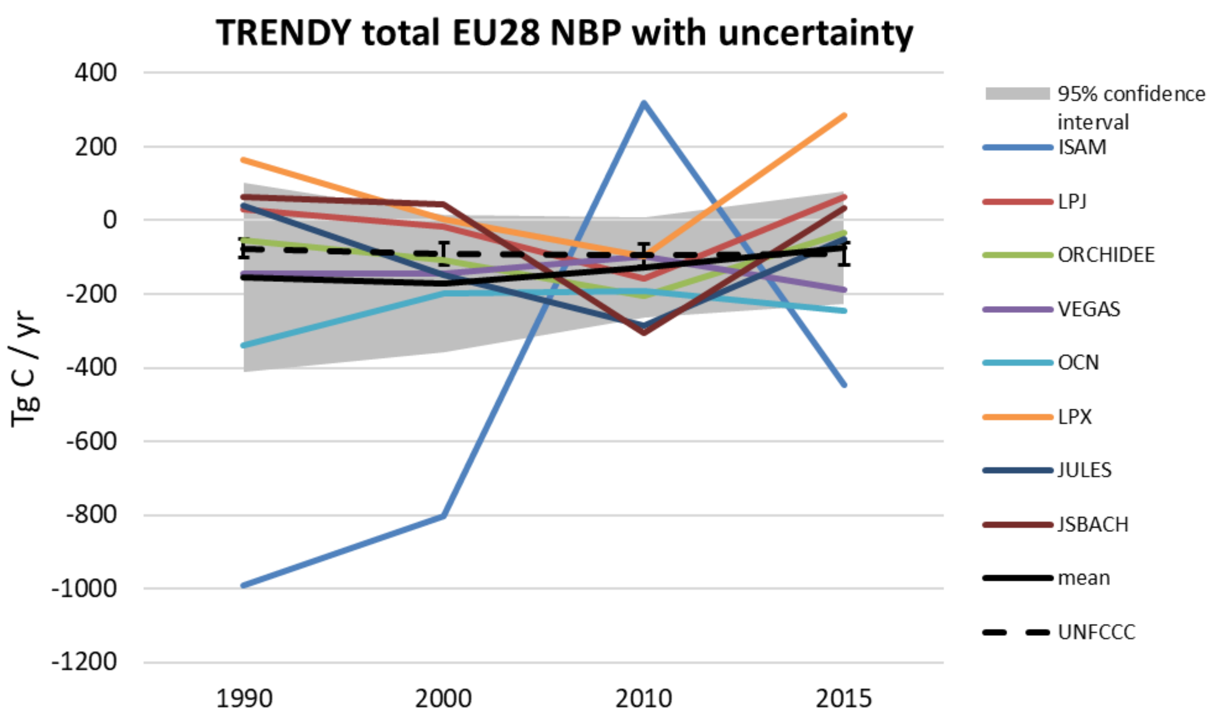
Figure 17: EU28 NBP from TRENDY.v6 models estimates and ensemble 95% confidence interval uncertainty. The error bar on UNFCCC represent the 32.6 % uncertainty estimate for the LULUCF sector, 2018 country submissions.



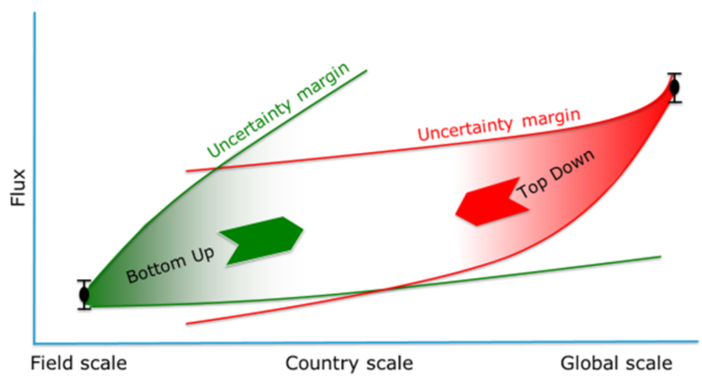
3.2. Top-down activity data and uncertainties

The atmosphere integrates the very heterogeneous fluxes of GHGs, resulting in gradients of GHG concentrations. Therefore, GHG concentration measurements obtained from ground-based stations and from satellites (Bergamaschi et al., 2013), can be used to estimate the fluxes using models of atmospheric transport and statistical optimization methods, called atmospheric inversions. The key sources of methodological uncertainty in the top-down approach are inaccuracies in modelled atmospheric transport, limited discretization of modelled fluxes, separation of the natural and anthropogenic part of the total column CO_2 measurements, poor quantification of a priori values and potential measurement biases .

The current atmospheric GHG network is coordinated by the Integrated Carbon Observation System (ICOS) infrastructure at the European level. VERIFY partners will develop inversions based on better, higher resolution, transport models to assimilate the precise ICOS GHG concentration data complemented by satellite retrievals of column CO_2 and CH_4 concentrations. The separation of fossil fuel emissions of CO_2 from natural sinks remains a fundamental research challenge. VERIFY will tackle it by using satellite and in situ measurements of ^{14}C and co-emitted tracers such as CO and NO_x produced during the combustion of fuels, based on pioneer work from e.g.

Konovalov et al. (2016). From the global increase in greenhouse gas concentrations, the global total fluxes are known very accurately and likewise at the field scale local measurements can be performed and fluxes are quantified very well. The biggest challenge remains the calculation of intermediate (e.g. country) scale uncertainty (Figure 18) of all sources because they will become larger upon extrapolation to other scales (Han Dolman, pers. comm.). This should be done by developing new measurement capabilities to reduce the uncertainties at those intermediate scales.

Figure 18: Bridging the scales towards the representation of a general methodology needed for total uncertainty calculation (Courtesy to Sander Houweling).



3.2.1. Inverse CH_4 and N_2O emissions

Global inverse models are widely used to estimate emissions of CH_4 at global/continental scale, using mainly high-accuracy surface measurements at remote stations (e.g. Bergamaschi et al., 2013; Bousquet et al.,2006; Mikaloff Fletcher et al., 2004a, b; Saunois et al., 2016).

Inverse modelling (top down) is a mass-balance approach, providing information from the integrated emissions from all sources. However, the quality of the derived emissions critically depends on the quality and density of measurements and the quality of the atmospheric models used. In particular, when aiming at verification of bottom-up inventories, thorough validation of inverse models and realistic uncertainty estimates of the top-down emissions are essential (Bergamaschi et al., 2018). Bergamaschi et al. (2015) showed that the range of the derived total CH_4 emissions from north-western and eastern Europe using four different inverse modelling systems was considerably larger than the uncertainty estimates of the individual models.

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Figure 19. Total inverse CH_4 emissions for all anthropogenic sectors for EU28 from an inverse model ensemble (Bergamaschi et al., 2018). Natural emissions (NAT) are from WETCHIMP inter-comparison (Melton et al., 2013).

