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Inventory reporting of livestock emissions: the impact of the IPCC 1996 and 2006 Guidelines

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Abstract

The livestock sector is a major contributor to agricultural greenhouse gas (GHG) and nitrogen (N) emissions and efforts are being made to reduce these emissions. National emission inventories are the main tool for reporting emissions. They have to be consistent, comparable, complete, accurate and transparent. The quality of emission inventories is affected by the reporting methodology, emission factors and knowledge of individual sources. In this paper, we investigate the effects of moving from the 1996 IPCC Guidelines for National Greenhouse Gas Inventories to the 2006 IPCC Guidelines on the emission estimates from the livestock sector. With Austria as a case study, we estimated the emissions according to the two guidelines, revealing marked changes in emission estimates from different source categories resulting from changes in the applied methodology. Overall estimated GHG emissions from the livestock sector decreased when applying the IPCC 2006 methodology, except for emissions from enteric fermentation. Our study revealed shifts in the relative importance of main emission sources. While the share of CH_4 emissions from enteric fermentation and manure management increased, the share of N_2O emissions from manure management and soils decreased. The most marked decrease was observed for the share of indirect N_2O emissions. Our study reveals a strong relationship between the emission inventory methodology and mitigation options as mitigation measures will only be effective for meeting emission reduction targets if their effectiveness can be demonstrated in the national emission inventories. We include an outlook on the 2019 IPCC Refinement and its potential effects on livestock emissions estimates. Emission inventory reports are a potent tool to show the effect of mitigation measures and the methodology prescribed in inventory guidelines will have a distinct effect on the selection of mitigation measures.

1. Introduction

In order to counteract climate change, many countries have committed to reducing greenhouse gas (GHG) emissions under the United Nations Framework Convention on Climate Change (UNFCCC), which covers the sources and sinks of the direct GHGs; carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and other pollutants. Building on the UNFCCC, the Kyoto Protocol, adopted in 1997, broke new ground with its legally-binding constraints on GHG emissions. In 2012, the Kyoto Protocol entered a second commitment period (2013–2020), and the EU committed to reduce GHG emissions by 20% compared to 1990 levels (UNFCCC 2020). The Emissions Database for Global Atmospheric Research (EDGAR) compiled global totals of CO_2, CH_4 and N_2O emissions for 2010 as 33.6 Pg CO_2 yr^{-1}, 0.34 Pg CH_4 yr^{-1}, and 7.2 Tg N_2O yr^{-1} (Janssens-Maenhout *et al* 2019). According to the 'United in Science report' published by the World Meteorological Organization (2019), the emissions gap that the world needs to close to reach the agreed goals in the Paris Agreement is now larger than ever.

To achieve the aims of the Kyoto Protocol, the European Commission set binding targets for the member states to reduce GHG emissions for the year 2020, prepared a framework and policy objectives for the period 2021–2030 and set up a long-term strategy for 2050. Key targets for 2030 are more stringent than in the previous period, aiming to a 40% cut in GHG emissions from 1990 levels. To meet the target, non-emission trading system sectors, including agriculture, need to reduce emissions by 30% compared to 2005 levels (European Comission 2020a). The 2050 long-term strategy aims to reach climate neutrality in the EU by 2050 (European Comission 2020b). This aim aligns with the objective of the Paris Agreement to keep the global temperature increase below 2°C and seeking efforts to limit it to 1.5°C (UNFCCC 2015).

In addition to the GHG commitments, United Nations Economic Commission for Europe (UNECE) countries also agreed on reducing air pollutants. The European Parliament introduced a new National Emissions Ceilings (NEC) EU Directive (2016/2284/EU) in 2016 which sets national emission reduction targets for NO_x, ammonia (NH_3) and other pollutants emissions for the years 2020 and 2030 (European Parliament and Council 2016). According to the new directive, NO_x emissions from agricultural activities, namely manure management and agricultural soils, have to be accounted for; by 2020, a 2.3% reduction of NH_3 and a 3.2% reduction of NO_x relative to the 2017 levels is required across the EU, and by 2030 16% and 40% reductions from 2017 levels are expected (EEA 2019a).

Many EU member states are failing to meet the 2020 targets for NH_3 emissions reduction, according to their own projections. For the 2030 emission reduction commitments, the NEC Directive projections report (EEA 2019b) paints an even worse picture: 19 EU member states will fail to meet reduction commitments for NH_3 and 19 countries will fail to meet their targets for NO_x. N_2O emissions are expected to increase in the future with increasing activities. Even with full implementation of mitigation measures by 2030, global emissions can only be reduced to the pre-2010 level (Winiwarter *et al* 2018). Riahi *et al* (2017) looked into the shared socioeconomic pathways including GHG emissions. They emphasize the magnitude of N_2O emissions sourced from agricultural soils and fertilizer use and show the significance of mitigation strategies.

While it is the total amount of GHG emissions that determine climate change globally, from a policy perspective it is essential that each emission source is correctly attributed to each sector. Vigan *et al* (2019) emphasize the importance of accurate knowledge of emission sources to implement effective mitigation strategies. All the GHG emission reduction and control policies point out that the emissions from the agricultural sector should be lowered with emissions from the livestock sector and emissions from agricultural soils. According to the latest IPCC Climate Change and Land report (Rivera *et al* 2017), the contribution of the sector Agriculture, Forestry and Other Land Use (AFOLU) to total net anthropogenic emissions (2007–2016) is 23%. In the livestock sector, advanced inventory methodologies are already available and offer opportunities for emissions mitigation by management of several key activities without reducing productivity.

The livestock industry generates a large proportion of global anthropogenic GHG emissions, estimated at around 14.5% (FAO 2017). The key emission sources CH_4 emissions from enteric fermentation, and CH_4 and N_2O emissions from manure management account for 44.1%, 5.7% and 4.3% of global livestock GHG emissions respectively (FAO 2017). 75% of NH_3 emissions from the agricultural sector are from livestock production, where manure management is the main source (Sajeev *et al* 2017). Manure application is also a major contributor to NH_3 emissions. CH_4 and N_2O emissions are two main non-CO_2 GHG emissions from manure management, processing and application. According to the European Environment Agency (EEA) emission inventory report, in the EU 92% of the NH_3 emissions come from the agricultural sector and the main contributing categories are: animal manures applied to soils, inorganic N-fertilizers and manure management from non-dairy cattle, making up 54% of total NH_3 emissions from the agricultural sector, followed by manure management from pigs and dairy cattle (European Environment Agency 2019).

