ETC HE Report 2022/21

Emissions of ammonia and methane from the agricultural sector

Emissions from livestock farming

Authors:

Laure Malherbe (Ineris), Richard German (Aether), Florian Couvidat (Ineris), Laurène Zanatta (Ineris), Lewis Blannin (Aether), Aiden James (Aether), Laurent Létinois (Ineris), Simone Schucht (Ineris), Brice Berthelot (Ineris), Justine Raoult (Aether)

European Environment Agency
European Topic Centre
Human health and the environment

Cover design: EEA
Cover image: Kurt Bouda, Pixabay
Layout: EEA / ETC HE / Ineris

Publication Date: April 2023
ISBN 978-82-93970-25-5

How to cite this report:
Malherbe, L., German, R., Couvidat, F., Zanatta, L., Blannin, L., James, A., Lètinois, L., Schucht, S., Berthelot, B. & Raoult, J. (2022). *Emissions of ammonia and methane from the agricultural sector. Emissions from livestock farming* (Eionet Report - ETC HE 2022/21). European Topic Centre on Human Health and the Environment.

The report is available from https://www.eionet.europa.eu/etcs/all-etc-reports and https://zenodo.org/communities/eea-etc/?page=1&size=20.

EEA activity : climate change mitigation and adaptation; human health and the environment

ETC-HE coordinator: NILU - Stiftelsen Norsk institutt for luftforskning (NILU - Norwegian Institute for Air Research)

ETC-HE consortium partners: Federal Environment Agency/Umweltbundesamt (UBA), Aether Limited,
Czech Hydrometeorological Institute (CHMI), Institut National de l'Environnement Industriel et des Risques (INERIS),
Swiss Tropical and Public Health Institute (Swiss TPH), Universitat Autònoma de Barcelona (UAB),
Vlaamse Instelling voor Technologisch Onderzoek (VITO), 4sfera Innova S.L.U., klarFAKTe.U

European Topic Centre on
Human health and the environment (ETC-HE)
https://www.eionet.europa.eu/etcs/etc-he

Contents

List of tables

List of figures

List of maps

Summary

The agricultural sector is the largest anthropogenic emitter of ammonia (NH_3) and methane (CH_4) in the air in Europe, accounting for 94 % and 54 % of NH_3 and CH_4 emissions, respectively, in the EU-27 in 2020 (EEA, 2022a and 2021). NH_3 is a precursor of secondary particles and can damage terrestrial and aquatic ecosystems through deposition. CH_4 is the second most important greenhouse gas contributing to climate change after carbon dioxide, it can also be involved in the formation of ozone and have an indirect effect on $PM_{2.5}$ concentrations by affecting the concentrations of oxidants.

According to previous studies, and in particular a study from IIASA (2017), livestock farming is by far the main agricultural sub-sector responsible for NH_3 and CH_4 emissions, manure management and enteric fermentation being respectively the most contributing sources of these two pollutants.

In that context this study examines the current state of NH_3 and CH_4 emissions from livestock farming in Europe by investigating three topics:

- the spatial distribution of these emissions and the emission contribution of the farms according to their size and the type of animal;
- the existence and efficiency of technical measures to reduce emissions and their implementation by Member States;
- the assessment of the impacts of these emissions on health and the environment.

To address spatial distribution of emissions and farm contribution, a methodology is defined and implemented to estimate NH_3 and CH_4 emissions at NUTS2 (~regional) level in the EU-27 for 2019, by farm size class and animal category. Inputs to the calculations consist of activity data available on Eurostat and emission factors proposed in EMEP/EEA and IPPC guidance. Given the limitations encountered in the input data, the results of these calculations are adjusted according to the national totals reported by the Member States. Installations with more than 100 livestock units (LSUs), which only represent 4.7 % of the farms, account for a major fraction of the emissions (66.8 % and 56.8 % for NH_3 and CH_4 respectively). As regards the type of livestock, cattle appear to be the first source of NH_3 and CH_4 emissions, followed by swine.

The possibility of studying the spatial distribution of these emissions in more detail is then studied by considering different data sources: a dataset constructed by INRAE of livestock information by NUTS 3 regions in 2010; national data made available by countries; emission data reported to the E-PRTR; gridded emission datasets i.e. EMEP (2019) for NH_3 and EDGAR modelled emission data (2019) for CH_4. Whereas the E-PRTR accounts for only a limited fraction of the emissions, the comparison of the results obtained with the other data sources shows that the emissions disaggregated over Europe with the INRAE dataset make a reliable representation of NH_3 and CH_4 emissions at NUTS3 level. These results enable the identification of regions where emission density (emission levels per unit of area) is higher: Ireland, Brittany (France), Belgium, the Netherlands, some parts of Germany and Poland, Lithuania, the Po Valley and Naples region (Italy), northern Spain. They also highlight the variability of emissions across NUTS3 regions.

As an introduction to the second topic (existence and efficiency of reduction measures), an overview of European rearing systems is provided, presenting some meaningful production figures for each main type of animals.

Key mitigation measures to reduce NH_3 and CH_4 emissions are then reviewed, limiting the inventory to those techniques and good practices applicable to cattle, pigs and poultry, as these species are the main emitters of NH_3 and, regarding the first two, of CH_4 in Europe. A method based on the UNECE approach established for the Ammonia Guidance Document is applied to review technical measures to reduce NH_3 air emissions.

As far as techniques to reduce methane emissions are concerned, there is no equivalent to the UNECE document. Several documents have been consulted, in particular the report from the European EIP-AGRI Focus Group on reducing emissions from cattle farming.

Opportunities to reduce ammonia emissions from livestock operations, from building to land application, are well identified and in part, already implemented. However, there are limits to applicability depending on the type of building and the techniques cannot necessarily be applied in existing buildings. Thus, significant investments are required to make them widespread. In addition, ammonia emission reductions must be integrated into a nitrogen management system to avoid deleterious cross-effects and fully exploit the benefit of a measure reducing nitrogen loss. In addition, manure management on farms consists of several linked stages in sequence, from building to land application, and measures to reduce emissions upstream are ineffective if measures are not also applied downstream.

The possibilities to reduce CH_4 emissions from cattle farms, the main emitters, are mainly related to feed adaptation and the use of feed additives. To a lesser extent, improving productivity and genetic improvement of animals can contribute to a reduction in CH_4 emissions but these solutions are not necessarily easy to deploy. In addition, anaerobic digestion appears to be a solution for managing effluents to reduce methane emissions.

As well as future uptake of mitigation measures, production levels are an equally (if not more) important driver of emissions, the relative impact of each driver depending on the livestock species and rearing systems. Projections of animal numbers per Member State for 2025, 2030 and in some cases 2040 were extracted from projections reported under the NECD and Governance Regulation in 2021. According to these data and to an analysis of published scenarios, for the EU as a whole, numbers of dairy and non-dairy cattle are projected to fall slightly by 2030 and 2040 compared with 2020, whereas numbers of poultry are projected to rise significantly by 2040 compared with 2020. For pigs results are more mixed. These projected trends could, however, be affected by changes in the demand due to demand-side measures, like measures aiming to cause dietary shift towards products with a lower CH_4 or NH_3 emissions footprint or to reduce food waste.

As the third topic of this study, the impacts of NH_3 and CH_4 emissions on human health and the environment are first studied from a methodological point of view. Different numerical tools that can be used to simulate the effect of emission changes on atmospheric concentrations and deposition are reviewed: chemistry-transport modelling, source-receptor matrices, surrogate models. Then a methodology based on a previous ETC study is set up to estimate the consequences of reducing NH_3 and CH_4 emissions by a given percentage. It is based on chemistry-transport modelling (CHIMERE model) and health impact assessment (Alpha-RiskPoll tool). Applying this approach, we provide estimates of the $PM_{2.5}$ concentrations reduction resulting from a 15 % reduction of ammonia emissions on the one hand, and the $PM_{2.5}$ and ozone (through the SOM35 indicator) concentrations reduction resulting from a 50 % reduction of global CH_4 anthropogenic emissions on the other hand.

On an annual basis $PM_{2.5}$ concentrations avoided by a 15 % reduction of ammonia emissions are generally below 0.5 µg/m^3 and represent 1 to 4 % of $PM_{2.5}$ concentrations. Reductions can be higher in a few areas, in particular in the Po Valley, northern France, Belgium, Germany, Poland, The Balkans, and Turkey. Avoided damage costs are the largest for Germany, Italy, Poland, France, Spain and Belgium.

The $PM_{2.5}$ concentrations avoided by a 50 % reduction of methane anthropogenic emissions are generally under 0.1 µg/m^3 but can exceed 0.2 µg/m^3 in a few areas, especially in the Po Valley, in Rome region, in the north of Belgium and in the Netherlands. The avoided SOMO35 (health indicator for ozone) is higher in southern Europe.

When taken as an EU27 average, the avoided damage costs are about 30 to 100 k€ per tonne of non-emitted NH_3 and about 0.05 to 0.15k€ per tonne of non-emitted CH_4.

Acknowledgements

The ETC task manager was Laure Malherbe (Ineris). The EEA task manager was Levente Molnár with the support of Katarzyna Kowalczewska (EEA).

Other contributors were Richard German (Aether), Florian Couvidat (Ineris), Laurène Zanatta (Ineris), Lewis Blannin (Aether), Aiden James (Aether), Laurent Létinois (Ineris), Simone Schucht (Ineris), Brice Berthelot (Ineris), Justine Raoult (Aether).

The authors are thankful to Elsa Real and Palmira Messina from Ineris, the French helpdesk from Eurostat, Bertrand Dumont from INRAE, and to Wilfried Winiwarter and Zbigniew Klimont from IIASA, for providing detailed answers to their questions. They are grateful to the Member States' representatives who responded to the questionnaire which was sent to them in the scope of this work. The modelling results of the Copernicus Atmosphere Monitoring Service (CAMS) Policy Service coordinated by INERIS for ECMWF were also used to estimate methane damage costs.

The authors would like to thank Augustin Colette and Jean-Marc Brignon (Ineris) and Katarzyna Kowalczewska (EEA) for their feedback and comments.

1 Introduction

1.1 Context

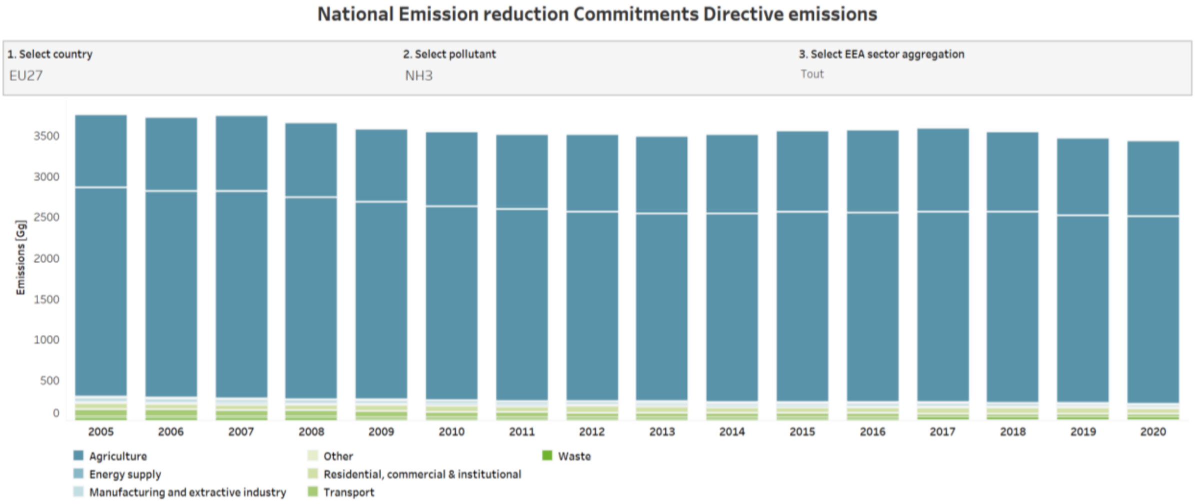
The agricultural sector is the largest emitter of ammonia (NH_3) and methane (CH_4) in the air in Europe, accounting for 94 % and 54 % of NH_3 and CH_4 emissions, respectively, in the EU-27 in 2020 (source: EEA, 2022a(1) and 2021(2), based on data reported by countries). Livestock farming represents the main agricultural source of both gases, with a contribution depending on the number and type of animals.

NH_3 is a secondary particulate matter precursor. Under conducive weather conditions, it combines with other compounds in the atmosphere like nitric and sulphate acids to form ammonium salts, thus contributing to the total particle load. In addition, the emissions of ammonia contribute to the atmospheric deposition of reactive nitrogen, which can disrupt terrestrial and aquatic ecosystems.

According to a study from the International Institute for Applied Systems Analysis (IIASA, 2017), manure management from livestock farming is the main source of agricultural emissions of NH_3 in Europe, representing a contribution of 75 % in the EU-28 in 2015. This contribution mainly originates from farms housing more than 50 livestock units(3) (LSUs) which account for about 78 % of NH_3 emissions released by livestock farming in 2015; this percentage was 22 %, only considering farms with more than 500 LSUs.

Contrary to the trends observed for other main air pollutants ($PM_{2.5}$, NO_x, SO_2, NMVOCs), NH_3 emissions in Europe have shown limited change over the last two decades, displaying a small decrease until 2013 followed by a slight increase between 2013 and 2017 and a slow decrease since 2017 (Figure 1.1).

Figure 1.1: Emissions of NH_3 by sector, 2005-2020



Source: EEA data viewer[1], 2021.

---

(1) https://www.eea.europa.eu/data-and-maps/dashboards/national-air-pollutant-emissions-data.
(2) https://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer.
(3) Livestock unit (LSU) is a reference unit used to enable comparison and aggregation across different livestock species and ages, based on feed requirements. 1 LSU is defined as 1 adult dairy cow producing 3000kg milk annually. Coefficients are applied to the numbers of heads of other species or ages to convert them to the LSU equivalent number. See https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Livestock_unit_(LSU) for more details.

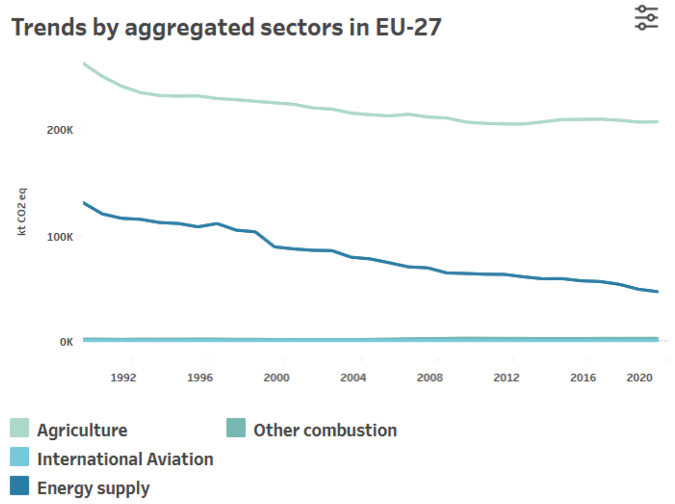
CH_4 is the second most important greenhouse gas contributor to climate change following carbon dioxide. While it is relatively short-lived in the atmosphere (ca. 10 years), it has an about 28 and 84 higher global warming potential than carbon dioxide (CO_2) on a 100- and 20-year time scale, respectively(4).

As a volatile organic compound, it is a ground-level ozone (O_3) precursor, participating in O_3 formation in conditions of sunlight and heat. It can also affect the concentrations of oxidants, thus having an indirect effect on the formation of secondary aerosols.

Livestock is also by far the largest source of emission of CH_4, globally and in most countries (Saunois et al., 2020). Enteric fermentation of feed in the stomachs of livestock, particularly cattle, is the largest single source of CH_4 in the EU-27, followed by anaerobic decomposition of livestock manure during storage (manure management) (Eurostat, 2022(5)).

Like NH_3 emissions, CH_4 emissions in Europe have decreased only slowly over the past two decades, in particular in the agricultural sector (Figure 1.2).

Figure 1.2: Emissions of CH_4 in EU-27 by sector, 1990-2020 (in kt CO_2 eq)



Source: EEA data viewer^2, 2021.

1.2 Objectives

The aim of this work is to assess the current situation as regards the distribution of NH_3 and CH_4 emissions from agriculture across Europe, the availability and uptake of mitigation measures and the way of evaluating their impacts at the European scale. This study is exclusively focused on livestock farming given the predominant contribution of this activity to NH_3 and CH_4 agricultural emissions. It also presents the methodologies that have been built for that purpose and which may be reused in future updates.

More precisely, this study is organized in three main parts.

---

(4) https://energy.ec.europa.eu/topics/oil-gas-and-coal/methane-emissions_en; GWPs based on the IPCC 5th Assessment Report https://www.ipcc.ch/assessment-report/ar5/

(5) https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Climate_change_-_driving_forces#Agricultural_emissions

In the first part, a methodology is developed and applied to estimate and map emissions (total quantities or densities) at NUTS2 resolution by type of animal, type of activity and size of farm. The possibility of reaching the higher NUTS3 resolution is then explored considering different approaches and sources of information: spatial reallocation of NUTS2 estimates; use of emissions reported under E-PRTR regulation; use of emissions reported under National Emission reduction Commitment (NEC) Directive.

Uncertainties and limitations due to gaps and quality issues in the input data and the assumptions required for the calculations are presented.
As a complement, this part briefly introduces an alternative approach to assess emissions at local scale, based on measurement campaigns.

The second part is based on a review of scientific and technical literature in order to present an overview of European livestock rearing systems and a series of key technical mitigation measures per type of livestock. It also examines the current and possibly future level of uptake of those measures by the Member States, based on national policies and measures and on various published EU-level modelling exercises. Finally, the contribution of changes in livestock numbers and production levels to mitigation is reviewed, based on numbers presented by national projections and the same published EU-level modelling exercises.

In the third part, a methodology building on previous ETC work is proposed to assess the impact of reducing NH_3 and CH_4 emissions on human health and ecosystems. This approach is then applied, focusing on human health. It consists in estimating the prevented pollutant concentrations due to a reduction in NH_3 and CH_4 emissions over Europe, namely $PM_{2.5}$ concentrations as regards the precursor NH_3, and concentrations of $PM_{2.5}$ and O_3 as regards the precursor CH_4, and in deriving the corresponding avoided costs (health benefits).

1.3 Links to EU policy

This study takes place in the context of the on-going revision of the Industrial Emission Directive and the review of the Gothenburg Protocol under the Air Convention.

It is connected with the EU strategy to reduce methane emissions (European Commission, 2020), the Farm to Fork Strategy and the Zero Pollution Action Plan.

2 Identification of the main emitters of methane and ammonia in the livestock sector at regional level

2.1 NUTS2 level

As mentioned in the introduction, the agricultural sector, and in particular livestock farming, is the main source of methane and ammonia emissions in Europe. Moreover, statistics indicate that holdings housing a large number of livestock heads account for a major part of these emissions.

It is therefore interesting to determine where the large farms are located in Europe and to which extent they contribute to the emissions of NH_3 and CH_4. For this analysis, we will consider as large farms the last two Eurostat LSU classes: more than 500 LSUs and between 100 and 500 LSUs. Different statistics and maps will be elaborated to provide a synthetic and spatial view of NH_3 and CH_4 emissions from livestock in EU-27, distinguishing between the type of activity and type of animal.

Methodology

Spatial emission inventories exist but the information provided is not sufficiently detailed to precisely determine the origin of the pollution in a given area. For NH_3, national gridded emissions maps at 0.1° x 0.1° resolution are reported by EU Member States under the National Emissions reduction Commitment Directive, but these do not distinguish the contribution of different livestock types or different farm sizes. For CH_4, there are no requirements for Member States to report spatial emissions maps, and international datasets available (e.g. EDGAR(6)) are based on simplified methods.

Therefore, the use of refined activity data and emission factors could help to assess and locate the areas in which these large installations emit most of the methane and ammonia.

Two guidebooks (EMEP/EEA, 2019 and IPCC, 2019) provide guidance to evaluate ammonia and methane emissions from livestock activity. Activity data (livestock numbers) at NUTS2 level are available from the Eurostat website(7) but are not sufficient to use the best methodologies proposed in guidebooks. As a result, reported emissions available at national level should be used as baseline data.

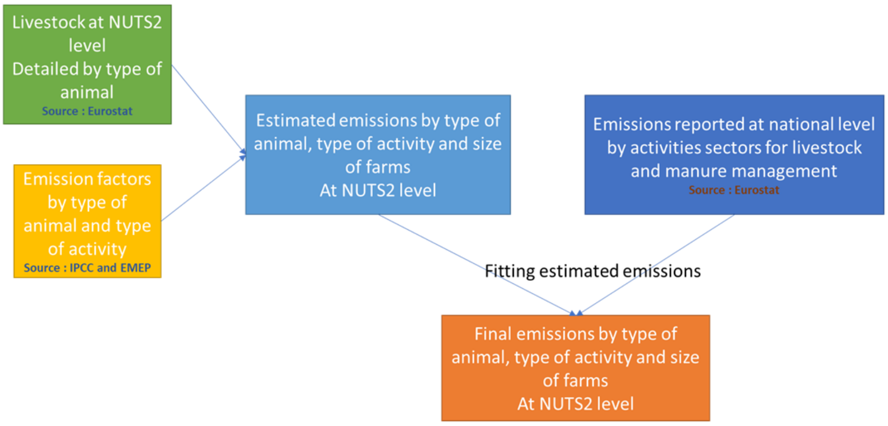
Therefore, the methodology developed for this study proposes to calculate emissions from available activity data and emission factors and then to adjust them with the reported emission data (Figure 2.1).

---

(6) https://edgar.jrc.ec.europa.eu/.

(7) https://ec.europa.eu/eurostat/data/database.

Figure 2.1: Methodology developed to assess emissions at NUTS2 resolution



Input data

To evaluate emissions, the method mostly used is to combine activity data with emission factors (EF). Activity data have been collected from Eurostat and emission factors were issued from official guidebook (EMEP and IPCC).

- *Emission factors*

Two guidebooks were used to collect emission factors and to prepare them to calculate emissions

Ammonia emission factors

The joint EMEP/EEA air pollutant emission inventory guidebook(8) provides guidance to elaborate national emissions inventories. More specifically, the chapter 3 dedicated to agriculture activities proposes a methodology and emission factors to evaluate ammonia emissions from livestock (chapter 3.B). Depending on the data available, different methods can be used (Tier 1 to Tier 3, the most advanced calculation method). For this study, activity data have been limited to the information on livestock numbers available from Eurostat at NUTS 2 region level. More accurate data are probably available but would need to be obtained from each Member State.

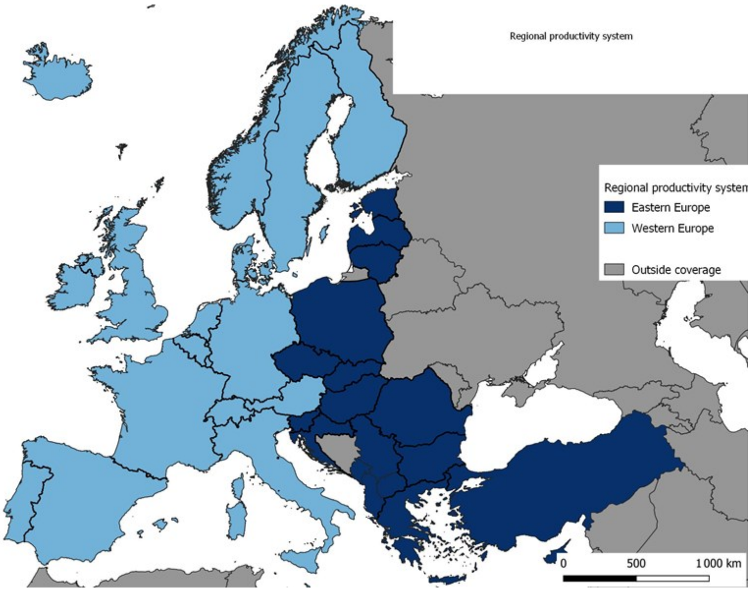
Only Tier 1 methodology can be used with Eurostat data. Aggregated emission factors are provided to evaluate NH_3 emissions according activity sectors and type of animals. Three activity sectors are assessed: manure management from livestock, manure applied to soils and excreta deposited by grazing livestock. Animals are classified by species and some sub-categories. Emission factors are also distinguished by slurry and solid only for cattle and swine.

Lastly, emission factors depend on the productivity system used in the country. This table identifies two types of country: western and eastern European countries, respectively high-productivity systems, and low-productivity systems. For this study, European countries were distributed as showed in Map 2.1.

---

(8) https://www.eea.europa.eu/publications/emep-eea-guidebook-2019.

Map 2.1: Type of animal waste management system used in European countries



Collected activity data should match those emission factors. In particular they should fit at least with sub-categories of animals defined in the Tier 1 methodology, which is not fully the case as presented in the following section (livestock data). They should also allow the distinction between slurry and solid. The estimated share of manure managed in slurry and solid systems was based on the animal waste management system regional averages given in the table 10A.6 (NEW) from the 2019 Refinement to the 2006 IPCC Guidelines (Vol 4, Chapter 10).

Methane emission factors

The Intergovernmental Panel on Climate Change (IPCC) provides guidelines in a guidebook(9) to elaborate national greenhouse gas inventories. The volume 4(10) (2019 edition) gives methodologies to evaluate emission from agriculture, forestry and other land use. Chapter 10(11) describes how to estimate emissions from livestock and manure management.

As described for ammonia, different methodologies are proposed in accordance with the availability of the activity data. Tier 1 method has been also used for this study.

Methods are provided for two different source categories: enteric fermentation and manure management from livestock. Animals are categorised by species and some sub-categories. It should be noted that no emission factor has been established for enteric fermentation in poultry.

As for ammonia, emission factors are dependent on the productivity system of the country: the same country allocation was used as presented in Map 2.1.

CH_4 emissions from manure management are also sensitive to temperature. Emission factors depend on the climate zone where the emissions are estimated. Geographic information about climate zone as a raster file compatible with GIS systems was not available from IPCC; only maps are provided in reports (like Map 2.2).

However, a raster file(12) was found on the website of the European soil data centre (ESDAC) and was used to evaluate the climate zone of each NUTS2 region in Europe using GIS processing (Map 2.3).

---

(9) https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html.

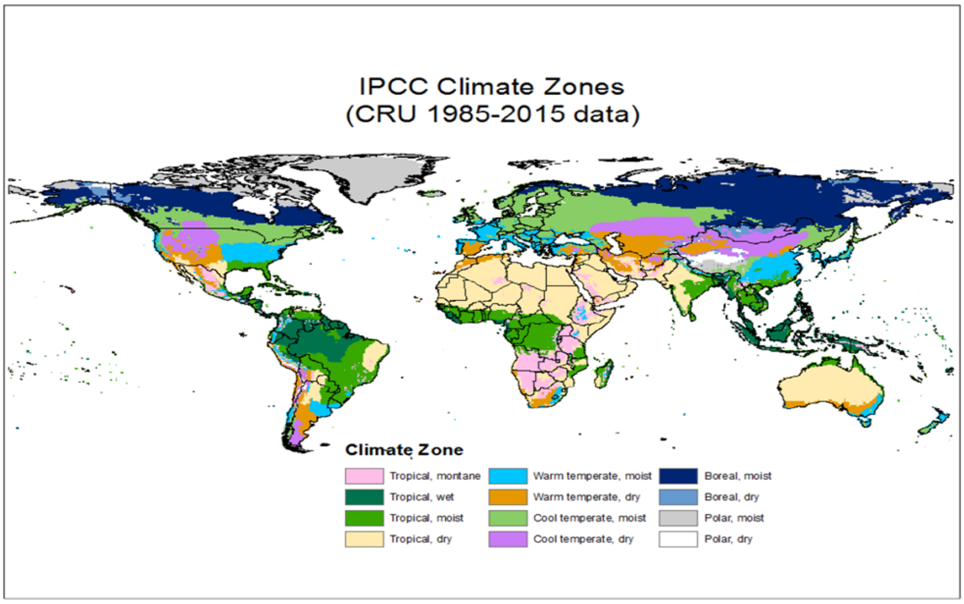
(10) https://www.ipcc-nggip.iges.or.jp/public/2019rf/vol4.html.

(11) https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4_Volume4/19R_V4_Ch10_Livestock.pdf.

(12) https://esdac.jrc.ec.europa.eu/projects/RenewableEnergy/.

The CH_4 methodology is a little more complex to implement than the one used for ammonia. Different equations have to be applied to obtain aggregated emissions factors according to activity sectors, type of animals, productivity sector and climate zone (manure only).
As written in the previous section concerning NH_3, data activities collected should fit at least with sub-categories of animals defined in the Tier 1 methodology.

Map 2.2: IPCC climate zones from IPCC guidebook



Map 2.3: Climate zone from ESDAC website

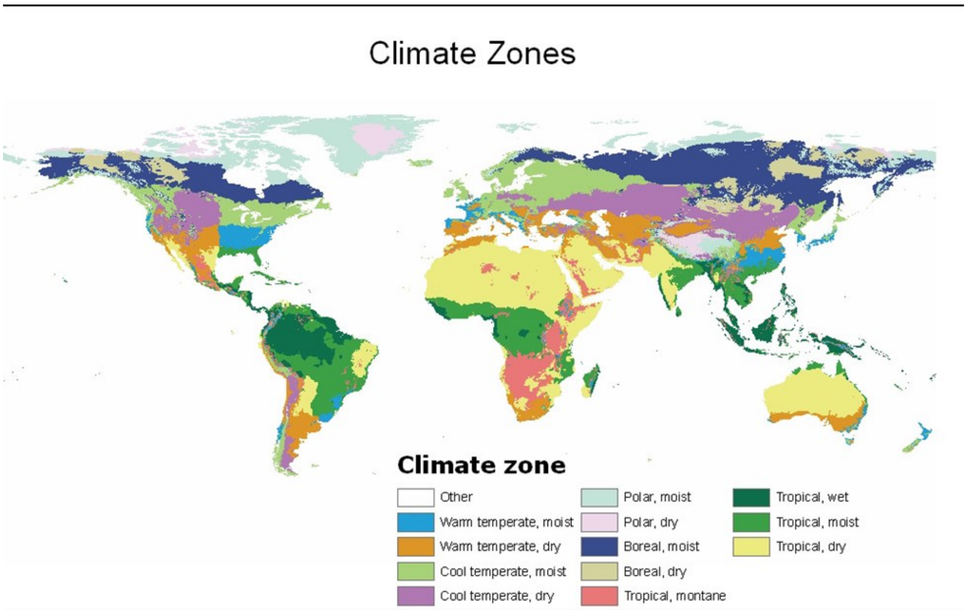


Table 2.1 summarizes the data sources on which NH_3 and CH_4 emission factors used in this study are based.

Table 2.1: Data sources used to obtain NH_3 and CH_4 emission factors

Pollutant	Source	Object	
NH_3	EMEP/EEA air pollutant emission inventory guidebook - chapter 3.B - Table 3.2	Emission factors from manure management	
CH_4	IPCC guidebook (2019 edition) -TABLE 10.14 (UPDATED)	Methane emission factors by animal category, manure management system and climate zone	
NH_3 and CH_4	IPCC guidebook (2019 edition) - table 10A.6, 10A.7, 10A.8 & 10A.9 (NEW)	Animal waste management system (awms) regional averages allocation	
CH_4	IPCC guidebook (2019 edition) - table 10A.5	Default values for live weights for animal categories (kg)	
CH_4	IPCC guidebook (2019 edition) - table 10.13A	Default values for volatile solid excretion rate	
CH_4	IPCC guidebook (2019 edition) - table 10.10 & 10.11 (UPDATED)	Enteric fermentation emission factors for tier 1 method	

- *Livestock data*

Eurostat provides numerous statistics for the agricultural sector at European, national, and sub-national level. The use of emission factors requires sufficiently accurate activity data: detailed data by sub-categories of animals. In addition, one of the objectives of the study is to assess the distribution of emissions according to farm size and their location. And finally, it is necessary to assess emissions for the year 2019 to fit with available national emissions inventories. Different datasets were investigated to meet these objectives.

Table 2.2 presents the different Eurostat datasets that could be used for this study.

Table 2.2: Eurostat datasets

Name of the dataset	**Theme**	**Information**		**Comments**
ef_olslsureg	Number of farms and heads of animals by livestock units (LSU) and NUTS 2 regions	Time coverage	2005 to 2013	Does not cover 2019
		Units of data	Number of heads, number of holdings (farms).	
		Animal categories	Detailed sub-categories	Compliant with emission factors

Name of the dataset	**Theme**	**Information**		**Comments**
		Distinguished by size of farm	Yes, expressed in LSU	The activities of different animal species can be combined by size of farms
ef_lsk_main	Main livestock indicators by NUTS 2 regions	Time coverage	2013 and 2016	Does not cover 2019
		Units of data	Units of data: Number of heads, number of holdings.	
		Animal categories	Main categories: Live bovine, swine, sheep, poultry, goats, horses, asses, mules and hinnies	Only main categories are provided: no sub-categories available. Not compliant with emission factors.
		Distinguished by size of farm	Yes, expressed in LSU	The activities of different animal species can be combined by size of farms
ef_lsk_bovine, ef_lsk_gpig, ef_lsk_sheep and ef_lsk_poultry	Sub-categories of categories of animals by NUTS 2 regions	Time coverage	2013 and 2016	Does not cover 2019
		Units of data	Number of heads, number of holdings.	
		Animal categories	Detailed sub-categories	Compliant with emission factors. Data from horses are missing.
		Distinguished by size of farm	Yes, but expressed in number of heads and not in LSU	The activities of different animal species cannot be combined by size of farms.
Agr_r_animal	Animal 21eductions by	Time coverage	1977 until 2021	Compliant with time period expected
		Units of data	Number of heads	No statistic can be derived from the number of holdings.

Name of the dataset	**Theme**	**Information**		**Comments**
	NUTS 2 regions	Animal categories	Detailed sub-categories	Data from poultries and horses are missing. Data are not available at NUTS2 level for some countries (Germany for example).
		Distinguished by size of farm	No	Data are not dispatched according to size of farm.

It can be noted that none of these datasets perfectly meets the needs of our study.

The dataset "ef_olslsureg" initially seemed to be closest to what was required, but when these data were pre-processed, inconsistencies made it impossible to use them. This table gives two information for each NUTS2 (NUTS1 or country) and animal sub-categories: the total number of heads and the number of heads according to each LSU classes. The sum of LSU classes should be equal to the total number of heads. In practice, this is not always true. These inconsistencies were confirmed by Eurostat.

Adjustments were therefore required and applied by combining three sets of data following the three steps below:

- ef_lsk_bovine, ef_lsk_gpig, ef_lsk_sheep and ef_lsk_poultry were used to dispatch activities according to detailed sub-categories of animals.

  For horses, mules and asses, no detailed data were available. Aggregated data from el_lsk_main were used.
  More specifically, detailed statistics of sheep were missing in the ef_lsk_sheep dataset for Bulgaria and Estonia. Another source was found to fill in the gap. This file refers to old data (2010) coming from Eurostat.
  The processing of these data provided a dataset detailed by NUTS2 and sub-classes of animals for the year 2016. Sub-classes of animals of this dataset are presented in Annex 1.

- ef_lsk_main dataset gives for each NUTS2 region the distribution of number of animals by farm size for each animal species: cattle, pig, sheep, poultry and horses. In this dataset, the size of a farm is expressed as LSU (Livestock unit). Eurostat wrote(13) : "*The livestock unit is a reference unit which facilitates the aggregation of livestock from various species and age as per convention, via the use of specific coefficients established initially on the basis of the nutritional or feed requirement of each type of animal*". It allowed for the present study to aggregate statistics from different species and to calculate emissions by size of farms.