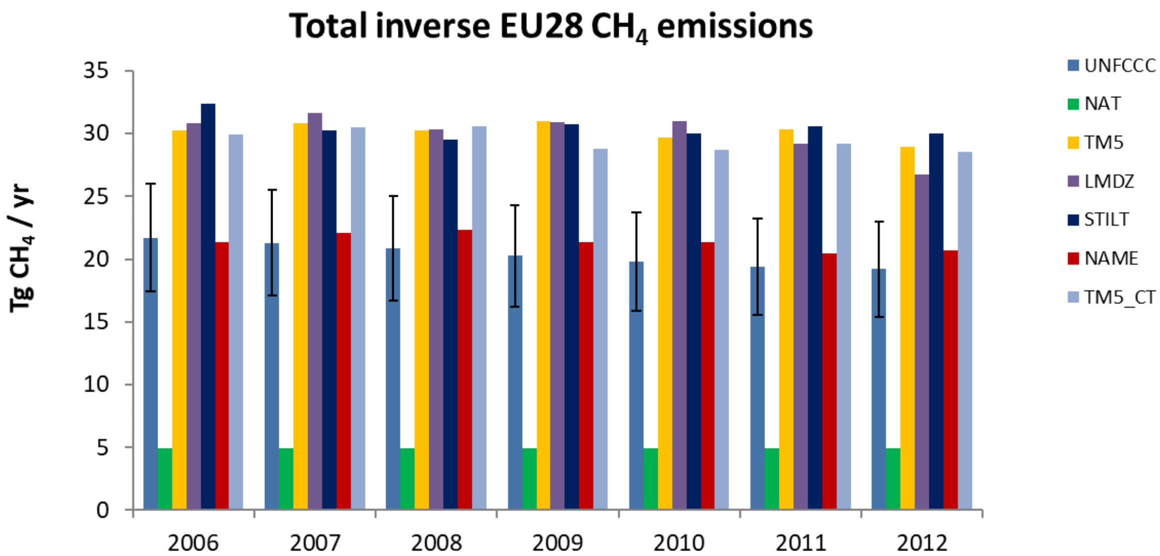

Figure 19 shows the total European CH_4 emissions (average 2006–2012) derived from five inverse models (Bergamaschi et al., 2018). The results show in general a good agreement between the models, especially for TM5-4DVAR, LMDZ, STILT, and TM5_CT, while the NAME models provides generally lower estimates. The difference with emissions from UNFCCC country submissions could be partly due to natural CH_4 sources such as peatlands, wetlands, and wet soils, which are estimated to be 4.3 (2.3–8.2) Tg CH_4 yr^{-1} based on the Wetland and Wetland CH_4 Inter-comparison of Models Project (WETCHIMP). The error bar on the UNFCCC estimates was calculated in Bergamaschi et al. (2015) and represents the relative UNFCCC uncertainty for all anthropogenic EU28 emissions excl. LULUCF and accounts for 19.8%.

Global atmospheric inversions of N_2O provide a mass balance constraint on the N_2O budget, estimating the total emission from land and ocean while either calculating or using a prescribed value for the atmospheric sink. Inversion estimates for the global source of N_2O vary from 15.9 to 18.8 Tg N yr^{-1} (Hirsch et al., 2006; Huang et al., 2008; Saikawa et al., 2014; Thompson et al., 2014b; Wells et al., 2018). Top-down approaches, use atmospheric measurements of N_2O, which are related to the emissions through atmospheric mixing and transport (JRC InGOS report). A dataset of atmospheric N_2O in situ measurements from 13 European stations has been prepared by adjusting all observations to a common calibration scale. This dataset has been used to derive European N_2O emissions for 2006 to 2012, applying four different inverse modelling systems (Fig. 20) (Inverse modelling workshop report, Bergamaschi et al., 2018). The top-down estimates of total N_2O emissions for EU28 are broadly consistent with the values reported to the UNFCCC within the very large uncertainties (~100%) of the reported values. However the top-down estimates are in the upper part of UNFCCC uncertainty range.

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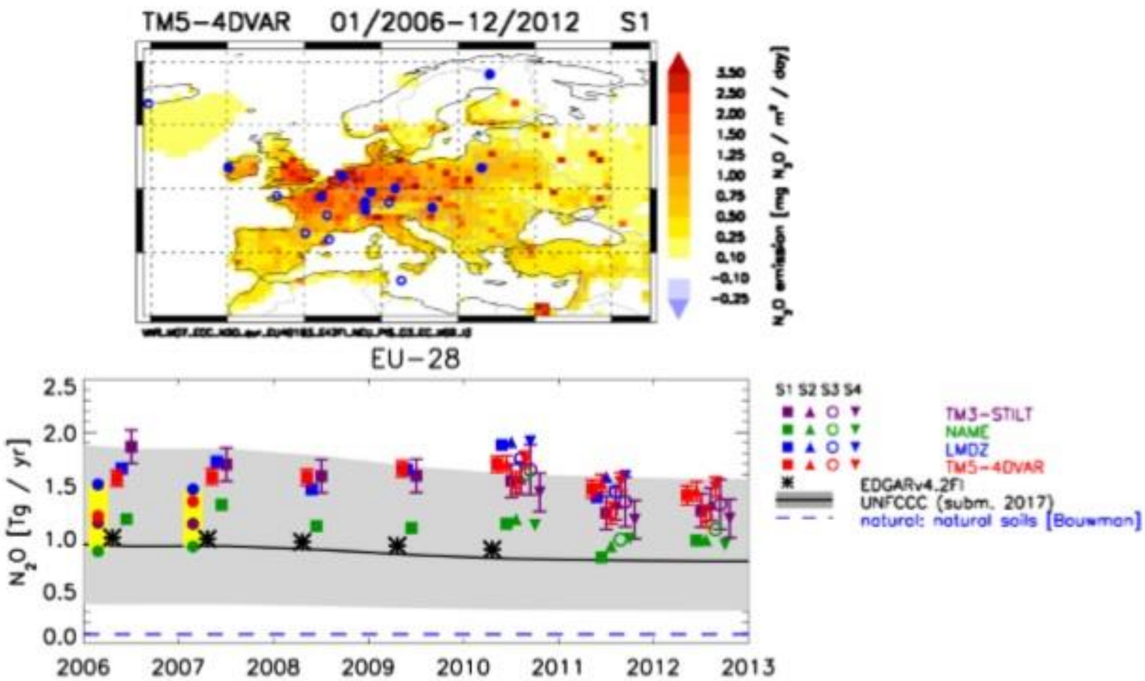
Figure 20: European N_2O estimates from InGOS inverse modelling workshop report (Bergamaschi et al., 2018). Top: European N_2O emissions derived from one of the applied inverse models; blue circles are the locations of the measurement stations. Bottom: EU28 annual total N_2O emissions derived by four different inverse models (colored symbols). Anthropogenic N_2O emissions reported to UNFCCC (submission 2017) are shown by the black line and the estimate of natural soil N_2O emissions (Bouwman et al., 1995) are shown by the blue dashed line.



The natural N_2O emissions are assumed to be small, but should be better quantified in the future to allow a more accurate comparison between bottom-up (anthropogenic sources only) and top-down estimates. The range of the top-down estimates of the applied model ensemble is smaller than the uncertainty range of the bottom-up inventories, which demonstrates the potential of inverse modelling to significantly reduce the uncertainties in emission estimates. In addition, the top-down estimates all show a negative trend in emissions, consistent with the UNFCCC and global inversion estimates.

3.2.2. Inverse total natural CO_2 fluxes

Atmospheric inversions or top-down analyses provide estimates of carbon fluxes that are optimally consistent with atmospheric CO_2 concentration measurements, but that depend on the choice of an atmospheric transport model. The inversion approach provides coarse scale CO_2 fluxes. Its resolution and precision depends on the regional density of atmospheric networks, and on the assigned prior error budgets. Inversions result are ‘comprehensive’ in the sense that all CO_2 fluxes, inclusive of fossil fuel emissions, plus all ecosystems sources and sinks plus all other

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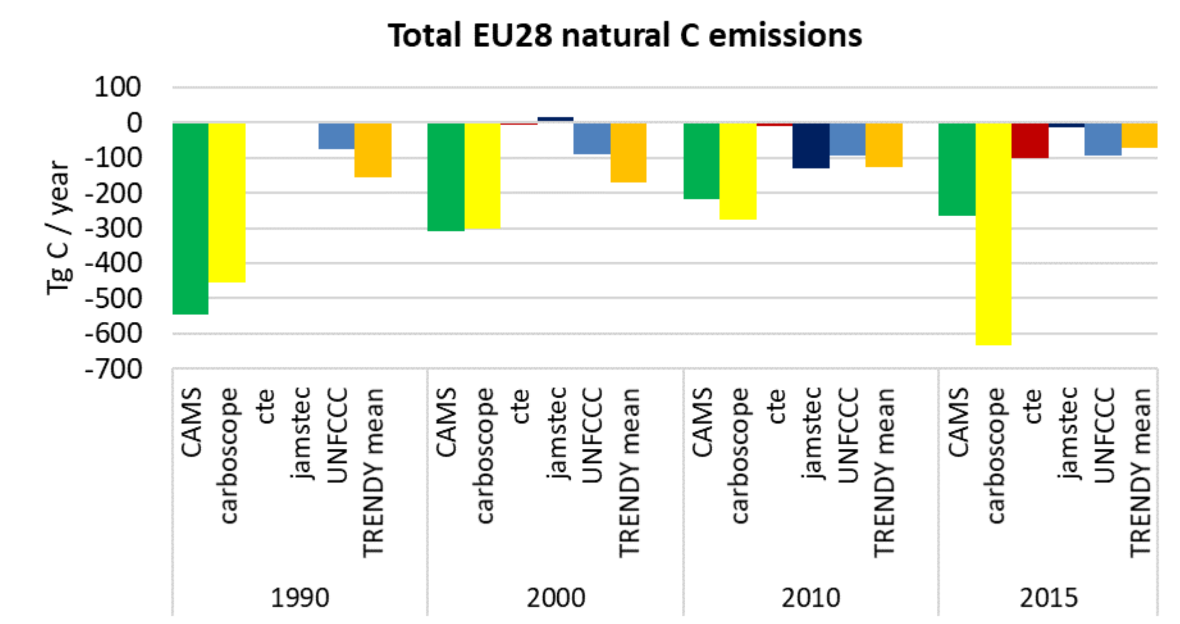
processes emitting or absorbing CO_2, are in principle captured by the atmospheric signals (http://www.globalcarbonproject.org/reccap/protocol.htm)
The four global inversion systems used in this report are the CarbonTracker Europe (CTE; van der Laan-Luijkx et al., 2017), the Jena CarboScope (Rödenbeck, 2005), CAMS (Chevallier et al., 2005) and Jamstec (Model of the Japan Agency Marine-Earth Science and Technology). We present below their C estimates from atmospheric inversions for four years, 1990, 2000, 2010 and 2015 compared to total EU28 natural carbon emissions from UNFCCC and TRENDY.v6 mean.