The legally binding obligations to reduce both GHG and NH_3 emissions from agriculture require transparent and accurate emissions reporting. National emissions inventory reports (NIR) have become the main instrument for reporting emissions. They must be prepared annually to assess the status and track progress towards meeting the GHG and NH_3 reduction commitments. To support the compilation of NIR and to ensure that the information they provide is consistent, comparable, complete, accurate and transparent, the Intergovernmental Panel on Climate Change (IPCC) drew up its first GHG reporting guidelines in 1995, and published them in revised form in 1996 (IPCC 1996, 2015, Pulles 2013). A new version of the IPCC guidelines was launched in 2006, with important suggestions for improvement and restructuring the source categories to make the guidance clearer, more accurate (updated methods, improved default values) and more complete (more sources and sinks, more gases) (IPCC 2006). From 2015, these new guidelines became mandatory for Annex I[8] countries as part of their UNFCCC reporting obligations (UNFCCC 2014). A refinement of the IPCC 2006 Guidelines was prepared between 2016 and 2019 and was adopted during the 49th Session of the IPCC in May 2019. The IPCC 2019 Refinement updates, supplements, and further elaborates the 2006 IPCC guidelines and is meant to be used in conjunction with them (IPCC 2019). Finally, the EMEP/EEA air pollutant emission inventory guidebook sets out methodologies for emissions estimation, compatible with and complementary to the IPCC guidelines, and has also recently been updated (EEA 2019a).

Emissions are calculated by multiplying 'activity data'—quantitative estimates of the extent of specific types of agricultural practice—with emission factors (EF) that are intended to represent the emission rates from each of these practices. Therefore, high resolution activity data and realistic EFs are needed to create accurate emission inventories (Amon *et al* 2011). Only detailed knowledge of sources and EFs enable development, application and/or enforcement of targeted mitigation measures (Reidy *et al* 2008, Bell *et al* 2014, Smith *et al* 2014).

Emissions inventory guidelines have to find an appropriate balance between general, internationally comparable and relatively easily applicable procedures, and more accurate and specific information at national level, which requires methodologies that are more sophisticated. While this has been a common point of critique of earlier versions of the IPCC guidelines (see e.g. Salt and Moran 1997, Brown *et al* 2001), the guidelines have been improved and now allow for a reasonable and productive way to deal with the trade-offs between comparable procedures and more accurate information at national level. The IPCC guidelines do this mainly by providing 'Tiers' of methodology for use by different groups of countries depending on their ability to produce their own empirical data. Tier 1 is the simplest method and uses default values for EF and equations for each animal subcategory while Tier 2 is a more detailed approach requires country specific information on livestock and manure management (IPCC 2006). Tier 3, introduced with the 2006 IPCC guidelines, enables countries to do the most sophisticated analysis and modelling (IPCC 2006, 2019). This has the potential advantages of more accurate accounting and of discovering real and demonstrable mitigation opportunities that are less disruptive of agricultural practice and therefore easier to implement. NIRs are also expected to become more accurate and detailed with the IPCC 2019 Refinement, which provides supplementary methodologies, updates on default EFs considering the latest available scientific knowledge, and additional guidance on the 2006 IPCC Guidelines.

There is a range of publications that cover different pollutants (all GHG, non-CO_2 gases (CH_4 and N_2O), NH_3) at European and national levels, usually coupled with some form of uncertainty or sensitivity analysis. For instance Rypdal and Winiwarter (2001) provided a review on uncertainties in national GHG inventories. An inventory of N_2O emissions from agriculture in the UK including uncertainty and sensitivity analysis was published by Brown *et al* (2001). Fauser *et al* (2011) studied uncertainties of the Danish GHG emission inventory. NH_3 emission inventories from agriculture have been published for Switzerland (Kupper *et al* 2015), the Netherlands (Velthof *et al* 2012), and Denmark (Hutchings *et al* 2001). Covering Europe as a whole, Backes *et al* (2016) developed a dynamic NH_3 emission inventory using temporal profiles and geographical information, Reidy *et al* (2009) assessed NH_3 emissions from litter-based manure systems for beef cattle and broilers. The Austrian air emission inventories are based upon an integrated and consistent N-flow approach, where N losses estimated under the UN/CLRTAP inventory directly feed into GHG inventory estimations (Anderl *et al* 2013).

Focusing either on a broad range of GHG or on selected ones, NIRs have been validated by comparing them to specific (national) methods, measurements, or models, e.g. N_2O and CH_4 emissions for the UK (Brown *et al* 2001, Silgram *et al* 2001, Polson *et al* 2011) or N_2O emissions for the Netherlands (Van Der Laan *et al* 2009), Denmark (Fauser *et al* 2011, 2013), Norway (Borgen *et al* 2012) or globally (Seikaaab *et al* 1996, Mosier *et al* 1999, Van Amstel *et al* 1999, Nevison 2000, Cushman 2003, Lokupitiya and Paustian 2006). Studies on GHG emission inventories have also been published for countries such as Israel (Koch *et al* 2000) or China (Zhang *et al* 2015), and the specific challenges for developing countries have been discussed by Ogle *et al* (2013). Some more recent studies focused on ensuring comparability by the consistent use of clear methodologies, in order to assess policy effectiveness on all scale levels. Blujdea *et al* (2016) and Petrescu *et al* (2020) compared the different approaches used by EU member states for GHG inventories for the land use, land-use change, and forestry (LULUCF) and AFOLU sectors. Other authors have analysed regional (Garren and Brinkmann 2012) or local community

[8] Annex I Parties include the industrialized countries that were members of the OECD (Organisation for Economic Co-operation and Development) in 1992, plus countries with economies in transition (the EIT Parties), including the Russian Federation, the Baltic States, and several Central and Eastern European States (UNFCC, Parties and Observers).

levels (Sippel 2011, Brander *et al* 2013). Wolf *et al* (2017) explore the influence of the methodology on global and US livestock methane emissions estimates when applying a Tier 1 versus a Tier 2 (IPCC 2006) approach.