  Assuming that the distribution of animals in the sub-categories is the same regardless of the size of the farm, ef_lsk_main was used to dispatch the 2016 data from the previous dataset into five different sizes of farms: less than 15 LSU,15 to 49.9 LSU,50 to 99.9 LSU, 100 to 499.9 LSU,500 LSU or over.

- agr_r_animal dataset gives the evolution of livestock activity from 1977 to 2021. It is supposed to give NUTS2 statistics for every year and country. But for some countries, data are not available for most recent years at NUTS2 level. They are only available at NUTS1 or national levels and sometimes not at all available for 2016 and 2019 in this dataset but available in ef_lsk_main for 2016.

---

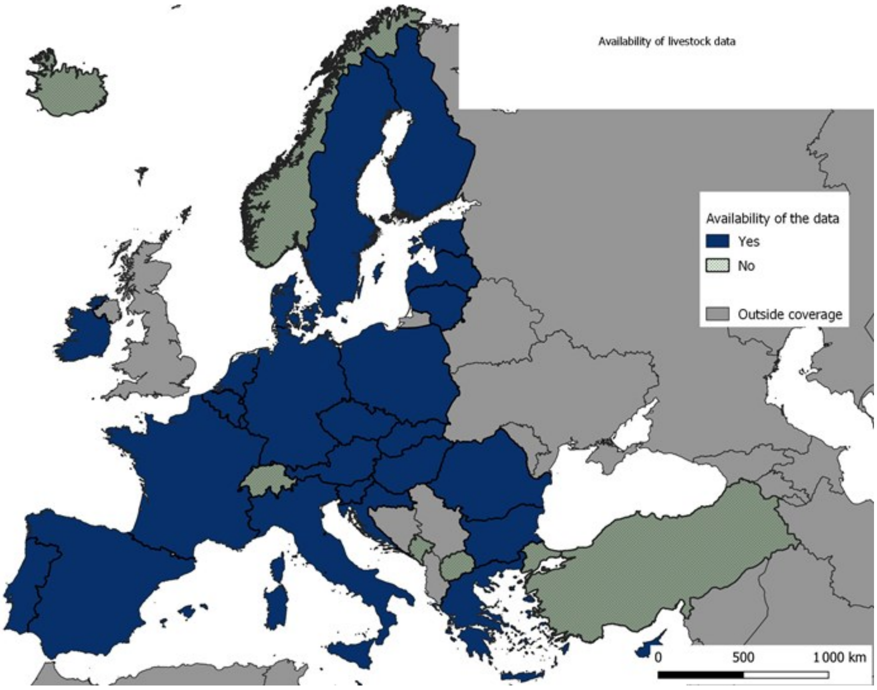
(13) https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Livestock_unit_(LSU).

This dataset was used to adjust the detailed 2016 data calculated at the previous step to 2019 activities based on available data (national, NUTS1 or NUTS2 level).

In summary, many adjustments were required to finalise this work.

Eurostat proposes livestock statistics from 34 countries but for some countries, data were partially available or totally missing. Only data from the EU-27 countries were analysed. They are presented in Map 2.4 and Table A2.1 (Annex 2).

Map 2.4: Countries with available livestock data



Adjustment using national-level reported emissions

Combining emission factors and livestock activity provided emissions data at NUTS2 level. These emissions were estimated from a Tier1 method due to a lack of refined activity data. Therefore, to improve the quality of these results, emissions reported by the European Member States were used to fit the emissions calculated. The latter were adjusted by emitting activity: enteric and manure management.

Results

Livestock activity, emission factors and emissions reported were combined to calculate final emissions for **the year 2019**. These calculated emissions are provided for the 27 countries of the European Union (EU-27) and detailed by local region (NUTS2) according to the type of animals, the activity sector and the size of the farms. Let us recall that these results cover only emissions from livestock activities. Other activities like inorganic nitrogen fertilisers are not evaluated.

Results are given in an Excel file attached to this report and maps are provided in the annexes.

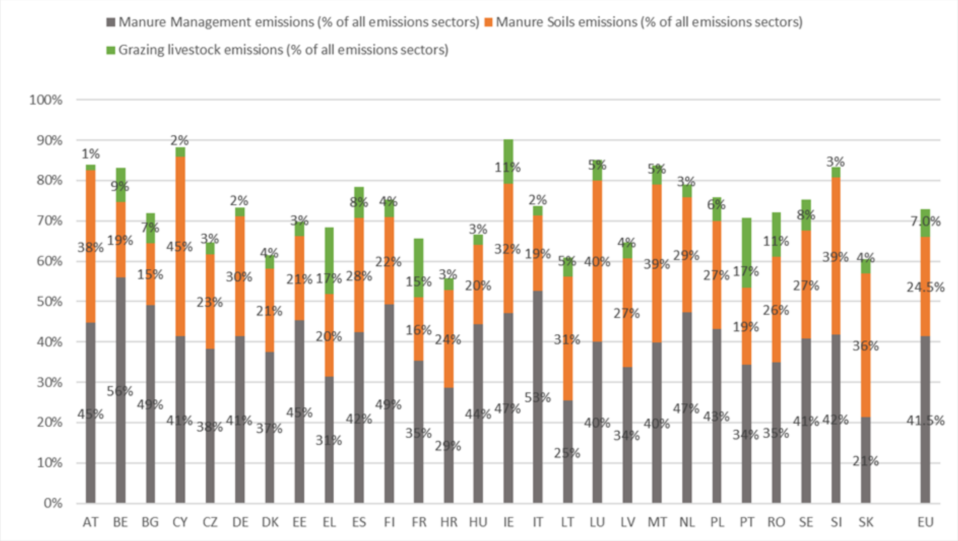
When analysing the results, as mentioned earlier in this chapter, we consider as large farms the last two Eurostat LSU classes: more than 500 LSUs; between 100 and 500 LSUs. Whereas the last class (more than 500 LSUs) generally accounts for less than 25 % of NH_3 or CH_4 emissions, considering both categories allows to focus on facilities of significant size while accounting for more than 50 % of the emissions.

NH_3 emissions

European and national level

Manure management, manure soils and grazing livestock emissions contribute to 73 % of the total of ammonia emissions in the EU-27. 41.5 %, 24.5 % and 7.0 % are respectively emitted from manure management from livestock, manure applied to soils and excreta deposited by grazing livestock (Figure 2.2). Results may vary by country from 56 to 90 % of the total emissions of the country. Manure management mostly accounts for the majority of livestock emissions followed by manure soil emissions.

Figure 2.2: Contribution of livestock to NH_3 national emissions in 2019.

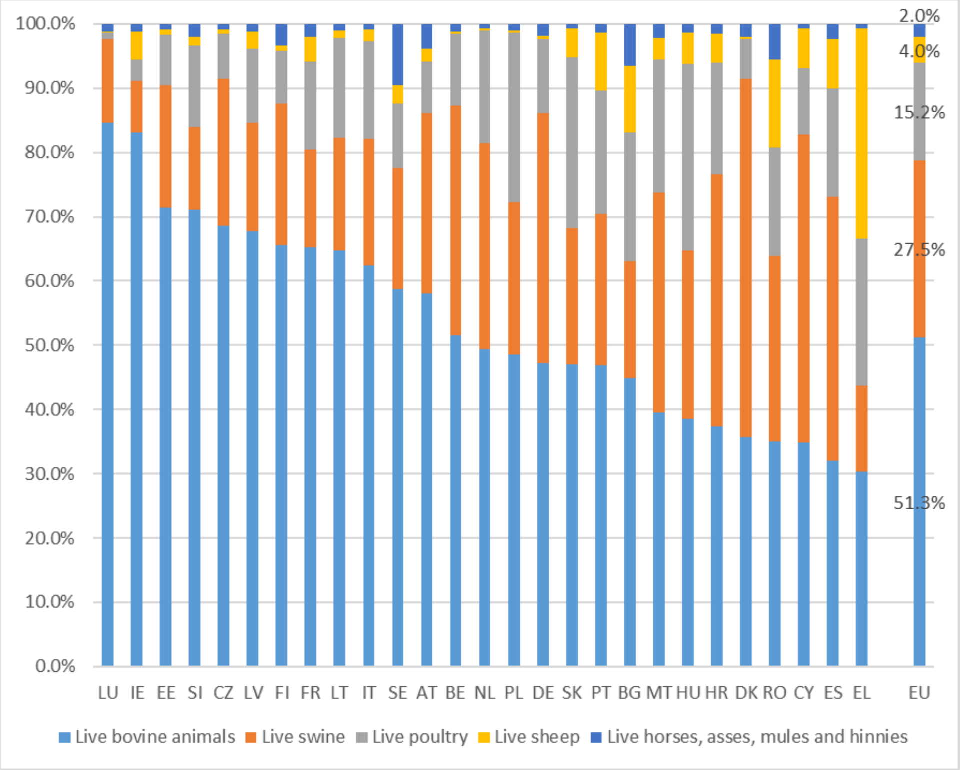


More specifically, among the activities covered by this study, manure management almost always predominates as the main emitter of NH_3, followed by manure applied to soils. Figure 2.3 shows the results for these activities.

Figure 2.3: Contribution of sub-SECTORS to NH_3 livestock emissions in 2019

Regarding the distribution of emissions according to the type of animals (Figure 2.4), cattle is the main emitter with a contribution of 51.3 %, followed by swine (27.5 %), poultry (15.2 %), sheep (4 %) and horses, asses and mules (2 %).

Figure 2.4: Distribution of NH_3 emissions by animal species in 2019 (only emissions from livestock)



Regarding the distribution of emissions according to the size of the holdings, the large farms (more than 100 LSU) emit 66.8 % of the estimated emissions over 27 European countries (Figure 2.5). This result can be compared with the number of these holdings (Figure 2.6) which represent only 4.7 % of the farms. Except for some countries, these farms are the main emitters.

Figure 2.5: Distribution of NH_3 emissions by farm size in 2019 (only emissions from livestock)

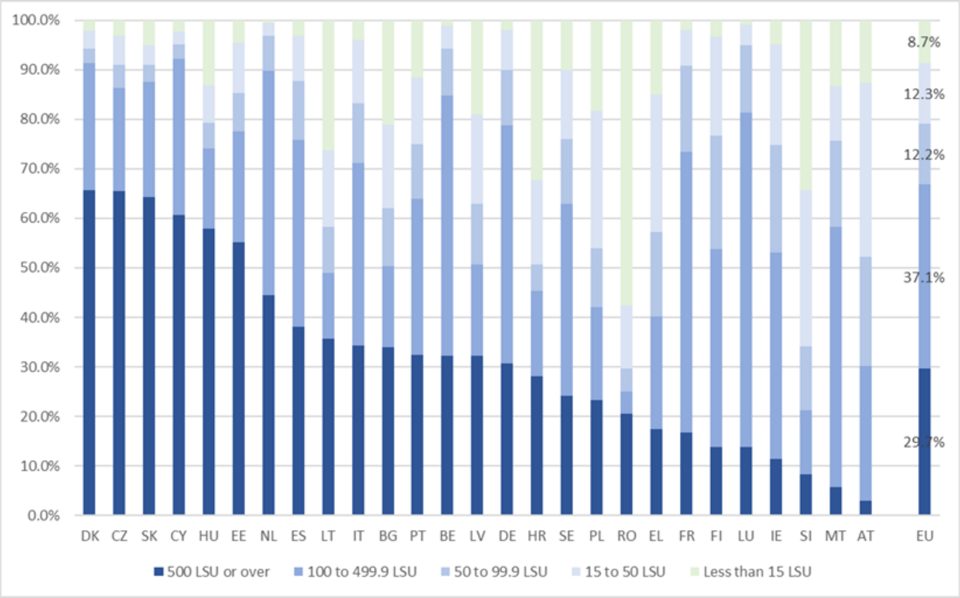
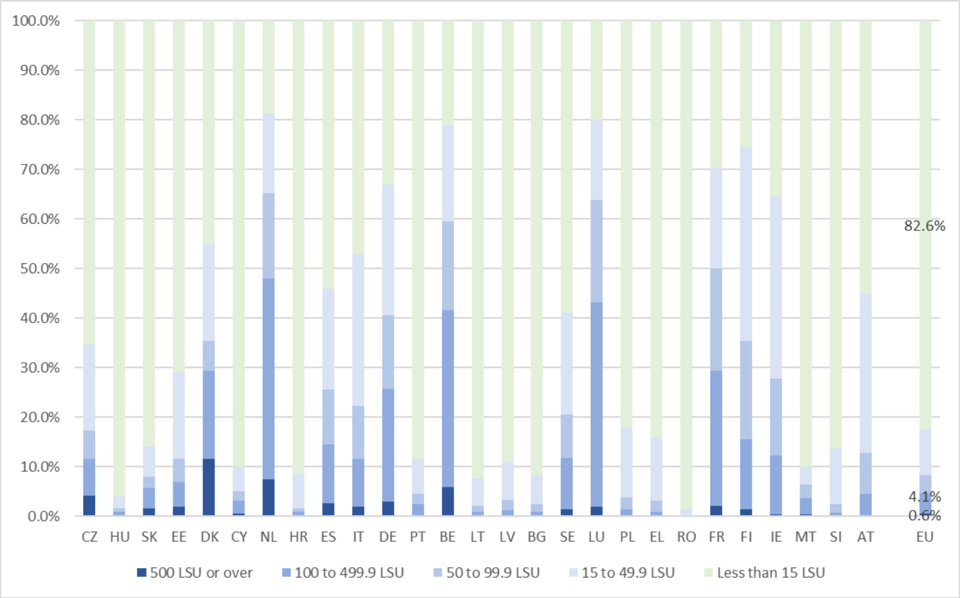
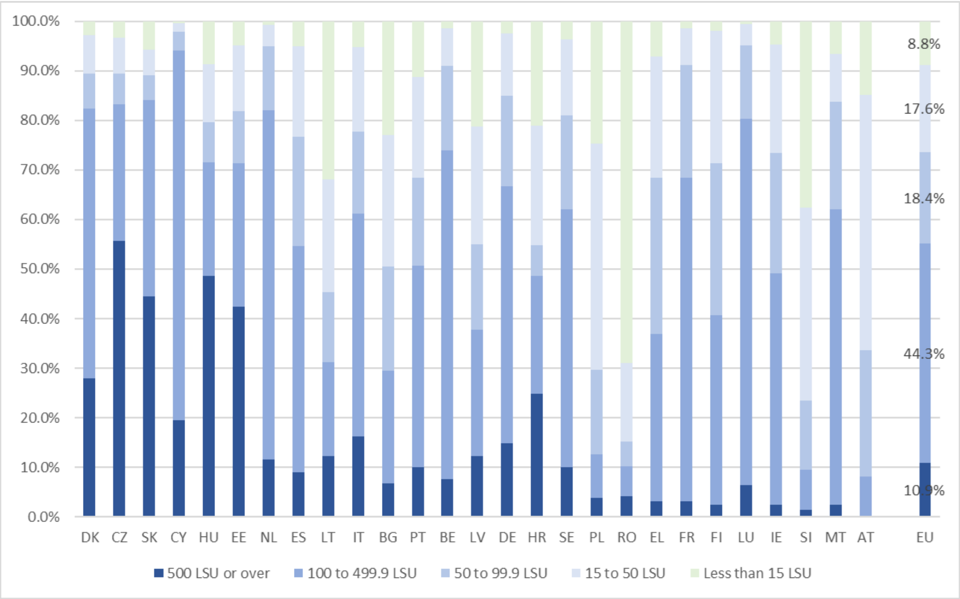


Figure 2.6: Distribution of farm sizes by LSU in 2019



The large cattle farms represent the main contribution (55.2 %) to NH_3 emissions emitted by cattle (Figure 2.7). Graphs for other species are presented in Annex 3.

Figure 2.7: Distribution of NH_3 emissions by farm size in 2019 (only emissions from cattle)



Annexes 5 and 6 provide maps of the distribution of estimated livestock emissions at national level: respectively total emissions (kt) and intensity of emissions per unit area (kg/km²). Emissions are detailed by sectors activities (enteric and manure management) and type of animals.

NUTS 2 level

In Annexes 7 and 8, the spatial distribution of emissions at NUTS 2 level are presented in the same manner as described in the previous paragraph for national-level emissions. This allows hot spots to be highlighted on the maps. Location of hotspots may vary depending on the sector of activity targeted by the map.

Maps in the Annex 9 specifically focus on large farms with different representations:

- contribution of large holdings in each NUTS2 to the national emissions: shows for each country which NUTS 2 regions are the main emitters,
- contribution of large holdings to each NUTS 2: indicates which NUTS 2 regions are mostly impacted by large farms,
- and contribution of large holdings for each species to each NUTS 2: indicates which type of animal from large holdings are the main emitters.

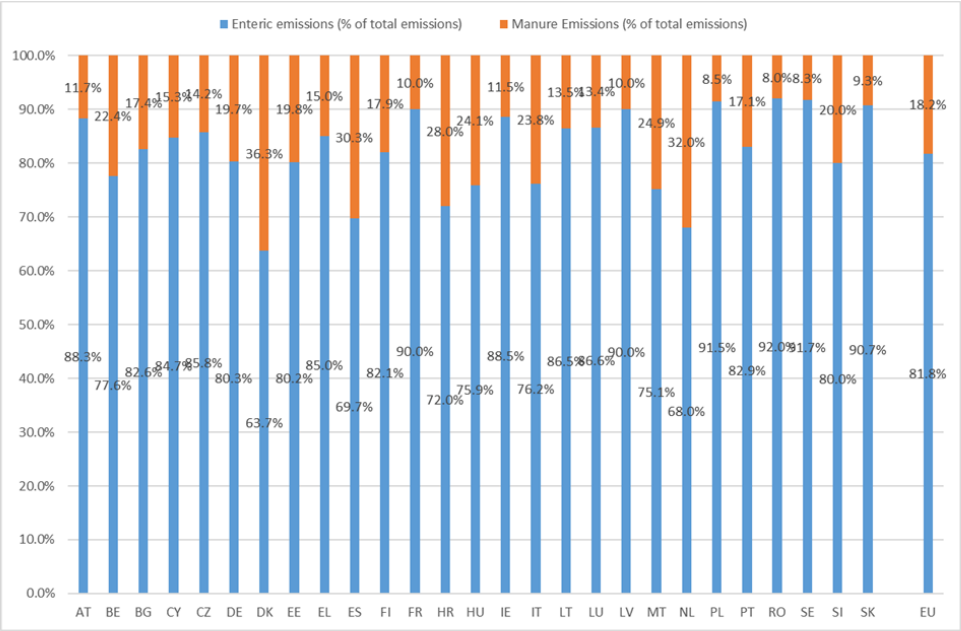
Cattle, pigs and to a lesser degree poultry are the main emitters for NH_3 from livestock in many NUTS 2 regions.

CH_4 emissions

European and national level

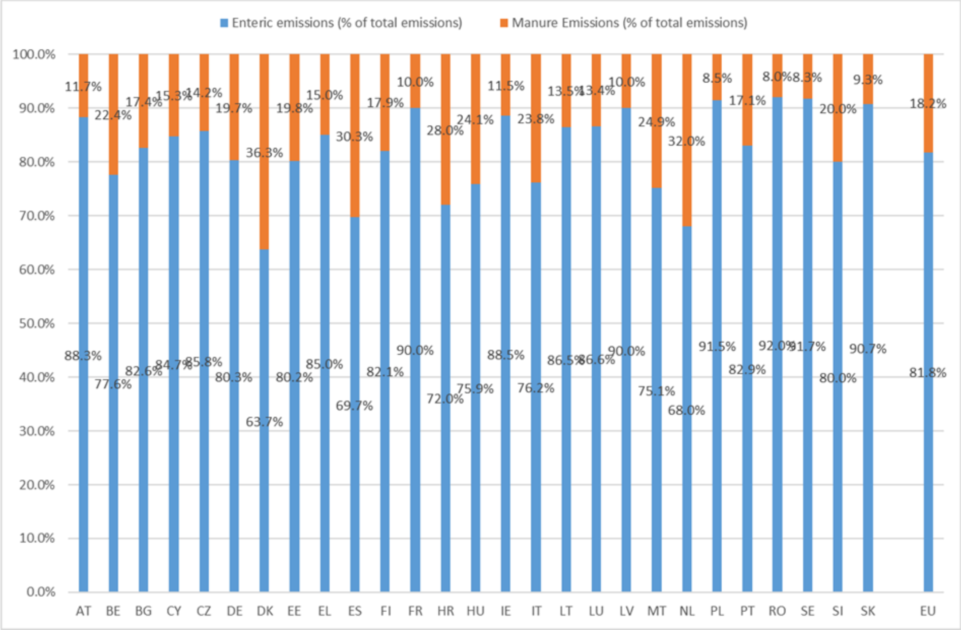
Enteric emissions and manure management emissions together account for 53.4 % (43.7 % and 9.7 % respectively) of the total of methane emissions in the EU-27 (Figure 2.8). Results vary by country, from 23 to 93 % of the total emissions of the country.

Figure 2.8: Contribution of livestock to CH_4 national emissions in 2019



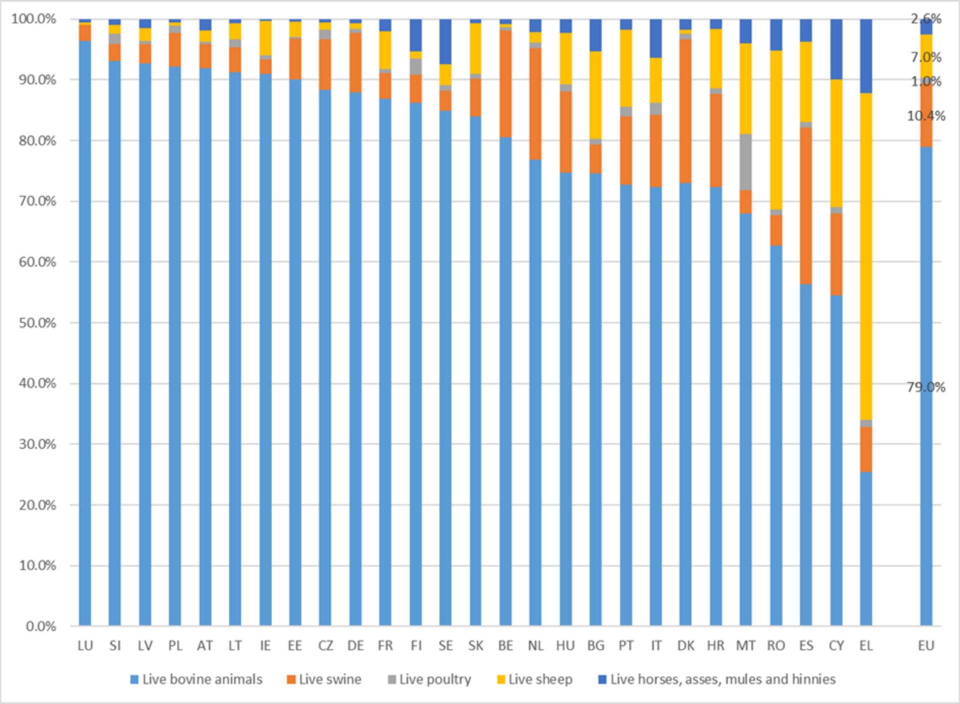
More specifically, among the activities covered by this study, enteric emissions of CH_4 always predominate. Figure 2.9 shows the results for these activities.

Figure 2.9: Contribution of sub-sectors to CH_4 livestock emissions in 2019



Regarding the distribution of emissions according to the type of animals (Figure 2.10), cattle are the main emitter a contribution across the EU-27 of 79 %, followed by swine (10.4 %), sheep (7 %), equidae (2.6 %) and poultry (1 %).

Figure 2.10: Distribution of CH_4 emissions by animal species in 2019 (only emissions from livestock)



Regarding the distribution of emissions according to the size of the holdings, the large farms (more than 100 LSU) emit 56.8 % of the estimated emissions in the EU-27 (Figure 2.11). This result can be compared with the number of these holdings (Figure 2.12) which represent only 4.7 % of the farms. Except for some countries, these farms are the main emitters.

Figure 2.11: Distribution of CH_4 emissions by farm size in 2019 (only emissions from livestock)

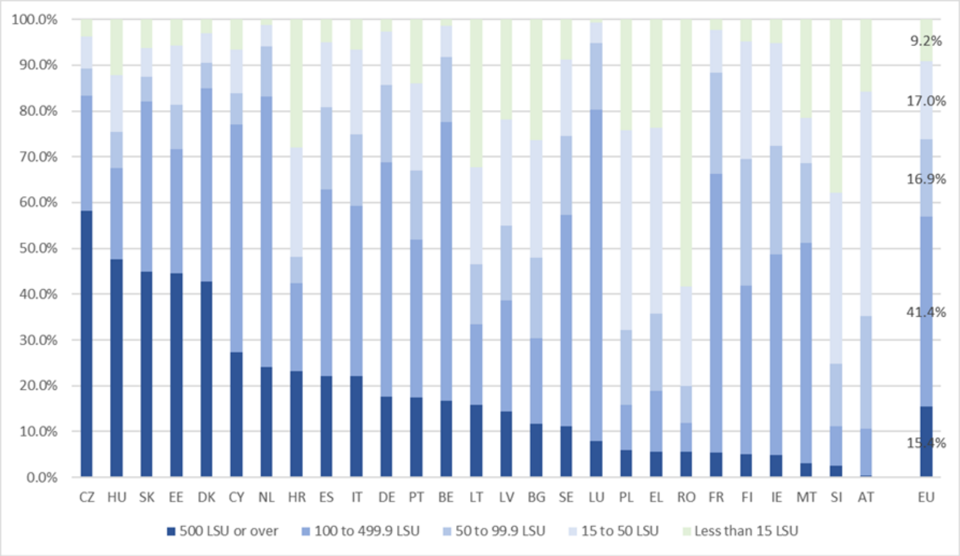
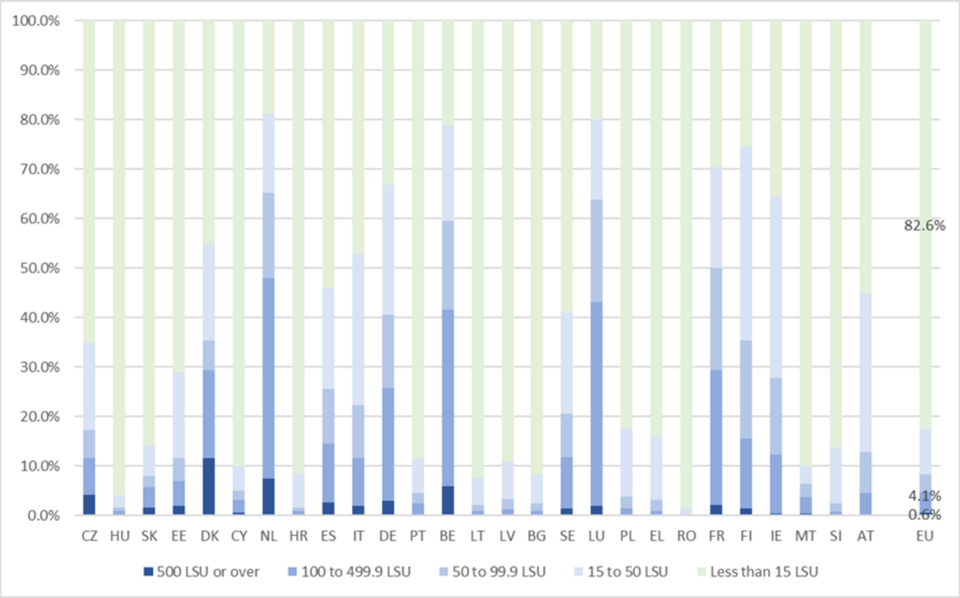
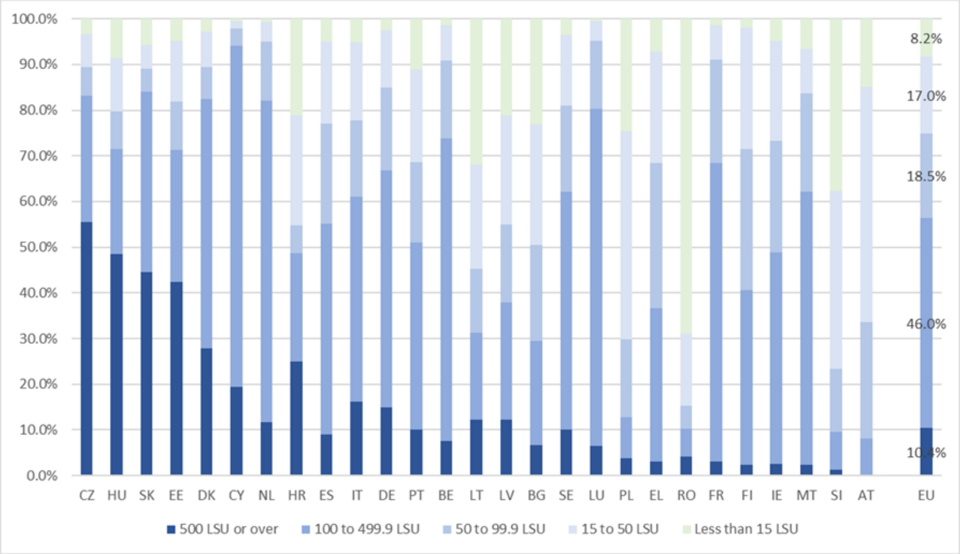


Figure 2.12: Distribution of farm sizes by LSU in 2019



The large cattle farms emissions represent the majority (56.4 %) of CH_4 emissions emitted by cattle (Figure 2.13). Graphs for other species are presented in Annex 4.

Figure 2.13: Distribution of CH_4 emissions by farm size in 2019 (only emissions from cattle)



Annexes 10 and 11 provide maps of the distribution of estimated livestock emissions at national level: respectively emissions weighted by area (kg/km²) and intensity of emissions (kT). Emissions are detailed by sectors activities (enteric and manure management) and type of animals.

NUTS 2 level

In Annexes 12 and 13, the spatial distribution of emissions at NUTS 2 level are presented in the same manner as described in the previous paragraph for national-level emissions. This allows hot spots to be highlighted on the maps. Location of hotspots may vary depending on the sector of activity targeted by the map.

Maps in the Annex 14 specifically focus on large farms with different representations: contribution of large holdings in each NUTS2 to the national emissions, contribution of large holdings to each NUTS 2 and contribution of large holdings for each species to each NUTS 2.

Contrasting with NH_3 emissions, these last maps show that large cattle farms are the main emitters of CH_4 from livestock in many NUTS 2, unlike other animals which show a high contribution in only some NUTS 2.

2.2 NUTS3 level

The highest resolution of publicly available livestock data provided by Eurostat is at NUTS 2 level. In this part of the task, more spatially granular livestock data were sought to derive NUTS 3 level CH_4 and NH_3 emissions estimates for 2019 (assuming allocation proportional to number of livestock), from the results of the NUTS 2 analysis described above.

There were several potential sources of information pursued:

- Publicly available NUTS 3 (or finer) level livestock data published by or available on request from individual Member States;
- Europe-wide data on livestock numbers for 2010, from INRAE;
- E-PRTR point source emissions data for large poultry and pig rearing installations;
- Gridded emissions data, from EDGAR (CH_4) and NECD gridded emissions reporting (NH_3).

The following sections describe the methodology and results of exploring each of these potential sources.

INRAE 2010 Europe-wide NUTS 3 livestock populations

Methodology

A dataset constructed by INRAE of livestock information by NUTS 3 regions in 2010(14) (Dumont et al., 2018), based upon Eurostat data, was able to be used as a foundation upon which to allocate the NUTS 2 emissions estimates down to NUTS 3 level. Amongst other data, the INRAE dataset comprised of numbers of livestock heads by livestock type for each 2010 NUTS 3 region. Although this data is relatively old, it is likely that the broad spatial distribution of the main livestock types – namely cattle, equidae, pigs, poultry, and sheep – within NUTS 3 regions has not changed dramatically between 2010 and 2019, as these patterns relate partly to quite stable climatic and geographic factors.

The general approach taken was to map the livestock populations in the 2010 NUTS 3 regions onto the equivalent 2016 NUTS 3 classification, taking into account aggregation, disaggregation and boundary changes that occurred between the different NUTS versions.

Amendments to the NUTS classification were made in 2013 and 2016, but there were no changes between 2016 and 2019. Accordingly, correspondence tables from Eurostat were used to identify which NUTS 3 regions had undergone significant boundary changes between 2010 and 2016. Such changes entailed regions being split up, merged with other regions, or discontinued in favour of a

---

(14) https://data.inrae.fr/file.xhtml?persistentId=doi:10.15454/O78MYF/IDFXPZ&version=2.3.

newly defined regions. Regions not included in the tables were also subject to boundary adjustments, but to such a small extent that the distribution of livestock was assumed to have remained unchanged. For regions included in the tables and subject to boundary amendments, an analysis was carried out within GIS software to closely examine the spatial changes between the 2010 and 2016.

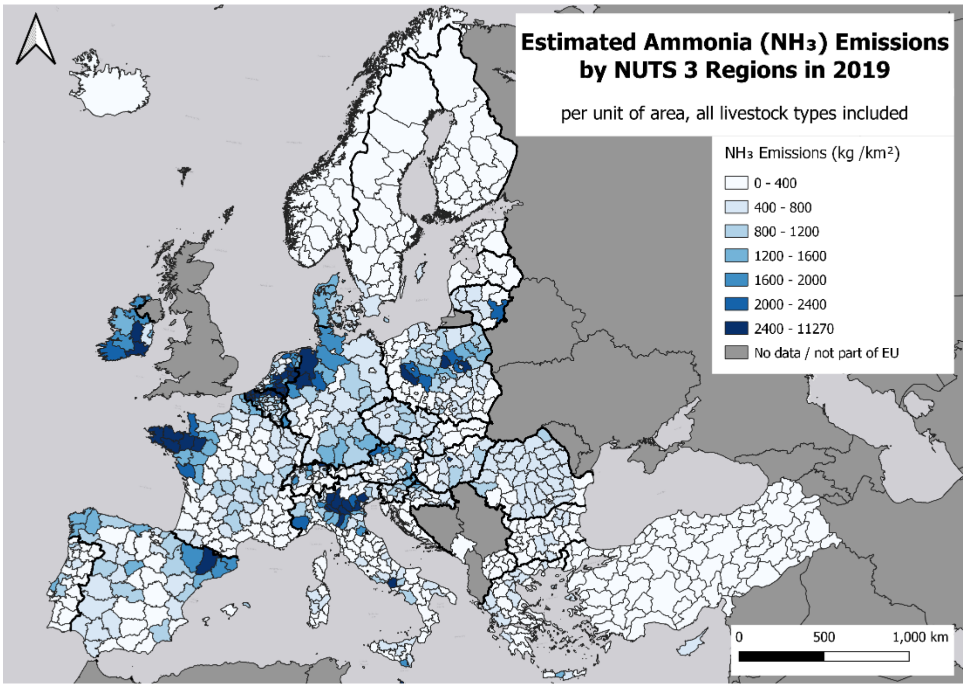
The output of this process was a spatial profile of the segments of 2010 NUTS 3 regions forming the 2016 regions. The area of each segment within a given 2016 region was divided by the area of the original 2010 region it belonged to, and the corresponding 2010 livestock head totals for that region were multiplied by this factor. Aggregating these estimates of livestock heads, by livestock type, for each segment, yielded estimates of the livestock distribution for a given 2016 NUTS 3 region.

To estimate emissions at NUTS 3 level, the NUTS 2 emissions estimates described in section 2.1 were allocated in proportion to the livestock populations in each constituent NUTS 3 region. For each livestock type, the NUTS 3 livestock heads estimate was divided by the sum of all NUTS 3 livestock heads estimates within a given NUTS 2 region to provide an allocation factor. This factor was used to allocate the 2016 NUTS 2 emission estimates to NUTS 3 regions.