Between the four models we observe that there is a good agreement between two of them, CAMS and CarboScope_85 while CTE considerably underestimates the emissions. The fourth one, Jamstec has only emissions for 2010 and 2015 and underestimates as well the emissions in 2015 while in 2010 reports a source. The first three inversions use atmospheric CO_2 observations from various flask and in situ networks. The three inversions are based on the same Bayesian inversion principles that interpret the same, for the most part, observed time series (or subsets thereof) but use different methodologies. These differences mainly concern the selection of atmospheric CO_2 data, the used prior fluxes, spatial breakdown (i.e. grid size), assumed correlation structures, and mathematical approach. Other differences may also be related to their interhemispheric transport and other inversion settings. (Le Quere et al., 2017). The details of these approaches are documented extensively in the references provided above.

Figure 21: Total EU28 natural carbon emissions from four global GCP inversions plotted against UNFCCC and TRENDY.v6 mean for four years. The negative signs denote land uptake.



When we compare it with UNFCCC country submissions and mean TRENDY.v6 estimates which agree well, we observe that there is a factor 2 or higher overestimation from the inverse models. One reason could be the fact that TRENDY.v6 models do not include lateral transport of carbon

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by rivers but it is taken into account by inversions. Another difference can come from different bottom-up (TRENDY.v6) and top-down (GCP) approaches and methodologies. In the future we expect to be able to use the EUROCOM high resolution inversions (https://eurocom.icos-cp.eu/).

3.3. Country specific examples

From the EU28 level we downscaled and looked at some individual countries. We selected six countries/groups which are best constrained by atmospheric observations as defined by the inverse CH_4 emissions model setup of Figure 18. These example countries/groups are Germany, France, UK+Ireland, BENELUX, Czech Republic and Poland.

3.3.1. CH_4

a) Agriculture

Below (Figure 22) we plotted the agriculture CH_4 emissions for Enteric Fermentation, Manure Management and Rice Cultivation for the selected six countries/groups for five data sources (UNFCCC, EDGAR, CAPRI, FAO and GAINS).

We note that within its current model setup GAINS does not differentiate between enteric and manure emissions, therefore the values include both of them. The reason is that GAINS first split livestock by type of manure management (liquid or solid). Then only for animals on liquid manure management GAINS accounts separately for enteric and manure emissions. For animals on solid manure systems only the sum of emissions is calculated. For most countries CAPRI simulates the highest emissions from enteric fermentation. The difference is caused by the very detailed choice of activity data and emission factors used by the model but exactly how this may trigger such high emissions needs to be further investigated.

The error bars EDGAR provide represent the asymmetric uncertainty minimum and maximum calculated as lognormal distribution. For BENELUX, CZE+SVK and UK+IRL the uncertainty were calculated applying the correlated uncertainty calculation formula. To note that this data is preliminary and needs to be updated.

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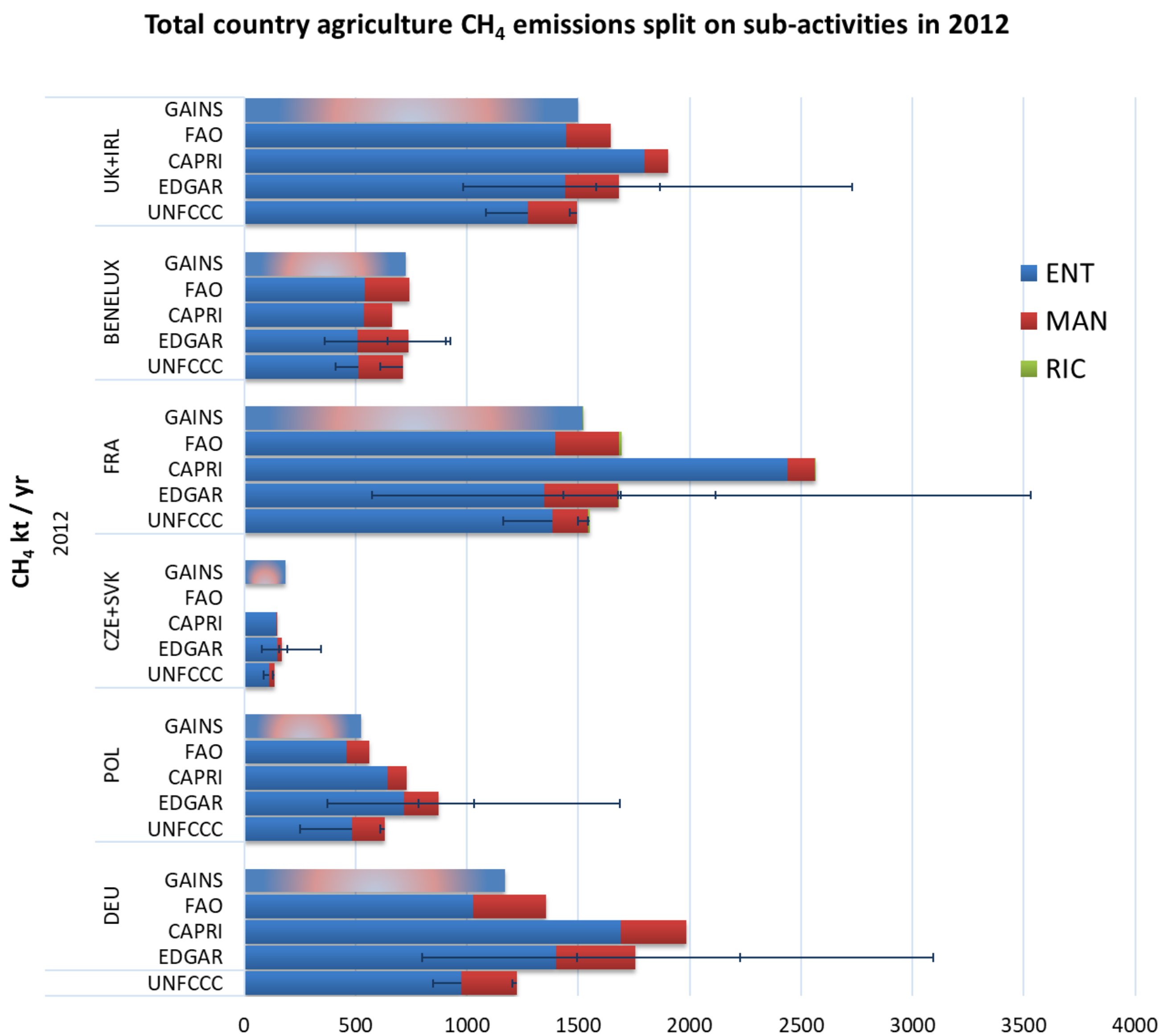
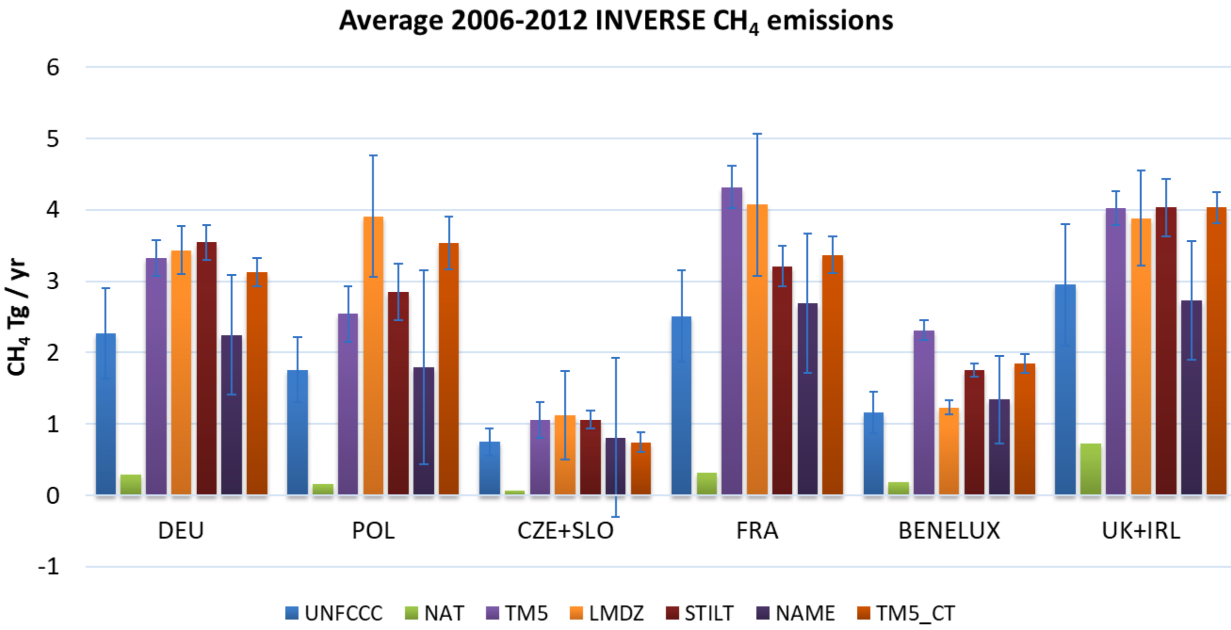
Figure 22: Agriculture CH_4 emissions for six EU countries in 2012. The emissions are split in three activities: enteric fermentation (blue), manure management (red) and only for France rice cultivation (green). Note that emissions from GAINS are the sum of enteric fermentation and manure management.