The impact of the inventory method on emission estimates has not yet been quantified despite some papers having tackled some inventory aspects. Recently, Thorman *et al* (2020) worked on country specific N_2O EFs for manure application to show processes and factors controlling emissions and how to enhance national inventory reporting. Tian *et al* (2020) reported an in depth analysis of global N_2O sources and sinks pointing out the emerging growth in the N_2O emissions. Lagerwerf *et al* (2019) described in detail the methodologies to estimate agricultural emissions in the Netherlands.

This study was designed to investigate the effects of moving from the 1996 IPCC Guidelines to the 2006 IPCC guidelines when estimating emissions from the livestock sector. We took Austria as a case study and estimated the emissions from the livestock sector using the two IPCC guidelines, aiming (1) to reveal the change in the relative importance of emission sources that can solely be deduced on a change in the inventory methodology, (2) to investigate the implications of methodological changes on improvement of future guidelines and on implementation of mitigation measures, and (3) to shed light on potential implications of the IPCC (2019) refinement. By using identical activity data for two inventory methodologies (IPCC 1996, 2006) we isolate the effect of methodological changes from the effect of changes in activity data. This is a laborious task, as it required the estimation of two complete national inventories. Such an isolation of the impact of the effect of the methodology has not yet been performed. Investigating the effect of such changes in the IPCC guidelines is of utmost relevance for inventory compilers, policy makers, farmers and scientific community, as it allows a detailed insight into the effects of inventory guidelines on the apparent relative importance of different emission sources and on the capability of the national inventories to show the effects of different mitigation measures.

2. Methods

We estimated CH_4 and N_2O emissions from the livestock sector using the IPCC guidelines 1996 and 2006, for the 2 years 1990 and 2011. We chose Austria as the study country because it covers all relevant livestock categories and manure management systems in its emission inventory and its farming and livestock systems are representative for Central Europe countries. Building upon previous studies (Amon and Hörtenhuber 2008, 2010), we focussed on the methodology *per se*, i.e. factors and approaches that have changed from 1996 to 2006 guidelines, as well as on the derived results.

The following livestock emission sources were considered:

Category 3.A (previously 4.A): CH_4 emissions from enteric fermentation;

Category 3.B (previously 4.B): CH_4 and N_2O emissions from manure management;

Category 3.D (previously 4.D): Direct and indirect N_2O emissions from agricultural soils including emissions from manure excreted on pasture, rangeland, and paddocks by grazing livestock.

These general emission source categories from the livestock sector remained unchanged in the 2006 IPCC Guidelines. New emission source categories were added in the sector ‘other sources’: field burning of agricultural residues, liming and urea application, and mineralization/immobilization associated with loss/gain of soil organic matter. This study focuses on GHG emissions from livestock. However, for completeness we also estimated direct and indirect N_2O emissions from managed soils from other sources such as synthetic fertilizer application, crop residue decomposition, and sewage sludge application (supplementary information (available online at stacks.iop.org/ERL/16/075001/mmedia)).

The IPCC (1996) guidelines provide two methodological approaches for emissions estimations, Tier 1, and Tier 2; the 2006 guidelines introduced the additional Tier 3. Countries can decide which Tier to use depending on data availability, but are encouraged to use the higher tiers where possible. Reporting of key categories must be done with Tier 2 or Tier 3. Tier 1 is the simplest approach and uses default values for EFs and equations for each animal subcategory; the only country-specific data needed are animal populations. Tier 2 is a more complex method and requires country-specific information on livestock characteristics and manure management; country-specific EFs can also be included. Tier 3 is the most complex approach, and includes models and reflects national conditions. It demands high-resolution activity data, comprehensive field measurements and monitoring, but offers more accurate estimates as well as opportunities to demonstrate the effectiveness of mitigation measures.

2.1. Emission calculations for the livestock management chain

Emissions from the livestock management chain were calculated for Austria following IPCC Tier 1 methodologies with default IPCC EFs. Key emission categories were estimated with a Tier 2 approach. These are: (1) cattle CH_4 emissions from enteric fermentation and (2) cattle and swine CH_4 emissions from manure management. Here, emission estimates used country-specific EFs and activity data. The IPCC (1996) guidelines suggest a Tier 2 methodology for enteric CH_4 emissions for cattle, while the 2006 guidelines suggest Tier 2 also for buffalo and sheep. Activity data for Austrian national emissions estimates were obtained from national statistics, surveys and studies (Anderl *et al* 2013). Coefficients depending on the animal diet such as gross energy intake (GE), volatile solids excretion and N excretion (N_{ex}) for different livestock categories were taken from previous studies (Gruber and Steinwidder 1996) (Amon *et al* 2002) (Pötsch *et al* 2005) (Schechtner 1991). Detailed calculations on CH_4 from enteric fermentation, CH_4 from manure management, N_2O from manure management and N_2O from managed soils are shown in supplementary information.

CH_4 emissions from manure management of cattle and swine were estimated using Tier 2 methodology, which required detailed characterization of animal categories and information on Austrian animal waste management systems (AWMS). AWMS data was based on the surveys of Amon *et al* (2007a) and (Konrad 1995); AWMS for key livestock categories are presented in supplementary information. Methane conversion factors (MCF) for manure management systems in Western European cool climatic regions taken from the IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (2000) as default values can be found in supplementary information. Country-specific MCF values for liquid systems of cattle and swine were estimated based on a three-year field measurement campaign in Austria (Amon *et al* 2006, 2007b), including estimates of the amounts of slurry stored in cold and warm seasons (supplementary information).

2.2. Activity data and emission factors

This paper is intended to demonstrate the effects of the change in calculation methods, comparing the IPCC 1996 and 2006 guidelines. Thus, it was of crucial importance to avoid biases by changing activity data at the same time. Consequently, the same sets of input data on animal numbers, N_{ex}, housing systems, activity data on manure storage and manure application were used to calculate national emissions with both methodologies for the selected years 1990 and 2011 (e.g. Anderl *et al* 2013). For a side-by-side comparison of the two IPCC guidelines for each emissions category, see supplementary information. The tables on the uncertainties of activity data and EFs can be found in supplementary information.

3. Results

3.1. Reporting category 3.A: enteric fermentation

Table 1 shows CO_2-eq of CH_4 emissions from enteric fermentation for the years 1990 and 2011 estimated with the IPCC (1996) and the IPCC (2006) guidelines. CH_4 emissions for 1990 and 2011 increased from 178.7 to 192.8 Gg CH_4 yr^{-1} and 153.1 to 165.0 Gg CH_4 yr^{-1} respectively switching from the IPCC (1996) to the IPCC (2006) guidelines. Overall, emissions from enteric fermentation are almost exclusively determined by cattle, and the estimates of total emissions from this source increased by almost 8% when moving from the IPCC (1996) to the IPCC (2006).