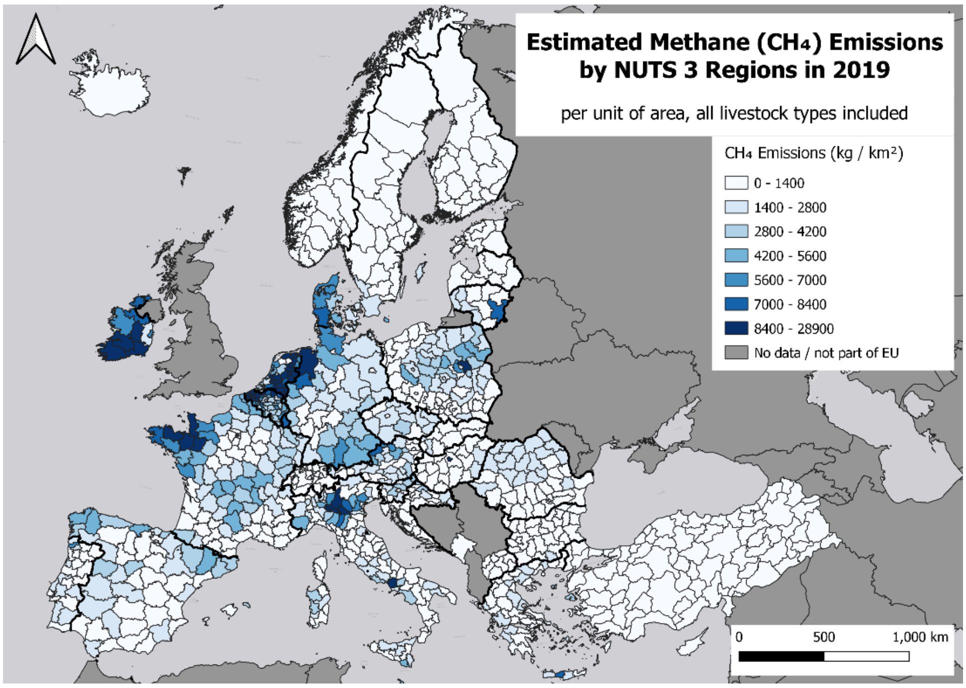
Finally, the newly calculated NUTS 3 emission estimates were divided by the area of each corresponding region in square kilometres, so that the estimates were per unit of area. This enabled the identification of regions where livestock emissions were more concentrated (Map 2.5; Map 2.6).

Results

Map 2.5: Disaggregation of Ammonia Emissions estimates from NUTS2 to NUTS 3 Regions in 2019 using INRAE (2010) dataset



Map 2.6: Disaggregation of Methane Emissions estimates from NUTS2 to NUTS 3 Regions in 2019 using INRAE (2010) dataset



Member state published NUTS 3 level livestock populations

Methodology

Member States (MS) may make available NUTS 3 (or finer) scale livestock population statistics online via statistical agencies, but the location of these data is not always obvious. For this reason, a short questionnaire was sent to representatives of each EU-27 MS, requesting NUTS 3 level data for 2019 (or link to an online location) to be provided to the team.

Responses were received from 10 MS. Some responses indicated that no suitable data are currently available, but for several MS appropriate data seem to be available (see Table 2.3 below):

Table 2.3: Summary of responses received from EU MS to the questionnaire sent

Country	**NUTS 3 (or finer) level available?**	**Public / not public**	**Link (if available)**	**Comment**
Austria	No	-		Data only at federal province level, equivalent to NUTS2
Croatia	Yes	Public	https://stocarstvo.mps.hr/izvjestaji-o-broju-domacih-zivotinja-jrdz-i-isporucenim-kolicinama-mlijeka-slkm/	
Cyprus	No	-		
France	Yes	Public	https://agreste.agriculture.gouv.fr/agreste-saiku/?plugin=true&query=	Data are for Departments – NUTS codes not provided

Country	NUTS 3 (or finer) level available?	Public / not public	Link (if available)	Comment
			query/open/SAANR_6#query/open/SAANR_6	
Ireland	Yes	Public	https://data.cso.ie/table/AAA09	Dublin is combined with another NUTS 3 region
Italy	Yes	Not public		NUTS 2 data (regions) are public, NUTS 3 (provinces) are not
Luxembourg	Yes	Public		NUTS 2 and NUTS 3 regions are identical, so no need for additional data
Netherlands	?	Public	https://opendata.cbs.nl/statline/#/CBS/nl/dataset/80783ned/table?ts=1654599094784	Data available for Provinces and Landbouwgebieden, but more work is required to determine how these align with NUTS 3 regions
Portugal	Yes	?		Old NUTS codes used
Slovenia	Yes	Public		2016 is the latest year

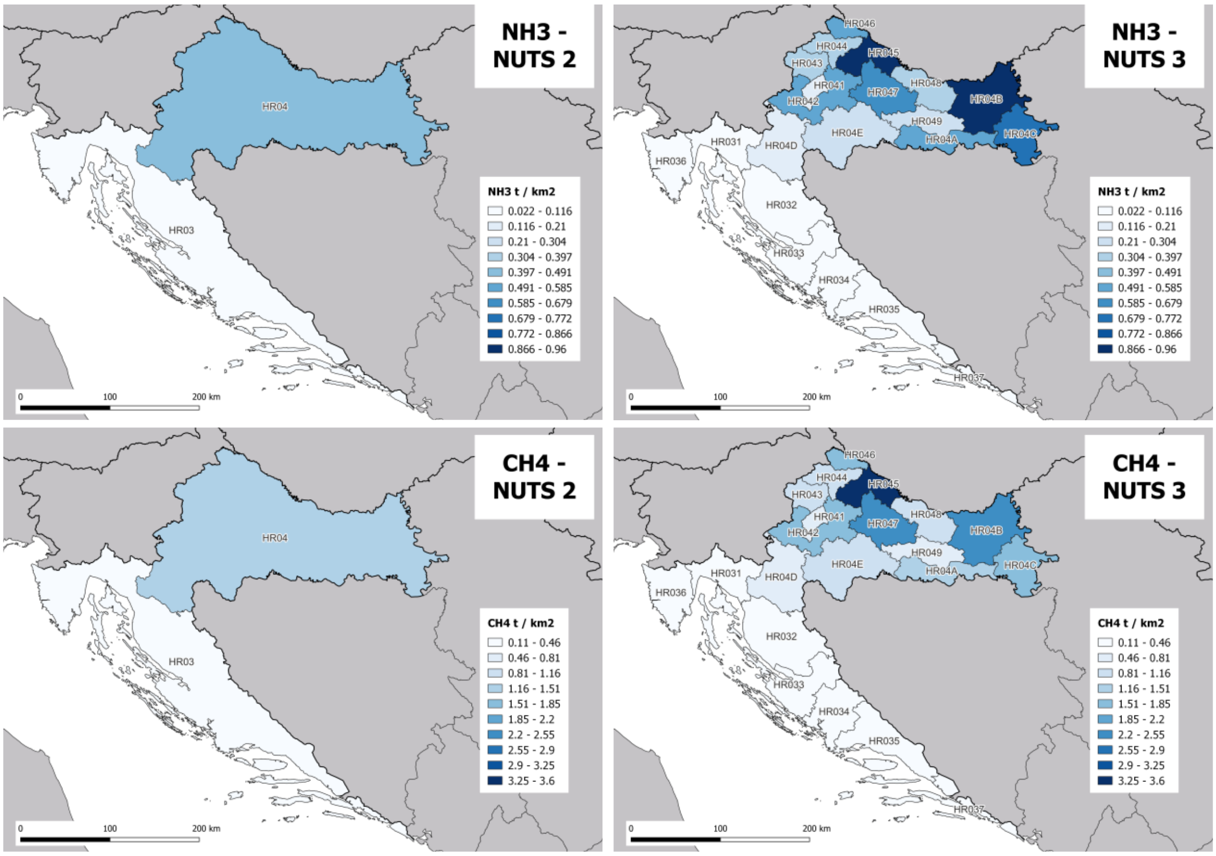
There was insufficient time available in this project to collate the NUTS 3 level data provided for all MS. Some effort would be required to harmonise the spatial basis where old versions of the NUTS classification are still used (such as for Portugal), and where regions have been split or boundary changes have occurred uncertainty would be introduced due to the need to specify an allocation rule. Therefore, the scope of the exploration of national livestock data was limited to an example case-study country – Croatia – where the spatial basis, year and livestock classification were compatible with the NUTS 2 level results presented in Section 2.1.

NUTS 2 level emissions were disaggregated to NUTS 3 regions for each livestock species separately. Emissions were allocated in proportion to the share of the parent NUTS 2 population of livestock species X contained in each of the constituent NUTS 3 regions.

Given additional time and resources to obtain responses from other MS and collate data, such a method could be applied across many more MS of interest, if this brings tangible benefits for mapping key emissions sources.

Results

Map 2.7: Demonstration of disaggregation of emissions from NUTS 2 to NUTS 3 level using national livestock data for Croatia; all livestock combined.



NH3 - NUTS 2

NH3 - NUTS 3

CH4 - NUTS 2

CH4 - NUTS 3

Map 2.7 above presents the results of disaggregating NUTS 2 level emissions estimates (expressed as emissions intensity per area tonnes / km^2 to control for the area of regions), into NUTS 3 regions.

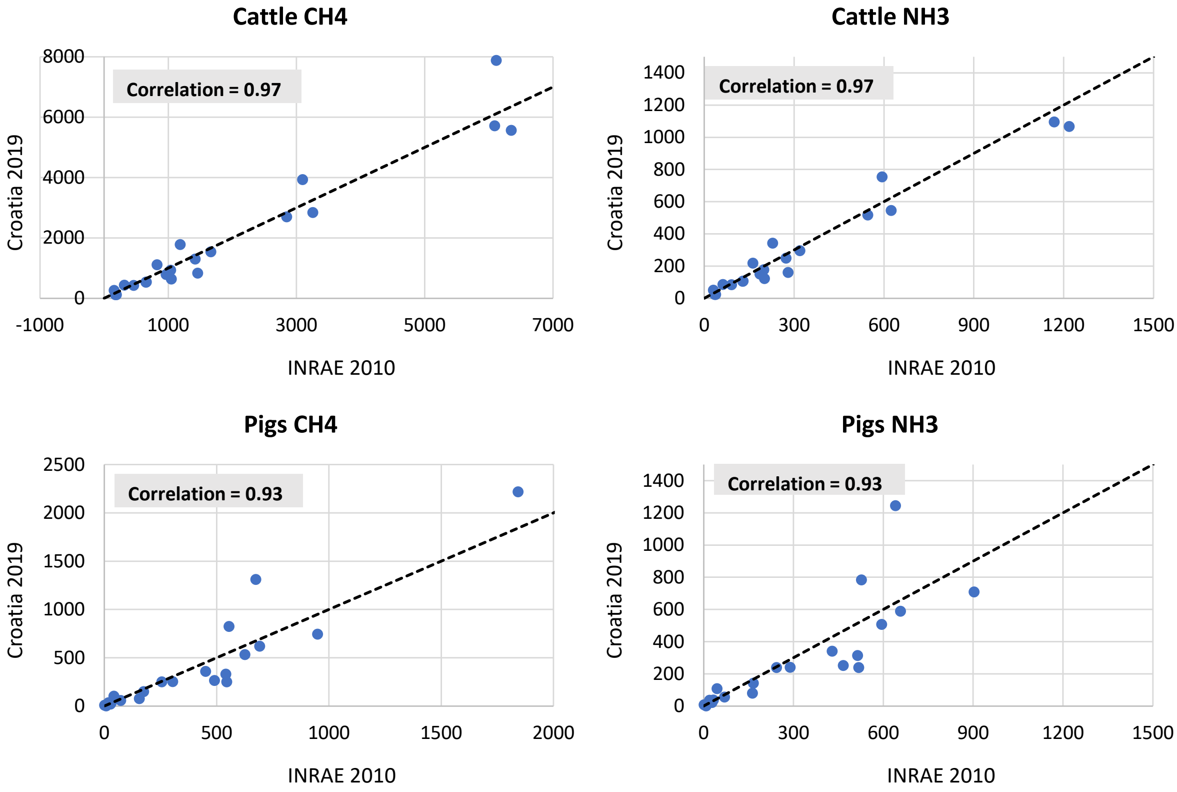
In this example, it is clear that there is considerable variation in emissions intensity across the NUTS 3 regions making up Kontinentalna Hrvatska (HR04), with the highest emissions intensity of both NH_3 and CH_4 being in Koprivničko-križevačka županija (HR045).

Validation of the NUTS 3 level maps created from INRAE 2010 data

In addition to demonstrating the potential for national data to be used to disaggregate NUTS 2 emissions estimates, the Croatian national data were also used to validate the accuracy of the Europe-wide NUTS 3 emissions estimates for Croatia, created from INRAE data on 2010 livestock populations (see previous section).

Given the age of the INRAE data and allocation assumptions necessary when NUTS boundaries have changed, it would not be surprising if the spatial distribution of livestock populations seen in the INRAE data and in the Croatian national data are rather different. However, in fact they are rather similar, with a correlation of 0.97 for cattle emissions and 0.93 for emissions from pigs, with no particular high or low bias either way (Figure 2.14).

Figure 2.14: Comparison of estimated NUTS 3 level emissions using livestock population data from INRAE 2010 and Croatian national statistics for 2019



Note: Dotted black line indicates exact equality.

Although this validation was only undertaken for Croatia, it nonetheless gives some confidence that the 2010 livestock spatial distributions underlying the Europe-wide NUTS 3 emissions estimates may still be relatively valid in 2019.

E-PRTR point source emissions

Methodology

Reporting of emissions from intensive rearing of pigs and poultry under the European Pollutant Release and Transfer Register (E-PRTR; EEA, 2022a) is another potential source of spatially explicit emissions information. Such point-source data can potentially support very fine-scale emissions mapping and impact modelling.

However, for agriculture where there are many sources of emissions, both point and areas sources, there are issues of completeness. Chief among these is the omission of facilities rearing cattle or other ruminants from reporting under the IED or E-PRTR, which for CH_4 in particular represent a high proportion of emissions. Also relevant are the activity and pollutant release thresholds (see Table 2.4 below) for reporting to the E-PRTR, meaning that potentially a significant quantity of emissions from small facilities falling below these thresholds are not covered. Finally, there are issues of geographical completeness where certain Member States fail to report emissions for particular activities and years.

Table 2.4: Activity and pollutant release thresholds for relevant activities covered by E-PRTR reporting

Activity code	Activity description	Activity threshold	Pollutant release threshold
7(a)(i)	Installations for the intensive rearing of poultry or pigs: 40 000 places for poultry	40 000 animal places	CH_4: 100 000 kg NH_3: 10 000 kg
7(a)(ii)	Installations for the intensive rearing of poultry or pigs: 2 000 places for production pigs (over 30kg)	2 000 animal places	CH_4: 100 000 kg NH_3: 10 000 kg
7(a)(iii)	Installations for the intensive rearing of poultry or pigs: 750 places for sows	750 animal places	CH_4: 100 000 kg NH_3: 10 000 kg

In this project, the coverage of E-PRTR emissions was assessed in terms of the fraction of total emissions from all pigs and poultry that are accounted for in the E-PRTR. The aim of this is to consider if, and where, E-PRTR data may be suitable for input into emissions mapping.

In order to make this assessment, reported emissions from pig and poultry facilities in the E-PRTR in 2016 (defined by the Activity codes listed in Table 2.4) were summed up within NUTS 2 regions. This was done based on a spatial join (in QGIS) between the facility point coordinates provided in the E-PRTR data and the NUTS 2 shapefile. 2016 was chosen as the reference year, as in this year the reporting of E-PRTR data by some key MS was relatively complete. The NUTS 2 E-PRTR totals were then compared against the NUTS 2 emissions estimates for 2016 developed as described in Section 2.1.

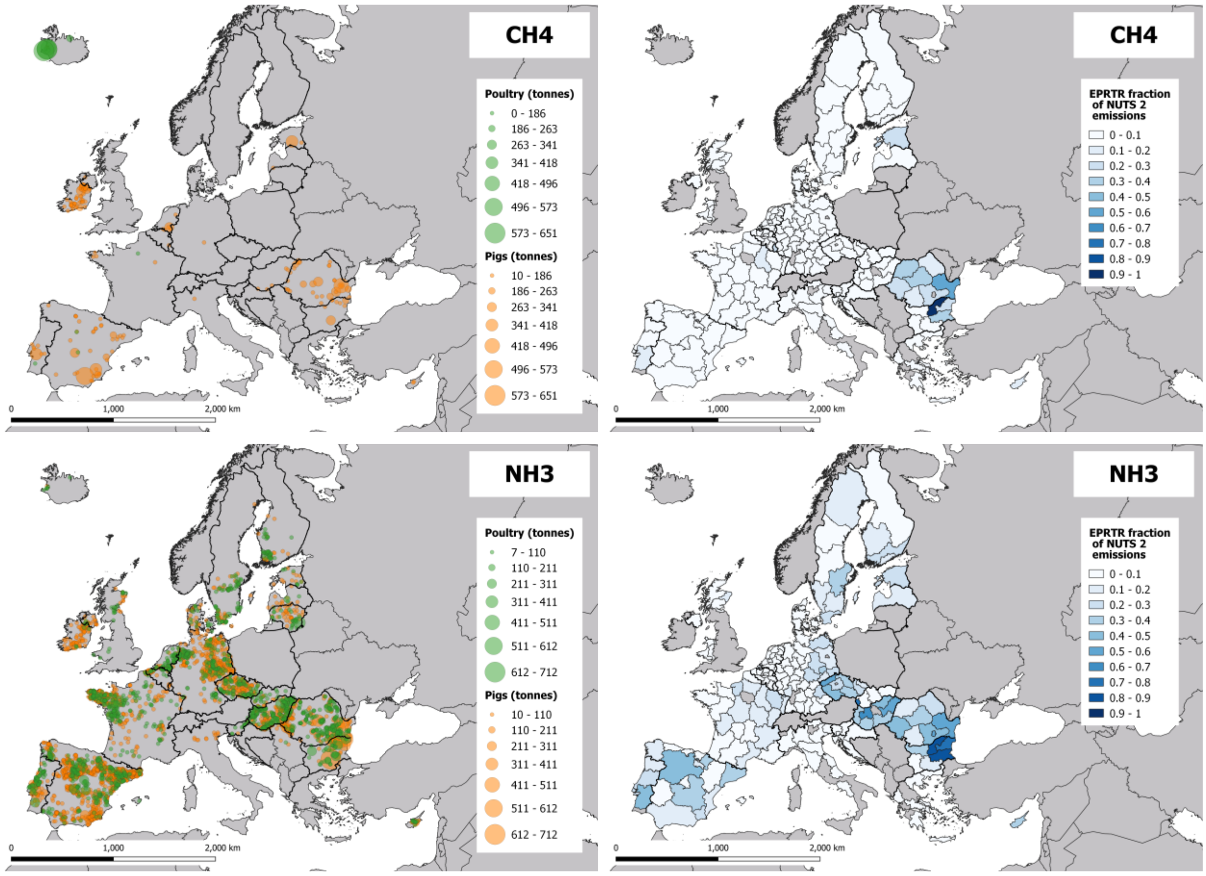
Results

In general, the proportion of total pig and poultry emissions accounted for by facilities reporting to the E-PRTR is low. The E-PRTR has generally better coverage for NH_3 than it does for CH_4, likely due to the lower pollutant release threshold for NH_3 meaning that a higher proportion of facilities actually report emissions. This can be seen in the much denser distribution of point locations in the map for NH_3 than for CH_4 (Map 2.8; left hand side).

Similarly, the proportion of total pig and poultry NH_3 emissions accounted for by E-PRTR facilities was higher than for CH_4 (Map 2.8; right hand side), with E-PRTR data accounting for less than 20 % of CH_4 emissions in almost all NUTS 2 regions.

Also noticeable is the variation in the fraction of emissions covered by the E-PRTR across MS. Some MS do not report any emissions (denoted by the grey tone in the maps on the right hand side of Map 2.8) and some comparisons could not be made due to NUTS code differences between the analysis presented in 2.1 and the aggregated E-PRTR data (e.g. in Ireland and Lithuania). On the other hand for some MS such as Bulgaria, E-PRTR reporting accounts for the majority (and in some NUTS 2 regions almost 100 %) of emissions. In such well-represented locations, E-PRTR data may be a very useful input into emissions modelling.

Map 2.8: Distribution of E-PRTR point-source emissions (left) for pigs (orange) and poultry (green), and the proportion of NUTS 2 level emissions accounted for by E-PRTR points (right). 2016 data



Notes: In the right-hand column, grey regions are those where no E-PRTR data are available.

Data source: E-PRTR data from https://www.eea.europa.eu/data-and-maps/data/industrial-reporting-under-the-industrial-6, version «1215_Public_Product_Full Access_v7».

Gridded emissions data

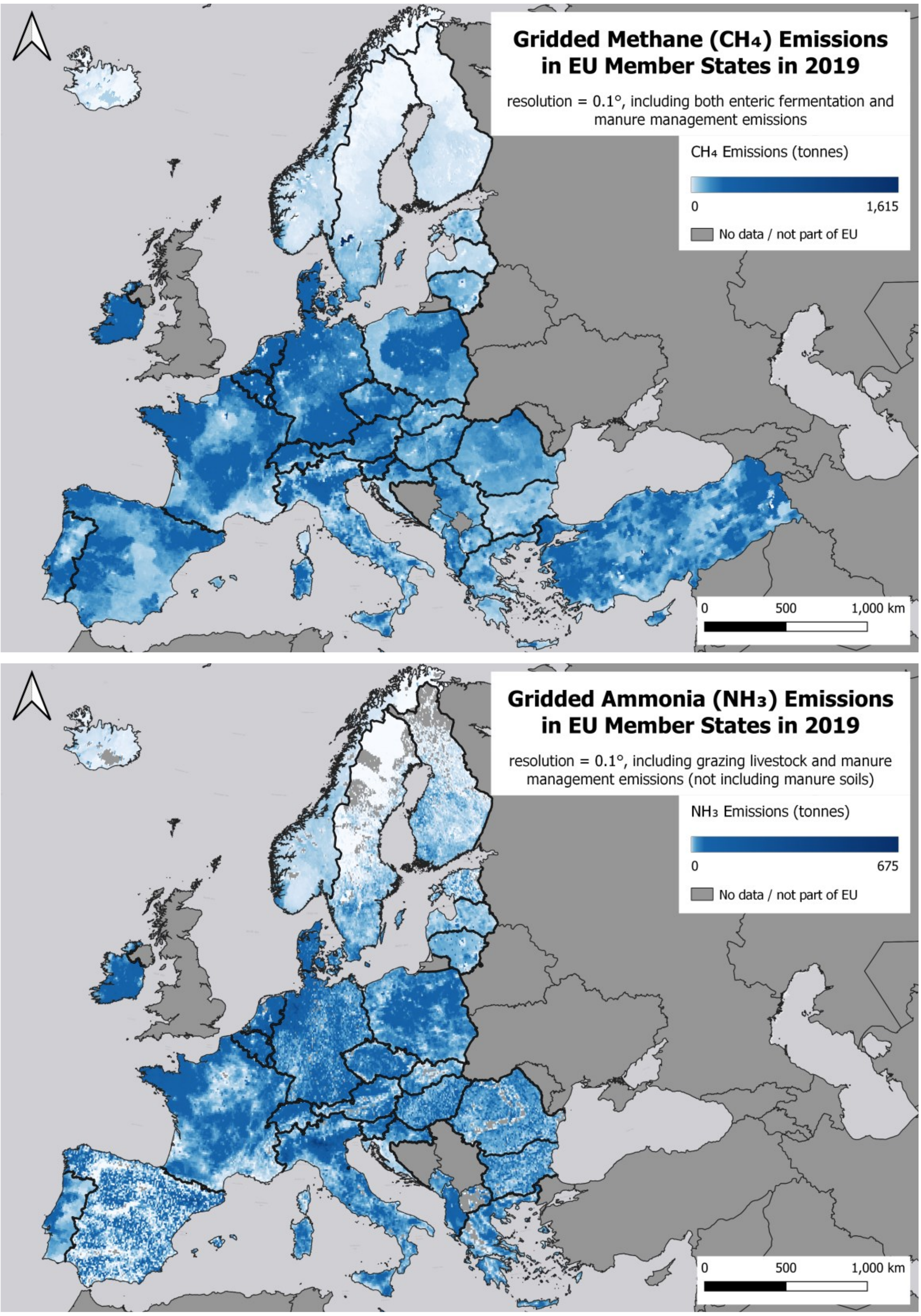
Gridded emissions datasets provide a consistent and relatively fine spatial resolution across Europe. Due to these attributes, they are frequently used as inputs to modelling. However, from a review of available datasets, there are no publicly available datasets on a consistent basis across the whole of Europe which a) are based on the most accurate national reporting, and b) contain a detailed breakdown of emissions by livestock category.

For NH_3, MS report aggregate gridded emissions at a 0.1° x 0.1° resolution every 4 years at aggregated NFR (GNFR) code level; K_AgriLivestock and L_AgriOther. K_AgriLivestock combines together all emissions from all emissions reported under category 3B (manure management). A gridded dataset for the entire EMEP (European Monitoring and Evaluation Programme) region is available for 2019 from the EMEP Centre on Emission Inventories and Projections (CEIP, 2022). As far as possible, this makes use of MS-reported gridded emissions data, and therefore takes advantage of country-specific estimation methodology, and any fine-scale data on livestock distribution available to national inventory compilers. Gaps are filled by TNO using data from CAMS (Copernicus Atmospheric Monitoring Service) and EDGAR (Emissions Database for Global Atmospheric Research), which is augmented by point source information available under the E-PRTR.

For CH_4, EDGAR data (Cripa et al., 2019) were located for 2019 . This also has 0.1° x 0.1° resolution. Unlike the NH_3 data, layers are available for different emissions categories, but on the other hand this does not take into account reported emissions by MS – it is a purely modelled dataset with uniform methodology.

Map 2.9 hereafter presents the gridded emissions maps for NH_3 (GNFR K_AgriLivestock) and CH_4 (EDGAR).

Map 2.9: Gridded emissions data for 2019 for ammonia and methane



Sources:
Gridded Ammonia – CEIP https://www.ceip.at/the-emep-grid/gridded-emissions.
Gridded Methane – EDGAR https://edgar.jrc.ec.europa.eu/dataset_ghg70.

Due to the limitations of each dataset mentioned above, the gridded data were not deemed suitable for disaggregating NUTS 2 level emissions to NUTS 3 level. However, they were used as a sense-check to validate the results obtained from applying the INRAE 2010 livestock distribution data (see next section).

The map of gridded NH3 emissions above (Map 2.9; bottom panel) clearly shows different qualities of spatial patterns of emissions in different countries; for example in Spain there appears much fine-scale variation in emissions, as though associated mainly with point sources, compared with neighbouring Portugal where they vary more smoothly over larger scales. Some of this variation may relate to real differences in production system, but differences in mapping methodology also exist between countries and this reduces comparability across the whole of Europe.

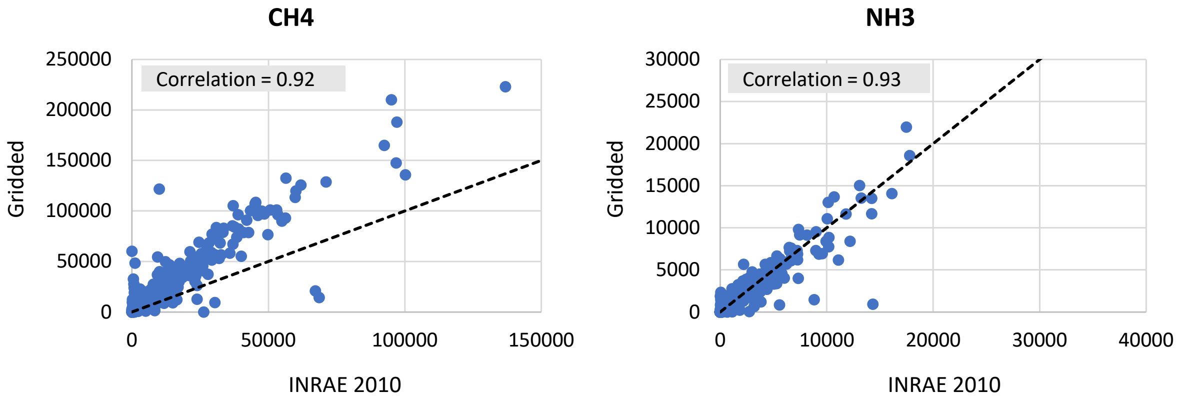
In Section 4, gridded emissions data from the Copernicus Atmospheric Monitoring Service (CAMS-REG-AP version 5.1_REF2.1) are used as an input into the damage cost modelling. These data make use of sectoral national totals reported by countries under the Convention on Long-range Transboundary Air Pollution (CLRTAP), but the spatial distribution within a given country is based on a consistent methodology for the whole of Europe rather than being based on the gridded maps reported by countries. This enhances comparability across Europe, but at the same time may not take into account the most detailed spatial activity data available from any one country.

Therefore, when seeking to use gridded emissions data, the choice of dataset may depend on the geographic scope of analysis required, as well as other considerations like sectoral resolution required.

Validation of the NUTS 3 level maps created from INRAE 2010 data

In order to validate the NUTS 3 maps developed using INRAE 2010 livestock distribution data, first the gridded emissions data were aggregated to NUTS 3 level using the zonal statistics tool in QGIS. The emissions from each NUTS 3 region (for all livestock types and emissions categories combined) obtained from each method were then plotted against one another and a correlation coefficient calculated (Figure 2.15).

Figure 2.15: Comparison of estimated NUTS 3 level emissions using livestock population data from INRAE 2010 and gridded emissions for 2019; total emissions from all livestock



Note: Dotted black line indicates exact equality.

It is clear from Figure 2.15 that there is in general a high level of correlation between the estimates obtained from gridded emissions on the one hand, and from the estimates based on INRAE 2010 data on the other.

This provides confidence that:

- the livestock spatial distribution across NUTS 3 regions recorded in 2010 has not substantially altered since then; and
- that the assumption that emissions can be disaggregated in direct proportion to livestock populations (i.e. ignoring any fine-scale variation in emission factors related to production systems, for example), does not severely affect accuracy.

For NH_3, the magnitude of emissions in each NUTS 3 region is very similar from the gridded data and INRAE 2010 data, shown by how the points fall along the dotted line of equality. However, for CH_4 the gridded data appears higher than from the INRAE 2010 estimates. The reasons for this bias are unclear, but may relate to conservative assumptions used in the EDGAR dataset - which does not take the national official data into account -, producing higher emissions than MS's own estimates.

2.3 Alternative methodologies to assess emissions at local level

Experimental approaches are being developed to characterize all the emission sources of an emitting installation, measure or estimate those emissions and provide fine data for local scale assessment. The potential for such approaches to assess emissions from agricultural installations is illustrated in Annex 15 through a recently conducted project, MethanEmis (Ineris, 2021), which coupled environmental monitoring with numerical modelling.

This project aimed to identify and quantify methane emissions from three methanisation facilities considered in their whole. The developed methodology was organized according to the following parts:

- Monitoring campaigns including :
  - On-site measurements of methane concentration and meteorological conditions during approximately 3 months. This duration seemed appropriate to cover different operating conditions of the installation and thus identify the influence of different sources or emitting operations.
  - Quantification of emissions from cogeneration engines;
  - Leak detection and quantification;
- Processing and statistical analysis of collected data;
- Inverse atmospheric dispersion modelling to estimate the emissions from sources that could not be quantified (diffuse sources and specific activities). This method had been applied, for example, in the context of industrial discharges or for the estimation of NH_3 emissions in an agricultural context (Herrero et al., 2021).

3 Technical mitigation measures and uptake scenarios

3.1 Overview of European livestock rearing systems

Cattle

Dairy cows

Emission levels, emission patterns and potential mitigation measures vary, depending on the type of production (dairy cow or beef), the size of the farm and whether it is more or less intensive.

There were 23.4 million dairy cows in the EU in 2015, unevenly distributed across the EU. Germany recorded the highest number of dairy cows in 2017 with 4.2 million, making up 18 % of the total EU-28 dairy cow population. France ranked second with 3.6 million units (15 %). The Netherlands have one of the biggest productivity.

The EU's dairy sector is its second biggest agricultural sector in terms of output value and the EU was the biggest producer. Vegetables and horticultural sector is the biggest one. 97 % of milk produced in Europe in 2016 was cows' milk. Most of the EU cow milk production comes from a limited number of countries. Indeed, Germany, France, the Netherlands, Poland and Italy together provided about two thirds (65.0 %) of the EU's raw cows' milk in 2020 (Eurostat, 2021).

The sector is characterized by a diverse range of farm and herd sizes across Europe. More than 50 % of the specialized dairy farms in the EU are large or very large installations. They are mainly found in the north-western part of Europe. Housing systems for cattle vary across the UNECE region. While loose housing is most common, dairy cattle are still bred in tied stalls in some countries. In loose housing systems, all or part of the excreta is collected in the form of slurry. In systems where solid manure is produced (such as straw-based systems), it may be removed from the house daily or it may remain there for up to the whole season, such as in deep litter stables. Housed cattle systems are generally set on concrete bases (UNECE, 2020).

Furthermore, the scale and layout of naturally ventilated cattle buildings vary considerably across the EU, making it a challenge to provide widely applicable mitigation techniques. There is also a large diversity in respective regulations and implementations of mitigation techniques throughout the EU. Currently, implementation of mitigation measures is concentrated in a few countries such as The Netherlands, Flanders (Belgium), Denmark and Germany (Amon, et al., 2017).

Beef

In 2016, the EU was the third largest beef production area in the world, behind the USA and Brazil; the EU has produced 11.5 % of the global beef production. The EU produced mainly beef from culled cows and young bulls with differences between milk-oriented countries and countries with specialized herd for beef production. Cull cows in milk producing herds are the main type of meat from females while males are either fattened as calves (mainly in Spain, France or the Netherlands) and young bull or steers (Ireland, the UK). In specialized herds, the main products are cull cows, young bull and heifers (INRAE, 2021). Half of the EU's beef was produced in three Member States: France (20.8 %), Germany (17.9 %) and Italy (11.7 %). About 70 % of the EU's veal meat was also produced in three Member States: the Netherlands (26.4 %), Spain (24.2 %) and France (19.9 %) in 2019. Half of the EU's beef was produced in three Member States: France (20.8 %), Germany (17.9 %) and Italy (11.7 %) (Eurostat, 2020).

Swine

In 2019, the 143 million pigs reared across the EU-27 represent the largest livestock category and the EU pig meat sector alone accounts for nearly half of total EU meat production. They were mainly produced in Spain (2 %), Germany (21 %), France (9 %), Poland (8 %), the Netherlands (7 %) Denmark (7 %) (Eurostat, 2020). In 2015, there were 2.2 million pig farms in the EU. They are highly diverse, with huge differences in rearing methods and sizes in and between Member States. This ranges from small farms with only a few animals to industrial installations with thousands of animals and from extensive organic farming to conventional intensive production. In general, only 3 % of the pig herd in the EU is kept in small farms, and this share is even lower in most major producing Member States. In Denmark, for example, almost all pigs are kept on farms with 1 000 or more animals. Overall, over 75 % of EU pigs are in large commercial holdings. Among the biggest producer countries, Denmark has the largest commercial holdings with an average of 4 700 heads and Germany the smallest with an average of 1 900 heads per holding. The number of large farms, defined as those requiring an environmental permit(15) as per Annex I to Directive 2010/75/EU on Industrial Emissions were there was a total of 8 443 such large farms in the EU in 2013.