b) All anthropogenic sources

Using the same ensemble of models as Figure 12 we highlight below in Figure 23 the current situation and CH_4 budgets from Inverse simulations performed with the ensemble of five models (TM5, LMDZ, STILT, NAME and TM5-CT). We observe that there is a reasonable agreement between UNFCCC and the models. The differences in system boundary can be explained by the natural emissions (plotted in green) which can be seen in more detailed in Figure 12.

Figure 23: Average CH_4 emissions for six countries/groups as simulated by an ensemble of five models and compared to UNFCCC (blue) and natural (NAT (green)) wetland CH_4 emissions from WETCHIMP model inter-comparison.



In Figure 24 we calculated the confidence interval based on all sources except UNFCCC estimate. We can notice again a close agreement between the mean and the UNFCCC.

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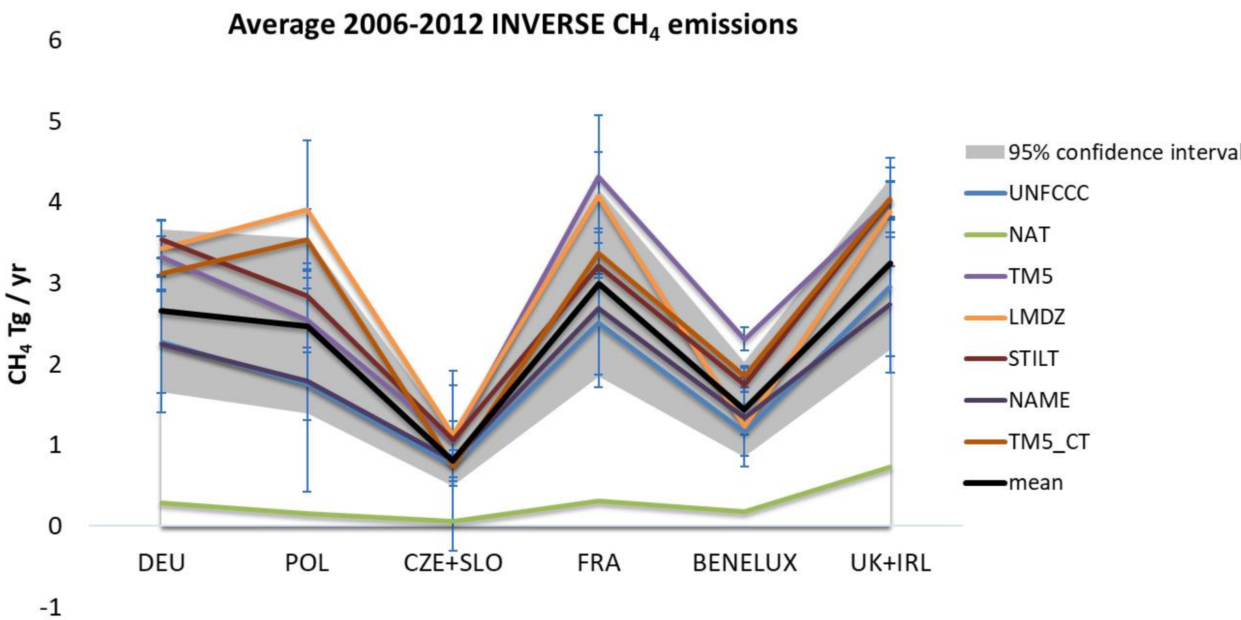
Figure 24: Average CH_4 emissions for 2006-2012 from inverse ensemble with 95% confidence interval uncertainty, without the UNFCCC value. The error bars represent the uncertainties calculated for each model (as in Bergamaschi et al., 2018). The error bar on the UNFCCC estimate accounts for 5 % excl. LULUCF and was calculated for all EU28 countries and all anthropogenic sectors, according to 2018 country submissions for the 2012-2016 inventories. The NAT (natural) CH_4 emissions are from the WETCHIMP (Melton et al., 2013) model intercomparison.



3.3.2. N_2O-N direct soil emissions

N_2O fluxes from agricultural soils are the most uncertain emissions source in GHG inventories submitted to the UNFCCC annually. The reason is that N_2O fluxes are characterized by a very large spatial and temporal variability due to their strong dependence on environmental factors. Soil type farm management including nitrogen additions, concentration of organic material in the soil, temperature, precipitation and drainage all influence the level of N_2O fluxes that are measured in the field (Leip et al., 2011).

Even though models have been applied on a national and even continental scale there is a trade-off between model complexity and data availability, thus making the results at small geographical scales highly uncertain. This is a clear drawback since the use of default (IPCC tier 1) or soil and land-use dependent emission factors (IPCC Tier 2) do not capture in sufficient detail the impacts of land (Lugato et al., 2017). Leip et al., 2010 concludes that N_2O emissions from agricultural soils are found to dominate the uncertainty. If uncertainties are combined for the whole of Europe the correlation plays an important role. The biggest challenge seems to be to conceptually harmonize the uncertainty estimates for the activity data (which tend to be underestimated) and emission factors (which tend to be overestimated).

In their study Leip et al. (2011) looked at different estimates from models and compared the N_2O-N soil fluxes to EDGAR and UNFCCC emissions as an average of 1990-2000. We define that study as being a pre VERIFY estimate and we aim to monitor whether during future years these estimates have improved.

Therefore, for the same countries/groups as used by inverse models (POL, DEU, CZE, FRA, BENELUX and UK+IRL), we looked at estimates from UNFCCC, EDGAR, CAPRI, GAINS and FAO for 1990-2000 (as in Leip et al., 2011 study) and 2001-2012 for the pre-VERIFY data including the DayCent model described in Lugato et al. (2017) and Parton et al. (1988).

The results show a very good match between sources with decreasing emission tendency towards 2012.

Table 2: Estimates of direct N_2O fluxes from agricultural soils (Gg N_2O-N yr^{-1}) by the different model approaches for the six countries or country groups considered as in Leip et al., 2011. Comparison is made with estimates from pre-VERIFY data (UNFCCC, EDGARv4.2, CAPRI and FAO) for 1990-2000 and with UNFCCC, EDGARv4.2, CAPRI and FAO and Lugato et al.,2017 for 2001-2012.