Table 1. Comparison of the IPCC (1996) and the IPCC (2006) results for reporting category 3.A, enteric fermentation.

Year	Emissions from enteric fermentation CO_2-eq (Gg yr^{-1})		
	IPCC 1996 (4.A)	IPCC 2006 (3.A)	Recalculation difference
1990	3753	4820	+1067 (+28.4%)
2011	3215	4125	+910 (+28.3%)
Trend 1990–2011	−14.3%	−14.4%	

The EF for enteric CH_4 emissions per average Austrian dairy cow and year increased by approximately 21% with increasing milk yields (from 3791 kg milk in 1990 to 6227 in 2011) and the related feed and gross GEs between the 2 years were analysed. The enteric methane conversion rate (Y_m) for cattle also increased (from 6.0% to 6.5% of feed GE; IPCC (2006)) and as a result of that, enteric CH_4 emissions increased (table 2). The increase of suckler cows' milk yield from 3000 to 3500 kg according to Häusler (2009) also increased enteric CH_4 emissions.

Emissions per kg milk decreased between 1990 and 2011 as the number of dairy cows continuously decreased and milk yields increased. The number of suckler cows in pasture-based beef production systems increased in the same period. The ratio of CH_4 emissions from dairy cattle and other cattle remained nearly constant between the 1996 and 2006 guidelines. The overall trend in enteric CH_4 emissions during the period was −14%. Using the IPCC (2006) guidelines did not change the overall trend in enteric CH_4 emissions, but increased the total amount of CH_4 emissions by about 8%.

3.2. Reporting category 3.B: manure management

The most relevant effects of the revision for reporting category 3.B differed between the key animal categories cattle and swine. The change in methodology from the IPCC (1996) to the IPCC (2006) reduced GHG emissions from swine on average from 1990 to 2011 by 8%, whereas in total GHG emissions from cattle remained relatively constant, resulted in 2% decrease on average from 1990 to 2011. However, in absolute numbers (CO_2-equivalents) the method change resulted in a higher decrease of GHG emissions from cattle than for swine. Two divergent changes are prominent: as a result of changed EFs, CH_4 emissions slightly increased (+4%), while N_2O emissions decreased substantially (about 50%). The increase in

Table 2. Change in CH_4 emissions from enteric fermentation due to the increased Y_m.[a]

Livestock subcategory	Emission factors kg CH_4 head^{-1} yr^{-1} IPCC 1996	kg CH_4 head^{-1} yr^{-1} IPCC 2006
Breeding heifers 1–2 years conventional farming	66	71
Breeding heifers 1–2 years organic farming	59	6
Fattening heifers, bulls, oxen 1–2 years conventional farming	66	71
Fattening heifers, bulls, oxen 1–2 years organic farming	59	64
Cattle < 1 year conventional farming	33	36
Cattle < 1 year organic farming	28	31
Cattle > 2 years conventional farming	64	70
Cattle > 2 years organic farming	63	68

[a] Y_m increased from 0.06 in the 1996 Guidelines to 0.065 in the 2006 Guidelines, which resulted in an increase in the CH_4 emission factor (see supplementary information).

Table 3. Comparison of the IPCC (1996) and the IPCC (2006) results for reporting category 3.B (manure management).

	CH_4 emissions (Gg CH_4 yr^{-1})			N_2O emissions (Gg N_2O yr^{-1})		
Year	IPCC 1996 (4.B)	IPCC 2006 (3.B)	Recalc. difference	IPCC 1996 (4.B)	IPCC 2006 (3.B)[a]	Recalc. difference
1990	20.5	23.5	+3.0 (+14.4%)	3.0	1.5	−1.5 (−51.2%)
2011	15.6	17.8	+2.2 (+14.0%)	3.0	1.5	−1.5 (−50.8%)
Trend 1990–2011	−23.9%	−24.2%		−1.2%	−0.3%	

[a] Including indirect N_2O emissions from housing and manure management N emissions.

CH_4 emissions is mainly due to a doubling of the MCF for untreated solid manure storage (from 0.01 to 0.02). The substantial decrease in N_2O emissions is mainly attributable to a reduction of the EF for solid manure storage (−75%; from 0.02 to 0.005), and to a smaller extent to the reduced EF in the IPCC (2006) guidelines for digested manure in biogas plants (EF: 0), for composting (0.02–0.006) and for aerobic treatment (aerated slurry; −75%; 0.02–0.005). In contrast, the N_2O EF for liquid slurry increased from 0.001 to 0.005 with the introduction of the IPCC (2006) guidelines.

For Austria, nationally derived CH_4 EFs are used for emissions from liquid manure systems in the key animal categories cattle and swine[9]. Hence, in Austria the switch from the IPCC (1996) to the IPCC (2006) only affects the EF for solid manure storage in these animal categories. The IPCC (2006) uses a CH_4 EFs applicable for the whole year and an average animal. EFs differentiate between climate zones and manure management systems. The IPCC (2006) breaks down the categories ‘chicken’ and ‘other poultry’ to ‘chicken’ (mainly laying hens), ‘broilers’, ‘turkeys’ and ‘other poultry’ (ducks, geese, etc) and assigns specific EFs to these animal categories. In the Austrian inventory, overall results from category 3.B were hardly affected by the methodology update. This is due to the fact that manure CH_4 emissions in Austria are dominated by the national EFs for CH_4 emissions from liquid manure stores for the key animal categories cattle and swine.

Table 4. Comparison of the IPCC (1996) and the IPCC (2006) results in total CO_2-eq for reporting category 3.B (manure management).

	Total CO_2-eq (Gg yr^{-1})	
Year	IPCC 1996	IPCC 2006
1990	1365 (31.6% from CH_4 and 68.4% from N_2O emissions)	1025 (57.3% from CH_4 and 42.7% from N_2O emissions)
2011	1251 26.2% from CH_4 and 73.8% from N_2O emissions	882 (50.5% from CH_4 and 49.5% from N_2O emissions)
Trend 1990–2011	−8.3%	−14.0%

The revision according to the IPCC (2006) leads to a decrease of 51.2% in overall N_2O emissions in the category 3.B manure management, resulting from a change in the EF (table 3). Indirect N_2O emissions from housing and manure management systems previously reported in section 4.D (soil) were moved to section 3.B in the IPCC (2006) guidelines. The N_2O EF for these indirect emissions was reduced from 1.25% to 1.0% of applied N. In total, when all emissions from 3.B are converted into (CO_2-eq), they decrease on average from 1990 to 2011 by about

[9] Swine is the general term used in the IPCC guidelines for pigs.