Pig farming is based on a production cycle that can be divided into two parts: farrowing sows for the production of weaned piglets, and the rearing of those piglets as future breeding animals or as pigs for slaughter. From a geographical point of view, the major production region extends from Denmark through northern Germany into the Netherlands and Belgium where pig farming is particularly concentrated. Other regions with a relatively high density of pigs are found in Spain, France, Poland and Italy. The EU pig production sector is not as vertically integrated as the poultry sector; the different rearing stages are usually carried out in separate facilities (although some countries as Denmark and Spain have developed integrated production systems). This means that some companies provide the feed, pigs and production standards, while farmers are contracted to breed and fatten the animals (Augère-Granier, 2020).

The reference system, used commonly in Europe, is a fully slatted floor with a deep manure pit underneath and mechanical ventilation (Bittman and others, 2014).

Poultry

Poultry meat

Poultry meat is the second most produced and consumed meat in the European Union. Broiler chicken production is by far the largest sub-sector of the poultry meat production, followed by turkey and duck.

According to Eurostat, some 891.4 million broilers were produced on more than two million farms across the EU in 2013. Among the latter, 19 260 farms had at least 5 000 broilers for a total of 840 million broilers. Farms with more than 5 000 broilers represent only 1 % of all broiler farms but account for 93.5 % of broilers, while farms with more than 100 000 head account for 38 % of total poultry numbers. In 2013, the average number of chickens on commercial farms was 43 632. It is likely that both very small and very large commercial farms exist in all Member States. Despite variations in the production structure, poultry farms of all sizes are found throughout the EU. Poultry farming system is one of the most intensive ones in Europe with most of meat chickens reared in closed buildings with high-stocking densities (around 33 kg/m²). In such systems, the use of fast-growing breeds which are slaughtered at 5 or 6 weeks is preferred. However, alternative chicken production systems (free-range and organic) are on the increase in many EU countries. Around 5 % in less intensive indoor systems, up to 5 % in free range systems and 1 % in organic systems. In 2021, the main poultry meat producers in

---

(15) Such a permit is required for intensive pig units with more than 2 000 places for production pigs (over 30 kg), or with more than 750 places for sows. The permit covers all aspects of farm management, including feed and manure, and is granted to farms that meet the criteria for minimizing the risk of pollution to air, land and water.

terms of tonnes of product weight in the EU include Poland (19 %), France (13 %), Spain (12 %), Germany (12 %) and Italy (10 %) (Eurostat, 2020) (Agriculture and rural development, 2022).

Laying hens

The European Union is the world's second largest producer of eggs; more than 400 million laying hens are kept throughout the EU. Nevertheless, the majority is concentrated in a limited number of Member states: France, Germany, Italy, Spain, the Netherlands and Poland. The organizational structure in the egg sector is very different from the poultry meat sector and varies greatly between countries. There is a link between housing systems for hens (either enriched cages or non-cage systems), farm size and level of production chain integration (either semi-integrated or with no coordination). There are four main systems for keeping laying hens. In 2021, approximatively 55 % of laying hens were kept in a free-range system. It encompasses barns (35,6 %), free-range (12,8 %) or organic rearing systems (6,6 %). Barns are large enclosures with litter on the floor and freedom of movement for the birds within the poultry house. Free-range systems are similar to barn systems with access to an outdoor run. 45 % of laying hens were kept in enriched cage(16) in 2021: Ireland and Austria have the highest shares of laying hens kept in free range systems (Eurostat, 2022).

Other significant livestock (mainly sheep and goats)

The EU's sheep and goat population totalled 71 million head in December 2021 with 60 million sheep and 11 million goats. The highest population of sheep is found in Spain which accounted for a quarter of animals, and Greece has the largest number of goats. The population of sheep and goats saw a downward trend between 2010 and 2021, falling by 10 % and 13 % respectively in 2021 compared with 2010.

Sheep and goat rearing takes place mostly on pastureland in remote and disadvantaged rural areas, often on common land, where it plays a key role in delivering public goods in terms of landscape and biodiversity conservation. In 2013, there were about 850 000 farms rearing sheep and 450 000 rearing goats. The average number of animals per farm varies significantly throughout the EU (Eurostat, 2020).

3.2 Key mitigation measures available

Methodology

This inventory of key mitigation measures to reduce air emissions from livestock is limited to those techniques applicable to cattle, pigs and poultry, as these species are the main emitters of NH_3 and, as regards the first two, of CH_4 in Europe. The list of techniques and good practices presented below focus on practical steps for emission reduction at farm level: feed, animal houses, outside stores of slurry/manure and spreading of animal effluents. Higher level policy levers (training, financial support etc.) are out of scope of this section. The techniques presented focus on ammonia for all species, but methane for cattle only as cattle contribute the majority of CH_4 emissions.

The international expert community within the UNECE Task Force on Reactive Nitrogen has assessed and selected relevant measures concerning the emission reduction potential of NH_3 and the availability of measures. The assessment is based on the UNECE approach established for the Ammonia Guidance Document, where each abatement/mitigation measure is assigned one of the three following categories according to expert judgement:

---

(16) Cages equipped with perches, nests, scratching areas and nail shorteners, which replaced the conventional battery cages banned by the EU in 2012.

- Category 1 techniques and strategies: These are well-researched, considered to be practical or potentially practical and there are quantitative data on their abatement efficiency at least on the experimental scale;
- Category 2 techniques and strategies: These are promising, but research on them is at present inadequate, or it will always be difficult to generally quantify their abatement efficiency. This does not mean that they cannot be used as part of a nitrogen abatement strategy, depending on local circumstances;
- Category 3 techniques and strategies: These have not yet been shown to be effective or are likely to be excluded on practical grounds.

A draft of this document was released in 2020, and it is currently the most comprehensive and up to date source of information for this section of the report. Note that within this guidance document on Integrated Sustainable Nitrogen Management the impact of all relevant measures on the different nitrogen compounds is presented. As this inventory is focused on available techniques, only category 1 techniques having a positive effect on NH_3 emissions have been reported. That means that the impact on other nitrogen compounds is not considered here.

Regarding techniques to reduce methane emissions, there is no equivalent of UNECE document. Several documents have been consulted; especially the report from the EIP-AGRI Focus Group(17) on reducing emissions from cattle farming which explored possibilities for mitigating emissions of methane and ammonia from cattle in a cost effective way.

Cross-cutting nutrient management, manure management and manure application measures

The UNECE Task Force on Reactive Nitrogen (TFRN) has prepared a guidance document on Integrated Sustainable Nitrogen Management, which puts ammonia emission reduction in the broader context of more efficient use of nitrogen in agriculture (TFRN, 2020) (assessment report on ammonia, 2020).

An integrated policy strategy is needed to avoid that ammonia reduction measures would increase other nitrogen related problems, and to optimize potential synergies. Potential synergies and trade-offs can also be found beyond the nitrogen cycle. Losses of other nutrients, methane emissions and carbon sequestration are also linked to changes in the nitrogen cycle. Housing (40 %), storage (20 %), application (35 %) and grazing (5 %) are the main stages in the manure-chain that cause ammonia emissions. These stages are not independent of each other (assessment report on ammonia, 2020).

Feed and herd management measures

Livestock feeding strategies decrease NH_3 emissions from manure in both housing and storage and following application to land. They also have the potential to reduce methane emissions from cattle. The crude protein content and composition of the animal diet is the main driver of nitrogen excretion in urine and faeces. **Adaptation of crude protein** in the diet to the needs of the animal is therefore the first and most efficient measure to mitigate nitrogen emissions throughout the entire manure management chain (UNECE, 2020).

Pigs and poultry

Nutritional management to reduce ammonia emissions from pigs and poultry is described in the Best Available Techniques (BAT) Reference Document (BREF) for Intensive Rearing of Pigs and Poultry

---

(17) https://ec.europa.eu/eip/agriculture/en/focus-groups/reducing-emissions-cattle-farming.

(IRPP). Best Available Techniques (BATs), for both productions, include: **phase feeding** with a diet formulation adapted to the requirements of animals; **formulating diets based on digestible/available nutrients**; and **using low-protein amino acid-supplemented diets and feed additives/supplements** which reduce the total nitrogen excreted (UNECE, 2020) (BREF IRPP, 2017).

For poultry, the potential for reducing N excretion through feeding measures is more limited than for pigs because the conversion efficiency currently achieved on average is already high and the variability within a flock of birds is greater (UNECE, 2020).

Dairy cow and beef

By applying appropriate feeding strategies, it is possible to reduce greenhouse gas emissions or lower ammonia emissions. As described for pigs and poultry, **adaptation of proteins intake** for cattle is an effective way to reduce NH_3 emissions and overall N loss. In general, increasing the energy/protein ratio of the diet by using "older" grass or swathed forage cereal and/or supplementing grass by high energy feeds is a well-proven strategy for reducing levels of crude protein. By **feeding a diet balanced in amino acid supply**, better feed N-use efficiency can be achieved. Mitigation of ammonia emissions from cattle can therefore be achieved by a better management of the protein and specific amino acids in the feed according to the age and the type of animals (UNECE, 2020). As ruminants, some specific feeding measures can influence the level of CH_4 emissions so dietary strategies need to consider the possible trade-offs in emissions (UNECE, 2020). Specific dietary measures and additives would have the potential to reduce enteric methane emissions. The **digestibility of forage** can impact the production of enteric methane. Increasing quality or digestibility of forages will increase production efficiency and this will likely result in decreased methane emissions per unit of product. Providing concentrated feed or starch, more digestible, can positively impact methane emissions per unit of product especially for dairy cows. Intensive beef production in general already has a high content of starch in the feed. Supplementation of animal diets with lipids reduces methane emissions. They are usually added to the feed of lactating dairy cows to increase the energy concentration of the ration (EIP-AGRI Focus Group, 2017).

Some chemical compounds as 3-NOP (3-nitroxypropanol), nitrate or seaweeds for instance, can have an inhibitory effect on methane-generating rumen micro-organisms, thereby lowering the overall methane production per animal (Yáñez-Ruiz, et al., 2017). A meta-analysis identified strategies to decrease CH_4 per unit meat or milk and absolute enteric CH_4 emissions while maintaining or increasing animal productivity. Increasing feeding level, decreasing grass maturity, and decreasing dietary forage-to-concentrate ratio—decreased CH_4 per unit meat or milk by on average 12 %. CH_4 inhibitors, tanniferous forages, electron sinks, oils and fats, and oilseeds decreased daily methane by on average 21 % (Arndt, et al., 2022).

Increasing longevity and productivity are category 2 techniques from UNECE to reduce NH_3 emissions but can be mentioned because they can reduce CH_4 emissions. **Breeding programmes** and changes in feed composition can improve production efficiency. There is a potential in breeding for lower overall methane emissions per cow. This will yield lower emissions of ammonia and methane per kg of milk or meat but will not necessarily reduce overall emissions on a local or national scale. Emissions of NH_3 per unit of animal production are reduced by increasing productivity in terms of products (meat and milk) and will also lead to a reduction of enteric methane emissions. However, optimum productivity levels vary according to breed and region and must also take into consideration the fact that ruminants can only cope with a certain amount of concentrates and require sufficient roughage in their diet to stay healthy. Especially for dairy cattle, productivity can be increased though increasing milk production per year and through increasing the number of milk production cycles per animal. Optimized diet and housing conditions enable a higher longevity of dairy cattle. Improving the longevity of dairy cattle also decreases the number of young cattle necessary for replacement.

Extending the productive life of dairy cows reduces relative methane emissions per product unit (EIP-AGRI Focus Group, 2017).

Manure management measures

Measures related to manure storage and processing

For ammonia, urine and faeces contain nitrogen compounds like urea and uric acid which are rapidly converted to ammonia in solution or ammonium compounds after excretion, so there is a physical stock of it ready to be emitted. The rate of ammonia emissions depends therefore on temperature, surface area, air movement, as well as pH which alters the NH4+ <-> NH3 equilibrium.
Methane is produced more slowly by anaerobic decomposition of volatile solids. The main factors are the amount of oxygen present and the temperature (though clearly pH is important here too).

A decrease of the surface area of the storage (liquid/solid) and of the potential to emit are the main principles to mitigate NH_3.

These principles are generally applicable to slurry storages and manure storage. However, the practical feasibility of implementing the principles are larger for slurry storages than for manure storages (Bittman, Dedina, Howard, & Oenema, 2014).

Covering slurry and manure reduces ammonia emissions. Different types of cover are applicable to slurry storage; these are **rigid, flexible and floating covers** (natural crust; floating flexible cover…). Reduction levels vary by type.

Manure heaps can also be covered by using a sufficient thickness of dispersed coverings or by a flexible cover. The approach works by protecting manure surfaces from air movement (UNECE, 2020) (BREF IRPP, 2017), reducing the rate of diffusion of ammonia out of the manure or slurry.

The **acidification** of slurry during storage leads to a drop in ammonia and methane emissions. In general, the addition of acid is carried out just before spreading. While feedstock for biogas production can only contain limited amounts of acidified slurry, acidification after anaerobic digestion can help to reduce subsequent NH_3 emissions (UNECE, 2020). **Anaerobic digestion** associated with production of CH_4 biogas reduces emissions of CH_4 from subsequent storage of the digestate. However, as ammonium content and pH in digested slurry are higher than in untreated slurry, more NH_3 may be emit so the use of covered stores and low-emission manure spreading is required. As part of an integrated package of measures, anaerobic digestion can reduce NH_3.

Manure application measures

While straw-based solid manure can emit less NH_3 than slurry after surface spreading on fields, slurry provides a greater opportunity for reduced emissions application methods (UNECE, 2020) such as trailing hose, trailing shoe and injection. These techniques can be applied on both cropland and grassland. Additionally, **mechanical solid-liquid slurry separation** can also be applied prior to application to further reduce emissions, because the liquid fraction (containing most of the available ammoniacal N) infiltrates more easily due to its lower dry-matter content than slurry, reducing NH3 emissions. On the other hand, although solid manure does not infiltrate, it mainly consists of organic N forms so NH_3 emissions occur more slowly. For solid manure and slurry, rapid incorporation (within 1, 4 or 12 hours) into the soil through tillage is the primary mitigation measure, although this can only be implemented prior to sowing a crop (i.e. not on permanent grassland and or during the growing season). Acidification of slurry reduces ammonia emissions during field application. Application of diluted slurry leads to weaker ammonia emissions because of the faster infiltration into the soil (Bittman, Dedina, Howard , & Oenema , 2014), (UNECE, 2020).

Measures applicable to organic fertilizers

Integrated nutrient management involves considering all of a farm's crop needs using all organic and inorganic sources of nutrients. Organic sources should be favoured and supplemented with inorganic inputs. Application of nutrients at the appropriate rate and time limits N-losses. Seasonal crops requirements, characteristics of the soil and nutrient content of organic/inorganic fertilizer are all aspects to consider when setting the rate of application. Providing nitrogen to the soil when needed for growing crops reduces the risk of nitrogen losses to water and soil. Split fertilisation (applying fertiliser in 2 or more phases) reduces the risk of leaching and allows subsequent feeding to be adjusted according to yield expectations. The suitable time should consider the climatic characteristics, as well as the weather forecast.

Various tools can be used to estimate the quantities of nitrogen provided by the spreading of livestock manure and crop requirements; they also help to determine the quantities and the suitable moment to supplement the organic supplies with inorganic supplies.

Cattle-specific measures

Cattle-specific housing measures

In animal housing, reduction measures mainly address ammonia emissions and they are relatively limited. This can be attributed to the fact that emissions from naturally ventilated barns which are typical for cattle housing, are more difficult to assess and control, compared to those from mechanically ventilated barns. It is worth to note that a few methods also have an effect on methane emissions (EIP-AGRI Focus Group, 2017)

Straw-based systems producing solid manure for cattle are unlikely to emit less NH_3 in the animal houses than slurry-based systems (UNECE, 2020).

Existing techniques need to be optimized and new abatement techniques have to be developed by focusing on factors as emitting surface area of slurry/manure sources or their residence time.

In floor-based systems, ammonia emissions can be reduced by **separating urine and faeces** or **limiting air exchange** with the pit, mainly applied in dairy in medium to large scale farms. Scrapers and robots can be used for the regular **cleaning of the floor** but the system requires a proper maintenance to avoid higher ammonia emissions, because clogging problems can occur for instance (EIP-AGRI Focus Group, 2017).

The **immediate segregation of urine and faeces** consists in a physical separation of faeces and urine in the housing system which reduces hydrolysis of urea so less ammonia is emitted (UNECE, 2020).

Litter based systems

Litter-based systems are more common with beef cattle and typically consist of straw. The use of bedding material that absorbs urine in cattle housing can reduce NH_3 emissions by immobilizing nitrogen. It is required to increase the quantity of bedding material. Using a selection of alternative organic sources can reduce ammonia emissions through lowering pH higher absorption of ammonium for instance. The availability of practical options is currently very limited and performance and emission reduction efficiency is largely unknown (UNECE, 2020).

Slurry management techniques at pit level

Slurry acidification mitigates emissions of NH_3 because the balance in the slurry is shifted from NH_3 to NH_4+. Moreover, the acidification in the livestock house will reduce NH_3 emissions throughout the manure management chain.

The frequent slurry removal from under the slats in an animal house to a (covered) outside store can substantially reduce NH_3 emissions by reducing the emitting surface and the slurry storage temperature. It also reduces CH_4 emissions as manure is stored outside, under cooler conditions (UNECE, 2020).

Indoor climate control techniques

In houses with traditional slatted floors, **barn climatization** with slurry cooling, roof insulation and/or automatically controlled natural ventilation can reduce NH_3 emissions due to reduced temperature and air velocities and can also **help reduce CH_4 emissions**.

End-of-pipe techniques (air scrubbers)

Implementation of air scrubbers in cattle barns necessitate more forced ventilated building in order to maximize the ratio treated/untreated air. Alternatively, another approach lies in air extraction from the pit headspace. Air treatment can be obtained by both chemical, biological or mixed scrubber systems (EIP-AGRI Focus Group, 2017) (UNECE, 2020).

Measures for grazing livestock

Grazing is an effective measure to reduce ammonia emissions from housing by reducing the amount of animal excrement in animal houses. Total annual emissions (including housing, storage and spreading) from dairy systems may decrease by up to 50 per cent with nearly all-day grazing, as compared with animals that are fully confined. Effectiveness of this management tool depends on the time spent outside and on the cleanliness of the house. Grazing is category 1 if the animals are grazed all day or if very little floor area is contaminated with manure each day. Less than 18 grazing hours per day must be considered as category 2 because of the uncertainty in quantifying emissions. In some cases grazing can contribute to increased leaching or increased pathogen and nutrient loading of surface water (Bittman, Dedina, Howard , & Oenema , 2014) (UNECE, 2020).

In some cases, grazing can lead to higher emissions of CH_4 (EIP-AGRI Focus Group, 2017).

Ammonia emissions arising from grazing livestock are much smaller than for managed manure (for example, from housed animals) because of the rapid infiltration of urine into the soil. Where climate and soil conditions allow, extending the grazing season will result in a higher proportion of excreta being returned via dung and urine during grazing, thereby reducing NH_3 emissions.

Swine-specific measures

Principles and technics to reduce NH_3 emissions from pig housing systems have been described in detail in the IPPC document on Best Available Techniques (BATs) (BREF IRPP, 2017).

Slurry based building

The **reduction of emitting surface** and the **regular cleaning of floors** by mechanical scrapers or robots have the potential to reduce ammonia emissions. Several techniques can be applied to limit the surface of emissions as the frequent and complete vacuum-assisted drainage of slurry from the floor of the pit. Other floor designs can be used, including partially slatted floors, use of inclined smoothly finished surfaces and use of V-shaped gutters. Partly slatted floors (~50 per cent area) generally emit less NH_3, particularly if the slats are smoother than concrete (e.g metal or plastic coated). Emissions from the non-slatted areas are reduced by inclined, smooth surfaces, by locating the feeding and watering facilities to minimize fouling of these areas, and by good climate control in the building. Moreover, the regular removal, with vacuum or gravity removal systems or by flushing systems, of slurry from under the slats in the pig house to an outside store can reduce NH_3 emissions by reducing the emitting surface and the slurry storage temperature. It also reduces CH_4 emissions as manure is stored outside, under cooler conditions.

Changing properties of slurry by **acidification** mitigate ammonia emissions by shifting the equilibrium towards ammonium as described above for cattle.

Increase of bedding material (pigs with solid manure)

Use of bedding material that absorbs urine in pig housing can reduce NH_3 emissions by immobilizing nitrogen.

Barn climatization to reduce indoor temperature and air flow

Surface cooling of slurry with fans using a closed heat exchangers or thanks to circulating groundwater or other cooling agents in floating heat exchangers or walls of slurry can substantially reduce NH_3 emissions if temperature is bellowed to at least 12 °C. In slurry systems, this technique can often be retrofitted into existing buildings. More globally, lowering the indoor temperature and ventilation rate, taking into account animal welfare and production considerations, can lower ammonia emissions.

End of pipe techniques (biological and acid scrubbers)

Exhaust air from pig buildings can be treated by **acid and biological scrubbers**. Acid scrubbers use an acidic solution to bind the ammonia as ammonium sulphate whereas biological air-scrubbers operate with bacteria that remove NH_3 and odours from the exhaust air.

Poultry-specific measures

This section identifies various principles and techniques for reducing ammonia emissions from poultry operations. Some are specific to broilers and others to laying hens.

In general

The IRPP BREF details the main rules and technics to apply in order to reduce NH_3 emissions in livestock buildings. Manure should be removed from the building frequently. Drying manure quickly will also reduce the hydrolysis of uric acid into ammonia. This hydrolysis can be modulated by lowering the temperature and ventilation in the buildings, as long as this is compatible with animal welfare. Easily washable surfaces are preferable. Finally, air from the house can be treated by a scrubber (biological scrubber, acid scrubber)

Laying hens

Ammonia emissions from cage system housing can be lowered by reducing the moisture content of the manure by ventilating the manure pit. The collection of manure on belts and the subsequent removal of manure to covered storage outside the building can also reduce NH3 emissions, particularly if the manure has been dried on the belts through forced ventilation.

Aviary systems with manure belts for frequent collection and removal of manure to closed storages reduce emission NH3 emissions compared with the deep litter housing system.

Broilers

Moist litter in poultry houses favours ammonia emissions so in order to limit them, it is considered BAT to keep the litter as dry as possible. To do that, spillage of water from the drinking system has to be avoided by using “nipple drinkers” instead of “bell drinkers” (UNECE, 2020). Moisture content of the litter can also be reduced by using the indoor air to keep it dry.

End-of-pipe techniques

Treatment of exhaust air by acid scrubber has been successfully employed to reduce NH3 emissions in several countries. The main difference from pig systems is that poultry houses typically emit a much larger amount of dust. To deal with dust loads, multistage air-scrubbers with pre-filtering of coarse particles have been developed (UNECE, 2020).

The importance of integrated packages of measures for reducing NH_3 emissions

As mentioned in connection with some mitigation measures in the above sections, for NH_3 emissions, a key consideration is the package of different measures employed due to interactions among pollutants and between stages of the manure management chain. There are several key principles that are outlined below:

1. **Nitrogen input control measures influence all N loss pathways**. This is a useful heuristic when assessing potential for co-benefits or pollution-swapping, as reduction in overall N flows are likely to reduce most or all forms of N loss and pollution. Measures that reduce overall N flows should also ultimately reduce global demand for synthetic fertilisers. If this leads to reduced levels of fertilizer production, then there is a double-win, as reactive nitrogen and GHG emissions (N2O, CH_4 and CO_2) associated with energy-intensive fertilizer manufacturing processes will also be reduced.
2. Manure management on farms consists of several linked stages in sequence, and measures to reduce emissions upstream are ineffective if measures are not also applied downstream. This message is made clear in UNECE (2020) as well as the UNECE guidance on ammonia mitigation (Bittman et al., 2014). The practical implication of this is that measures targeting manure application practices are particularly important, and the marginal abatement cost of upstream and downstream measures should be considered as part of a package, rather than independently.
3. A measure to reduce ammonia emissions from manure leaves more organic N available in the farming system, so that more is available to meet crop and animal needs. In order to fully

exploit the benefit of a measure to reduce N loss (and to avoid pollution swapping), the nitrogen saved by the measure needs to be matched by either reduced N inputs, increased storage, or increased N in harvested outputs. If, for example, a livestock farmer switches to slurry injection to reduce losses of ammonia from slurry application, this should be accompanied by a reduced manure application rate to the land. However, given that the quantity of manure available to the livestock farmer has not been reduced, an alternative fate needs to be found for that manure. This therefore implies the need for transport of manure from locations of high manure production to locations of low manure production and high crop production.

4. **There are interactions between measures, which change cost-benefit calculations.** If two measures are applied at the same stage of manure management (e.g. fitting a lid on a manure store and acidification), then the cost effectiveness of the marginal abatement achieved by the second measure is reduced considerably. In other cases, the measures may be mutually exclusive, or be applicable in completely different circumstances.

3.3 Current and potential additional uptake of measures

Member-state reported information on uptake of mitigation measures

Methodology

Information reported by the 5 Member States (MS) with the greatest agricultural NH_3 emissions was reviewed to understand the projected future uptake of policies and measures (PaMs) that mitigate NH_3 emissions in the livestock sector. The focus was on NH_3 emissions only, because the information reported around PaMs relating to CH_4 emissions is being studied in detail by another EEA project (EEA, 2022b) so does not need to be duplicated here. Information sources consulted included informative inventory reports (IIR) submitted under CLRTAP and NECD, national air pollutant control plans (NAPCPs), and the database of reported national PaMs submitted under the NECD and collated by the EEA.

Spain

With existing measures (WEM) NH_3 emissions are predicted to remain close to constant in Spain up to 2030 (IIR, 2021). An increase of emissions due to changes in livestock populations is expected to balance out small reductions achieved with the currently existing measures. Additional measures have been proposed that aim to reduce NH_3 emissions by 43.6kt/year compared to 2016. This would just meet reduction commitments.

7 measures are proposed in Spain's national air pollution control programme (NAPCP, 2019) to reduce NH_3 emissions under a scenario with additional measures (WAM scenario). 1 measure relating to feeding of livestock, 4 in housing and 2 in manure storage.

Phase feeding strategies are planned to be implemented for all livestock species by being incorporated into future industry standards. Uptake is projected to be 100 %. Frequent removal of manure from livestock holdings of swine and cattle has been proposed. This would apply to all facilities apart from facilities where this is deemed not possible. The NAPCP lists small farms and facilities with extensive production as examples. A 30 % and 20 % reduction in NH_3 is expected on participating facilities by 2030 compared to the reference technique for swine and cattle respectively.

All new cattle, pig and poultry installations are to introduce BAT (best available technique) housing measures that reduce NH_3 emissions (apart from those where it is deemed not possible for a facility to do so). How to achieve this reduction is not mentioned. Existing poultry facilities are expected to introduce livestock housing measures that reduce NH_3 emissions by 30 % compared to the reference technique. Housing measures for existing swine and cattle facilities are not mentioned.
All new and existing swine and cattle installations are expected to introduce BAT manure storage measures (apart from those where it is deemed not possible for a facility to do so). Poultry facilities are not mentioned.

For Spain, greater details of PaMs uptake projection are not mentioned. It can be assumed that a gradual uptake of the measures mentioned above has not been modelled. While strong measures are mentioned for feed, animal housing and manure storage no measures that impact the spreading of manure are proposed. There is potential for greater emissions reductions in this area and greater uptake.

Germany

Livestock numbers have slightly reduced since 2015 in Germany, however emissions have remained similar due to an increase in emissions per animal. In the future, cattle numbers are predicted to remain similar while swine and poultry are projected to increase slightly.
Under the current measures, NH_3 emissions in Germany are predicted to reduce by around 4 % in 2030 compared to 2018 levels (IIR, 2022). With additional measures (WAM) NH_3 emissions are predicted to reduce by an additional 11 %. Under this scenario the emissions would just meet reduction commits. The difference between the two scenarios are the additional mitigation measures proposed, some of which impact livestock.
The new Fertilizing Ordinance (DÜV, 2020) has been included in the WEM scenario. In this measure, liquid manure applied to uncultivated arable land by broadcast method must be incorporated within 1 hour.

The WAM scenario includes the following additional measures by 2030:

- 70 per cent of cattle and pig slurry is digested in biogas plants
- No use of broadcast application on uncultivated arable land. Liquid manure is incorporated within an hour. This goes slightly further than the measures introduced by the new Fertilizing Ordinance (DÜV, 2020) which is included in the WEM scenario
- Leachate is to be incorporated within 1 hour
- Uncovered external storage facilities for liquid manure / digestates are at least covered with a plastic sheet or comparable technology. Facilities with natural covers would be replaced by this measure
- Air scrubber systems are present in 75 % of agricultural installations regulated under the IED (up from 8.2 % of pig, 0.6 % of laying hen and 1.8 % of broiler animal places in 2020). 25 % of the agricultural IED installations' operation reduce 40 per cent of emissions through further system-integrated measures in housing
- 75 % of the agricultural operations smaller than IED operations reduce emissions from housing by 40 %. The remaining 25 % do not reduce emissions

- 50 % of slurry storage underneath slatted floors is replaced by external storage with at least a plastic film cover
- 5 % reduction of N excretion by protein-optimized feeding in cattle husbandry
- System integrated housing measures such as the introduction of grooved floors, is implemented by 50 % of cattle housing that has greater than 100 cattle
- Liquid manure is implemented on 50 % of tilled fields and grassland only with injection / slot techniques or acidification

There is a good range of measures proposed.
When not specified, in this projection of future emissions under a WAM scenario uptake is assumed to be 100 % (e.g. for compliance with regulation), and uptake is assumed to happen as soon as the policy is implemented. However, the assumed time that it will take for each measure until it reaches its effect in practice, is accounted for.
Germany has specified a comparatively large number of PaMs in its WAM scenario. For some of the measures, uptake has been considered and has not been projected to be 100 %. However, gradual uptake is not mentioned.

Italy

Cattle numbers have declined slightly since 2015 in Italy and this trend is predicted to continue (IIR, 2022). However, swine numbers are predicted to increase in the future. NH_3 emissions are predicted to decline slowly under current measures (WEM). With additional measures (WAM), a greater reduction is expected however, the difference between the two scenarios is not large. Although, under a WAM scenario Italy would just reach the NECD emission reduction target for 2030.

The NAPCP makes clear that the small difference between the two scenarios is because of PaMs that focus on reducing the consumption of nitrogen fertilizers (NAPCP, 2021). Currently, even under a WAM scenario NH_3 emissions from livestock does not significantly change from mitigation measures. The NAPCP identifies the livestock sector as one that needs further intervention in order to reduce ammonia emissions. However, two livestock related PaMs are mentioned in PaMs database: a ban of the construction of new slurry lagoons, and use of floating manure covers.
This indicates that much greater uptake of livestock emissions mitigation measures are possible, but are not currently planned.

A 2018 study by the Research centre for animal production (CRPA) estimated the potential regional NH_3 emissions reductions possible by 2030 if technical livestock measures relating to nutrition, animal housing, storage and spreading were applied to 86 % of relevant livestock. These measures came from a variety of sources, such as the NECD, Nitrates Directive and the Nitrates Action Programs. Urea application followed a business-as-usual scenario and no other NH_3 reducing PaMs were modelled. There was found to be a total emissions reduction of 16.1 % in 2030 compared to 2005. This provides an estimate of the NH_3 emissions that could be reduced if Italy were to implement technical livestock measures.

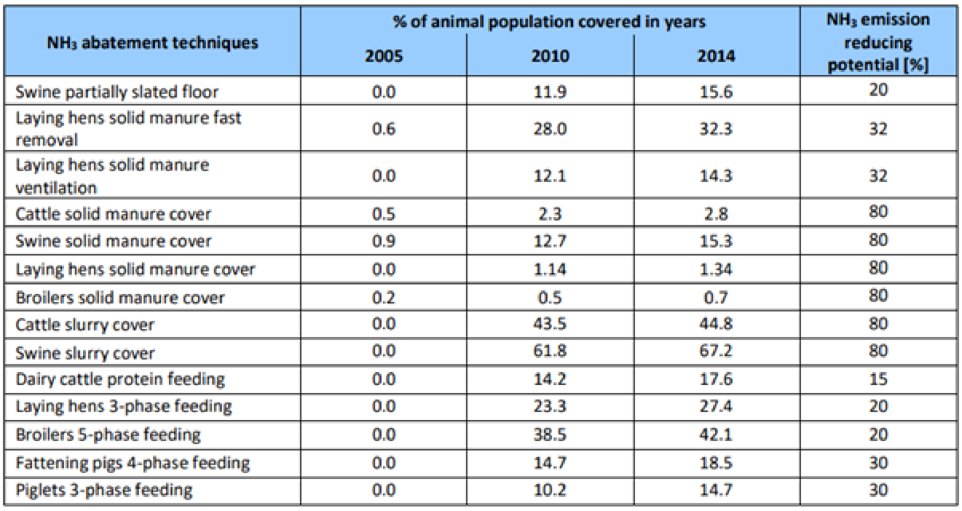
Poland

In the 2022 IIR, the percentage of the livestock population that is covered by different NH_3 abatement techniques does not include an update to data since 2014 (IIR, 2022). Due to this, emissions per head estimates have not changed significantly in recent years. In 2012, 10.5 % of dairy cattle, 5.1 % of other cattle and 24.3 % of swine were estimated to be covered by liquid manure management systems.

Poland makes clear in the IIR that it views liquid manure management as being more suitable for reducing NH_3 emission, but there is difficulty in increasing the prevalence of this system in Poland as there is a high proportion of small farms. In small farms, solid systems are commonly used due to the lower investment cost.

The prevalence of other livestock ammonia mitigation measures is well covered in the IIR, however the latest year with data is 2014 (Table 3.1).

Table 3.1: NH_3 abatement techniques by % of livestock population covered in Poland



NH_3 abatement techniques	% of animal population covered in years			NH_3 emission reducing potential [%]
	2005	2010	2014	
Swine partially slated floor	0.0	11.9	15.6	20
Laying hens solid manure fast removal	0.6	28.0	32.3	32
Laying hens solid manure ventilation	0.0	12.1	14.3	32
Cattle solid manure cover	0.5	2.3	2.8	80
Swine solid manure cover	0.9	12.7	15.3	80
Laying hens solid manure cover	0.0	1.14	1.34	80
Broilers solid manure cover	0.2	0.5	0.7	80
Cattle slurry cover	0.0	43.5	44.8	80
Swine slurry cover	0.0	61.8	67.2	80
Dairy cattle protein feeding	0.0	14.2	17.6	15
Laying hens 3-phase feeding	0.0	23.3	27.4	20
Broilers 5-phase feeding	0.0	38.5	42.1	20
Fattening pigs 4-phase feeding	0.0	14.7	18.5	30
Piglets 3-phase feeding	0.0	10.2	14.7	30

In 2014, no measures have a particularly complete uptake. Slurry cover for swine manure is the only mitigation measure with over 50 % of the livestock population covered. Manure removal and cover is low for swine, cattle and poultry. This has the largest NH_3 emissions reducing potential of the measures mentioned in the table. Additionally, diet control measures also have a low percentage cover. This table indicates that in 2014 Poland had potential for much greater uptake of measures.

In Poland, livestock numbers have increased slightly since 2015. Projections predict that cattle and pig numbers will remain constant in the future, but poultry will increase by 14 % between 2020 and 2030. Manure management system share is predicted to change towards increasing the share of bedding-free systems for dairy cattle (to about 70 %) and pigs (to about 75 %). This will be caused by the further concentration of animal production. In the case of meat cattle, this share will remain at a level of about 4 %.