N_2O -N kt / yr	average 1990-2000						
pre VERIFY (Leip et al., 2011)							
	Germany	Poland	Czech Republic	France	BENELUX	UK_IRE	Total
TM5-4DVAR a priori	43	27	13	49	12	40	184
TM5-4DVAR a posteriori	55	29	16	61	13	37	211
INTEGRATOR	39	18	13	51	18	43	182
EDGARv4.0	46	27	12	50	12	43	190
FISE	40	32	20	37	8	57	194
SuB-FIE-JRC	49	20	14	64	17	45	208
DNDC	59	59	21	46	15	26	227
IDEAg	55	48	38	53	14	22	229
UNFCCC	63	26	16	66	18	47	236
SuB-JRC	59	42	26	77	17	49	270
pre VERIFY data collection	average 1990-2000						
UNFCCC	55	29	8	75	29	41	237
EDGARv4.2	42	26	4	40	12	26	150
CAPRI	51	20	4	50	18	36	179

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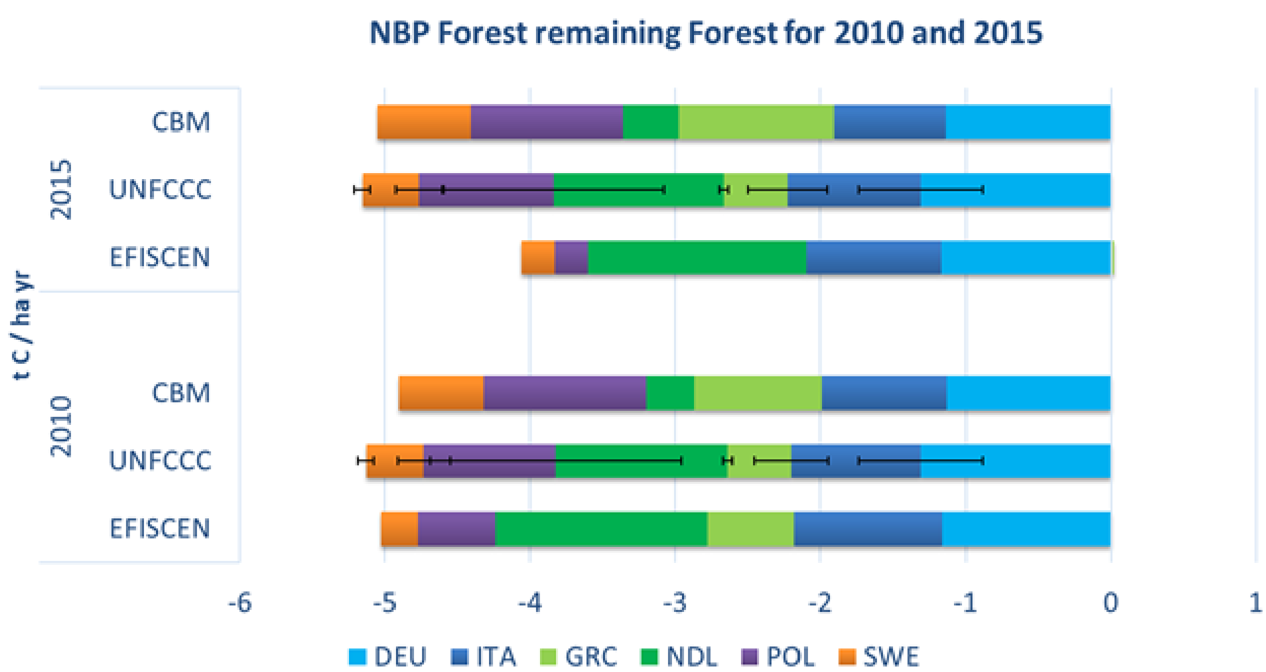
FAO	42	20	NA	53	11	40	166
	average 2001-2012						
UNFCCC	54	28	7	72	21	37	219
EDGAR	42	26	4	39	10	23	144
CAPRI	52	23	6	50	17	36	184
FAO	39	22	NA	49	14	34	158
Lugato et al., 2016 (2010-2014)	61	38	7	77	18	71	272

3.3.3. Carbon

For Carbon as NBP we looked at some examples of countries which have different land uses, for example Poland a country with intensive agriculture versus Sweden where forests are predominant, Greece with a dry climate versus Netherlands with wet climate, while Italy and Germany have similar climate, area and mix of forest/agricultural land. From Figure 25 we see that, except for Greece in 2015 when EFISCEN predicted a source, all countries report sinks.

Figure 25: Forest remaining Forest total NBP from three sources (CBM, UNFCCC and EFISCEN) for 2010 and 2015 for six countries. Negative sign denotes carbon sink.



In terms of comparability between models and country estimates we see that Germany, Italy, Poland and Sweden are best simulated by the two models compared to UNFCCC, CBM giving the best estimate. There is a larger variability between estimates from smaller countries.

This study did not look into other sources for C losses except for data on soil eroded C. In Lugato et al. (2016) the cumulative soil organic carbon (SOC) for the EU level, totaled 0.010 Pg C yr^{-1} which represents a very small amount compared to the total SOC stock of 14.9 Pg C in the top 0–30 cm and about 1% of annual net primary production.

4. Summary and Conclusions

After analyzing all the data we note that for CH_4 and N_2O the main differences may be caused by the following:

Different AD and EFs are not always easy to find (sometimes given individual expert judgment);
Different methodology is used for uncertainty calculation – countries reporting to UNFCCC use mainly Tier 1 approach as described by the IPCC guidelines while models run with more accurate data being able to disaggregate better the activities.

We also noticed the fact that not all countries report sub-sectoral uncertainties (e.g. Greece for grazing, not presented in this report) and that emissions or uncertainties methodologies for uncertainty calculation differ even within model ensembles.

For carbon (NBP) we noticed that the main problem triggering different estimates are the definitions used by different models. There is not always consistency in model set-up and a model ensemble shows very large range of estimates where not always uncertainties are available.

We conclude that, at EU28 level, countries are generally doing well in reporting their total greenhouse gas budget but there is room for improvement mainly when looking at differences between UNFCCC Tier 1 and models at Tier 2 or 3 (e.g. for CH_4 from agriculture 10-20% difference). To be able to reduce these differences between estimates we will need more data, more information on the uncertainties, to start narrowing down the analysis to sensitive parameters (AD, EF) which may trigger the differences.

There is also a 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.

The following matrix summarizes our current best estimates for the total EU28 estimates for CH_4, N_2O and C (NBP):

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	2012 Total EU28 CH_4 emissions kt / yr									Inversions (Peter B.)				
	Sector	UNFCCC	uncertainty emissions UNFCCC	EDGAR	CAPRI	GAINS	FAO	WETCHIMP	GCP (Ben Poulter) (average 11 models)	TM5	LMDZ	STILT	NAME	TM5_CT
1A	Energy Industries	2088	336	923		1088								
1.B.1	Fugitive emissions from solid fuels	1274	171	1054		1757								
1.B.2	Fugitive emissions from oil and gas	1432	192	3359										
2.B	Chemical Industry	56	7	18										
2.C	Metal Industry	7	1	1										
3.A	Enteric Fermentation	8304	996	7576	10609									
3.B	Manure management	1816	343	2263	1168	8951	8115							
3.C	Rice Cultivation	110	20	103	92									
3F	Agricultural field burning	38	20	48		99								
5.A	Solid Waste Disposal	4672	626	4978		4472								
5.D	Wastewater Treatment and Discharge	816	109	1921		757								
	TOTAL Anthropogenic	20612								28980	26760	30020	20670	28510
	Natural wetlands							4930	3039.16					

	2012 Total EU28 N_2O emissions kt / yr							
	Sector	**UNFCCC**	**uncertainty emissions UNFCCC**	**EDGAR**	**CAPRI**	**GAINS**	**FAO**	**Inversions InGOS**
1A	Energy Industries	100	2	247		98		
1.B.2	Fugitive emissions from oil and gas	0	0	0				
2.B	Chemical Industry	33	3	128		44		
2D +2G	Solvent and other product use	14		17		25		
3B2	Manure management	77	63	49	73	67	45	
3D1	Direct soil emissions		548		443			
3D12a	Manure in pasture/range/paddock	568	91	627	259	604	556	
3D2	Indirect N2O from agriculture		124		88			
3F	Agricultural waste burning	1	1	1				
5C	Waste incineration	2	3	1				
5D	Wastewater Treatment and Discharge	27	37	33		52		
5E	Other waste handling	0	0	4				
	TOTAL anthropogenic	**822**		**1108**	**863**	**890**	**601**	**~1500**