14.0% when applying the IPCC (2006) and by about 8.3% when applying the IPCC (1996) (table 4). Beside the changes of CH_4 and N_2O EFs, this is also attributable to the increase of the CH_4 Global Warming Potential (GWP-100) factor (from 21 to 25) and to the slightly contrary effect of the decrease of the N_2O GWP-100 factor (from 310 to 298).

3.3. Reporting category 3.D agricultural soils (N_2O emissions)

Direct emissions of N_2O from agricultural soils (currently 3.D, previously 4.D) decreased on switching from the IPCC (1996) to the IPCC (2006) as a result of several effects (table 5). The reduced EF (1.0% of applied N instead of 1.25% of applied N emitted as N_2O-N) decreased soil-N_2O emissions by up to 20%, although soil emissions are now calculated with a higher amount of N input, since NH_3-N losses are not subtracted beforehand. N_2O-N emissions from mineral fertilizer application decreased by about 17% as a result of the reduced EF. N_2O emissions from biologically fixed nitrogen had to be calculated and reported following the (revised) IPCC (1996) guidelines. According to the IPCC (2006) guidelines, nitrogen from biological fixation does not contribute to N_2O anymore. However, the calculation of N_2O from residues of all crops has been implemented. Due to their N-fixation capabilities, N content in the above- and below-ground crop residues of N-fixing crops are considerably higher than those of grain crops (IPCC 2006). The N_2O emissions from biological nitrogen fixation itself (in N-fixing crops) are not accounted for any more according to the IPCC (2006) guidelines. However, the fraction of N from these N-fixing crops incorporated in crop residues must be considered as an N input and emission source. Additionally, the updated calculations concerning N from crop residues now include N from (ploughed) temporary pastures. Overall, direct N_2O-N emissions from both N fixation and from crop residues were reduced by about 11% through the revision.

Digested N from energy crops of biogas slurry was introduced into the inventory calculations in accordance with the 2006 guidelines in addition to digested N from animal manures. This is an additional N source applied to agricultural land and responsible for increased emissions. N_2O-N emissions from applied animal manure slightly decreased from 1.38 to 1.32 Gg for the year 2011 (by about 4%) as a consequence of the reduced EF. Changes in reporting category 3.B (for N_2O), which are also influenced by changes in NH_3-N emissions in the NEC inventory, also contributed to the reduction of N_2O-N. The already small N_2O-N emissions from sewage sludge further decreased by approximately 5% following the change of the EF. However, this emission source is reallocated to chapter '5.E Other waste' in the IPCC (2006) guidelines.

In addition to direct N_2O emissions, indirect N_2O emissions from leaching and atmospheric deposition decreased substantially in chapter 3.D. This was mainly due to a reduced EF for leaching, and to the reallocation of indirect N_2O emissions from manure management (now category 3.B). In total, N_2O emissions from the source '3.D Soils' decreased by 37% and 38% for the years 1990 and 2011, due to the revision. As a consequence of the reduced EF for indirect N_2O emissions from NH_3 and NO_x-N (housing and manure management systems as well as indirect soil emissions), overall indirect N_2O emissions decreased by 65% and 61% for 1990 and 2011, respectively. In terms of CO_2-eq, these N_2O-emissions show a further decrease due to the decreased GWP for N_2O.

Following the IPCC (2006), the main sources of N_2O emissions from agricultural soils were those from the sources animal waste application (38.6% for 2011), synthetic fertilizer use (29.2%) and crop residues (25.5%). Further sources contribute only small amounts to direct N_2O emissions: These are grazing (4.4% according to the IPCC (2006) for 2011), the energy crop component of biogas slurry (1.9%), and sewage sludge application (0.5% of total direct N_2O for 2011). Indirect N_2O emissions were mainly related to leaching according to the IPCC (1996) method, but are mainly influenced by deposition of gaseous NH_3/NO_X losses according to the IPCC (2006).

3.4. Importance of different emission sources

The IPCC (2006) guidelines resulted in significant changes for two emission categories: the category 4.A Enteric fermentation (now: 3.A) increased in importance (+8% of CH_4), particularly when expressed as CO_2-eq (+28%). In contrast, the formerly significant source 4.D Agricultural soils (now: 3.D) significantly declined (−35% of N_2O, about −38% in CO_2-eq). Category 3.A now accounts for about 59% of agricultural CH_4 and N_2O emissions in CO_2-eq, 3.D (Agricultural Soils) for only 28% and 3.B (Manure Management) for 13%. About 2% of total emissions in the agriculture sector were from CO_2 emissions from liming and urea application for the years 1990 and 2011. For emission results converted to CO_2-eq, the change of GWP factors for CH_4 and N_2O from 21 to 25 and 310–298, respectively, resulted in further deviations.

The results of this study show that estimated GHG emissions from the agricultural sector decreased when the IPCC (2006) methodology was applied, except for the emissions from enteric fermentation. Figures 1–3 show an overview of the different shares of emission sources for the entire agriculture sector in Austria. It is obvious that the relative magnitude of estimated emissions from enteric fermentation has become greater, while the relative magnitude of estimated emissions from manure management and agricultural soils have become smaller. Due

Table 5. Comparison of the IPCC-1996 and the IPCC-2006 results for N_2O emissions for reporting category 3.D (direct and indirect N_2O from soils).