The WAM scenario is expected to contribute a further reduction in emissions of 17 % compared to the WEM scenario. WEM assumes the covering of all storage tanks of liquid manure by 2030. The WAM scenario includes two additional PaMs which are relevant to livestock:

- 60 % of slurry is applied to soils using low-emission spreading techniques
- incorporating 90 % of manure to arable land within 12 hours.

With the additional measures it is projected that Poland will meet the NECD 2030 target for ammonia emissions.

Based on the data from 2014 a significant amount of NH_3 emissions could be reduced by ensuring that the proportion of the animal population covered by the mitigation measures is increased. However, the PaMs in the WAM scenario do not apply to these measures.

The details of the uptake of these measures are not specified.

France

NH_3 emissions due to livestock have declined in recent years in France. This change is mainly due to a decline in population of dairy cows. Notable reductions have also been caused by uptake of mitigation measures. In swine, the uptake of two-phase feeding and the treatment of manure have reduced NH_3 emissions. Additionally, the gradual disappearance of deep pit systems in laying hens and the adjustment of feed to nitrogen needs have contributed to the decline in ammonia emissions.

Under current measures as of 2017 (the 2019 release of the IIR provides the most relevant projection data for France) a slight drop in NH_3 emissions is expected in *3B Manure management* which includes livestock emissions. This can be explained partly by a reduction in CP % of dairy cattle feed in winter from 14.7 % in 2019 to 14.2 % in 2050, but the reduction is mostly accounted for by a small drop in the population of cattle. There is assumed to be no change to the uptake of air scrubbing for pigs and poultry, covering of manure stores and spreading methods.

In addition to modelling the effect of current measures on livestock, a WAM scenario was also modelled. The additional measures include a changing public diet to reduce demand for livestock and increasing public support for environmental and agricultural issues allows for greater money to be spent on mitigation measures. For France, the WAM scenario does not use planned measures like for other Member States. France, unlike the other MS assessed here, have provided multiple year uptake projections of different measures and their effect on the livestock sector.

Under the WAM scenario, the reduced demand for animal protein has caused a greater reduction in cattle, swine and poultry population than for the WEM scenario.

Under the two scenarios, the proportion of manure management system is projected to be different. For dairy cattle, the manure management system with the highest proportion is pasture. Under the WEM scenario this proportion decreases and the other systems increase. Under the WAM scenario, the percentage of pasture manure management systems increases slightly from 39.7 % to 41.5 % between 2020 and 2030 while the other systems decrease slightly. A similar pattern is observed for other cattle. Dairy cattle in the WAM scenario have feed with lower nitrogen than in the WEM scenario, 14.5 % in 2030 for the WEM scenario compared to 14.2 %. This leads to lower nitrogen excretion per cattle in the WAM scenario. Changes in manure spreading techniques between the scenarios cause a greater reduction in NH_3 emissions in the WAM scenario for both liquid and solid manure.

The additional PaMs in the WAM scenario cause a reduction in emissions of 14 % between 2016 and 2030 compared to a reduction of only 4 % in the WEM scenario.

Summary of Member-state reported information

The uptake of NH_3 mitigation measures assumed in projections is not something that has been consistently included by the 5 Member States with the greatest NH_3 emissions in their IIR. All of the MS are projecting to only just reach NH_3 emissions targets, so if the uptake of mitigation measures occurs more slowly or to a lesser extent than assumed in projections in practice, it is possible that the targets will not be met. There are some mitigation measures described in section 3.2 that do not appear to have been included in WAM scenarios that could contribute to NH_3 emission reductions, for example:

- Acidification of slurry in housing or during storage (Germany do include acidification prior to application);
- Mechanical solid-liquid manure separation;
- Increased grazing time to reduce the amount of manure deposited in housing

However, it is possible that these measures are included but not well-documented in the IIR.

Assumptions and findings on potential uptake of measures from published scenarios

This section examines the assumptions made by a selection of key scenario modelling studies on uptake rates of particular technologies.

Clean Air Outlook 2 (CAO2)

The Clean air outlook 2 modelling (Amann et al. 2020) was undertaken in GAINS to model potential NH_3 emissions from the agriculture sector. Three of the scenarios are considered here:

- Baseline, considering current legislation as of 2017;
- «NAPCP» which considers the impact of additional air pollutant control measures from MS's national air pollution control plans (NAPCPs); and
- Maximum technically feasible reduction, assuming uptake of all technical measures included in the GAINS model to their maximum possible extent (TFR_Max)

Detailed results from the model output on uptake rates were made available to the project team, so average uptake of a range of NH_3 mitigation measures by year, livestock type and scenario could be extracted. From a range of individual measures including low-protein feed, low-emission housing, covered storage (low, medium and high efficiency), low-emission application (low, medium and high efficiency), and air scrubbing, the GAINS output provided an estimated uptake rate for each combination of one or more measures (up to 5 in some cases).

Results from individual countries were first aggregated to the EU level by calculating the number of heads of livestock in each country and system to which a particular combination of measures (which includes «no control» as one option) were applied, then summing across countries. Dividing this number by the total number of livestock in each system in the EU then gives an EU-average uptake rate of each combination of measures.

The results of this analysis are presented in the tables below. Note that in order to summarise total uptake of a given individual measure (as in Table 3.2; Table 3.3; Table 3.4), the uptake rates of all combinations including that measure were summed.

In the tables, a colour scale has been applied to cells to facilitate interpretation. Red, yellow and green indicate low, medium and high uptake rates respectively.

Table 3.2: Results of the CAO2 modelling on evolution of uptake (% of heads) of low-protein feeding strategies (all combinations including that measure) across the EU-27

Low-protein feeding					
System type	**Scenario**	**2005**	**2020**	**2030**	**2050**
Dairy cows – liquid systems	Baseline	9.9%	12.8%	12.2%	12.8%
	NAPCP			28.3%	28.4%
	TFR_Max			74.8%	75.3%
Dairy cows – solid systems	Baseline	0.0%	0.0%	0.0%	0.0%
	NAPCP			6.9%	6.9%
	TFR_Max			45.4%	46.0%
Laying hens	Baseline	12.0%	27.4%	28.5%	28.3%
	NAPCP			36.2%	36.1%
	TFR_Max			63.7%	63.9%
Other poultry	Baseline	10.5%	25.9%	27.0%	29.6%
	NAPCP			31.9%	32.8%
	TFR_Max			64.8%	64.7%
Pigs – liquid systems	Baseline	12.9%	36.9%	36.8%	36.1%
	NAPCP			47.0%	47.0%
	TFR_Max			90.7%	90.9%
Pigs – solid systems	Baseline	2.5%	5.0%	5.6%	5.0%
	NAPCP			15.9%	15.5%
	TFR_Max			57.8%	57.2%

Source: GAINS Europe, own calculations.

Note: Red, yellow and green cell shading indicate low, medium and high uptake rates respectively.

Table 3.3: Results of the CAO2 modelling on evolution of uptake (% of heads) of covered storage or low emission housing (all combinations including those measures) across the EU-27

Covered storage or low-emission housing*					
System type	**Scenario**	**2005**	**2020**	**2030**	**2050**
Dairy cows – liquid systems	Baseline	56.5%	64.5%	64.6%	66.0%
	NAPCP			65.3%	66.3%
	TFR_Max			97.7%	97.9%
Laying hens	Baseline	34.5%	50.2%	50.3%	51.0%
	NAPCP			56.0%	56.3%
	TFR_Max			85.5%	84.9%
Other cattle – liquid systems	Baseline	48.0%	50.5%	49.6%	48.7%
	NAPCP			54.2%	54.0%
	TFR_Max			79.1%	78.4%
Other poultry	Baseline	19.9%	35.0%	35.8%	37.4%
	NAPCP			43.3%	43.7%
	TFR_Max			92.1%	91.4%
Pigs – liquid systems	Baseline	29.9%	48.0%	47.8%	47.0%
	NAPCP			52.6%	52.7%
	TFR_Max			90.2%	89.5%

*In the GAINS modelling, covered storage and low-emission housing were never applied together, so we have assumed low-emission housing includes some element of low-emission storage.

Source: GAINS Europe, own calculations.

Note: Red, yellow and green cell shading indicate low, medium and high uptake rates respectively

Table 3.4: Results of the CAO2 modelling on evolution of uptake (% of heads) of low-emission manure application (all combinations including that measure) across the EU-27

Low-emission manure application					
System type	**Scenario**	**2005**	**2020**	**2030**	**2050**
Dairy cows – liquid systems	Baseline	31.6%	37.2%	35.8%	36.6%
	NAPCP			70.2%	69.9%
	TFR_Max			82.8%	82.7%
Dairy cows – solid systems	Baseline	34.4%	39.4%	35.6%	36.6%
	NAPCP			50.0%	50.6%
	TFR_Max			69.4%	70.3%
Laying hens	Baseline	39.5%	40.1%	40.5%	40.6%
	NAPCP			59.6%	59.4%
	TFR_Max			77.8%	77.4%
Other cattle – liquid systems	Baseline	22.6%	28.1%	28.9%	28.1%
	NAPCP			64.8%	64.5%
	TFR_Max			82.7%	82.7%
Other cattle – solid systems	Baseline	25.6%	28.0%	29.0%	28.8%
	NAPCP			57.3%	57.0%
	TFR_Max			81.5%	81.7%
Other poultry	Baseline	35.4%	36.8%	38.4%	40.2%
	NAPCP			65.5%	66.0%
	TFR_Max			80.8%	80.8%
Pigs – liquid systems	Baseline	38.1%	58.2%	58.3%	57.3%
	NAPCP			76.6%	76.2%
	TFR_Max			92.5%	92.2%
Pigs – solid systems	Baseline	59.5%	56.1%	51.1%	51.9%
	NAPCP			69.3%	69.6%
	TFR_Max			82.9%	83.1%

Source: GAINS Europe, own calculations.

Note: Red, yellow and green cell shading indicate low, medium and high uptake rates respectively.

As discussed in Section 3.2, it is also relevant to think about uptake of combinations of different measures, as the net abatement effect of measures depends on measures applied “downstream” in the manure management chain. Table 3.5 below shows the modelled uptake of combinations of measures which include both low-emission housing and/or storage, and low emission application.

Table 3.5: Results of the CAO2 modelling on evolution of uptake (% of heads) of all combinations of measures including housing/storage and application controls across the EU-27

Combination of low-emission housing/storage* and low-emission application (and low-protein feed in some cases)					
System type	**Scenario**	**2005**	**2020**	**2030**	**2050**
Dairy cows – liquid systems	Baseline	24.5%	29.5%	28.1%	29.0%
	NAPCP			44.6%	45.0%
	TFR_Max			81.3%	81.4%
Laying hens	Baseline	22.5%	27.7%	28.4%	29.3%
	NAPCP			41.5%	41.7%
	TFR_Max			77.1%	76.7%
Other cattle – liquid systems	Baseline	18.1%	21.8%	21.5%	20.7%
	NAPCP			35.3%	34.6%
	TFR_Max			68.4%	67.3%
Other poultry	Baseline	9.2%	15.6%	17.3%	20.0%
	NAPCP			32.5%	33.4%
	TFR_Max			80.6%	80.7%
Pigs – liquid systems	Baseline	11.7%	31.5%	31.3%	30.4%
	NAPCP			48.1%	47.9%
	TFR_Max			89.4%	88.8%
Pigs – solid systems	Baseline	0.0%	0.0%	0.0%	0.0%
	NAPCP			9.2%	8.7%
	TFR_Max			46.1%	45.1%

*In the GAINS modelling, covered storage and low-emission housing were never applied together, so we have assumed low-emission housing includes some element of low-emission storage.

Source: GAINS Europe, own calculations.

Note: Red, yellow and green cell shading indicate low, medium and high uptake rates respectively.

It is noteworthy from all of these scenarios that there is a moderate increase in uptake rate for most technologies in the baseline scenario between 2005 and 2020, but from that point relatively little change over time. Nevertheless, there is a stark difference between the 3 scenarios for all measures and livestock systems studied. In general the NAPCP scenario is closer to the baseline than it is to the maximum technically feasible scenario, except perhaps for low-emission manure application where NAPCP policies seem to bring uptake rates almost up to the technically feasible level.

JRC report 1: «Modelling environmental and climate ambition in the agricultural sector with the CAPRI model»

This recent report from the JRC (Barreiro-Hurle et al., 2021) models the impact of ambitious implementation of the common agricultural policy (CAP) reform proposals Farm to Fork (F2F) and Biodiversity strategies (BS) including the Commission's quantitative legal proposals (LP) put forward under these. In addition, it takes into account the Next Generation EU (NGEU) funding proposals which may help with investment costs in Green Deal priorities.

The modelled uptake rates (based on CAPRI optimisation) of livestock-related measures in the baseline and the maximum ambition scenario (F2F and BDS targets & CAP LP + NGEU) are shown in Table 3.6 below.

Table 3.6: Modelled uptake of mitigation technologies in 2030 in the JRC report «Modelling environmental and climate ambition in the agricultural sector with the CAPRI model»

Technology	Adoption rate in 2030 (as % of eligible heads)		Mitigation potential (where this can be attributed to methane), ktCO2e in 2030 relative to baseline
	Baseline	F2F and BDS targets & CAP LP + NGEU	
Low protein feed	0	0	
Feed additives: Linseed	0	10	- 3,428 (for all kinds of additive)
Feed additives: Nitrate	0	3	
Cattle genomics: Higher milk yield	0	31	
Cattle genomics: Higher ruminant efficiency	5	15	
Anaerobic digestion	2	28	- 7,868
Low-emission housing	12	26	
Covered manure storage	14	31	
Air scrubbing	0	14	

Source: adapted from tables 10 and 21 from Barreiro-Hurle et al., 2021.

In total, the uptake of these measures is expected to decrease EU-27 emissions in 2030 (relative to the baseline) as follows:

CH4: -16.8 % from enteric fermentation, -23.4 % from manure management.

NH3: -35 % from manure management and application.

However, 47 % of non-CO2 GHG emissions are «leaked» to other regions, so the savings quoted here are local, not global.

JRC report 2: ECAMPA-3

The ECAMPA-3 report(18) - «Economic assessment of GHG mitigation policy options for EU agriculture» (Pérez Domínguez et al., 2020) explores potential uptake and mitigation potential of individual measures in 2030. Unlike the Barreiro-Hurle et al. (2021) study above, this study did not model specific policy scenarios, but took several approaches to explore potential uptake. First, it modelled the maximum possible uptake of individual measures when implemented in isolation and cost not considered. Second, it then modelled uptake of measures when all measures are considered simultaneously and taken up in sequence based on their cost-effectiveness based on a marginal abatement cost curve (MACC). In the second approach, the cost of measures per tonne of CO_2 saved

---

(18) https://op.europa.eu/en/publication-detail/-/publication/cce2a349-8052-11ea-b94a-01aa75ed71a1/language-en.

increases with uptake rate, so that a given measure is only taken up to the extent at which it becomes more expensive than the next cheapest measure.

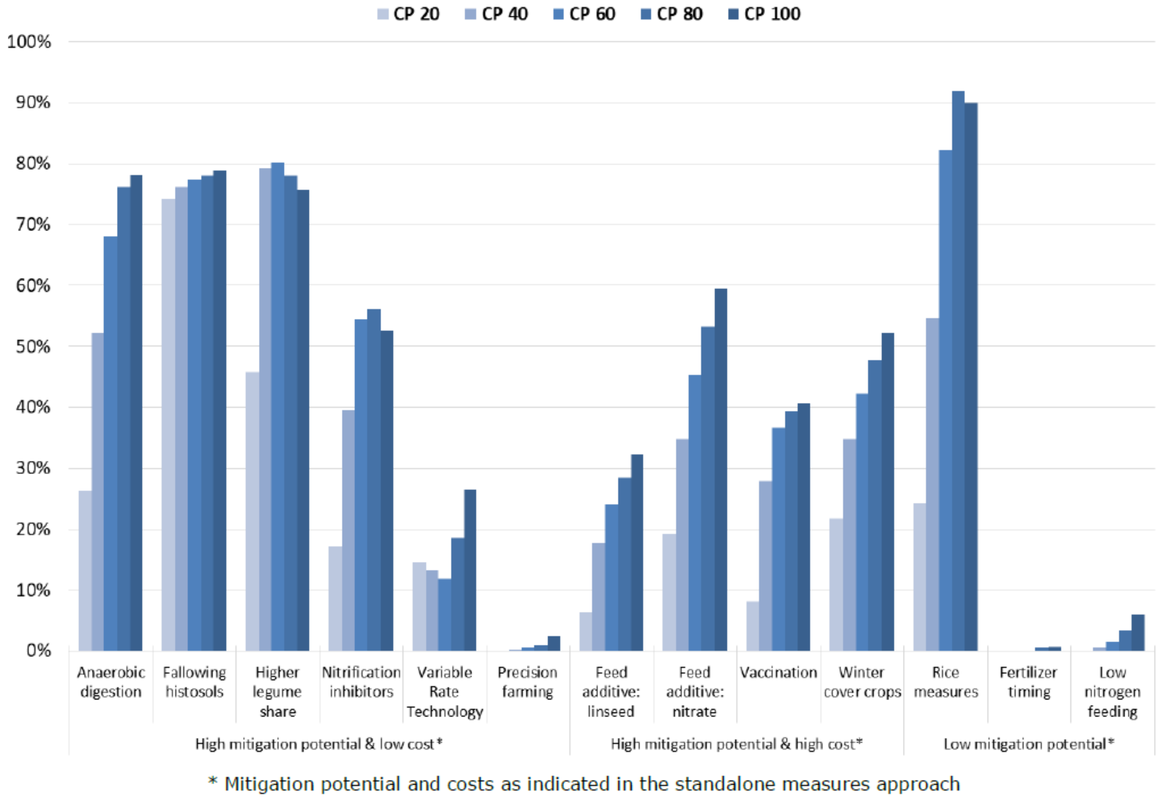
Table 3.7 below shows modelled maximum possible uptake rates of various technologies when considered in isolation and without consideration of cost effectiveness.

Table 3.7: Maximum possible uptake rate (EU-28) and mitigation potential of selected measures in 2030, when considered in isolation and without considering cost effectiveness

Technology	Adoption rate (% of heads) (maximum possible); 2030	GHG Mitigation potential compared with reference scenario (kt CO2e); 2030, including production effects.
Low protein feed	54 %	-1193.2
Feed additives: Linseed	28 %	-16889.8
Feed additives: Nitrate	42 %	-8936.8
Cattle genomics: Higher milk yield	100 %	1863.7
Cattle genomics: Higher ruminant efficiency	100 %	-4854.3
Vaccination	100 %	-8453
Anaerobic digestion	35 %	-10464.1

From the modelling of measures considered simultaneously and taken up in sequence based on their cost-effectiveness, unfortunately no tabular data on uptake rate or mitigation potential were provided in the ECAMPA-3 final report. However, Figure 3.1 below shows information graphically about how consideration of multiple measures simultaneously and taking cost-effectiveness into account in a MACC affects mitigation potential (which is closely tied to uptake rate here).

Figure 3.1: Percentage of maximum possible mitigation potential achieved (per measure) in the ECAMPA-3 combined measures scenarios with different carbon prices; 2030



Source : ECAMPA-3 final report (Pérez Domínguez et al., 2020), figure 18.

This shows that uptake of most of the livestock measures is highly dependent on the carbon price, with much higher uptake rates at €100 per tonne CO_2 saved compared with €20. Anaerobic digestion achieves almost 80 % of its maximum potential uptake at €100 per tonne CO_2 (35 % of heads), whereas low nitrogen feeding is modelled to be quite expensive and therefore can only achieve around 5 % of its maximum uptake. Some of the most cost-effective measures such as fallowing histosols and increasing the legume share in rotations have less dependency on the carbon price, reaching similar levels of uptake at €20 or €40 per tonne CO_2 saved as at €100.

EU Reference scenario 2020

The EU Reference scenario 2020([19]) (European Commission, 2021a) is an economy-wide «baseline» scenario making use of a variety of models such as PRIMES, CAPRI and GAINS. The framework considers current legislation only. It does not include the potential impact of Green Deal policies in the F2F strategy, fit-for-55 package or the contents of MS CAP Strategic plans.

The main report and annexes do not provide quantitative information on uptake rates of specific measures, but they do list the measures included in the GAINS modelling underpinning the agriculture sector results. Relevant measures taken into account are:

- Farm-scale anaerobic digestion;

([19]) https://energy.ec.europa.eu/data-and-analysis/energy-modelling/eu-reference-scenario-2020_en.

- Breeding to enhance livestock performance, health, fertility and longevity, to minimise CH_4 and NH_3 emissions intensity per unit of product;
- Feed additives or changed feed management to reduce enteric fermentation CH_4 emissions.

Uptake of farm-scale anaerobic digestion is expected to continue to increase to 2030, due to increased demand for renewable energy sources anticipated by the PRIMES model.

Ricardo AEA report «Effective performance of tools for climate action policy»

The Ricardo-AEA report «Effective performance of tools for climate action policy» (Ricardo-AEA, 2016)([20]) sought to analyse potential uptake of GHG mitigation measures through an expert consultation approach. For each MS, experts estimated the potential additional uptake over current levels (which were usually not known), taking into account costs, farm-level constraints, as well as socio-cultural barriers. Note that this study was published in 2016, so does not take into account recent policy initiatives which may make some of these technologies more or less viable.

The results are summarised in Table 3.8 below.

Table 3.8: Expert judgment of potential additional uptake (percentage points) over current levels, as a share of the total eligible livestock population. Source Ricardo-AEA 2016

Technology	Percentage points of additional uptake out of total eligible livestock (from unknown current level); range across MS
Livestock disease management	40-55 %
Use of sexed semen for breeding dairy cattle	5-50 %
Breeding for lower methane emissions in ruminants	0-5 %
Feed additives for ruminants [to lower enteric methane]	10-35 %
Low protein diets	30-60 %

Summary of measures in published scenarios and Member State projections

Common measures in Member State projections or published scenarios

Of the effective NH_3 and CH_4 mitigation measures presented in section 3.2, it is interesting to summarise which of these are consistently expected to have high additional uptake in the future, as these may represent the most promising measures. In this project, comprehensive data sources on current uptake rates of measures were not found, so the differences over time or between scenarios in published modelling studies must be relied upon to provide information on potential for additional uptake. Results vary considerably between the studies considered, and so the summary below is a qualitative attempt to draw out the most consistently included and high-uptake measures from the studies in question. Note that Member State projections are mainly relevant only for NH_3, as CH_4 measures for Member States were not included within the scope of this research (see above).

([20]) https://climate.ec.europa.eu/system/files/2016-11/cap_mainstreaming_en.pdf.

NH_3 mitigation measures:

- **Low protein/low nitrogen feed** is mentioned in all the studies reviewed above except the EU Reference scenario 2020. CAO2 (Ammann, 2020) shows low current uptake of the measure, and Ricardo-AEA (2016) suggests quite high potential for additional uptake (30-60 percentage points of eligible livestock) according to expert judgment, and low-nitrogen or phase-feeding is included in the projections for 3 of the 5 Member States considered. However, the picture is mixed as the scenarios in Pérez Domínguez et al. (2020) and Barreiro-Hurle et al. (2021) project very low uptake of this measure.
- **Low-emission manure application** measures show high potential for additional uptake under the CAO2 scenarios, shown by the large difference between the baseline and NAPCP scenarios. High uptake of these measures is also expected in projections of Germany and Poland.
- High uptake of **covered slurry storage and low-emission housing** (including air-scrubbers) are expected in projections for Germany, Spain and Poland, through compliance with BAT. Barreiro-Hurle et al., 2021 also shows a considerable impact of Green Deal policies on uptake of these measures in 2030 compared to a baseline. CAO2 scenarios on the other hand show lower expected additional uptake of these measures under NAPCPs, due to already high uptake under the baseline scenarios in 2020.

CH_4 mitigation measures:

Anaerobic digestion is a measure included in all scenarios relating to GHGs, with high uptake indicated in modelling by Pérez Domínguez et al. (2020) and Barreiro-Hurle et al. (2021). Due to the income or cost savings provided by generated heat and electricity, this measure is relatively cost-effective over the long term (though investment costs are high) (see Figure 3.1).

- **Genomics and breeding** for enhanced livestock performance is included as a measure in the EU Reference scenario 2020, Pérez Domínguez et al. (2020) and Barreiro-Hurle et al. (2021). The uptake rate for the specific example of breeding for higher milk yield predicted in Barreiro-Hurle et al. (2021) from application of Green Deal policies is the highest of any measure.
- **Feed additives** nitrate and linseed to reduce enteric methane are also included in the EU Reference scenario 2020, Pérez Domínguez et al. (2020) and Barreiro-Hurle et al. (2021), but their expected uptake is relatively low compared with anaerobic digestion, for example.

It is worth noting that Member States' reported plans for both NH_3 and CH_4 mitigation will be updated in 2023, with submission of updated National Energy and Climate Plans (NECPs) and National Air Pollution Control Plans (NAPCPs), as well as updated agricultural policies following the ongoing approval process for CAP Strategic Plans.

Effective mitigation measures not covered or with low uptake in Member State projections or published scenarios

The measures included within CAO2 (Amann et al. 2020), ECAMPA-3 (Pérez Domínguez et al., 2020) and Barreiro-Hurle et al. (2021) are defined fairly broadly, and thus seem to encompass most of the effective measures listed in section 3.2.

The only measures not included in any of the scenarios analysed are:

- **Acidification of slurry** for storage or application. This measure is currently only common in Denmark(21) despite its high mitigation potential for both NH_3 and CH_4. This may relate to safety concerns related to handling of the strong acids required on farm. However, it is noteworthy that in Germany's NH_3 emission projections, the WAM scenario assumes that by 2030 50 % of slurry spread will either use injection, or acidification as an alternative to injection.
- **Solid-liquid separation of slurry.** This measure may have been excluded from published scenarios and the 5 Member State projections because it is more of a facilitative measure allowing application of other mitigation measures (anaerobic digestion of the solid fraction, injection of the liquid fraction into soils), rather than directly resulting in emissions reductions itself.
- **Rapid removal of slurry from housing into storage to reduce CH_4 emissions** is not explicitly mentioned as a measure in the GHG emissions scenarios. This could however be included under "low-emission housing" as included in Barreiro-Hurle et al. (2021).

However, it is worth noting that the broad measures defined in some of the scenarios and Member State projections such as «Low emission housing» could imply quite different uptake rates and mitigation efficiency depending on which of the more specific measures (e.g. air scrubbers, regular cleaning, floor design, climatisation etc.) are included within that.

Finally, it is noteworthy that ECAMPA-3 (Pérez Domínguez et al., 2020) and Barreiro-Hurle et al. (2021) consider linseed and nitrate as feed additives to reduce enteric fermentation emissions, but not 3-NOP, which has been approved in the EU and has been shown to be effective.

It would be sensible to include the uptake and impact of 3-NOP in future modelling studies.

Synergies and trade-offs between methane and ammonia emissions reductions from application of measures

Given the multi-dimensional nature of agriculture's impact on the environment, it makes sense to understand potential synergies or trade-offs between impacts when applying particular measures.

Below, some of the information on key synergies and trade-offs between CH_4 and NH_3 emissions reduction for measures listed in section 3.2 is summarised.

The following measures can act to reduce both NH_3 and CH_4 emissions:

- Feeding or genetic measures to increase production efficiency per animal – for example breeding for increased milk yields of dairy cows – can reduce emissions of both CH_4 and NH_3 per unit of product, through a higher feed-conversion efficiency
- Measures reducing the burden or livestock disease, increasing fertility and increasing longevity, which raises herd-level production efficiency
- Acidification of slurry
- Rapid removal of liquid manure from housing into storage

---

(21) https://www.researchgate.net/publication/286002139_Why_is_acidification_a_success_only_in_Denmark.

- Anaerobic digestion – but the effect on NH_3 emissions depends on appropriate storage and application of digestate.

There can be trade-offs between reducing NH_3 and CH_4 emissions from the following measures:

- Anaerobic digestion – NH_3 emissions can be increased if appropriate storage and application of digestate is not carried out
- Increasing or decreasing the proportion of time animals spend grazing can have impacts on CH_4 and NH_3 emissions, depending on the context. NH_3 emissions from urine and dung deposited directly on soil tend to be lower than from housing and storage, as urine infiltrates quickly into the soil. However, spending long periods grazing means that feed rations cannot be as easily optimised for low enteric fermentation CH_4 emissions, through addition of high-digestibility concentrates or inhibitors such as 3-NOP for example.

3.4 Scenarios of livestock numbers / production levels

As well as future uptake of mitigation measures, an equally (if not more) important driver of emissions is production levels.

Both livestock populations and productivity per animal are important factors, but more data are available in a consistent format on projected animal numbers than on production levels.

MS-reported projections

MS projections of animal numbers for 2025, 2030 and in some cases 2040 were extracted from projections reported under the NECD(22) and Governance Regulation(23) in 2021. The projected percentage changes in population for cattle, pigs and poultry by MS and at the EU level are presented in Table 3.9 below, based on the with existing measures (WEM) scenario. EU-level changes were calculated by summing MS-level projected populations.

---

(22) https://cdr.eionet.europa.eu/ReportekEngine/searchdataflow?dataflow_uris=http%3A%2F%2Frod.eionet.europa.eu%2Fobligations%2F751&years%3Aint%3Aignore_empty=&partofyear=&reportingdate_start%3Adate%3Aignore_empty=&reportingdate_end%3Adate%3Aignore_empty=&country=&release_status=released&sort_on=reportingdate&sort_order=reverse&batch_size= .

(23) https://reportnet.europa.eu/public/dataflow/113, Table 3 projected activity data.

Table 3.9: Projected (WEM) percentage change in livestock population by Member State from 2020 to 2030 (left) and 2040 (right)

MS	Projected % change in population 2020-2030			
	Dairy cattle	Non-dairy cattle	Pigs	Poultry
AT	3%	2%	-2%	-8%
BE	-8%	-8%	-3%	16%
BG	12%	23%	9%	2%
CY	-12%	-3%	2%	11%
CZ	2%	4%	13%	3%
DE	3%	1%	0%	3%
DK	4%	2%	14%	3%
EE	3%	10%	14%	12%
ES	-4%	-5%	1%	-4%
FI	-9%	-13%	-5%	-5%
FR	-2%	-5%	-3%	0%
GR	15%	15%	15%	15%
HR	-10%	3%	2%	-3%
HU	0%	3%	12%	12%
IE	13%	-11%	7%	19%
IT	-1%	-3%	3%	1%
LT	-5%	4%	0%	23%
LU	0%	-9%	0%	3%
LV	-7%	-3%	-12%	-1%
MT	-3%	0%	-7%	2%
NL	-8%	0%	-6%	0%
PL	-7%	6%	1%	16%
PT	-16%	-4%	20%	1%
RO	12%		13%	11%
SE	-7%	-20%	15%	7%
SI	0%	1%	41%	0%
SK	-3%	-3%	-15%	-3%
EU-27	**0%**	**-3%**	**3%**	**5%**

MS	Projected % change in population 2020-2040			
	Dairy cattle	Non-dairy cattle	Pigs	Poultry
AT	4%	3%	-5%	-9%
BE	-12%	-14%	-2%	21%
BG				
CY	-14%	-6%	0%	12%
CZ	4%	8%	47%	7%
DE	3%	1%	0%	3%
DK	-4%	-4%	0%	-3%
EE	5%	17%	14%	12%
ES	-11%	-10%	0%	-6%
FI	-17%	-18%	-6%	-7%
FR	-4%	-9%	-8%	0%
GR	30%	30%	30%	30%
HR	-16%	6%	1%	-7%
HU	-2%	3%	10%	21%
IE	14%	-12%	8%	21%
IT	-10%	-8%	8%	2%
LT	-21%	2%	18%	45%
LU	0%	-9%	0%	6%
LV	-11%	-5%	-16%	-2%
MT	-3%	1%	-7%	1%
NL				
PL	-10%	8%	-2%	40%
PT	-16%	-4%	20%	1%
RO	20%		27%	24%
SE	-9%	-30%	36%	6%
SI	0%	1%	41%	0%
SK	-19%	3%	-21%	-6%
EU (excl. BG and NL)	**-1%**	**-5%**	**2%**	**12%**

Note: Livestock projections for 2040 were not available for Bulgaria or the Netherlands, so these MS are excluded from the overall EU percentage changes quoted for 2020-2040.

Table 3.9 shows a mixed picture across different livestock types and Member States. For the EU as a whole, numbers of dairy and non-dairy cattle are projected to fall slightly by 2030 and 2040 compared with 2020, whereas numbers of pigs and poultry are projected to rise, with a considerable (12 %) increase projected for poultry by 2040 compared with 2020. Sweden exemplifies this general shift away from cattle (especially beef) towards higher pig numbers.

However, the projected changes are not uniform across MS. For poultry numbers, Lithuania and Poland forecast increases of 40 % or more by 2040 compared with 2020, whereas some MS (such as Finland and Croatia) project decreases in their flocks. A similarly mixed picture is seen for pig numbers.

Moreover, as mentioned above, trends in livestock population may not fully reflect trends in production levels, if for example milk and beef yields per cow are expected to increase. Some assumptions on production levels in the EU are presented in the next section, based on EU-wide modelling scenarios.

Overall, the trends seen in the MS-level livestock projections would suggest that alone, changes in livestock production levels will not drive emissions reductions, under current policies and assumptions on demand.

Assumptions and findings on livestock numbers / production levels from published scenarios

The tables below (Table 3.10, Table 3.11) and subsequent text describe assumptions made by published scenarios about the future evolution of livestock numbers and/or production of animal products.

The **EU agricultural outlook 2021-2031** (European Commission, 2021b) is a key benchmark for this. However, as the details of implementation of the Green Deal (including F2F strategy and fit for 55 package) are yet to be finalised in MS CAP Strategic plans, these policies are not included. Instead, it assumes continuation of the 2014-2020 CAP implementation, but does include recent free-trade agreements and expert judgement on some aspects such as the proportion of organic farming. This report provides projections on both livestock numbers, and production of animal products.

Table 3.10: Projected evolution of animal numbers in the EU from several EU-wide modelling studies, either over time or relative to a baseline scenario

Study	Comparison	% change over time or compared to a baseline			
		Dairy cattle	Non-dairy cattle	Pigs	Poultry
Barreiro-Hurle et al., 2021	F2F and BDS targets & CAP LP + NGEU scenario, vs baseline in 2030 (approximate)	-12	-18	-14	-15
EU reference scenario 2021-2031 (European Commission, 2021a)	Change 2015 – 2030 (approximate)	-10	-10	0	
Clean Air Outlook 2 (CAO2; Amann et al., 2020)	Change 2020-2030	-8.1	0.8	2.2	8.3
EU agricultural outlook 2021-2031 (European Commission, 2021b)	Change 2021-2031	-6.9	-6.8		

Note: cells are shaded on a green to red scale, representing decreases and increases respectively. Grey shading indicates no data available.

All studies considered here project a fall in dairy cattle numbers between 2020 and 2030, alongside an increase in milk yield per cow (from EU agricultural outlook 2021-2031; see Table 3.11). However, this contrasts with the aggregation of MS-reported projections, which indicate no change in dairy cattle numbers. However, the decrease in non-dairy cattle numbers and increases in pig and poultry numbers (CAO2 only) seen in the modelled scenarios do generally align with the MS-reported projections.