2012 Total EU28 C (NBP) emissions Mg C / ha yr						
Sector			UNFCCC	uncertainty emissions UNFCCC	CBM	EFISCEN (2015)
4	LULUCF	FL-FL	-0.66	-0.13	-0.68	-0.63
2015 Total EU28 C (NBP) Tg C / yr						
			UNFCCC	uncertainty	TRENDY	Lugato et al., 2016
4	Average	All land uses	-91.96	-29.98	-72.06	
		Eroded C soils				10.00

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Further steps:

Based on the conclusion of this report we need to further investigate:

- *Why UNFCCC has consistent high emissions?*
- *What is the individual model setup and basic assumptions each model uses?*
- *How are all sub-sectoral / sectoral emissions aggregated for each data source?*
- *Which are the exact sources for activity data and emissions factors?*
- *How to calculate total country uncertainty from all sources and all sectors looking at uncertainty versus variance?*

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5. References

Annual European Union greenhouse gas inventory 1990–2016 and inventory report 2018: https://www.eea.europa.eu//publications/european-union-greenhouse-gas-inventory-2018

Bouwman A. F., K. W. Van Der Hoek, J. G. J. Olivier (1995). Uncertainties in the global source distribution of nitrous oxide. *Journal of Geophysical Research*, *100*(D2), pp. 2785-2800.

Bergamaschi, P., A. Danila, R. F. Weiss, P. Ciais, R. L. Thompson, D. Brunner, I. Levin, Y. Meijer, F. Chevallier, G. Janssens-Maenhout, H. Bovensmann, D. Crisp, S. Basu, E. Dlugokencky, R. Engelen, C. Gerbig, D. Günther, S. Hammer, S. Henne, S. Houweling, U. Karstens, E. Kort, M. Maione, A. J. Manning, J. Miller, S. Montzka, S. Pandey, W. Peters, P. Peylin, B. Pinty, M. Ramonet, S. Reimann, T. Röckmann, M. Schmidt, M. Strogies, J. Sussams, O. Tarasova, J. van Aardenne, A. T. Vermeulen, F. Vogel, Atmospheric monitoring and inverse modelling for verification of greenhouse gas inventories, EUR 29276 EN, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-88938-7, doi:10.2760/759928, JRC111789.

Bergamaschi, P., Karstens, U., Manning, A. J., Saunois, M., Tsuruta, A., Berchet, A., Vermeulen, A. T., Arnold, T., Janssens-Maenhout, G., Hammer, S., Levin, I., Schmidt, M., Ramonet, M., Lopez, M., Lavric, J., Aalto, T., Chen, H., Feist, D. G., Gerbig, C., Haszpra, L., Hermansen, O., Manca, G., Moncrieff, J., Meinhardt, F., Necki, J., Galkowski, M., O'Doherty, S., Paramonova, N., Scheeren, H. A., Steinbacher, M., and Dlugokencky, E.: Inverse modelling of European CH4 emissions during 2006–2012 using different inverse models and reassessed atmospheric observations, Atmos. Chem. Phys., 18, 901-920, https://doi.org/10.5194/acp-18-901-2018, 2018.

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 CH_4 and N_2O emissions based on four different inverse models, Atmos. Chem. Phys., 15, 715–736, https://doi.org/10.5194/acp-15-715-2015, 2015.

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 CH_4 in the first decade of the 21st century: Inverse modeling analysis using SCIAMACHY satellite retrievals and NOAA surface measurements, J. Geophys. Res.-Atmos., 118, 7350–7369, https://doi.org/10.1002/jgrd.50480, 2013.

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.

VERIFY is a research project funded by the European Commission under the H2020 program. Grant Agreement number 776810.

Chevallier, F., Fisher, M., Peylin, P., Serrar, S., Bousquet, P., Bréon, F.-M., Chédin, A., and Ciais, P.: Inferring CO_2 sources and sinks from satellite observations: Method and application to TOVS data, J. Geophys. Res., 110, D24309, https://doi.org/10.1029/2005JD006390, 2005.

Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J., Chhabra, A., DeFries, R., Galloway, J., Heimann, M., Jones, C., Le Quéré, C., Myneni, R. B., Piao, S., and Thornton, P.: Carbon and Other Biogeochem. Cy., in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013.

Denman, K.L., G. Brasseur, A. Chidthaisong, Ph. Ciais, P. Cox, R.E. Dickinson, D. Hauglustaine, C. Heinze, E. Holland, D. Jacob, U. Lohmann, S. Ramachandran, P.L. da Silva Dias, S.C. Wofsy, X. Zhang, 2007: Couplings Between Changes in the Climate System and Biogeochemistry, Chapter 7 in: Climate Change 2007: The Physical Science Basis, The IPCC Fourth Assessment Report, Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge.

EU LULUCF Regulation, article 7https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.156.01.0001.01.ENG&toc=OJ:L:2018:156:FULL – last access September 2018

EUROCOM high resolution inversions (https://eurocom.icos-cp.eu/).

Friedlingstein, P., Houghton, R. A., Marland, G., Hackler, J., Boden, T. A., Conway, T. J., Canadell, J. G., Raupach, M. R., Ciais, P., and Le Quéré, C.: Update on CO_2 emissions, Nat. Geosci., 3, 811–812, doi:10.1038/ngeo1022, 2010.

Grassi Giacomo, Jo House, Werner A. Kurz, Alessandro Cescatti, Richard A. Houghton, Glen P. Peters, Maria J. Sanz, Raul Abad Viñas, Ramdane Alkama, Almut Arneth, Alberte ondeau, Frank Dentener, Marianela Fader, Sandro Federici, Pierre Friedlingstein, Atul K. ain, Etsushi Kato, Charles D. Koven, Donna Lee, Julia E. M. S. Nabel, Alexander A. Assikas, Lucia Perugini, Simone Rossi, Stephen Sitch, Nicolas Viovy, Andy Wiltshire & Sönke Zaehle (2018) Reconciling global-model estimates and country reporting of anthropogenic forest CO_2 sinks, N*ature Climate Change* volume 8, pages914–920.

Global Carbon Project, http://www.globalcarbonproject.org/methanebudget/13/hl-compact.htm - last access October 2018

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:1010.1029/2004GB002443, doi:doi:10.1029/2004GB002443, 2006.

VERIFY is a research project funded by the European Commission under the H2020 program. Grant Agreement number 776810.

Höglund-Isaksson, L. Global Anthropogenic methane emissions 2005-2030: technical mitigation potentials and costs. *Atmospheric Chemistry and Physics* 12:9079-9096 (2012)

Houghton, R., J. House, J. Pongratz, G. van der Werf, R. DeFries, M. Hansen, C. L. Quéré, and N. Ramankutty (2012), Carbon emissions from land use and land-cover change, Biogeosciences, 9(12), 5125–5142.

http://www.globalcarbonproject.org/reccap/protocol.htm

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 multinetwork measurements, a chemical transport model, and an inverse method, J. Geophys. Res.Atmos., 113(D17), doi:10.1029/2007jd009381, 2008.

IPCC guidelines 2006 https://www.ipcc-nggip.iges.or.jp/public/2006gl/ - last access September 2018.

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.

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.

Kim Naudts, Yiying Chen, Matthew J. McGrath, James Ryder, Aude Valade, Juliane Otto, Sebastiaan Luyssaert, 2016, Europe'sforest management did not mitigateclimatewarming, Science, VOL 351 ISSUE 6273, doi10.1126/science.aac9976.