	N_2O/CO_2-eq-emission (Gg yr^{-1})								
	IPCC 1996 (4.D)			IPCC 2006 (3.D)			Recalculation difference		
Year	Direct (including grazing)	Indirect	Total	Direct (including grazing)	Indirect	Total	Direct (including grazing)	Indirect	Total
1990	6.7/2078	4.4/1352	11.1/3430	6.1/1817	1.2/346	7.3/2162	−0.6/−261	−3.2/−1006	−3.7/−1268 (−37.0%)
2011	6.3/1957	3.7/1145	10.0/3103	5.4/1605	1.1/318	6.5/1923	−0.9/−352	−2.6/−827	−3.5/−1180 (−38.0%)
Trend 1990–2011	−5.8%	−15.3%	−9.6%	−11.6%	−8.0%	−11.1%			

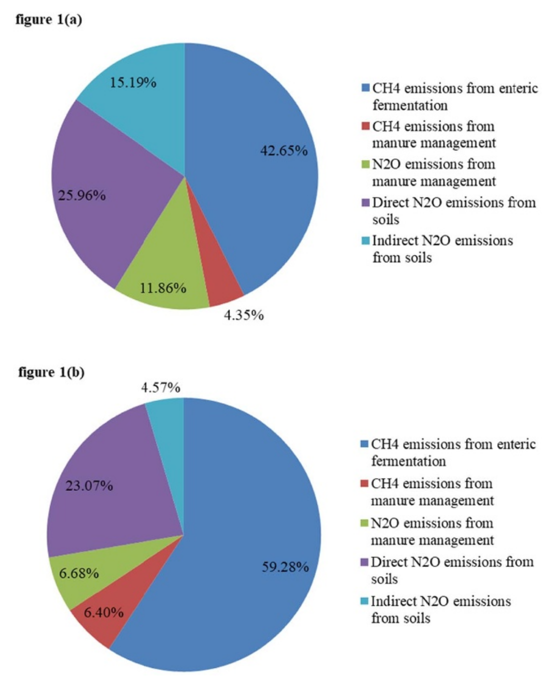

Figure 1. A comparison of GHG emissions contributions from the livestock sector for the year 2011 estimated with the IPCC-1996 (a) and the IPCC-2006 (b) guidelines, respectively.

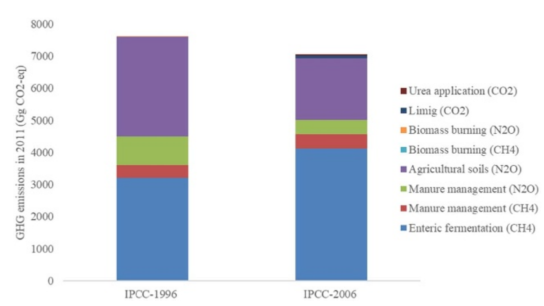

Figure 2. A comparison of total GHG emissions for the year 2011 estimated with the IPCC-1996 and the IPCC-2006 guidelines, and share of emission sources.

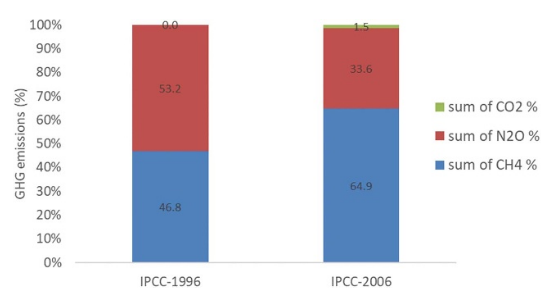

Figure 3. Contribution of CO_2, CH_4 and N_2O emissions to total agricultural GHG emissions for the year 2011 estimated with IPCC-1996 and IPCC-2006 guidelines.

to the change from the IPCC (1996) to the IPCC (2006), the total amount of emissions decreased for the year 1990 by 5.2% (i.e. by 446 Gg CO_2-eq) and for 2011 by 7.0% (i.e. by 446 Gg CO_2-eq). Liming and urea application remain minor emission contributors (about 1.0%–1.5% according to the revision), but the reassignment to the agriculture sector is considered important for a correct sectoral representation and transparency of emission estimates.

4. Discussion

4.1. Model comparison of Austrian livestock management chain emissions

Our estimates of Austrian GHG emissions from the livestock management chain with the IPCC (1996) and the IPCC (2006) guidelines show the effects of the changes in the reporting guidelines on the relative magnitude of emissions emission source categories. Moving from the IPCC (1996) to the IPCC (2006), the relative magnitude of emissions from enteric fermentation became greater, while the relative magnitude of emissions from manure management and managed soils became smaller.

Our findings agree with studies that worked on a model comparison, such as the work of Petrescu *et al* (2020) who studied GHG emissions from 'agriculture, forestry and other land use' sectors (AFOLU) in the European Union by comparing different global datasets and models for the period 1990–2016. They calculated agricultural GHG emissions using different data sources for EU 28 countries. CH_4 and N_2O emission were calculated using EDGAR,[10] FAOSTAT,[11] GAINS,[12] CAPRI[13] and UNFCCC[14] methods.

The results for Austrian agricultural GHG emissions for the years 1990 and 2011 from Petrescu *et al* (2020) showed that trends of total CH_4 emissions of the five estimates obtained with the methods named above are consistent but there are distinct differences in the contribution of emission sources between the models. These differences are attributed to the different sources of activity data and tiers used in the models. The UNFCCC methodology uses country-specific activity data following IPCC guidelines and country-specific information for higher tiers, while the EDGAR model uses statistics such as IEA and FAOSTAT for activity data, and derives EFs following the IPCC Tier 1 and Tier 2 approaches. The GAINS model, on the other hand, does not differentiate between CH_4 emissions from manure management and enteric fermentation and calculates them together as CH_4 emissions from agriculture, using

[10] EDGAR: Emission Database for Global Atmospheric Research.

[11] FAOSTAT: Food and Agricultural Organization Corporate Statistical Database.

[12] GAINS: Greenhouse Gas–Air Pollution Interactions and Synergies.

[13] CAPRI: Common Agricultural Policy Regionalised Impact Modelling System.

[14] UNFCCC: United Nations Framework Convention on Climate Change.

activity data from FAOSTAT statistics and country-specific livestock data to calculate EFs. The CAPRI model also takes activity data from FAOSTAT while applying IPCC Tier 2 methodology for CH_4 emissions from cattle and Tier 1 for all the other livestock categories. Petrescu *et al* (2020) clearly show that the inventory methodology has a crucial influence on emission estimates.

The biggest increase recorded in 2017 global N_2O emissions are from manure excreted by grazing livestock on pasture, rangeland, and paddocks, and synthetic nitrogen fertiliser application (Olivier and Peters 2018). Emissions for the key source categories, N_2O from manure management and direct and indirect N_2O from agricultural soils were also calculated with the same models in Petrescu *et al* (2020). Similar to CH_4 emissions, even though the total N_2O emissions between different models showed consistency, there are distinct differences for the source categories in the models depending on the activity data and the methodology applied in the models.