Table 3.11: Projected change in production of key animal products 2021-2031 from the baseline scenario in the EU agricultural outlook 2021-2031

%Change 2021 – 2031				
Milk production	Beef and veal	Pig meat	Poultry meat	Eggs
4.6	-7.8	-7.8	4.0	8.1

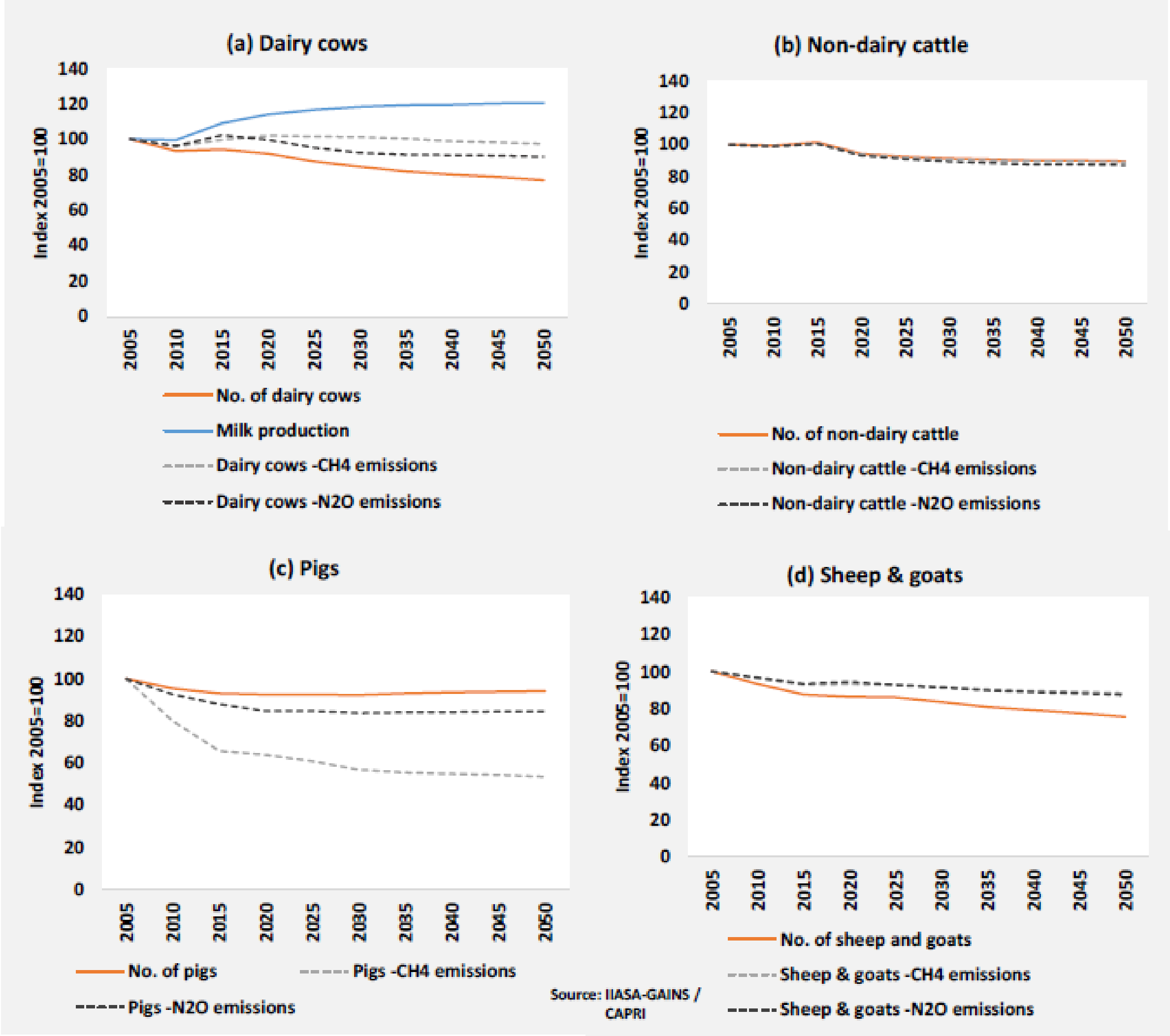
The results of the EU agricultural outlook for trends in pig meat (a 7.8 % decrease) contrast with the expected change in pig numbers seen in MS reported projections, CAO2 and EU reference scenario 2021-2031.

The EU reference scenario 2020 (European Commission, 2021a) report does not provide tabular data on trends in livestock production, but does show graphical trends, as illustrated in Figure 3.2 below.

In this scenario, although dairy cow numbers fall by around 10 % between 2015 and 2030, due to increased milk production per cow CH_4 emissions only fall by 1.6 % over the same period.

Non-dairy cattle numbers are expected fall by around 10 % between 2015 and 2030, sheep and goat numbers by a similar amount, whereas no decline in pig numbers is expected (though CH_4 emissions from pig manure is expected to fall by 14 % due to continued uptake of anaerobic digestion).

Figure 3.2: Evolution of EU livestock numbers and associated non-CO2 emissions from the EU reference scenario 2020



Source: IIASA-GAINS / CAPRI

ECAMPA-3 (Pérez Domínguez et al., 2020) modelled the anticipated changes in agricultural emissions taking into account changes in production levels and production mix. Overall, across all carbon prices, changes in production levels and production mix accounted for 22-25 % of the total reduction in GHG emissions in 2030 (relative to baseline scenario), compared with around 11 % of the total contributed by mitigation technologies (the remaining 65 % relates to LUC emissions).

Demand-side measures

Despite the conclusion above drawn from current MS projections of livestock numbers, potential policies and measures which may affect demand for livestock products, and in turn EU livestock production, do exist and if adopted by MS may cause the assumptions underlying projected livestock numbers to be revised in future. Demand-side measures are not the focus of this report and there is not space to discuss these in detail, but a brief summary of options and potential impact is given below.

Demand-side measures generally aim to cause **dietary shift** towards products with a lower CH_4 or NH_3 emissions footprint, or a **reduction in food waste** which in turn reduces the need for additional primary production.

Animal products tend to have higher GHG and reactive nitrogen (including NH_3) footprints than plant products (Searchinger et al, 2018, Westhoek et al., 2015), and of animal products ruminant meat has especially high GHG and reactive nitrogen emissions due to the low feed conversion efficiency and enteric fermentation emissions.

Member-State reporting of demand-side measures

An ETC/CME report from 2021 (ETC/CME, 2021) summarised the prevalence of demand-side policies and measures currently implemented or adopted by EU MS.

The report found that six MS reported policies and measures related to dietary shift. These included relatively "soft" measures to promote consumer behavioural change, such as research on eating habits and awareness raising, and low-carbon food labelling. There were no "hard" measures reported such as a carbon tax on meat. Responses to a questionnaire issued as part of the ETC/CME task indicated that in some countries there is low political support for dietary shift away from animal products, and that in some countries current policies even incentivise meat consumption. Other respondents commented that although a carbon tax on meat may be effective, it would have to be paired with a carbon border adjustment mechanism to prevent emissions leakage through increased imports.

Seven MS reported measures to reduce food waste. These comprised education to change consumer behaviour, legislation to promote short supply chains, removal of "waste" status of certain by-products allowing their use in the human or animal food chains, investing in home composting, and broader strategies to increase collaboration across the food supply chain. France indicates plans for an "anti-waste" food label certification scheme, with associated technical standards.

The EU Farm to Fork Strategy(24) proposes measures to incentivise dietary shift and reduction of food waste, as well as a plan to introduce mandatory food waste reduction targets across the EU.

Assumptions made by key published scenarios

Most forecasting exercises undertaken at the European level tend to rely on economic optimisation of demand for agricultural products using CAPRI and other models, which do not take into account shifts in consumer preferences or assumptions around food waste reduction. Even the latest EU agricultural outlook projections(25) and the JRC report on the impact of CAP reform do not take into account any possible new policies and measures on food waste or dietary change that may be implemented in MS finalised CAP Strategic Plans, stemming from the Green Deal or Farm to Fork strategy. This may relate to difficulty in modelling such potential changes in demand.

However, other modelling exercises have been conducted which model the impacts of a particular pre-defined shift in diet and/or reduction in food waste (see Table 3.12).

---

(24) https://food.ec.europa.eu/horizontal-topics/farm-fork-strategy_en#Strategy

(25) https://agriculture.ec.europa.eu/news/eu-agricultural-outlook-2021-31-sustainability-and-health-concerns-shape-agricultural-markets-2021-12-09_en

Table 3.12: Results of modelling impact of specific dietary shift and food waste reduction on NH_3 and GHG emissions (selected studies)

Source	**Diet scenario**	**Assumptions**	**Total reactive nitrogen loss**	**NH_3 emissions**	**GHG impact (N_2O and CH_4)**
Westhoek et al. (2015)	-50 % pork and poultry in the EU (Greening scenario)	No change in food waste, calories maintained by increase in cereal intake	NA	c. -16 % (EU)	c. -5 % (EU)
Westhoek et al. (2015)	-50 % beef and dairy (Greening scenario)	No change in food waste, calories maintained by increase in cereal intake	c. -26 % (EU)	-26 % (EU)	c. -35 % (EU)
Westhoek et al. (2015)	-50 % all meat and dairy (Greening scenario)	No change in food waste, calories maintained	-42 % (EU)	-43 % (EU)	-42 % (EU)
IDDRI (Poux & Aubert, 2018)	Average sustainable European diet in 2050 compatible with agroecology	-6 % total calories (EU) -17 % protein intake and -50 % animal protein -10 % food waste -3 % beef consumption -60 % pork and -66% poultry Increase in plant-based protein, especially legumes. Includes wholesale shift to organic farming	Increase in crop NUE from 63 % -> 92 % (Europe)	NA	-30 % overall; -8 % enteric fermentation
Eshel et al. (2010)	Purely plant-based diet (vegan)	Synthetic modelled diets for a typical US citizen, based on typical fertilization requirements of different crops	-71 % decrease in N_r inputs (USA)	NA	NA

Source: Adapted from WWF (2021).

Westhoek et al. (2015) estimated that reducing all meat and dairy consumption by 50 % (a «demitarian» diet) would result in a 43 % reduction in NH_3 and 42 % reduction in total GHG emissions from EU agriculture. The impact of reducing beef and dairy consumption is greater than of reducing pork and poultry consumption, but reducing the latter may have stronger impacts on local NH_3 emissions due to the prevalence of large point-source facilities for swine and poultry.

Poux & Aubert (2018) modelled a sustainable diet for a completely «agro-ecological» EU farming system in 2050 (which, practically means elimination of synthetic fertilisers and net food imports to promote circularity of nutrient flows, and organic farming). This scenario is of interest, given the Green Deal objective to have at least 25 % of EU agricultural land under organic farming and reduce mineral fertiliser use by 20 % by 2030. Such a diet would have 10 % lower food waste, and 50 % lower animal protein consumption. CH_4 emissions from enteric fermentation would reduce by only 8 %, as ruminants would be a key part of maintaining circularity of resource use.

Impact of changes in livestock numbers compared to mitigation measures

When considering the future of NH_3 and CH_4 emissions from agriculture, a natural question to ask is how the mitigation potential through application of technical measures compares overall with potential for reducing emissions through reduction in activity levels.

There are different ways of addressing this question, but for the purposes of this report the most relevant way seems to be to try to compare the impact of projected changes in both livestock population or production, against that of uptake of mitigation measures, according to published scenarios.

The data from the Clean Air Outlook 2 (CAO2; Amann et al., 2020) study available for this project provides an opportunity to make this comparison in a robust way for NH_3 emissions from livestock.

Table 3.13 below shows the projected percentage change between 2020 and 2030 in livestock population, NH_3 emissions and NH_3 emissions per head (implied emission factor) for the baseline, NAPCP and maximum technically feasible reduction (TFR_Max) scenarios across the EU-27.

Table 3.13 Percentage change in livestock population, NH_3 emissions and implied NH_3 emission factor between 2020 and 2030 as modelled by the Clean Air Outlook 2, by scenario for the EU-27 as a whole

System type	Scenario	% change 2020-2030		
		Livestock population	NH_3 Emissions	Implied NH_3 emission factor
Dairy cows - liquid systems	Baseline	0 %	1 %	1 %
	NAPCP	0 %	-13 %	-14 %
	TFR_Max	0 %	-33 %	-33 %
Dairy cows - solid systems	Baseline	-22 %	-20 %	2 %
	NAPCP	-22 %	-22 %	0 %
	TFR_Max	-22 %	-32 %	-13 %
Laying hens	Baseline	5 %	4 %	-1 %
	NAPCP	5 %	-10 %	-14 %
	TFR_Max	5 %	-45 %	-47 %
Other cattle - liquid systems	Baseline	0 %	-1 %	-1 %
	NAPCP	0 %	-14 %	-14 %
	TFR_Max	0 %	-25 %	-25 %
Other cattle - solid systems	Baseline	2 %	1 %	-1 %
	NAPCP	2 %	-4 %	-5 %
	TFR_Max	2 %	-7 %	-9 %
Other poultry	Baseline	10 %	9 %	-1 %
	NAPCP	10 %	-9 %	-17 %
	TFR_Max	10 %	-58 %	-62 %
Pigs - liquid systems	Baseline	4 %	4 %	0 %
	NAPCP	4 %	-15 %	-18 %
	TFR_Max	4 %	-57 %	-59 %
Pigs - solid systems	Baseline	-11 %	-10 %	2 %
	NAPCP	-11 %	-18 %	-7 %
	TFR_Max	-11 %	-46 %	-39 %

Source: GAINS Europe, own calculations.

Note: Red and green cell shading indicates the magnitude of increases and decreases respectively.

Changes in the implied emission factor per head occur mainly due to uptake of mitigation measures.

In the CAO2 results above, the relative importance of changes in livestock numbers and mitigation measures clearly vary across the different livestock species and systems and across scenarios. Under the NAPCP and TFR_Max scenarios changes in implied emission factors (impact of mitigation measures) dominate projected changes in emissions from dairy cow, non-dairy cattle and pig manure managed in liquid systems, and from poultry manure. Under the baseline scenario, changes in livestock numbers dominate emissions trends for most species and systems. For dairy cow and pig manure in solid systems, even under the NAPCP scenario livestock numbers are expected to have a larger impact than mitigation measures to 2030.

Regarding the livestock numbers, the scenarios of ambitious reductions in food waste and/or dietary shift (Table 3.12) may provide a good benchmark for the hypothetical potential impact of reducing livestock numbers. However, the assumptions on changes in livestock numbers in these scenarios are much more extreme than those presented in Table 3.9 and Table 3.10.

The maximum technically feasible reduction scenario in CAO2 gives a useful benchmark for how far mitigation measures could hypothetically reduce emissions, and this shows a range of reductions in implied emission factor (IEF) between 9 % and 62 %, with the largest potential reductions for “other poultry” (broilers, ducks and geese, turkeys) and pigs in liquid systems due to high uptake of combinations of housing, storage and application measures with high abatement efficiency. Over 25 % reduction in IEF is achieved for all livestock except for cattle in solid systems. However, it must be noted that the uptake rates assumed in the maximum technically feasible reduction scenario are well above those modelled for the NAPCP scenario (see Table 3.2 to Table 3.5), so this may not be realistic.

For methane, within the scope of this study it was not possible to undertake such a quantitative analysis of the relative importance of changes in livestock numbers and mitigation measures as above for NH_3, but some qualitative comparison is possible. For example, JRC modelling (Barreiro-Hurle et al., 2021) described in section 3.3 modelled a modest uptake (up to around 30 % of eligible livestock heads) of a range of methane mitigation measures by 2030 under an ambitious interpretation of EU Green Deal policies, resulting in CH_4 emissions reductions of 16.8 % from enteric fermentation and 23.4 % from manure management. This was accompanied by a 12-18 % reduction in livestock numbers across the different species, so change in livestock numbers seems to be a slightly more important driver overall. ECAMPA-3 (Pérez Domínguez et al.,2020) found that changes in production levels and production mix accounted for 22-25 % of the total reduction in GHG emissions in 2030 (relative to baseline scenario), compared with around 11 % of the total contributed by mitigation technologies (the remaining 65 % relates to LUC emissions).

It is important to note however, that if EU-27 production goes down in the absence of a global reduction in demand, emissions will be leaked elsewhere. Whilst EU-27 CH_4 emission reductions benefit EU-27 air quality, only global CH_4 emissions matter for global warming impact.

4 Methods for deriving damage per tonne of pollutant values for human health and environmental impacts of ammonia and methane emissions from the livestock sector

Since the early 2000s, damage to health and the environment and the benefits (avoided damage) achievable by mitigation strategies for air pollution have been regularly assessed in policy analyses at the European level (for example ExternE 2005, NEEDS 2008 , Hurley et al. 2005, Holland 2013, Amann et al. 2020). When policy scenarios are analysed, damage assessments have generally been based on the full model chain, starting with:

i) emissions data;
ii) then calculating impacts of changes in emissions on concentration and deposition of pollutants based on chemistry transport models (full runs, e.g. with EMEP, or reduced versions thereof as in GAINS);
iii) then calculating population exposure to the pollutants; followed by
iv) a quantification of health and environmental impacts, and then
v) monetization through multiplication of the impacts with per unit monetary values per health or environmental impact (e.g. Amann et al. 2020).

Full chemistry model runs are time and resource consuming, and it is often impossible to use them for an assessment of high numbers of individual emission reduction measures or to assess the impact of a large number of individual facilities' emissions. A less time- and resource-intensive alternative is to apply reference costs, in the form of damage costs per tonne of pollutant. While the calculation of such reference costs itself requires full model runs, their use in the estimation of damage from individual measures or emission sources avoids having to use full model runs for each analysis. Instead, they allow damage estimates to be calculated through a simple multiplication of damage costs per tonne of pollutant by the quantity of emissions of the pollutant under consideration.

Reference costs, in the form of damage per tonne of emission values, are regularly calculated for a large set of pollutants (ExternE 2005, AEAT 2005, EEA 2011, EEA 2014; ETC/ATNI 2020/04; De Bruyn et al. 2018). Their uses are varied, including - *inter alia* - cost-benefit assessments, decision making for IED derogation dossiers, monetizing the cost of sectoral or regional air pollution, and setting levels of environmental taxes.

They are generally calculated based on an assessment of changes (a reduction) in pollutant concentrations and deposition at grid level over a region due to a change (reduction) in emissions of a given pollutant in a given country. Often, this work relies on EMEP Source Receptor Matrices(26) (SRMs). These calculations are applied to each precursor pollutant and country considered. Impact models are then used to quantify the (avoided) monetized health and environmental damage corresponding to the modelled changes in air quality. Division of the avoided damage numbers by the modelled emission reduction gives the estimate of the damage cost per tonne of pollutant emission (see for example ETC/ATNI 2020/04).

Calculating total damage cost based on a multiplication of emission data with estimates of cost per tonne of the respective pollutant implicitly assumes a linear relationship between emission change and the resulting change in concentrations. EMEP SRMs rely on a 15 % change in emissions, to indicate the consequences of a change that is large enough to affect model outputs, but sufficiently small that it does not generate significant non-linearities in the modelling.

In the related EEA work (ETC/ATNI 2020/04; and the upcoming update to be published by EEA in 2023) estimates of damage cost per tonne are calculated at country level, combined with sectoral adjustment factors to allow estimation of cost per tonne values at sector and country level. This sectoral

---

(26) https://www.emep.int/mscw/.

adjustment has so far been calculated at a high level of sector aggregation (SNAP1 level or GNFR), but not yet at a subsector level.([27])

In the present report, we aim to provide damage cost directly relevant to the livestock sector, which is a subsector of total agricultural emissions. We have therefore developed a specific methodology to infer health damage costs for both NH_3 and CH_4 related to livestock, building upon the methodology developed in previous ETC estimates of damage costs of air pollution.

The damage costs per tonne values for NH_3 are estimated with a 15 % reduction of NH_3 emissions not by country but overall over the EU27 and an estimate of the related impact on the formation of the secondary pollutant $PM_{2.5}$ is produced at grid level over EU27. For CH_4, the damage costs are based on a 50 % reduction in global anthropogenic emissions and an estimate of the related impact on the formation of the secondary pollutants $PM_{2.5}$ and O_3 is produced at grid level over EU27. Only damage to health is accounted for. This is the objective of section 4.3.

Although damage costs per tonne of pollutant have been developed in the past for NH_3 (e.g. EEA 2014, ETC/ATNI 2020/04), we have no knowledge of damage costs for CH_4 as an air pollutant and its impact on human health.

The linearity assumption behind these values may be particularly important for ammonia. Indeed, theoretically, the atmospheric chemistry of ammonia is non-linear, suggesting that the damage costs per tonne of ammonia emissions may depend on the percentage by which emissions are reduced. NH_3 is involved in the formation of ammonium nitrate particles and ammonium sulphate particles. In order for ammonium nitrate to be formed, sulphate particles must be first neutralized by ammonia (because sulfuric acid is a stronger and less volatile acid than nitric acid). Once sulphate particles are neutralized by ammonia, ammonium nitrate can be formed. This formation is limited by both the amount of ammonia and nitric acid available. Therefore, if ammonia is in great excess in the atmosphere, reducing ammonia may not affect PM concentrations. Alternatively, if not enough ammonia is present in the atmosphere to neutralize sulphate particles, reducing ammonia emissions will only have a little effect on PM concentrations (as sulphate particles are non-volatile, they do not need ammonia to be formed contrary to ammonium nitrate). Other non-linear effects involving ammonia may occur in the atmosphere via several indirect effects (for example impact of ammonia on particle hygroscopicity that may affect the partitioning of hydrophilic organic aerosols, impact of ammonia on cloud and particle pH that may affect aqueous phase chemistry).

In order to determine the importance of non-linearity effects and propose a damage cost per tonne of emitted ammonia, simulations with the air quality model CHIMERE were performed for different NH_3 emission reductions relative to the European livestock sector scenarios (section 4.2).

CH_4 is a precursor of ozone but can also have an indirect effect on $PM_{2.5}$ concentrations (by affecting the concentrations of oxidants and the formation of secondary aerosols). Simulations were also performed to evaluate the impact over Europe of a 50 % reduction in global anthropogenic CH_4 emissions and determine a global damage cost over Europe of CH_4 emissions. Note, that effects of methane on climate change, which itself can affect health, are not accounted for. Effects on the environment via the contribution of methane to the formation of tropospheric ozone are not accounted for either.

This work is preceded by a short summary of numerical tools available to simulate the impact of emission reduction on pollutant concentrations and deposition (section 4.1).

([27]) Sub-sector estimates are available for the transport sectors (European Commission 2019), but we are not aware of such values for the livestock sector.

Impacts on ecosystems are not quantified in this study but the current approach to assess them and existing studies attempting to are summarized in section 4.4.

4.1 Numerical tools to simulate the impact of emission changes on pollutant concentrations and deposition

The usual method to assess the impact of emission scenarios on pollutant concentrations relies on the use of numerical models.

Three types of models are used to calculate atmospheric pollutant concentrations and simulate the effects of emission changes on these concentrations:

- Chemistry-Transport Models (CTMs);
- Source-Receptor Matrices (SRMs);
- Surrogate Models.

These models can also be used to quantify the deposition of nutrients, of sulphur or of other compounds and assess the impact of emission variations on deposition levels and critical load exceedances (see section 4.4 on ecosystems).

Chemistry-Transport Models

Chemistry-Transport Models are models that aim to represent the atmospheric physicochemical processes influencing the transport and transformation of main pollutants, in order to calculate both atmospheric concentrations and deposition. Such models use meteorological fields and emissions as an input. Two kinds of CTMs are generally distinguished: global models and regional models. The latter can be used to simulate concentrations (generally at a higher resolution than global models) over a region of the globe, but have to use the results from a global model as boundary conditions (concentrations at the limit of the domain).

Several European regional CTMs (CHIMERE, EMEP, EURAD-IM, LOTOS-EUROS, MATCH, MOCAGE, SILAM, DEHM, GEM-AQ, MONARCH, MINNI) are used in the Copernicus Atmospheric Monitoring Service (CAMS) to perform air quality forecasts over Europe. Regional models can be used to determine the effect of emissions reductions over Europe on concentrations and deposition of pollutants. By performing (hypothetical) simulations of NH_3 emission reductions from the livestock sector, it is therefore possible to determine their impact on PM concentrations. As CH_4 is a pollutant with a high lifetime in the atmosphere (about 10 years), and as it can therefore be transported over very long distances, simulation scenarios have to be performed at the global scale. Even at global scale, in order to avoid 10 year-long simulations, rather than simulating the effect of a 50 % reduction of CH4 emissions, CH4 concentrations at the approximate levels corresponding to this 50 % reduction are prescribed in the global CTM. In order to provide estimates at high spatial resolution which are relevant to population exposure and not only representative of tropospheric chemistry, the results of such a scenario simulated with a global CTM are used as boundary conditions for a regional CTM run.
We rely here partly on modelling results conducted in the framework of the CAMS Policy Service (Timmermans et al., forthcoming publication). This exercise was performed in CAMS (CAMS_71 WP 7150) to study the impact over Europe of a decrease of 50 % of CH_4 anthropogenic emissions at the global scale.

Source-receptor matrices

Source-receptor matrices (SRMs) give the change in various pollutant indicators in each receptor country resulting from a change in anthropogenic emissions from each emitter country. Such matrices are generated with a CTM for each country by reducing emissions for each country of one or more precursors by a given percentage. Numerous simulations need therefore to be performed with a CTM. SRMs computed with the EMEP model are available on the EMEP website([28]) and can be used to estimate the changes due to a change in emissions from each emitter country for PM, NO_2 and O_3 concentrations and for oxidized nitrogen and reduced nitrogen deposition. However, the EMEP SRMs are not calculated for the different emission sectors but are provided for a reduction of 15 % of the emissions from all sectors together. EMEP SRMs therefore cannot be used to study a non-linear response of concentrations and depositions to emissions, or to study specifically the emissions from a single sector. Moreover, the EMEP matrices are not determined for methane as it would be necessary to perform simulations over the whole globe with the EMEP CTM.

The EMEP source-receptor matrices have been used in the ETC/ATNI 2020/04 report to estimate the damage costs from industrial facilities in Europe for several pollutants, amongst which particulate matter ($PM_{2.5}$, PM_{10}), sulphur dioxide (SO_2), ammonia (NH_3), nitrogen oxides (NO_X), non-methane volatile organic compounds (NMVOCs).

The surrogate model approach

The main disadvantages of Chemistry-transport models are that they are complex and take time to run. Therefore, the number of scenarios they can compute is limited. One possible approach to avoid this issue is to use a surrogate model (model aiming at reproducing the behaviour of CTMs through a simplified numerical formulation).

One example of surrogate models is the Air Control Toolbox (ACT([29])), developed by Ineris as part of the Copernicus Atmosphere Monitoring Service (CAMS) dedicated to policymakers. ACT is a surrogate model based on a polynomial function and trained on a dozen CTM sensitivity scenarios in which primary pollutant emissions are reduced. It is designed to be updated on a daily basis, i.e. the fitting of the parameters of the polynomial function is re-calculated every day based on the scenario CTM runs. ACT is able to reproduce the non-linearity in CTM response to changes in NOx and VOC emissions that are important precursors for O_3. In the present study where annual metrics are considered, we therefore use 365 individual ACT response model calculations to compute annual O_3 metrics. ACT is made available through a web-interface[2] and is able to produce daily metrics for defined areas within the underlying CTM model domain. The model is also designed to capture the daily means of both the PM_{10} and $PM_{2.5}$ fractions of particulate pollution and nitrogen dioxide (NO_2). The spatial coverage is the greater European continent. A full description of the ACT surrogate model design is given in Colette et al. (2022), where it is demonstrated that it shows relative errors below 1 % at 75 % of the grid points and days, below 2 % at 95 % of the grid points and days, and below 10 % for any grid point and day.

ACT is configured to accept parametric emission changes in four activity sectors based loosely on the SNAP categorization. These are Agriculture (including livestock emissions and emissions from use of fertilizers), Industry (combustion in energy and transformation industries, combustion in manufacturing industry, extraction and distribution of fossil fuels and geothermal energy), residential heating (non-industrial combustion plants) and road transport (urban and non-urban roads and

---

([28]) https://www.emep.int/mscw/mscw_moddata.html.

([29]) https://policy.atmosphere.copernicus.eu/CAMS_ACT.php.

motorways). Currently, ACT does not distinguish the livestock emissions from other agricultural emissions, but the surrogate model could be modified to treat the livestock sector separately. ACT also does not simulate the impact of emissions on the deposition of nutrients, but a surrogate model for deposition could be developed based on the ACT methodology. Such a surrogate methodology is also constructed from the results of a global model to determine the effects of CH_4 emission changes on air quality based on the HTAP modelling ensemble (Turnock et al., 2018).
One advantage of the surrogate model approach as designed in ACT is the possibility to account for the non-linear response of concentrations to a reduction in emissions.

4.2 Selected method to assess the health damage costs of NH_3 and CH_4 livestock emissions

In this section, in order to be able to work on the agricultural livestock sub-sector, we used the regional CTM CHIMERE, combined with the Health Impact Assessment tool (Alpha-RiskPoll – ARP), to determine the damage costs of NH_3 and CH_4 livestock emissions. CHIMERE was run over a domain covering the European continent for the year 2018 at a resolution of 0.2°x0.2° by using the Integrated Forecasting System (IFS) meteorological data from the European Centre for Medium-range Weather Forecasts (ECMWF). The determined avoided concentrations were used with the health impact assessment tool ARP to quantify the avoided impacts on human health.

Description of CHIMERE

The air quality model CHIMERE (Menut et al., 2021) is co-developed by the CNRS (the French National Council for Scientific Research) and Ineris (French National Institute for Industrial Environment and Risks). It is a computer programme that gathers a set of equations representing the transport and transformation of chemical species to simulate the temporal evolution of air pollutants over a range of spatial scales, from the regional scale (several thousand kilometres) to the urban scale (spatial resolution of a few kilometres).

Using meteorological and emission data, CHIMERE models three-dimensional concentrations for various pollutants (such as O_3, NO_2 or PM) with hourly outputs. The model integrates a chemical mechanism containing more than one hundred chemical reactions. It simulates the formation and evolution of airborne particles with diameters ranging from a few nanometres to 10 µm. Particles in CHIMERE consist of primary PM (anthropic or natural) emitted directly into the air and of secondary PM that is formed by chemical reactions in the atmosphere (nitrate, ammonium, sulphate and secondary organic aerosols). The aerosol module of CHIMERE as well as its evaluation against measurements of inorganic aerosol are presented in Couvidat et al. (2018).

Hypothetical NH_3 scenarios

In order to test the validity of the linearity assumption in damage per tonne of pollutant calculations for NH_3, 5 hypothetical scenarios were simulated with CHIMERE for 2018:

- Reference (no reduction)
- 15 % reduction of livestock ammonia emissions
- 30 % reduction of livestock ammonia emissions
- 50 % reduction of livestock ammonia emissions
- 100 % reduction of livestock ammonia emissions

Emission reductions are applied to all livestock ammonia emissions in the simulation domain. 5 additional scenarios were also performed by combining the 5 scenarios listed above with a reduction of 50 % of the NOx emissions from all sectors. These scenarios will give an indication on whether the determined reference costs will remain valid under conditions where NOx emissions are also reduced.

The emission inventory used for Europe is the CAMS-REG-AP version 5.1_REF2.1 for the year 2018 (Granier et al., 2019).

CAMS-REG-AP emissions are based on emissions reported by European countries to the Air Convention (Convention on the Long Range Transboundary Air Pollution – CLRTAP(30)) and are developed following the sector aggregation basis of TNO_MACC-II and TNO_MACC-III emission inventories (Kuenen et al., 2014). From the point of view of the spatial distribution, CAMS-REG-AP is based on a consistent methodology across the whole European continent, in contrast to the gridded emissions submitted to the CLRTAP (i.e., the EMEP inventory) where each reporting country applies its own gridding methodology and proxies. So, at a national scale, the reported amounts of emissions are identical in these two inventories whereas their precise location within each country may differ. The national NH_3 emissions are given in Table 4.1.

---

(30) https://unece.org/fileadmin/DAM/press/pr2009/09env_p29e.htm.

Table 4.1: National livestock NH_3 emissions in the CAMS-REG inventory for year 2018 for the different countries of EU

Country code (ISO alpha-2)	National NH_3 livestock emissions (kT)
AT	29.1
BE	39.1
BG	22.1
CY	5.1
CZ	27.4
DE	267.0
DK	35.2
EE	4.5
ES	208.1
FI	18.3
FR	232.6
GR	21.6
HR	10.2
HU	35.7
IE	55.7
IT	206.1
LT	8.7
LU	2.5
LV	6.5
MT	0.8
NL	55.6
PL	112.2
PT	20.9
RO	65.0
SE	22.0
SI	7.4
SK	9.5

CH_4 scenarios

Several CH_4 reduction emissions scenarios were performed in the framework of the CAMS Policy Service by the CHIMERE, LOTOS-EUROS, and EMEP models. We focus here on a CHIMERE simulation performed by Ineris over Europe for the year 2016 at a resolution of 0.2°x0.2° and using the Integrated Forecasting System (IFS) meteorological data from the European Centre for Medium-range Weather Forecasts (ECMWF).

One of the scenarios consisted of a 50 % reduction in the anthropogenic emissions of CH_4. In order to estimate the corresponding CH_4 concentration burden, we use the same methodology as in the UNEP Global Methane Assessment (UNEP, 2021). The present day CH_4 concentrations are 1834ppb in the IFS model for 2015, which is an excess of about 1100ppb above pre-industrial levels documented from ice-cores samples (722ppb). The long term effect of reducing 50 % anthropogenic emissions is therefore estimate at bringing concentration half way between current and pre-industrial levels, i.e. about 1298ppb, which is therefore equivalent to a 30 % reduction of methane concentrations.

Global simulations were performed by the European Centre for Medium-Range Weather Forecasts (ECMWF) with the Integrated Forecast System (IFS). This simulation and the reference simulation from IFS were used as boundary conditions for CHIMERE in order to determine the effect over Europe of a 50 % reduction in the global anthropogenic emissions of CH_4.

Health impact assessment

Once the avoided concentrations by a scenario are estimated, the avoided damage costs can be estimated via the quantification of avoided impacts on human health based on the health impact assessment (HIA) tool Alpha-RiskPoll (ARP; developed by EMRC, and described in Schucht et al. (2015) and Amann et al. (2020).

This HIA tool is regularly used in European policy analyses, such as the Clean Air For Europe (CAFE) programme or the European Commission's (EC) Clean Air Outlook (e.g. Amann et al, 2017 & 2020). ARP uses the methods for benefit assessment that were first developed under the EC funded ExternE project (External cost of Energy(31)) during the 1990s. These methods are extensively documented in several studies (Holland et al., 2005a; Holland et al., 2005b; Holland et al., 2005c; Holland et al., 2011 and Hurley et al., 2005). They have been applied since the end of the 1990s to cost-benefit assessments of EC and UNECE(32) policies and were thoroughly reviewed (Krupnick et al., 2005; WHO, 2013a, b). The version of the model used here implements the methods recommended by the World Health Organisation (WHO)/Europe review « Health Risks of Air Pollution in Europe » (HRAPIE) (WHO, 2013b, a), which is described in Holland (2014a, b). Recommendations made in HRAPIE and applied in ARP concern the Concentration-Response Functions, linking levels of pollutant exposure to a set of specific health endpoints (mortality and different morbidity impacts). The same concentration-response functions are used by the EEA (ETC/ATNI, 2019; ETC/ATNI, 2021) and also in Amann et al. (2020). They are shown in Table 4.2.

---

(31) https://www.ier.uni-stuttgart.de/en/research/projects/externe/.

(32) https://unece.org/environment-policy/air.