Kirschke, S., P. Bousquet, P. Ciais, M. Saunois, J.G. Canadell, E.J. Dlugokencky, P. Bergamaschi, D. Bergmann, D.R. Blake, L. Bruhwiler, P. Cameron-Smith, S. Castaldi, F. Chevallier, L. Feng, A. Fraser, M. Heimann, E.L. Hodson, S. Houweling, B. Josse, P.J. Fraser, P.B. Krummel, J.-F. Lamarque, R.L. Langenfelds, C. Le Quéré, V. Naik, S. O'Doherty, P.I. Palmer, I. Pison, D. Plummer, B. Poulter, R.G. Prinn, M. Rigby, B. Ringeval, M. Santini, M. Schmidt, D.T. Shindell, I.J. Simpson, R. Spahni, L.P. Steele, S.A. Strode, K. Sudo, S. Szopa, G.R. van der Werf, A. Voulgarakis, M. van Weele, R.F. Weiss, J.E. Williams, and G. Zeng, 2013: Three decades of global methane sources and sinks. *Nature Geosci.*, 6, 813-823, doi:10.1038/ngeo1955.

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

VERIFY is a research project funded by the European Commission under the H2020 program. Grant Agreement number 776810.

on forests by mitigation strategies, Carbon Balance and Management, 5, 8, doi:10.1186/1750-0680-5-8, 2010.

Konovalov, I. B., Berezin, E. V., Ciais, P., Broquet, G., Zhuravlev, R. V., and Janssens-Maenhout, G.: Estimation of fossil-fuel CO_2emissions using satellite measurements of "proxy" species, Atmos. Chem. Phys., 16, 13509-13540, https://doi.org/10.5194/acp-16-13509-2016, 2016.
Kucharczyk, B.: Activity of monolithic Pd/Al2O3 catalysts in the combustion of mine ventilation air methane, Polish J. Chem. Technol., 13, 57–62, doi:10.2478/v10026-011-0050-5, 2011.

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. i. , Nojiri, Y. , Padín, 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. , 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. (2017): Global Carbon Budget 2017 , Earth System Science Data Discussions, pp. 1-79 . doi: 10.5194/essd-2017-123.

Leip A., (2010) Quantitative quality assessment of the greenhouse gas inventory for agriculture in Europe, Climatic Change 103:245–261 DOI 10.1007/s10584-010-9915-5.

Leip A., M. Busto., M. Corazza, P. Bergamaschi, R. Koeble, R. Dechow, Suvi Monni and W. De Vries (2011) Estimation of N_2O fluxes at the regional scale: data, models, challenges, Environmental Sustainability, 3:328–338, DOI 10.1016/j.cosust.2011.07.002.

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.

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)000204, 2000.

Lugato E., Keith Paustian, Panos Panagos, Arwyn Jones, Pasquale Borrelli (2016) : Quantifying the erosion effect on current carbon budget of European agricultural soils at high spatial resolution, Global Change Biology (2016) 22, 1976–1984, doi: 10.1111/gcb.13198.

VERIFY is a research project funded by the European Commission under the H2020 program. Grant Agreement number 776810.

Lugato E, Paniagua L, Jones A, de Vries W, Leip A (2017) Complementing the topsoil informationof the Land Use/Land Cover Area Frame Survey (LUCAS) with modelled N_2O emissions. PLoS ONE 12(4):e0176111.https://doi. org/10.1371/journal.pone.0176111.

Luyssaert S, Jammet M, Stoy PC et al. (2014) Land management and land-cover change have impacts of similar magnitude on surface temperature. Nature Climate Change, 4, 389–393.

Luyssaert, S., Abril, G., Andres, R., Bastviken, D., Bellassen, V., Bergamaschi, P., Bousquet, P., Chevallier, F., Ciais, P., Corazza, M., Dechow, R., Erb, K.-H., Etiope, G., Fortems-Cheiney, A., Grassi, G., Hartmann, J., Jung, M., Lathière, J., Lohila, A., Mayorga, E., Moosdorf, N., Njakou, D. S., Otto, J., Papale, D., Peters, W., Peylin, P., Raymond, P., Rödenbeck, C., Saarnio, S., Schulze, E.-D., Szopa, S., Thompson, R., Verkerk, P. J., Vuichard, N., Wang, R., Wattenbach, M., and Zaehle, S.: The European land and inland water CO_2, CO, CH_4 and N_2O balance between 2001 and 2005, Biogeosciences, 9, 3357-3380, https://doi.org/10.5194/bg-9-3357-2012, 2012.

Melton, J. R., Wania, R., Hodson, E. L., Poulter, B., Ringeval, B., Spahni, R., Bohn, T., Avis, C. A., Beerling, D. J., Chen, G., Eliseev, A. V., Denisov, S. N., Hopcroft, P. O., Lettenmaier, D. P.,Riley,W.J.,Singarayer,J.S.,Subin,Z.M.,Tian,H.,Zürcher, S., Brovkin, V., van Bodegom, P. M., Kleinen, T., Yu, Z. C., and Kaplan, J. O.: Present state of global wetland extent and wetland methane modelling: conclusions from a model intercomparison project (WETCHIMP), Biogeosciences, 10, 753– 788, https://doi.org/10.5194/bg-10-753-2013, 2013.

Mikaloff Fletcher, S. E., Tans, P. P., Bruhwiler, L. M., Miller, J. B., and Heimann, M.: CH_4 sources estimated from atmospheric observations of CH_4 and its $^{13}C/^{12}C$ 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.: CH_4 sources estimated from atmospheric observations of CH_4 and its 13C/12C isotopic ratios: 2. Inverse modelling of CH_4 fluxes from geographical regions, Global Biogeochem. Cy., 18, GB4005, https://doi.org/10.1029/2004GB002224, 2004b.

Olivier J.G.J., Janssens-Maenhout G., Muntean M. and Peters J.A.H.W. (2016), Trends in global CO_2 emissions; 2016 Report, The Hague: PBL Netherlands Environmental Assessment Agency; Ispra: European Commission, Joint Research Centre; http://edgar.jrc.ec.europa.eu/news_docs/jrc-2016-trends-in-global-co2-emissions-2016-report-103425.pdf

Parton W.J., Stewart J.W.B., Cole C V. Dynamics of C, N, P and S in grassland soils: a model. Biogeochemistry. 1988; 5: 109–131.

Petrescu A.M.R., Annalea Lohila, Juha-Pekka Tuovinen, Dennis D. Baldocchi, Ankur R. Desai, Nigel T. Roulet, Timo Vesala, Albertus Johannes Dolman, Walter C. Oechel, Barbara Marcolla, Thomas Friborg, Janne Rinne, Jaclyn Hatala Matthes, Lutz Merbold, Ana Meijide, Gerard Kiely, Matteo

VERIFY is a research project funded by the European Commission under the H2020 program. Grant Agreement number 776810.

Sottocornola, Torsten Sachs, Donatella Zona, Andrej Varlagin, Derrick Y. F. Lai, Elmar Veenendaal, Frans-Jan W. Parmentier, Ute Skiba, Magnus Lund, Arjan Hensen, Jacobus van Huissteden, Lawrence B. Flanagan, Narasinha J. Shurpali, Thomas Grünwald, Elyn R. Humphreys, Marcin Jackowicz-Korczyński, Mika A. Aurela, Tuomas Laurila, Carsten Grüning, Chiara A. R. Corradi, Arina P. Schrier-Uijl, Torben R. Christensen, Mikkel P. Tamstorf, Mikhail Mastepanov, Pertti J. Martikainen, Shashi B. Verma, Christian Bernhofer, Alessandro Cescatti, 2015: The uncertain climate footprint of wetlands, 2015, PNAS 112 (15) 4594-4599; DOI: 10.1073/pnas.1416267112.

Pielke R. A. et al., Land use/land cover changes and climate: modeling analysis and observational evidence 2011, WIREs Clim. Change 2, 828.

Pielke R. A. Sr. et al., The influence of land-use change and landscape dynamics on the climate system: relevance to climate-change policy beyond the radiative effect of greenhouse gases. 2002, Philos. Trans. A Math. Phys. Eng. Sci. 360, 1705–1719.

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, 2387-2405, https://doi.org/10.5194/bg-14-2387-2017, 2017.

Pongratz, J., C. Reick, R. Houghton, and J. House (2014), Terminology as a key uncertainty in net land use and land cover change carbon flux estimates, Earth Syst. Dyn., 5(1), 177–195.