Our study comparing the IPCC 1996 and 2006 guidelines also reveals significant changes in the emissions from different source categories caused by changes in EF calculations and equations. Our results and those of Petrescu *et al* (2020) show that inventories can differ even when they are calculated for the same country. It becomes clear that the applied methodology has a significant effect on estimates for specific emission sources and consequently on the effects of mitigation measures. It is essential to understand the impact of the inventory methods on these estimates and especially on the apparent relative importance of the different sources.

4.2. Comparison of Austrian livestock management chain emissions with annual European greenhouse gas inventories

Our results can also be compared with the Annual European Union greenhouse gas inventory 1990–2011 and 1990–2018 as published by the EEA (2013, 2020). In the first of these reports, the EEA used the methodology of the IPCC 1996 guidelines and in the second, they followed the methodology of the IPCC 2016 guidelines. Therefore, a comparison of emissions estimated with both methods can only be done for the base year (1990).

When we compare the CH_4 emissions from enteric fermentation calculated for the year 1990 (table 6), we see an increase in CH_4 emissions in this category when using the 2006 guidelines for the other EU countries, similar to our results. One of the likely reasons of the increase in CH_4 emissions is the change of Y_m in the EF calculations for those countries.

For the category CH_4 emissions from manure management, we observe differences in EU-15 countries (table 7). Our results showed a slight increase of emissions in this category for Austria when changing from the 1996 to 2006 guidelines. Meanwhile EEA inventories show significant decreases in CH_4 emissions from manure management for France, Ireland and Portugal. A possible explanation for these differences might be the changed method and EF information when applying the IPCC 2006 guidelines and the influence of the share of emissions from grazing, liquid and solid manure management systems. Again, these results confirm the importance of detailed data and methodology used to report inventories. N_2O emissions from the same category for Sweden, France, Italy and Netherlands showed a similar decrease to Austrian emissions between the two guidelines (table 7). These results are likely to be related to the reduced solid manure management systems EFs in the 2006 guidelines. Spain reported higher N_2O emissions for the same category, which may be due to changing EFs from country-specific to default values when applying the IPCC 2006 guidelines.

The trend in direct N_2O emissions from managed soils showed differences for EU-15 countries. We observed a decrease in Austrian emissions, but according to the EEA inventories, emissions for Belgium, Denmark, France, Greece, Ireland and Sweden increased when changing from the IPCC 1996 to the IPCC 2006 guidelines. This is likely due to changed EF information and methods applied for these countries. Some countries began using country-specific EF instead of the default values and some adopted Tier 2 approaches alongside Tier 1. Meanwhile, indirect N_2O emissions for EU-15 countries showed significant decreases similar to our observations for Austria.

Table 6. EU-15 countries CH_4 emissions from enteric fermentation adapted from Annual European Union greenhouse gas inventory 1990–2011 and inventory report 2013, Annual European Union greenhouse gas inventory 1990–2018 and inventory report 2020 (EEA 2013, 2020) Reproduced with permission from [EEA].

	CH_4 emissions in 1990 (Gg CO_2-eq)	
Member states	IPCC 1996 GLs methodology	IPCC 2006 GLs methodology
Austria	3753	4821
Belgium	4118	5410
Denmark	3247	4039
Finland	1933	2417
France	30 611	38 630
Germany	29 561	35 353
Greece	3246	4024
Ireland	9574	11 357
Italy	12 278	15 497
Luxembourg	261	388
Netherlands	7653	9213
Portugal	2709	3521
Spain	11 120	15 937
Sweden	2951	3277
United Kingdom	18 593	25 392

Table 7. EU-15 countries CH_4 and N_2O emissions from manure management adapted from Annual European Union greenhouse gas inventory 1990–2011 and inventory report 2013 and Annual European Union greenhouse gas Inventory 1990–2018 and inventory report 2020 (EEA 2013, 2020). Reproduced with permission from [EEA].

	CH_4 emissions in 1990 (Gg CO_2-eq)			N_2O emissions in 1990 (Gg CO_2-eq)		
Member states	IPCC 1996 GLs methodology	IPCC 2006 GLs methodology	Trend (%)	IPCC 1996 GLs methodology	IPCC 2006 GLs methodology	Trend (%)
Austria	431	544	20.8	934	436	−114.2
Belgium	1429	1299	−10.0	962	912	−5.5
Denmark	993	1854	46.4	600	979	38.7
Finland	247	368	32.9	487	284	−71.5
France	8284	3463	−139.2	6145	2871	−114.0
Germany	6698	8100	17.3	3919	3913	−0.2
Greece	352	774	54.5	304	333	8.7
Ireland	2354	1406	−67.4	435	498	12.7
Italy	3462	3948	12.3	3921	2817	−39.2
Luxembourg	79	46	−71.7	41	33	−24.2
Netherlands	3053	5442	43.9	1183	940	−25.9
Portugal	1185	814	−45.6	526	276	−90.6
Spain	5172	6982	25.9	1345	1611	16.5
Sweden	234	245	4.5	733	369	−98.6
United Kingdom	3429	4733	27.6	1958	3443	43.1

Overall, we observe changes in the emissions from different source categories caused by changes in EFs and tier methods. These findings reflect the importance of applied methodology for estimating emission sources.

4.3. Implications for future improvement of inventory guidelines and on the potential take up of mitigation measures

Improvement of inventory guidelines is important to ensure that countries can select the most suitable mitigation measures and demonstrate their effects in the national inventories. Recent studies on mitigation measures emphasize the relationship between accurate emission measurements and effective mitigation options. Sajeev *et al* (2018) quantified the emission reductions of mitigation methods in the manure management chain and showed that mitigation options such as frequent removal of manure, anaerobic digesters and manure acidification reduced N_2O and CH_4 emissions simultaneously. Chadwick *et al* (2011) showed that optimization of the N content in the animal diet is an effective mitigation option for the manure management chain as it reduces N excretion from the beginning of the manure chain. Animal diet modification is now known to be one of the most prominent abatement options for CH_4 emissions from enteric fermentation and manure storage (Chadwick *et al* 2011, Caro *et al* 2016). Since the relative magnitude of CH_4 emissions became greater due to the GWP characterization factors, increase in Y_m and the increase in CH_4 emissions per dairy cows due to their increase in performance, mitigation measures for CH_4 emissions have also become a focus. It is therefore likely that mitigation measures for CH_4 emissions, and especially for enteric CH_4 emissions from cattle, will have a greater impact on emission reductions in the inventory. The slight increase of CH_4 emissions from manure management systems under the IPCC 2006 guidelines raises the possibility that the mitigation measures from manure management could have a greater impact on the emission inventory than with the previous methodology (IPCC 1996).