Table 4.2: Response functions used in the analysis

END POINT	IMPACT	POLLUTANT	RELATIVE RISKS	SOURCE FOR RESPONSE FUNCTION
Acute Mortality (All ages)	Premature deaths	O_3	1.0029, 95%CI 1.0014 to 1.0043 per 10 µg.m-3	Katsouyanni et al., 2009
Respiratory hospital admissions (>64)	Cases		1.0044, 95%CI 1.0007 to 1.0083 per 10 µg.m-3	
Cardiovascular hospital admissions (>64)	Cases		1.0089, 95%CI 1.0050 to 1.0127 per 10 µg.m-3	
Minor Restricted Activity Days (MRADs all ages)	Days		1.0154, 95%CI 1.0060 to 1.0249 per 10 µg.m-3	Ostro and Rothschild, 1989
Chronic Mortality (All ages (*)) YOLL	Life years lost	$PM_{2.5}$	1.062, 95%CI 1.040 to 1.083 per 10 µg.m-3	Hoek et al., 2013
Chronic Mortality (30yr +) deaths	Premature deaths	$PM_{2.5}$	1.062, 95%CI 1.040 to 1.083 per 10 µg.m-3	
Infant Mortality (1 month-1yr)	Premature deaths	PM_{10}	1.04, 95%CI 1.02 to 1.07 per 10 µg.m-3	Woodruff et al., 1997
Chronic Bronchitis (27yr +)	Cases	PM_{10}	1.117, 95%CI 1.040 to 1.189 per 10 µg.m-3	Abbey et al., 1995a, b, Schindler et al., 2009
Bronchitis in children aged 6 to 12	Added cases	PM_{10}	1.08, 95%CI 0.98 to 1.19 per 10 µg.m-3	Hoek et al., 2012
Respiratory Hospital Admissions (All ages)	Cases	$PM_{2.5}$	1.019, 95%CI 0.9982 to 1.0402 per 10 µg.m-3	APED study, 2000-2009 (***)
Cardiac Hospital Admissions All ages)	Cases	$PM_{2.5}$	1.0091. 95%CI 1.0017 to 1.0166 per 10 µg.m-3	
Restricted Activity Days (all ages)	Days	$PM_{2.5}$	1.047, 95%CI 1.042 to 1.053 per 10 µg.m-3	Ostro, 1987
Asthma symptom days (children 5-19yr)	Days	PM_{10}	1.028, 95%CI 1.006 to 1.051 per 10 µg.m-3	Weinmayr et al., 2010
Lost working days (15-64 years)	Days	$PM_{2.5}$	1.046, 95%CI 1.039 to 1.053 per 10 µg.m-3	Ostro, 1987

(*) The YOLL calculation is based on analysis that considered the over 30 years population only but expressed the result as the change in YOLL per ug.m-3 spread across the whole population. (**) Reduced to 1.008 per 10µg/m^3 from 1.02, 95%CI 1.01 to 1.04 per 10 µg.m^3 to account for double counting of impact with the function used for $PM_{2.5}$ mortality. (***) Reference to APED refers to a series of European studies reporting between 2000 and 2009 (Amann et al., 2020): further details are provided in the HRAPIE report (WHO, 2013b).

The health endpoint mortality due to chronic exposure(33) to $PM_{2.5}$ is expressed in two alternative metrics calculated on an annual basis: premature deaths and years of life lost (YOLL). Premature deaths are monetised using the value of statistical life (VSL), whilst life years lost are monetized using the value of a life year (VOLY). Accordingly, two levels of overall health costs are quantified: one summing the estimated damage for the health end points in Table 4.2 and using for mortality the indicator on life years lost (lower estimate) and the other one using for mortality the indicator on premature deaths (higher estimate). The monetary unit values per health endpoint are given in Table 4.3.

---

(33) Mortality is also calculated for ozone, but in this case acute mortality is estimated.

Table 4.3: Values adopted for health impact valuation (€, 2021 values)

Effect	Unit cost (in $€_{2021}$)	Main source(s)
Effects included by HRAPIE		
Mortality – value of statistical life (VSL)	€3.99 million	Based on OECD (2012)
Mortality – value of a life year (VOLY)	€103,669	Previous median estimate increased in proportion to the increase in mean VSL to reflect OECD (2012)
Infant Mortality (per death)	€5.99 million	Based on OECD (2012) (factor 1.5 higher than average for adults)
Chronic Bronchitis in adults (per case)	€69,895	Maca (2011), Holland (2014b) with concerns over severity of air pollution related bronchitis
Bronchitis in children (per event)	€393	Hunt et al. (2016)
Respiratory Hospital Admissions (per case)	€5,216	Broadly mid-range from estimates and similar to DCE (2018)
Cardiac Hospital Admissions (per case)	€6,520	Broadly mid-range from estimates and similar to DCE (2018)
Restricted Activity Days (per day)	€143	Hunt et al. (2016)
Minor restricted activity days (per day)	€52	Hunt et al. (2016)
Work loss days (per day)	€170	Amann et al. (2017)
Asthma symptoms, asthmatic children (per day)	€55	Holland (2014a), U.S. EPA (2011)

Data on population, mortality and life expectancy are taken from the UN World Population Prospects 2019([34]), medium variant. For a given country, the age distribution is assumed to be the same over all the country.

We calculate mortality impacts using only the central value of the confidence interval for the recommended concentration-response function. For the present work we do not estimate the uncertainties of the calculations with help of the minimum and maximum values of the confidence interval. This is a difference for example compared to ETC/ATNI (2019). As a further difference to this report, we account for total $PM_{2.5}$, not for a set of counterfactual cut-off points.

4.3 Application to the determination of health damage costs

Assessment of the potential bias from the linearity assumption for NH_3

The Map 4.1 shows the $PM_{2.5}$ concentrations avoided by a reduction of 15 % of livestock NH_3 emissions in Europe. The concentrations avoided are between 0 and 2 µg/m^3. The highest prevented concentrations are located in Italy, Northern France, Belgium, the Netherlands, Germany, Poland, the Balkans and Turkey.

---

(34) https://population.un.org/wpp/.

Map 4.1: Reduction in $PM_{2.5}$ concentrations (in µg/m^3) from a reduction of 15 % of livestock NH_3 emissions

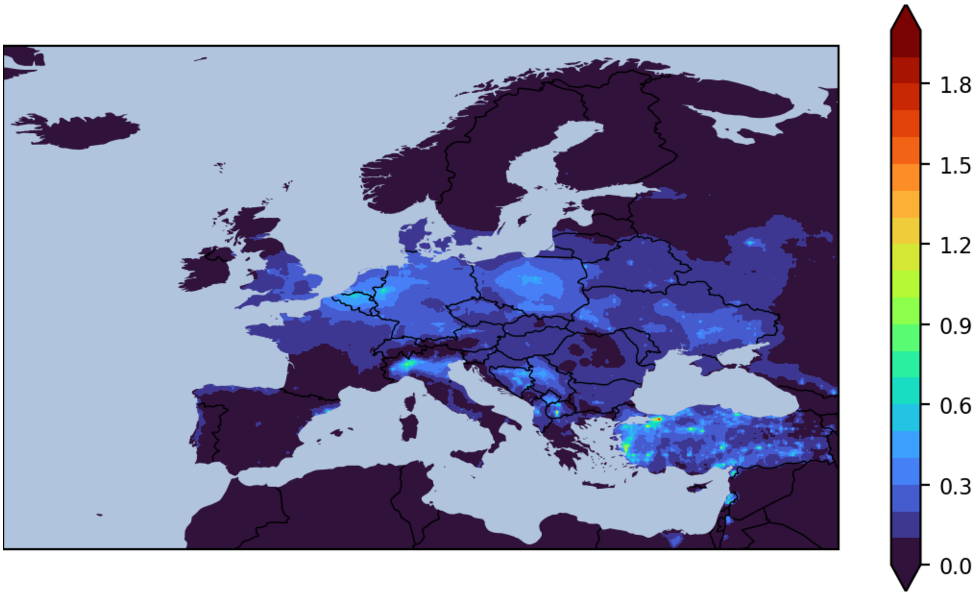


Figure 4.1 shows the prevented $PM_{2.5}$ concentrations weighted by population over EU-27 for different percentages of emission reduction. It also shows that for reductions between 0 and 30 % in NH_3 livestock emissions, the decrease in $PM_{2.5}$ concentrations can be considered as linear. Above a 50 % reduction, decreasing NH_3 livestock emissions seems to lead to a more efficient impact on $PM_{2.5}$ concentrations.

The non-linear effects on the prevented concentrations can be determined by comparing the avoided concentrations normalized by the respective percentage of emission (15 %, 30 %, 50 %, or 100 %) to the avoided concentrations for the 15 % reduction step (without NOx emission reduction). On average over EU-27, we estimated that the error is about 30 % when assuming that the response is linear. When NOx emissions are also reduced by a factor 2, a slightly lower impact of NH_3 livestock emission reductions on NH_3 concentrations was obtained, especially for a reduction of 50 %.

The non-linear effects are under 30 % for most countries but can reach 40 % for a few countries (Italy, Austria, Belgium, Denmark, France, the Netherlands, Slovenia), Figure 4-2.

The $PM_{2.5}$ concentrations avoided per percentage point of reduced NH_3 livestock emissions over EU-27 are presented in Figure 4.2. It shows a great variability in avoided $PM_{2.5}$ concentrations across the countries. The countries showing the largest impact of reducing NH_3 emissions from livestock are Belgium, the Netherlands, Italy and Germany due to the high amount of ammonium nitrates in this region of Europe (due to high ammonia and NO_X emissions). The countries showing the smallest impact are Finland and Sweden.

Figure 4.1: Average prevented $PM_{2.5}$ concentrations (weighted by population) over EU-27 resulting from incremental reductions in NH_3 emissions of 15 %, 30 %, 50 % and 100 %. The dashed line corresponds to the linear fit of the $PM_{2.5}$ concentration decrease when using only the estimate based on a 15 % reduction. The red line is a replicate of the 15 %, 30 %, 50 % and 100 % NH_3 reduction simulations but also reducing 50 % NOx emissions

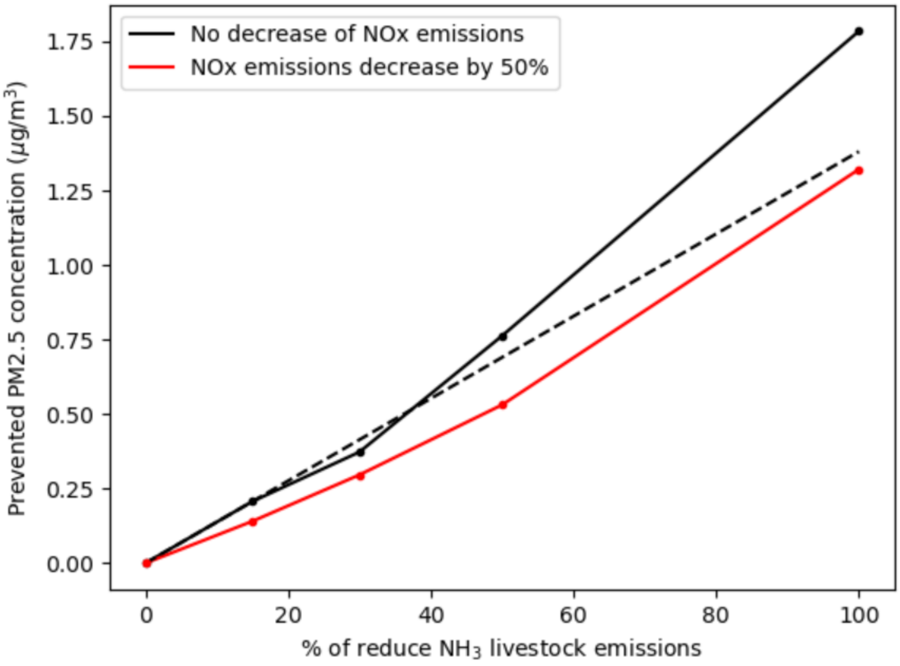
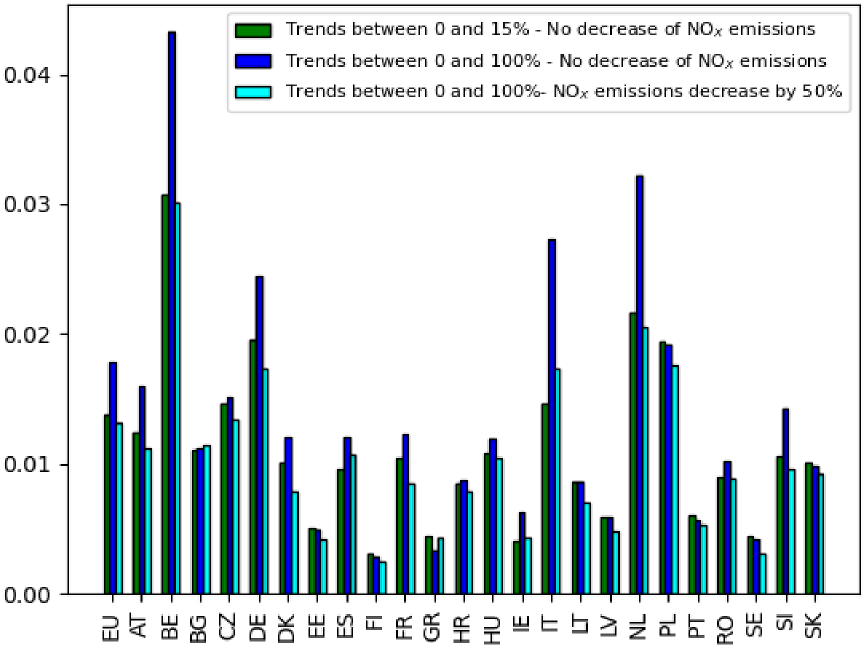


Figure 4.2: Averaged prevented $PM_{2.5}$ concentrations (weighted by population) in µg/m^3 per percentage point of reduced NH_3 emissions



Estimate of the health damage costs avoided by a 15 % reduction in NH_3 emissions and the damage costs per tonne of NH_3 emitted

Based on these results, the health damage costs avoided by a 15 % reduction(35) in livestock NH_3 emissions were calculated by country across the EU-27, based on the low estimate (accounting for mortality in terms of life years lost monetized by VOLY) and the high estimate (accounting for mortality in terms of premature deaths monetized by VSL). The avoided damage costs by country are shown in Table 4.4. At the scale of EU-27, they are estimated between 7 160 and 24 158 million € (M€) in 2018.

Table 4.4: Damage costs (in M€) avoided through a reduction of 15 % of livestock NH_3 emissions for a low (including mortality valued by VOLY) and a high (including mortality valued by VSL) estimate

	Avoided health damage (in M€$_{2021}$) in 2018	
Countries	Low estimate (VOLY)	High estimate (VSL)
Austria	126	409
Belgium	405	1 306
Bulgaria	113	444
Croatia	45	173
Cyprus	6	14
Czech Republic	194	623
Denmark	68	215
Estonia	9	30
Finland	20	64
France	746	2 376
Germany	1 888	6 869
Greece	53	192
Hungary	144	502
Ireland	22	48
Italy	961	3 508
Latvia	16	61
Lithuania	34	125
Luxembourg	7	17
Malta	2	6
Netherlands	415	1 240
Poland	939	2 842
Portugal	71	250
Romania	245	853
Slovakia	73	209
Slovenia	26	83
Spain	483	1 545
Sweden	48	154
Total EU-27	7 160	24 158

---

(35) With this percentage we follow EMEP's approach to a calculation of SRMs.

Based on the total amount of NH_3 emitted by the livestock sector (1 528 kt) and the percentage of reduction (15 %), average costs per tonne of livestock ammonia emission are estimated to be between 31 k€/t (low estimate) and 105 k€/t (high estimate). In the report ETC/ATNI 2020/04 the range of the marginal health damage costs from NH_3 calculated for a generic source (average over all sectors and locations) for the larger European area EEA38+UK goes from approximately 17 k€/t to 57 k€/t(36). This estimate is calculated as the sum over the externalities (country specific marginal damage costs multiplied by country emissions) divided by the sum over the emissions of the countries concerned and differs thus from the calculation in the present report. Also the chemistry-transport models used in the two exercises are not the same, and are likely to be amongst the reasons for the differences in costs per tonne estimated.(37) It should be noted that the uncertainties in these estimations due to the non-linear chemistry of ammonia in the atmosphere (estimated at around 30 %) are quite low compared to the differences between the two estimates of damage costs (around a factor 3). Therefore, the determination of these average costs per tonne of livestock ammonia can be assumed to be robust.

Estimate of the health damage costs avoided by a 50 % reduction in CH_4 emissions and the damage costs per tonne of CH_4 emitted

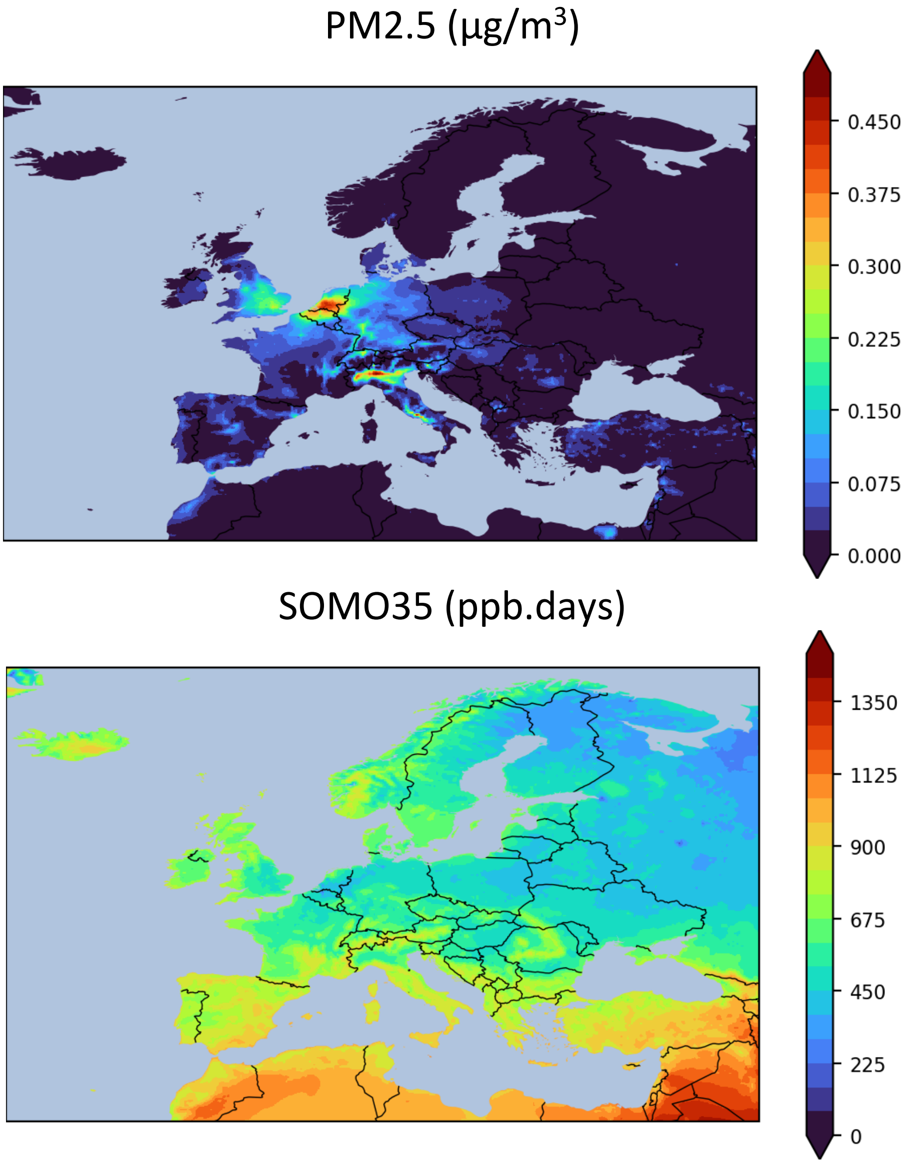
The Map 4.2 shows the concentrations of $PM_{2.5}$ and SOMO35 avoided through a reduction of 50 % of global anthropogenic emissions of methane. The prevented concentrations of $PM_{2.5}$ are generally under 0.1 µg/m^3 but can exceed 0.2 µg/m^3 in a few areas, especially in Italy, Belgium, and in the Netherlands. The avoided SOMO35 is higher in Southern Europe.

---

(36) Cf. Table 28 in https://www.eionet.europa.eu/etcs/etc-atni/products/etc-atni-reports/etc-atni-report-04-2020-costs-of-air-pollution-from-european-industrial-facilities-200820132017/@@download/file/ETC-ATNI_2020-4_Task-1222_FINAL_v2_17-08-2021.pdf.

(37) Indeed, the same order of difference as observed here between the costs per tonne estimated was also observed between the change in concentration due to a 15% change in emissions calculated in the two modelling exercises.

Map 4.2: Prevented concentrations of $PM_{2.5}$ (top) and prevented SOMO35 (bottom) by a reduction of global CH_4 emissions of 50 %



The corresponding avoided health damage costs by country are shown in Table 4.5. At the scale of the EU-27, the estimates of avoided damage costs are between 4 597 million € and 11 684 million € in 2018. Health damages from the contribution of CH_4 emissions to the formation of secondary particulate matter are higher than those from the contribution of CH_4 emissions to the formation of tropospheric ozone.

Table 4.5: Damage costs (in M€) avoided through a reduction of 50 % of global CH4 emissions for a low (including mortality valued by VOLY) and a high (including mortality valued by VSL) estimate

Countries	Avoided health damage (in M€$_{2021}$) in 2018		
	Low estimate (VOLY)	High estimate (VSL)	O_3 formation
	$PM_{2.5}$ formation		
Austria	54	174	29
Belgium	224	715	28
Bulgaria	6	24	37
Croatia	16	59	15
Cyprus	-3	-7	5
Czech Republic	37	117	33
Denmark	22	68	19
Estonia	1	3	4
Finland	3	9	15
France	364	1 133	210
Germany	832	2 978	248
Greece	3	10	50
Hungary	42	143	30
Ireland	14	29	15
Italy	606	2 152	251
Latvia	1	5	6
Lithuania	4	14	9
Luxembourg	5	12	2
Malta	0	-1	2
Netherlands	399	1 159	40
Poland	88	258	103
Portugal	28	95	45
Romania	57	191	73
Slovakia	23	63	16
Slovenia	18	57	7
Spain	212	657	207
Sweden	11	35	31
Total EU-27	3 066	10 154	1 530

Based on the total amount of global anthropogenic CH_4 emissions used by IFS (166 078 kT) and the percent of reduction (50 %), the average cost per tonne of CH_4 is estimated to be between 0.055 k€/t (low estimate) and 0.141 k€/t (high estimate).

4.4 Assessment of impacts on ecosystems

Impacts on ecosystems can be estimated by evaluating critical load exceedance, which is determined by comparing the atmospheric deposits to the critical load([38]). As CTMs simulate the deposition of sulphur, reduced nitrogen and oxidized nitrogen (Theobald et al., 2019), the methods described in section 4.2 can be used to estimate depositions and therefore to study acidification or eutrophication.

([38]) Critical loads represent an estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge.

The critical load database from the Working Group on Effects (Hettelingh et al. 2017, Geupel, et al. 2022, Bobbink et al., 2022) can be used to determine exceedances. This is not done here.

Critical loads exceedances for ecosystems are regularly calculated (but not monetised) by IIASA in the framework of the Clean Air outlook (Amann et al., 2020; Klimont et al., 2022; see also COM(2021) 3 final([39])), in the framework of the CLRTAP Gothenburg Protocol assessments by the Coordination Center for Effects (CCE) and the Center for Integrated Assessment Modelling (CIAM) (cf. the report "Scientific information for the review of the Gothenburg Protocol"([40])), and regularly summarised in the EEA Air quality reports (specific chapter on ecosystems impacts, e.g. the web report "Air Quality in Europe in 2022" ([41])).

Although uncertainty in quantifying ecosystems and biodiversity impacts is still high, in the ETC/ATNI report 2020/04 an attempt was made to calculate monetary biodiversity effects from exceedances of critical loads for eutrophication in Natura 2000 areas, following the approach of the ECLAIRE study (Holland et al., 2015 a & b). For monetisation, the study uses a willingness-to-pay estimate from a study assessing response to the UK's biodiversity action plan (Christie et al., 2012) for sites that need to be restored. This explains the limitation to Natura 2000 sites in the ETC/ATNI damage cost assessment. The limitation to eutrophication is due to exceedances of critical loads for acidification currently being much less important than for eutrophication.

Impacts accounted for are exceedances of critical loads for eutrophication in Natura 2000 areas from total deposition of nitrogen (dry and wet, oxidised and reduced nitrogen). They were calculated based on EPEP SRMs representing changes in the deposition of oxidised, reduced and total nitrogen for the precursors NO_x and NH_3. The calculations of critical loads exceedances were carried out by the Coordination Centre for Effects (CCE) under the LRTAP Convention, hosted by the Umweltbundesamt (UBA) in Germany, who develops and maintains the critical loads database. The work resulted, amongst others, in an estimate of damage costs per tonne of NH_3 emission by country. For details of the calculations, results and limitations see the report ETC/ATNI 2020/04.

---

(39) https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52021DC0003&from=EN.

(40) https://unece.org/sites/default/files/2022-10/ECE_EB.AIR_2022_4-2215181E.pdf.

(41) https://www.eea.europa.eu/publications/air-quality-in-europe-2022/impacts-of-air-pollution-on-ecosystems.

Conclusion

The agricultural sector is the first emitter of ammonia and methane in Europe. While NH_3 is a precursor of $PM_{2.5}$ particles and can cause negative effects on ecosystems by its deposition, CH_4 contributes to the formation of $PM_{2.5}$ and ozone and is a greenhouse gas. Both, $PM_{2.5}$ and O_3 are relevant for health impacts. Emissions of NH_3 and CH_4 have shown only slow decreases over the past two decades and in the context of the EU Green Deal and related environmental policies, additional efforts will be needed to reduce these emissions.

This study was focused on livestock farming, which is the most contributing source of NH_3 and CH_4 within the agricultural sector. NH_3 and CH_4 emissions from livestock farming were investigated through three topics.

Identification of the main emitters of NH_3 and CH_4 in the livestock sector at regional level

The first topic of study was to characterize the current spatial patterns of NH_3 and CH_4 emissions across Europe according to the size of the farms and the type of livestock. Using emission factors from EMEP/EEA and IPCC guidebooks (Tier1 method) and livestock numbers from Eurostat available for NUTS2 regions, emissions were estimated at NUTS2 level (regional level) for 2019. The application of the highest-tier methodologies recommended in the guidebooks, which would have required the collection and processing of detailed statistics on agricultural practices by country, was not feasible within this study.

Numerous data could be downloaded from the Eurostat website, however they were not available at the finest sectoral level, i.e. by size class of holding in LSUs and by sub-category of animals. Different datasets had thus to be combined and assumptions to be made to assess the emissions by category at NUTS2 level. The resulting values were consequently adjusted according to the reported national emissions, considered as baseline data.

The results of those calculations show that manure management accounts for the majority of livestock emissions of NH_3 (41.5 %) followed by manure applied to soils (24.5 %). Depending on the country, both sub-sectors together account for 53 % to 86 % of the total livestock emissions of the country.
In addition, the distribution of NH_3 emissions by type of animal indicates that cattle is the main emitter with a contribution of 51.3 % in the EU-27, followed by swine (27.5 %), poultry (15.2 %), sheep (4 %) and equidae (2 %).

Regarding the distribution of NH_3 emissions according to the size of the holdings, the farms of more than 100 LSUs (4.7 % of the farms) emit 66.8 % of the estimated emissions in the EU-27.

As regards CH_4, enteric emissions and manure management emissions together account for 53.4 % of the total of methane emissions in the EU-27. Results vary by country, ranging from 23 % to 93 % of the total livestock emissions of the respective country.
Again, cattle is the main emitter with a contribution of 79 % in the EU-27, followed by swine (10.4 %), sheep (7 %), equidae (2.6 %) and poultry (1 %).

Regarding the distribution of CH_4 emissions by holdings size, the farms of more than 100 LSUs (4.7 % of the farms) emit 56.8 % of the estimated emissions in the EU-27.

Complementary to those results, a set of maps was produced to represent the spatial distribution of total emissions and emission density and highlight the contribution of large farms.

In a second stage different sources of information were explored to reach finer spatial granularity and derive NUTS 3 level NH_3 and CH_4 emissions estimates for 2019.

NH_3 and CH_4 emissions obtained at NUTS2 level were disaggregated at the European scale, using a dataset constructed by INRAE of livestock information by NUTS 3 regions in 2010. Even though this dataset is rather old, it was considered that the broad spatial distribution of the main livestock types might not have changed drastically between 2010 and 2019. The result of this disaggregation enabled the identification of regions in EU-27 where livestock emissions were more concentrated: Ireland, Brittany (France), Belgium, the Netherlands, some parts of Germany and Poland, Lithuania the Po Valley and Naples region (Italy), northern Spain.

Another source of information consisted of national data made available by countries. Considering the answers to a questionnaire sent to Member States, Croatia was taken as a case study in view of the spatial basis, year and livestock classification which were compatible with the NUTS 2 level results.
This case study demonstrated the potential for using national data to disaggregate NUTS2 emissions and highlighted emission variability across NUTS3 regions. It was also used to check the accuracy of the emission data disaggregated with the INRAE dataset. Although this verification could only be performed for one country, it gave confidence in the consistency of the EU-wide NUTS3 distribution of emissions obtained with INRAE data. If other national data permit, it would be interesting to perform additional checks for some other types of countries (with regard to the country size, types of rearing systems etc.).

More partial and variable is the information provided by the E-PRTR. A major point is that the data do not cover cattle emissions which for now do not fall in the scope of the E-PRTR regulation. The coverage of E-PRTR emissions was then assessed in terms of the fraction of total emissions from all pigs and poultry that are accounted for in the E-PRTR. In general, this proportion is low, especially for CH_4 which has a higher reporting threshold than NH_3. Also noticeable is the variation in the fraction of emissions covered by the E-PRTR across Member States. Whereas some of them do not report any emissions (e.g. Ireland and Lithuania), for some others such as Bulgaria, E-PRTR reporting accounts for the majority (and in some NUTS 2 regions almost 100 %) of pig and poultry emissions.
The possibility of using E-PRTR emission data to support very fine-scale emissions mapping and impact assessment is therefore largely dependent on the location.

Finally, gridded emission datasets were reviewed: EMEP data (2019) for NH_3, which make use of MS-reported gridded emissions and EDGAR modelled emission data (2019) for CH_4. They are not available by livestock category but were used as an additional means of checking the results obtained from applying the INRAE 2010 livestock distribution data at the EU-scale. Good correlation was obtained (all types of livestock together), which tends to confirm the consistency of those results. For NH_3, the magnitude of emissions in each NUTS 3 region is very similar to the gridded data and INRAE 2010 data; for CH_4 the gridded data appears higher than from the INRAE 2010 estimates. The reasons for this are unclear but may relate to conservative assumptions used in the EDGAR modelled dataset, producing higher emissions than MS's own estimates.

These various analyses show that despite the limitations in the input data and the assumptions made, the methodology developed, from the calculation of emissions at NUTS2 level to their breakdown at NUTS3 level, provides a consistent estimate of the spatial distribution of livestock emissions over Europe. Further validation and strengthening of the methodology and the related processing chain could take place in a future study.

In the future, experimental approaches such as the one presented in the report, based on monitoring and inverse dispersion modelling, may constitute a supplementary source of information at the level of an installation. In addition to being an input to local scale assessments, the resulting data could serve as local comparison points in specifically selected areas with fine resolution estimated emissions.

Technical mitigation measures and uptake scenarios

As a second topic of study, technical measures to reduce air emissions from livestock and their uptake by Member States were reviewed.

Opportunities to reduce ammonia emissions from livestock operations, from building to land application, are well identified and, in part, already implemented. However, there are limits to applicability depending on the type of building and the techniques cannot necessarily be applied in existing buildings. Thus, for this and other emission items, significant investments are required to make them widespread. In addition, ammonia emission reductions must be integrated into a nitrogen management system to avoid deleterious cross-effects. A measure to reduce ammonia emissions from manure leaves more organic N available in the farming system, so that more is available to meet crop and animal needs. In order to fully exploit the benefit of a measure to reduce N loss, the nitrogen saved by the measure needs to be matched by either reduced N inputs, increased storage, or increased N in harvested outputs. Manure management on farms consists of several linked stages in sequence, and measures to reduce emission factors upstream are ineffective if measures are not also applied downstream.

The possibilities to reduce CH_4 emissions from cattle farms, the main emitters, are mainly related to feed adaptation and the use of feed additives. To a lesser extent, improving productivity and genetic improvement of animals can contribute to a reduction in CH_4 emissions but these solutions are not necessarily easy to deploy. In addition, anaerobic digestion appears to be a solution for managing effluents to reduce methane emissions.

It could be interesting to get more information on the efficiency of these different techniques.

As well as future uptake of mitigation measures, projection levels make an equally if not more important driver of emissions. Projections of animal numbers reported by Member States indicate that for the EU as a whole, numbers of dairy and non-dairy cattle are projected to fall slightly by 2030 and 2040 compared with 2020, whereas numbers of pigs and poultry are projected to rise, with a considerable (12 %) increase projected for poultry by 2040 compared with 2020. Findings from published scenarios are overall in agreement with these trends except for pig production for which projections are more mixed. According to data from the Clean Air Outlook 2 , the relative importance of mitigation measures and changes in production levels as a driver of NH_3 emissions varies across the livestock species and systems and considered scenarios. From recent publications, a change in livestock numbers might be a slightly more important driver of CH_4 emissions overall than the uptake of mitigation measures.

Methods for deriving damage values for human health and environmental impacts of NH_3 and CH_4 emissions from the livestock sector

The last topic investigated in this task dealt with existing methodologies to assess damage to human health and the environment due to NH_3 and CH_4 emissions and the benefits achievable (avoided health costs) by mitigation strategies for air pollution from the livestock sector.

Building on previous ETC work on the external costs of industrial emissions, a methodology consisting of chemistry-transport modelling (CHIMERE model) and health impact assessment (Alpha-RiskPoll tool) was applied to estimate the $PM_{2.5}$ concentrations and related health damage costs avoided by a 15 % reduction in livestock NH_3 emissions. The underlying linearity assumption was previously verified by reducing NH_3 emissions from 0 to 100 %. The same methodology was applied to estimate the $PM_{2.5}$ and O_3 concentrations and related health damage costs avoided by a 50 % reduction of CH_4 emissions.

$PM_{2.5}$ concentrations avoided by a 15 % reduction in ammonia emissions range between 0 and 2 µg/m^3 across Europe. Generally, below 0.5 µg/m$_3$ in the EU-27 countries, the benefit of NH_3 reduction is highest in Italy, Northern France, Belgium, the Netherlands, Germany, Poland, the Balkans and Turkey. Avoided costs are the largest for Germany, Italy, Poland, France, Spain and Belgium. The estimated health benefits per avoided tonne of emission of ammonia range between 31 k€/t (low estimate) and 105 k€/t (high estimate).

The $PM_{2.5}$ concentrations avoided by a 50 % reduction in methane emissions are generally under 0.1 µg/m^3 but can exceed 0.2 µg/m^3 in a few areas, especially in Italy, Belgium and in the Netherlands. The avoided SOMO35 (health indicator for ozone) is higher in southern Europe.
Avoided costs are the highest for Germany, Italy, France, the Netherlands, Spain and Belgium. The health benefits per avoided tonne of emission of methane range between 0.055 k€/t (low estimate) and 0.141 k€/t (high estimate).

The quantification of impacts on ecosystems and biodiversity and of the related damage costs was not included in this application. However, this question started to be studied in a previous ETC project and although uncertainties are still large, it could represent a subject for investigation in a follow-up of this work.