Poulter B., Philippe Bousquet, Josep G Canadell, Philippe Ciais, Anna Peregon, Marielle Saunois, Vivek K Arora, David J Beerling, Victor Brovkin, Chris D Jones, Fortunat Joos,Nicola Gedney, Akihito Ito, Thomas Kleinen, Charles D Koven, Kyle McDonald, Joe R Melton,Changhui Peng, Shushi Peng, Catherine Prigent, Ronny Schroeder, William J Riley, Makoto Saito,Renato Spahni, Hanqin Tian,Lyla Taylor, Nicolas Viovy, David Wilton, Andy Wiltshire, Xiyan Xu,Bowen Zhang, Zhen Zhang and Qiuan Zhu (2017), Global wetland contribution to 2000–2012 atmospheric methane growth rate dynamics Environ. Res. Lett. 12 09401

de Richter, R. and Caillol, S.: Fighting global warming: The potential of photocatalysis against CO_2, CH_4, N_2O, CFCs, tropospheric O-3, BC and other major contributors to climate change, J. Photoch. Photobio. C, 12, 1–19, doi:10.1016/j.photochemrev.2011.05.002, 2011.

Rödenbeck, C., Bakker, D. C. E., Gruber, N., Iida, Y., Jacobson, A. R., Jones, S., Landschützer, P., Metzl, N., Nakaoka, S., Olsen, A., Park, G.-H., Peylin, P., Rodgers, K. B., Sasse, T. P., Schuster, U., Shutler, J. D., Valsala, V., Wanninkhof, R., and Zeng, J.: Data-based estimates of the ocean carbon sink variability – first results of the Surface Ocean pCO_2 Mapping intercomparison (SOCOM), Biogeosciences, 12, 7251– 7278, https://doi.org/10.5194/bg-12-7251-2015, 2015.

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 N_2O, Atmos. Chem. Phys., 14(9), 4617-4641, doi:10.5194/acp-14-4617-2014, 2014.

Saunois, M., Bousquet, P., Poulter, B., Peregon, A., Ciais, P., Canadell, J. G., Dlugokencky, E. J., Etiope, G., 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., Kovey, 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., Weiss, R., Wiedinmyer, C., Wilton, D. J., Wiltshire, A., Worthy, D., Wunch, D. B., Xu, X., Yoshida, Y., Zhang, B., Zhang, Z., and Zhu, Q.: The Global Methane Budget 2000–2012, Earth Syst. Sci. Data, 8, 697–752, https://doi.org/10.5194/essd-8-697-2016, 2016.

Saunois, M., R. B. Jackson , P. Bousquet , B. Poulter and J. G. Canadell, 2017: The growing role of methane in anthropogenic climate change, Environ. Res. Lett. 11 (2016) 120207, doi:10.1088/1748-9326/11/12/120207.

Schlamadinger, B., and G. Marland, 1996, The Role of Forest and Bioenergy Strategies in the Global Carbon Cycle, Biomass and Bioenergy 10: 275-300.

Schulze, E. D., Luyssaert, S., Ciais, P., Freibauer, A., Janssens, I. A., Soussana, J. F., Smith, P., Grace, J., Levin, I., Tiruchittampalam, B., Heimann, M., Dolman, A. J., Valentini, R., Bousquet, P., Peylin, P., Peters, W., Rodenbeck, C., Etiope, G., Vuichard, ¨ N., Wattenbach, M., Nabuurs, G. J., Poussi, Z., Nieschulze, J., Gash, J. H., and Team, C.: Importance of methane and nitrous oxide emissions for europe's terrestrial greenhouse gas balance, Nat. Geosci.e, 2, 842–850, 2009.

Searchinger TD, Beringer T, Holtsmark B, Kammen DM, Lambin EF, Lucht W, Raven P, van Ypersele J-P (2018): Europe's renewable energy directive poised to harm global forests. Nature Communications 9, Article number: 3741. https://www.nature.com/articles/ s41467-018-06175-4

Stolaroff, J. K., Bhattacharyya, S., Smith, C. A., Bourcier, W. L., Cameron-Smith, P. J., and Aines, R. D.: Review of methane mitigation technologies with application to rapid release of methane from the Arctic, Environ. Sci. Technol., 46, 6455–6469, doi:10.1021/es204686w, 2012.

Thompson, R. L., F. Chevallier, A. M. Crotwell, 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.

Tian, Hanqin, Chaoqun Lu, Philippe Ciais, Anna M. Michalak, Josep G. Canadell, Eri Saikawa, Deborah N. Huntzinger, et al. “The Terrestrial Biosphere as a Net Source of Greenhouse Gases to the Atmosphere.” Nature 531, no. 7593 (March 9, 2016): 225–228.

Tubiello F.N., Salvatore M., Rossi S., Ferrara A., Fitton N. and Smith P. 2013. The FAOSTAT database of greenhouse gas emissions from agriculture, Environ. Res. Lett. 8 doi: 10.1088/1748-9326/8/1/015009.

UN, Kyoto Protocol to the United Nations Framework Convention on Climate Change (1998); http://unfccc.int/ kyoto_protocol/items/2830.php.

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, Ü., 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.

van der Laan-Luijkx, I. T., van der Velde, I. R., van der Veen, E., Tsuruta, A., Stanislawska, K., Babenhauserheide, A., Zhang, H. F., Liu, Y., He, W., Chen, H., Masarie, K. A., Krol, M. C., and Peters, W.: The CarbonTracker Data Assimilation Shell (CTDAS) v1.0: implementation and global carbon balance 2001–2015, Geosci. Model Dev., 10, 2785–2800, https://doi.org/10.5194/gmd-10-2785-2017, 2017.

VERIFY proposal H2020: Observation-based system for monitoring and verification of greenhouse gases.

Wania, R., Melton, J. R., Hodson, E. L., Poulter, B., Ringeval, B., Spahni, R., Bohn, T., Avis, C. A., Chen, G., Eliseev, A. V., Hopcroft, P. O., Riley, W. J., Subin, Z. M., Tian, H., van Bodegom, P. M., Kleinen, T., Yu, Z. C., Singarayer, J. S., Zürcher, S., Lettenmaier, D. P., Beerling, D. J., Denisov, S. N., Prigent, C., Papa, F., and Kaplan, J. O.: Present state of global wetland extent and wetland methane modelling: methodology of a model inter-comparison project (WETCHIMP), Geosci. Model Dev., 6, 617–641, https://doi.org/10.5194/gmd-6-617-2013, 2013.

Wells, K. C., D. B. Millet, N. Bousserez, D. K. Henze, T. J. Griffis, S. Chaliyakunnel, E. J. Dlugokencky, E. Saikawa, G. Xiang, R. G. Prinn, S. O'Doherty, D. Young, R. F. Weiss, G. S. Dutton, J. W. Elkins, P. B. Krummel, R. Langenfelds, and L. P. Steele, Top-down constraints on global N_2O emissions at optimal resolution: application of a new dimension reduction technique, Atmos. Chem. Phys., 18(2), 735-756, doi:10.5194/acp-18-735-2018, 2018.

6. Acronyms

AD – Activity Data
CAPRI – Common Agricultural Policy Regionalised Impact model (EC-JRC)
CBM – Carbon Budget Model (inventory-based model – EC-JRC)
CH_4 – methane
CO_2 – carbon dioxide
CTE - CarbonTracker Europe
DGVMs - dynamic global vegetation models
DIC – dissolved inorganic carbon
DOC – dissolved organic carbon
EDGAR – The Emissions Database for Global Atmospheric Research (EC-JRC and PBL)
EF – emission factor
EFISCEN - The European Forest Information SCENario Model (inventory-based model Alterra & EFI)
ESMs - Earth system models
EU – European Union, in this study EU28
FAO – The food and agriculture organization (UN)
FL-FL – Forest Land remaining Forest Land
GAINS – IIASA's scientific tool – air pollutants and greenhouse gases
GCP – Global Carbon Project
GHG – Greenhouse gases
ICOS Integrated Carbon Observation System
IIASA – International Institute for Applied Systems Analysis
InGOS – Integrated non-CO2 Greenhouse gas observing system
Jamstec - Model of the Japan Agency Marine-Earth Science and Technology
JRC – Joint Research Centre of the European Commission
LULCC - Land use and land cover change
MRV - Measuring, Reporting, and Verifying
N_2O – nitrous oxide
NBP – Net Biome Production
RECCAP – REgional Carbon Cycle Assessment and Processes
SOC – Soil organic carbon
TRENDY.v6 – an ensemble of Dynamic Global Vegetation Models (DGVM)
UNFCCC – United Nations Framework Convention on Climate Change
VOCs – volatile organic compounds
WUR – Wageningen University Research

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