We observed that N_2O emissions from manure management decreased significantly not only due to the GWP characterization factor but also because of the new findings on solid manure management, primarily the reduced N_2O EF for solid manure storage in the IPCC (2006) guidelines. Possibly installation of such manure management systems can be supported to reduce N_2O emissions.

N_2O emissions from agricultural soils also decreased due to various changes explained before in the results. In addition, in general the relative importance of N_2O emissions in relation to CH_4 emissions decreased. This leads to the undesirable effect that better nitrogen use efficiency (NUE) in crop production will have a less prominent role in the GHG emission inventories. However, we can infer that better NUE and less N losses will reduce NH_3 emissions in the NEC inventory and they will help meet the aims of the nitrates Directive. Therefore, even if they are less effective for reduction of N_2O emissions in the GHG inventories, their overall effect on various reporting obligations is still relevant.

Table 8. Updates in the livestock and manure management and soil N_2O categories adapted from the IPCC 2019 refinement.

Updates in the livestock manure management and soil N_2O—2019 Refinement to the 2006 IPCC Guidelines For National Greenhouse Gas Inventories—Overview	
Updates in livestock and manure management	• Tier 1 emission factors have been updated considering current productivity data and integrating differential emission factors and for high and low productivity systems. • Further, for major animal categories, Tier 1 parameters such as enteric fermentation EFs, volatile solids and nitrogen excretion are derived based on consistent data sources. • The Tier 1 method to estimate CH_4 emissions from manure management has been updated for consistency with N_2O emissions. • Certain Tier 2 parameters have been refined. The methane conversion rate (Y_m) for cattle and buffalo, varies based on animal diet and level of productivity. • The default methane conversion factor (MCF) values for animal waste management systems are presented based on climatic regions, as opposed to annual temperatures, and a simple calculation model for deriving the MCF based on monthly temperature regimes has been presented. • Improved guidance has been developed for the treatment of nitrogen transfers among livestock emission source categories and transfers to agricultural soils.
Updates in soil N_2O	• Tier 1 estimates have been updated based on the latest science for direct and indirect emission factors. A key development is the disaggregation of emission factors by climate region.

4.4. Further outlook: the IPCC 2019 refinement to the 2006 IPCC guidelines

Countries reporting national emissions inventories within the UNFCCC practice mostly use the IPCC 2006 guidelines, which were published 14 years ago. Although these guidelines still provide a sound methodological basis for national GHG estimations, there can still be gaps and uncertainties in the methodology. During the 26th meeting of the Task Force Bureau (TFB) it was decided that a refinement of the guidelines was required. With the approval of at the 40th IPCC Session, the Task Force on National Greenhouse Gas Inventories (TFI) started an assessment of the IPCC 2006 guidelines, which resulted in a decision to prepare the 2019 Refinement to the 2006 IPCC Guidelines. More than 280 scientists and experts developed the 2019 Refinement which was accepted in Kyoto/Japan during the 49th Session of the IPCC on 12th May 2019. The 2019 Refinement provides updates and supplements to the 2006 IPCC guidelines for continuous improvement of national GHG inventories and should be used along with them. In Volume 4 'Agriculture, Forestry and Other Land Use', updates were applied to various categories including livestock, manure management and soil N_2O. A list of key updates in the 2019 refinement are presented in table 8.

These are important updates for the future national inventory reports and are expected to change emissions estimates from livestock management chain depending on the methods that countries use. When we look at how these updates could influence Austrian national inventories, we observe that only some of the changes are relevant to Austrian emissions calculations. Changes in Tier 1 EFs for major animal categories and for high- and low-productivity systems do not apply to Austrian national inventories, since Austria uses a Tier 2 method for these categories. However, the refinement of the Y_m is expected to have a distinct impact. We expect that the change in the Y_m calculation will more accurately reflect the real situation. Guidance on the treatment of nitrogen transfers among livestock emission source categories and transfer to agricultural soils does not apply to Austria, since Austria already uses an N flow approach, but in other countries it is an important step towards applying an integrated N flow model. When it comes to MCF values, liquid manure management systems for cattle and swine will not be affected because Austria uses country-specific values for these. Other systems would be affected by the changes in the default MCF values from the IPCC guidelines. We believe that the shift towards more country-specific MCF calculations will also decrease CH_4 emission estimates from manure management. Disaggregation of soil N_2O EF to wet and dry climates may also result in interesting shifts. The EF for synthetic fertilizer input for wet climates increased from 0.01 to 0.016 and EF for other N inputs decreased from 0.01 to 0.006. Meanwhile the EF for N volatilization and re-deposition increased to 0.014 and the default value for EF leaching/runoff increased to 0.011 in the 2019 refinement. Since the Austrian climate is cold with high precipitation, it is possible that disaggregation for wet climates will decrease the estimated direct soil N_2O emissions but increase indirect soil N_2O emissions.

5. Conclusion

This study set out to show the effects of two IPCC methodologies on estimates of GHG emissions from the livestock sector. Austria was used as a case study for this exercise. Moving from the 1996 IPCC guidelines to the 2006 IPCC guidelines revealed prominent changes in livestock GHG emissions from different source categories. We observed an increase in emissions from enteric fermentation, while emissions from manure management and agricultural soils decreased. Examination of the applied methodology, EFs and approaches confirm their importance for generating more accurate and transparent emission inventories. The study also identified the impact of changes in emissions from different source categories on the effectiveness of mitigation measures. It was shown that there is a strong relationship between emission inventory methodology and mitigation options as the mitigation measures will only be effective for meeting emission reduction targets if their effectiveness can be demonstrated. Therefore, it is very much in the interest of the agricultural sector to report detailed and transparent inventories. An outlook on the 2019 IPCC Refinement revealed that the challenge of future inventory improvement will include the gathering of high-resolution data and accurate, country-specific EFs. Such improvements are worth the effort for policy makers, because inventory reports are a potent tool to implement mitigation measures and for farmers, because high-quality analysis reveals the potential emissions savings and efficiency gains that are easiest to access.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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