The three topics addressed in this exploratory study, namely the spatial characterization of emissions, mitigation measures, and the assessment of emission reduction scenarios were studied in parallel. A future development could involve building a closer connection between these parts.

List of abbreviations

Abbreviation	Name	Definition	Reference
ACT	Air Control Toolbox		
BAT	Best Available Technique		
BREF	Best Available Techniques Reference Document		
CAMS	Copernicus Atmospheric Monitoring Service		
CAO	Clean Air Outlook		
CAP	Common Agricultural Policy		
CH_4	Methane		
CLRTAP	Convention on Long-range Transboundary Air Pollution		
CTM	Chemistry-Transport-Model		
EEA	European Environment Agency		www.eea.europa.eu
EIP-AGRI	Agricultural European Innovation Partnership		https://ec.europa.eu/eip/agriculture/en/about
EMEP	European Monitoring and Evaluation Programme		https://www.emep.int
F2F	Farm to Fork strategy		https://food.ec.europa.eu/horizontal-topics/farm-fork-strategy_en
HIA	Health Impact Assessment		
HRAPIE	Health Risks of Air Pollution in Europe		
IED	Industrial Emissions Directive		
IEF	Implied emission factor		
IFS			
IIR	Informative Inventory report	The descriptive report accompanying submissions of air pollution inventories under the Convention on Long-Range Transboundary Air Pollution, and the NECD.	

Abbreviation	**Name**	**Definition**	**Reference**
IPCC	Intergovernmental Panel on Climate Change		https://www.ipcc.ch/
IRPP	Intensive Rearing of Poultry or Pigs		
JRC	Joint Research Centre of the European Commission		https://joint-research-centre.ec.europa.eu
LSU	Livestock Unit	The livestock unit is a reference unit which facilitates the aggregation of livestock from various species and age as per convention, via the use of specific coefficients established initially on the basis of the nutritional or feed requirement of each type of animal (source: Eurostat)	
MACC	Marginal abatement cost curve		
MS	Member State		
N	Nitrogen		
NAPCP	NAPCP		
NECD	National Emissions reduction Commitments Directive		
NMVOC	Non-methane volatile organic compound		
(G)NFR	NFR: Nomenclature for reporting GNFR: Nomenclature for reporting gridded emissions	Coding system used for reporting air pollutant emissions under the Convention on Long-Range Transboundary Air Pollution, and the NECD.	
NH_3	Ammonia		
NO_x	Nitrogen oxides		
NUTS	Nomenclature of territorial units for statistics	NUTS is a hierarchical system for dividing up the economic territory of the EU and the UK for the purpose of:	

Abbreviation	Name	Definition	Reference
		- The collection, development and harmonisation of European regional statistics - Socio-economic analyses of the regions - Framing of EU regional policies	
NUTS1, NUTS2, NUTS3		NUTS 1: major socio-economic regions NUTS 2: basic regions for the application of regional policies NUTS 3: small regions for specific diagnoses	
PaMs	Policies and measures		
$PM_{2.5}$	Particulate matter with diameter less than 2.5 µm		
SO_2	Sulfur dioxide		
SRM	Source-Receptor Matrix		
TFR	Technically feasible reduction		
TFRN	UNECE Task Force on Reactive Nitrogen		
UNECE	Economic Commission for Europe of the United Nations		
VOLY	Value of a life year		
VSL	Value of statistical life		
WAM	With additional measures		
WEM	With existing measures		
YOLL	Years of life lost		

References

Abbey, D.E., et al., 1995a, *Estimated long-term ambient concentrations of PM10 and development of respiratory symptoms in a non-smoking population*, International Archives for Occupational and Environmental Health, 50(2), pp. 139–152, (https://doi.org/10.1080/00039896.1995.9940891).

Abbey, D.E., et al., 1995b, *Chronic respiratory symptoms associated with estimated long-term ambient concentrations of fine particulates less than 2.5 microns in aerodynamic diameter (PM2.5) and other air pollutants*, Journal of Exposure Analysis and Environmental Epidemiology, 5(2), pp. 137–159.

AEAT, 2005*, Damages per tonne emission of PM2.5, NH3, SO2, NOx and VOCs from each EU25 Member State (excluding Cyprus) and surrounding seas*, Service Contract for Carrying out Cost-Benefit Analysis of Air Quality Related Issues, in particular in the Clean Air for Europe (CAFE) Programme.

Agriculture and rural development, 2022, *Market data on national and European agriculture provided by the European Commission's agricultural and rural development department*, (https://agridata.ec.europa.eu/extensions/dataportal/eggs-and-poultry.html).

Amann, M., et al., 2017, *Measures to address air pollution from agricultural sources*, IIASA Report, International Institute for Applied Systems Analysis, Laxenburg, Austria. European Commission, (https://ec.europa.eu/clima/sites/clima/files/forests/lulucf/docs/cap_mainstreaming_en.pdf).

Amann, M. et al., 2017, *Costs, Benefits and Economic Impacts of the EU Clean Air Strategy and their Implications on Innovation and Competitiveness*, IIASA Report.

Amann, M., et al., 2020, *Support to the development of the Second Clean Air Outlook, Specific Contract 6 under Framework Contract ENV.C.3/FRA/2017/0012*, Final report, International Institute for Applied Systems Analysis, Umweltbundesamt, EMRC, for European Commission Directorate General Environment.

Amon, B., et al., 2017, *Mini-paper – Housing techniques as mitigation options for emissions from cattle barns.* European Commission.

Arndt, C., et al., 2022, *Full adoption of the most effective strategies to mitigate methane emissions by ruminants can help meet the 1.5 °C target by 2030 but not 2050.* Proc Natl Acad Sci U S A.

Augère-Granier, M.-L., 2019, *The EU poultry meat and egg sector: main features, challenges and prospects.* European Parliament (EPRS), Éd. (https://www.europarl.europa.eu/thinktank/en/document/EPRS_IDA(2019)644195).

Augère-Granier, M.-L., 2020, The EU pig meat sector. European Parliament (EPRS), Éd. (https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2020)652044%20).

Barreiro-Hurle, J., et al., 2021, *Modelling environmental and climate ambition in the agricultural sector with the CAPRI model. Exploring the potential effects of selected Farm to Fork and Biodiversity strategies targets in the framework of the 2030 Climate targets and the post 2020 Common Agricultural Policy*, EUR 30317 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-20889-1, doi:10.2760/98160, JRC121368.

Bittman, S., et al., 2014, *Options for Ammonia Mitigation: Guidance from the UNECE Task Force on reactive nitrogen.* Edinburgh: Centre for Ecology and Hydrology.

Bobbink, R., et al., 2022, Review and revision of empirical critical loads of nitrogen for Europe, 110/2022, Umweltbundesamt.

CEIP, 2022, *Grid emissions in 0.1°x0.1° long-lat resolution,* (https://www.ceip.at/the-emep-grid/gridded-emissions).

Christie, M. and Rayment, M., 2012, *An economic assessment of the ecosystem service benefits derived from the SSSI biodiversity conservation policy in England and Wales*, Ecosystem Services 1, pp. 70–84, (https://doi.org/10.1016/j.ecoser.2012.07.004).

Colette, A., et al., 2022, *Air Control Toolbox (ACT_v1.0): a flexible surrogate model to explore mitigation scenarios in air quality forecasts*, Geosci. Model Dev., 15 (1441–1465, https://doi.org/10.5194/gmd-15-1441-2022).

Crippa, M., et al., 2019, *Fossil CO2 and GHG emissions of all world countries* - 2019 Report, EUR 29849 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-76-11100-9, https://doi:10.2760/687800, JRC117610.

DCE, 2018, *The Danish Air Quality Monitoring Programme, Annual Summary for 2017*, Scientific Report from DCE – Danish Centre for Environment and Energy No. 281, 2018, Aarhus University, (https://dce2.au.dk/pub/SR281.pdf) accessed 9 February 2021.

De Bruyn, S., et al., 2018, *Environmental Prices Handbook EU28 version: Methods and numbers for valuation of environmental impacts*. Delft: CE Delft.

Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control).

Directive 2016/2284 of the European Parliament and of the Council of 14 December 2016 on the reduction of national emissions of certain atmospheric pollutants, amending Directive 2003/35/EC and repealing Directive 2001/81/EC.

Dumont, B., et al., 2018, *"Eurostat_2010_ESCo_INRA_2016.xlsx", Typology of European livestock production areas*, (https://doi.org/10.15454/O78MYF/IDFXPZ).

DüV, 2020, *Ordinance on the use of fertilizers, soil additives, growing media and plant additives according to the principles of good professional practice when fertilizing*: Fertilizer Ordinance, 2020.

EDGAR, 2022, *Global Greenhouse Gas Emissions EDGAR v7.0*, (https://edgar.jrc.ec.europa.eu/dataset_ghg70).

EEA, 2011, *Revealing the costs of air pollution from industrial facilities in Europe*, EEA Technical Report 15/2011, European Environment Agency, Publications Office of the European Union, Luxembourg (https://doi.org/10.2800/84800).

EEA, 2014, *Costs of air pollution from European industrial facilities 2008–2012—an updated assessment*, EEA Technical Report 20/2014, European Environment Agency, Publications Office of the European Union, Luxembourg (https://doi.org/10.2800/23502).

EEA, 2019, *EMEP/EEA air pollutant emission inventory guidebook 2019*. EEA Report n°13/2019 (https://www.eea.europa.eu/publications/emep-eea-guidebook-2019).

EEA, 2022a, Industrial Reporting under the Industrial Emissions Directive 2010/75/EU and European Pollutant Release and Transfer Register Regulation (EC) No 166/2006 (https://www.eea.europa.eu/data-and-maps/data/industrial-reporting-under-the-industrial-6).

EEA, 2022b. Briefing no. 21/2022. *Methane emissions in the EU: the key to immediate action on climate change* (https://www.eea.europa.eu/publications/methane-emissions-in-the-eu/methane-emissions-in-the-eu).

EIP-AGRI Focus Group, 2017, *Reducing emissions from cattle farming.* European Commission.

Eshel, G., et al., 2010, *Land use and reactive nitrogen discharge: Effects of dietary choices*. Earth Interactions, 14(21), 1-15, doi: 10.1175/2010EI321.1

ETC/ATNI, 2019, *Health Risk Assessment of Air Pollution in Europe - Methodology description and 2017 results*, Soares, J., Horálek, J., González Ortiz, A., Guerreiro, C., & Gsella, A., Eionet Report - ETC/ATNI 2019/13.

ETC/ATNI, 2021, *Costs of air pollution from European industrial facilities 2008–2017*, Schucht, S., Real. E., Létinois, L. et al., Eionet Report - ETC/ATNI 2020/4 (https://www.eionet.europa.eu/etcs/etc-atni/products/etc-atni-reports/etc-atni-report-04-2020-costs-of-air-pollution-from-european-industrial-facilities-200820132017).

ETC/CME, 2021, *Agricultural climate mitigation policies and measures. Good practice, challenges, and future perspectives*, ETC/CME Report 6/2021, (https://www.eionet.europa.eu/etcs/etc-cme/products/etc-cme-reports/etc-cme-report-6-2021-agricultural-climate-mitigation-policies-and-measures-good-practice-challenges-and-future-perspectives).

European Commission, 2019, *Handbook on the external costs of transport, Version 2019*, European Commission, Directorate-General for Mobility and Transport, January 2019, Brussels (https://op.europa.eu/en/publication-detail/-/publication/9781f65f-8448-11ea-bf12-01aa75ed71a1).

European Commission, 2021b, *EU agricultural outlook for markets, income and environment, 2021-2031*. European Commission, DG Agriculture and Rural Development, Brussels. (https://agriculture.ec.europa.eu/data-and-analysis/markets/outlook/medium-term_en).

European Commission, 2022, *EGGS - MARKET SITUATION - DASHBOARD* .

European Commission, Directorate-General for Climate Action, Directorate-General for Energy, Directorate-General for Mobility and Transport, De Vita, A., Capros, P., Paroussos, L., et al., 2021a, *EU reference scenario 2020 : energy, transport and GHG emissions : trends to 2050,* Publications Office, 2021 (https://data.europa.eu/doi/10.2833/35750).

Eurostat, 2020, *Agriculture, forestry and fishery statistics.* Luxembourg: Publications Office of the European Union.

Eurostat, 2021, *Milk and milk product statistics.* https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Milk_and_milk_product_statistics#Milk_production

Eurostat, 2022, *Agriculture and rural development*
(https://agriculture.ec.europa.eu/system/files/2022-08/eggs-dashboard_en_1.pdf).

ExternE, 2005, *ExternE - Externalities of Energy, Methodology 2005 Update*, ExternE project (http://www.externe.info/externe_d7/?q=node/30).

Geupel, M., et al., 2022*, CCE Status Report 2022,* Coordination Centre for Effects (CCE), Texte 135/2022, Umweltbundesamt.

Herrero, E., et al., 2021, *Towards robust on-site ammonia emission measuring techniques based on inverse dispersion modelling*. Agricultural and forest meteorology, v.307 pp. 108517 (https://doi.org/10.1016/j.agrformet.2021.108517).

Hettelingh, J.-P., et al., 2017, *European critical loads: database, biodiversity and* ecosystems *at risk*: CCE Final Report 2017. Coordination Center for Effects, RIVM, Bilthoven, The Netherlands.

Hoek, G., et al., 2012, *PM10, and children's respiratory symptoms and lung function in the PATY study*. European Respiratory Journal, 2012 Sep, 40(3), pp. 538-47 (https://doi.org/10.1183/09031936.00002611).

Hoek, G., et al., 2013, *Long-term air pollution exposure and cardio-respiratory mortality: a review*, Environmental Health, 2013 May 28,12(1), 43 (https://doi.org/10.1186/1476-069X-12-43).

Holland, M., 2013, Cost-benefit Analysis of Policy Scenarios for the Revision of the Thematic Strategy on Air Pollution, corresponding to IIASA TSAP Report #10, EMRC.

Holland, M., 2014a, Implementation of the HRAPIE Recommendations for European Air Pollution CBA work. Health Impact Assessment and Cost Benefit Analysis. Retrieved from https://policycommons.net/artifacts/1955080/implementation-of-the-hrapie-recommendations-for-european-air-pollution-cba-work/2706848/ on 05 Mar 2023. CID: 20.500.12592/qgh72j.

Holland, M., 2014b, *Cost-benefit Analysis of Final Policy Scenarios for the EU Clean Air Package*, Version 2, Corresponding to IIASA TSAP Report 11, Version 1.

Holland, M., et al., 2015a, D18.3 Elaboration of the Modelling Approach for Benefits Analysis, Including Illustrative Examples, ECLAIRE Project: Effects of Climate Change on Air Pollution Impacts and Response Strategies for European Ecosystems, for the European Commission Seventh Framework Programme, Work package 18, Deliverable 18.3.

Holland, M., et al., 2015b, *D18.4* Scenario analysis to include policy recommendations and advice to other interest groups, ECLAIRE Project: Effects of Climate Change on Air Pollution Impacts and Response Strategies for European Ecosystems, for the European Commission Seventh Framework Programme, Work package 18, Deliverable 18.4

Holland, M., et al., 2005a, *Methodology for the Cost-Benefit analysis for CAFE: Volume 1: Overview of Methodology*, Service Contract for Carrying out Cost-Benefit Analysis of Air Quality Related Issues, in particular in the Clean Air for Europe (CAFE) Programme.

Holland, M., et al., 2005b, *Methodology for the Cost-Benefit analysis for CAFE: Volume 3: Uncertainty in the CAFE CBA: Methods and First Analysis*, Service Contract for Carrying out Cost-Benefit Analysis of Air Quality Related Issues, in particular in the Clean Air for Europe (CAFE) Programme.

Holland, M., et al., 2011, Cost Benefit Analysis for the Revision of the National Emission Ceilings Directive: Policy Options for revisions to the Gothenburg Protocol to the UNECE Convention on Long-Range Transboundary Air Pollution.

Holland, M., et al., 2005c, *Cost-Benefit Analysis of Policy Option Scenarios for the Clean Air for Europe programme*, Service Contract for Carrying out Cost-Benefit Analysis of Air Quality Related Issues, in particular in the Clean Air for Europe (CAFE) Programme.

Hunt, A., et al., 2016, *Social costs of morbidity impacts of air pollution*, OECD Environment Working Papers No. 99, OECD, Paris (https://www.oecd-ilibrary.org/docserver/5jm55j7cq0lv-en.pdf?expires=1595947296&id=id&accname=guest&checksum=518DFC4D0FC45F9C13E1ADAEB54F9E96).

Hurley, F., et al., 2005, *Methodology for the Cost-Benefit analysis for CAFE: Volume 2: Health Impact Assessment*, Service Contract for Carrying out Cost-Benefit Analysis of Air Quality Related Issues, in particular in the Clean Air for Europe (CAFE) Programme, AEAT.

Ineris 2021, Surveillance des émissions de méthane d'installations de méthanisation agricoles, MethanEmis, rapport final, 61 pages, (www.ademe.fr/mediatheque).

INRAE, 2021, *European and National overview of Beef production,* https://www6.inrae.fr/sustainbeef/Project/WP2.1-Description-of-beef-production-systems/WP2.1.1-Beef-production-national-statistics.

ISPRA, 2022. *Italian Informative Inventory Report 2022* (IIR 2022).

Katsouyanni, K., et al., 2009, *Air Pollution and Health: a European and North American Approach (APHENA)*, Boston, MA, HEI Research Report 142, Health Effects Institute, https://www.healtheffects.org/system/files/APHENA142.pdf.

Klimont, Z., et al., 2022, *Support to the development of the third Clean Air Outlook, Final report*, Specific Agreement 13 under Framework Contract ENV.C.3/FRA/2017/0012, International Institute for Applied Systems Analysis (IIASA), Umweltbundesamt Austria, MET Norway, EMRC, Joint Research Centre, RIVM, EMISIA, https://environment.ec.europa.eu/publications/third-clean-air-outlook_en.

KOBiZE, Poland, 2022. *Polish Informative Inventory report 2022* (IIR 2022).

Krupnick, A., et al., 2005, Peer Review of the Methodology of Cost-Benefit Analysis of the Clean Air For Europe Programme.

Maca, V., et al., 2011, *Presentation of unit values for health end-points: country-specific and pooled*, Deliverable 4.1.3 of the Heimtsa project, EC DG Research Project, EC grant GOCE-CT-2006-036913-2, University of Bath.

Ministry for Ecological Transition, Spain, 2019. *1st National Air Pollution Control Programme* (NAPCP 2019), Directorate-General for Biodiversity and Environmental Quality.

Ministry for Ecological Transition, Spain, 2021. *Informative Inventory Report* (IIR 2021).

Ministry of Ecological Transition, France, 2019. *French Informative Inventory report 2019* (IIR 2019).

NEEDS, 2008, *External costs per unit of emission, Deliverable No. 1.1 - RS 3a*, NEEDS integrated project, Priority 6.1, sub-priority 6.1.3.2.5: Excel sheets, an appendix to New Energy Externalities Developments for Sustainability (NEEDS), IER, University of Stuttgart

Ostro, B. D. and Rothschild, S., 1989, *Air pollution and acute respiratory morbidity: an observational study of multiple pollutants*, Environmental Research, 50, pp. 238–247, https://doi.org/10.1016/s0013-9351(89)80004-0.

Ostro, B. D., 1987, *Air pollution and morbidity revisited: a specification test*, Journal of Environmental Economics Management, 14(1), pp. 87–98.

Pérez Domínguez I., et al., 2020, *Economic assessment of GHG mitigation policy options for EU agriculture: A closer look at mitigation options and regional mitigation costs (EcAMPA 3)*, EUR 30164 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-17854-5, doi:10.2760/4668, JRC120355.

Piersanti, A., et al., 2021, *The Italian National Air Pollution Control Programme: Air Quality, Health Impact and Cost Assessment*, Atmosphere 2021, 12, 196, (https://doi.org/10.3390/atmos12020196).

Poux, X. and Aubert, P.-M., 2018, An agroecological Europe in 2050: multifunctional agriculture for healthy eating. Findings from the Ten Years For Agroecology (TYFA) modelling exercise, Iddri-AScA, Study N°09/18, Paris, France, 74 p.

Ricardo-AEA, 2016, *Effective performance of tools for climate action policy - meta-review of* Common *Agricultural Policy (CAP) mainstreaming*, report for Directorate General for Climate Action (European Commission), (https://ec.europa.eu/clima/sites/clima/files/forests/lulucf/docs/cap_mainstreaming_en.pdf).

Rossi, R., 2017, *The sheep and goat sector in the EUMain features, challenges and prospects.* European Parliament, (https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2017)608663).

Saunois M. and Stavert A.L., et al., 2020, *The Global Methane Budget 2000–2017,* Earth Syst. Sci. Data, 12, 1561–1623, (https://doi.org/10.5194/essd-12-1561-2020).

Schindler, C., et al., 2009, *Improvements in* PM_{10} *exposure and reduced rates of respiratory symptoms in a cohort of Swiss adults (SAPALDIA)*, American Journal of Respiratory and Critical Care Medicine, 179(7), pp. 579–587, (https://doi.org/10.1164/rccm.200803-388OC).

Schucht, S., et al., 2015, *Moving towards ambitious climate policies: Monetised health benefits from improved air quality could offset mitigation costs in Europe*, Environmental Science & Policy, 50, 252-269.

Searchinger, T.D., et al., 2018, *Assessing the efficiency of changes in land use for mitigating climate change*, Nature 564, 249–253, (https://doi.org/10.1038/s41586-018-0757-z).

Theobald, M. R., et al., 2019, *An evaluation of European nitrogen and sulfur wet deposition and their trends estimated by six chemistry transport models for the period 1990–2010*, Atmos. Chem. Phys., 19, 379–405, (https://doi.org/10.5194/acp-19-379-2019).

Timmermans, R., et al., 2022, *Air quality projections in Europe for 2050 under air quality and climate mitigation strategies*. Forthcoming publication.

Turnock, S. T., et al., 2018, *The impact of future emission policies on tropospheric ozone using a parameterised approach*, Atmos. Chem. Phys., 18, 8953–8978, (https://doi.org/10.5194/acp-18-8953-2018).

UBA (German Federal Environmental Agency), Germany, 2022, German Informative Inventory Report 2022 (IIR 2022), (https://unfccc.int/documents/273433).

UNECE, 2020, *Draft Guidance document on integrated sustainable nitrogen management.*

UNEP, 2021. *United Nations Environment Programme and Climate and Clean air Coalition, Global Methane Assessment, Benefits and Costs of Mitigating Methane Emissions*. Nairobi: United Nations Environment Programme, (https://www.unep.org/resources/report/global-methane-assessment-benefits-and-costs-mitigating-methane-emissions).

U.S. EPA, 2011, *The benefits and costs of the Clean Air Act from 1990 to 2020, Final Report – Rev. A*, U.S. Environmental Protection Agency, Office of Air and Radiation (https://www.epa.gov/sites/production/files/2015-07/documents/fullreport_rev_a.pdf).

Weinmayr, G., et al., 2010, *Short-Term Effects of PM10 and NO2 on Respiratory Health among Children with Asthma or Asthma-like Symptoms: A Systematic Review and Meta-Analysis*, Environmental Health Perspectives, volume 118(4), pp. 449-57 (https://doi.org/10.1289/ehp.0900844).

Westhoek H., et al., 2015, *Nitrogen on the Table: The influence of food choices on nitrogen emissions and the European environment, European Nitrogen Assessment Special Report on Nitrogen and Food*, (https://www.pbl.nl/sites/default/files/downloads/Nitrogen_on_the_Table_Report_WEB.pdf).

WHO, 2013a, Review of evidence on health aspects of air pollution –REVIHAAP – First results.

WHO, 2013b, Health risks of air pollution in Europe – HRAPIE – Recommendations for concentration-response functions for cost-benefit analysis of particulate matter, ozone and nitrogen dioxide.

Woodruff, T. J., et al., 1997, *The relationship between selected causes of postneonatal infant mortality and particulate air pollution in the United States*, Environmental Health Perspectives, 105(6), pp. 608–12 (https://doi.org/10.2307/3433606).

WWF, 2021, *A Comprehensive Approach to Nitrogen in the UK*, A Report Commissioned by WWF-UK, authors Hicks W. K., McKendree, J., Sutton M.A., Cowan, N., German, R., Dore, C., Jones, L. Hawley, J., Eldridge, H., (https://www.wwf.org.uk/sites/default/files/2022-02/WWF_Comprehensive_Approach_to_N_Final.pdf).

Yáñez-Ruiz, Det al., 2017, *Mini-paper – Feeding strategies to reduce methane and ammonia emissions.* EIP-AGRI Focus Group. European Commission.

Annex 1 Sub-categories of animals available in Eurostat dataset

Table A1.1: Sub-categories of animals available in Eurostat dataset

Code	Label	table
A5000	Live poultry	*ef_lsk_poultry*
A5000X5100	Live poultry excluding chicken (species)	*ef_lsk_poultry*
A5110O	Laying hens	*ef_lsk_poultry*
A5140	Broilers	*ef_lsk_poultry*
A5210	Ducks	*ef_lsk_poultry*
A5220	Geese	*ef_lsk_poultry*
A5230	Turkeys	*ef_lsk_poultry*
A5300	Other poultry	*ef_lsk_poultry*
A6521	Ostrich	*ef_lsk_poultry*
A3000	Live swine	*ef_lsk_pig*
A3110	Piglets, live weight of under 20 kg	*ef_lsk_pig*
A3120	Breeding sows, live weight 50 kg or over	*ef_lsk_pig*
A3130	Other pigs	*ef_lsk_pig*
A4100	Live sheep	*ef_lsk_sheep*
A4110	Ewes and ewe-lambs, breeding females	*ef_lsk_sheep*
A4120	Other sheep	*ef_lsk_sheep*
A2000	Live bovine animals	*ef_lsk_bovine*
A2010	Bovine animals, less than 1 year old	*ef_lsk_bovine*
A2020	Bovine animals, 1 to less than 2 years old	*ef_lsk_bovine*
A2120	Male bovine animals, 1 to less than 2 years old	*ef_lsk_bovine*
A2130	Male bovine animals, 2 years old or over	*ef_lsk_bovine*
A2230_2330	Female bovine animals, 2 years old or over	*ef_lsk_bovine*
A2220	Heifers, 1 to less than 2 years old	*ef_lsk_bovine*
A2230	Heifers, 2 years old or over	*ef_lsk_bovine*
A2300	Cows	*ef_lsk_bovine*
A2300F	Dairy cows	*ef_lsk_bovine*
A2300G	Non dairy cows	*ef_lsk_bovine*

Annex 2 Countries where livestock data were available

Table A2.1: Countries where livestock data were available

ID	Name	Missing data
AT	Austria	No
BE	Belgium	No
BG	Bulgaria	No
CH	**Switzerland**	**Yes**
CY	Cyprus	No
CZ	Czechia	No
DE	Germany	No
DK	Denmark	No
EE	Estonia	No
EL	Greece	No
ES	Spain	No
FI	Finland	No
FR	France	No
HR	Croatia	No
HU	Hungary	No
IE	Ireland	No
IS	**Iceland**	**Yes**
IT	Italy	No
LI	**Liechtenstein**	**Yes**
LT	Lithuania	No
LU	Luxembourg	No
LV	Latvia	No
ME	**Montenegro**	**Yes**
MK	**North Macedonia**	**Yes**
MT	Malta	No
NL	Netherlands	No
NO	**Norway**	**Yes**
PL	Poland	No
PT	Portugal	No
RO	Romania	No
SE	Sweden	No
SI	Slovenia	No
SK	Slovakia	No
TR	**Turkey**	**Yes**

Annex 3 Distribution of NH_3 emissions by animal species and farm size in 2019

Figure A3.1: Distribution of NH_3 emissions by farm size in 2019 (only emissions from swine)

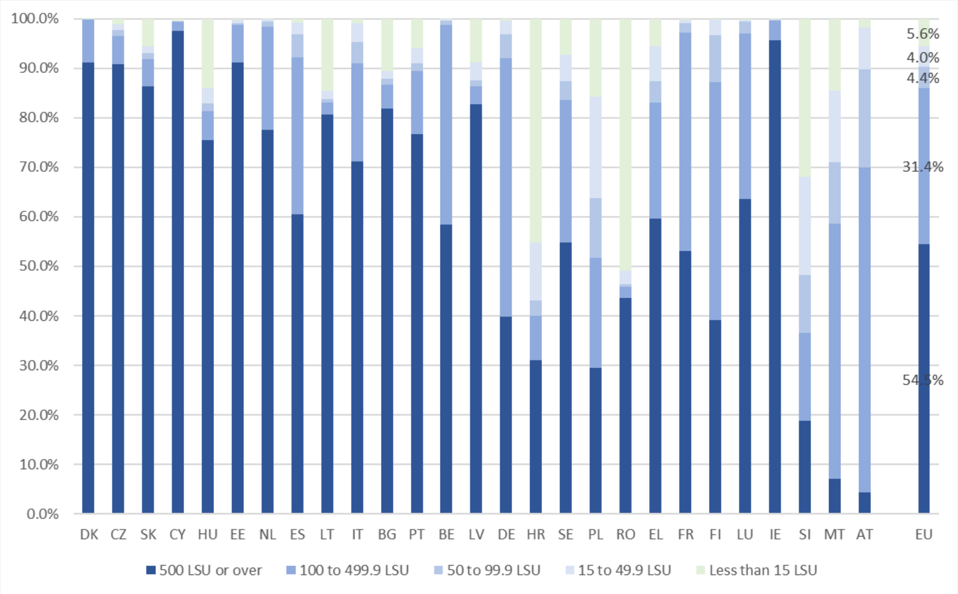


Figure A3.2: Distribution of NH_3 emissions by farm size in 2019 (only emissions from poultry)

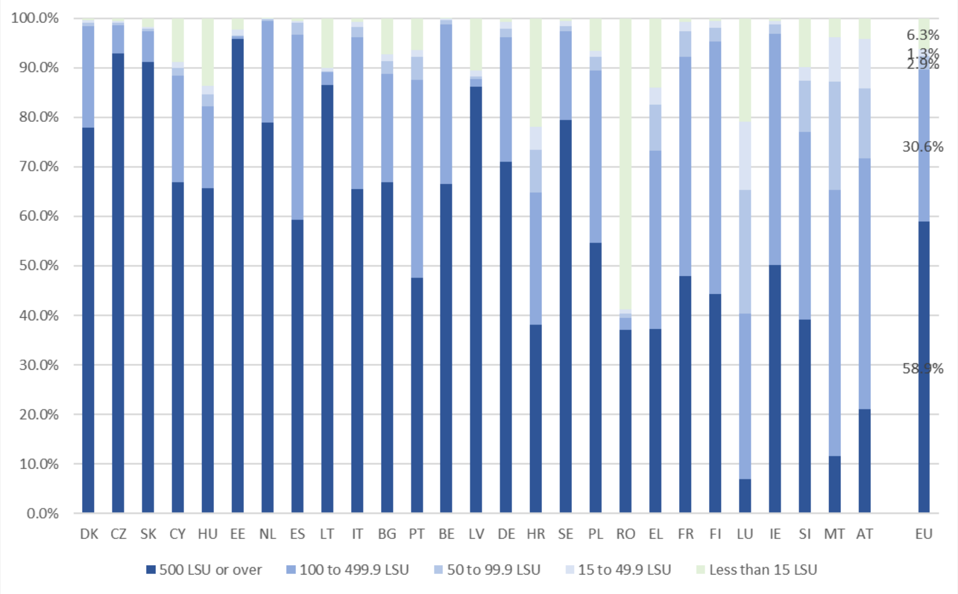


Figure A3.3: Distribution of NH_3 emissions by farm size in 2019 (only emissions from sheep)

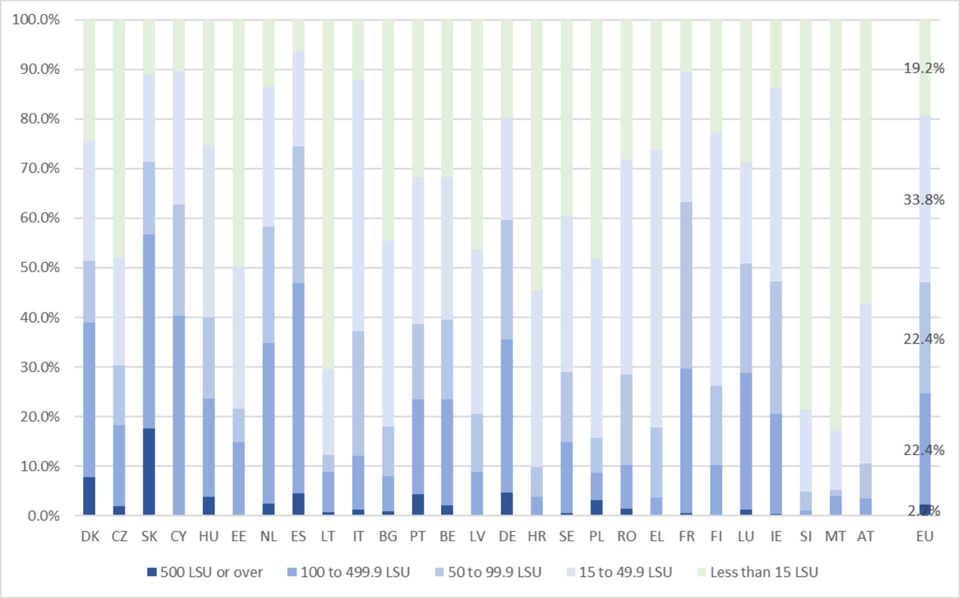
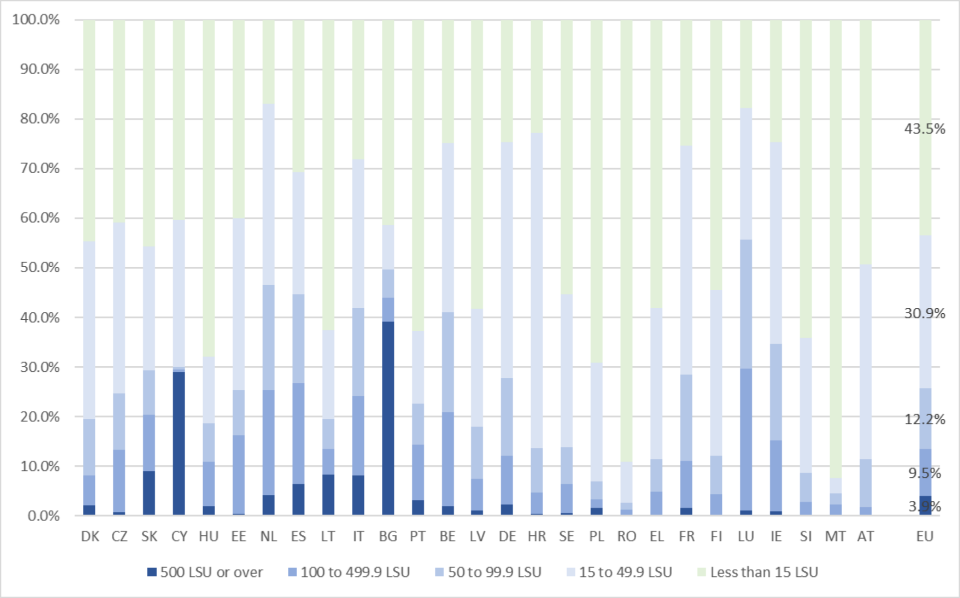


Figure A3.4: Distribution of NH_3 emissions by farm size in 2019 (only emissions from equidae)



Annex 4 Distribution of CH₄ emissions by animal species and farm size in 2019

Figure A4.1: Distribution of CH₄ emissions by farm size in 2019 (only emissions from swine)

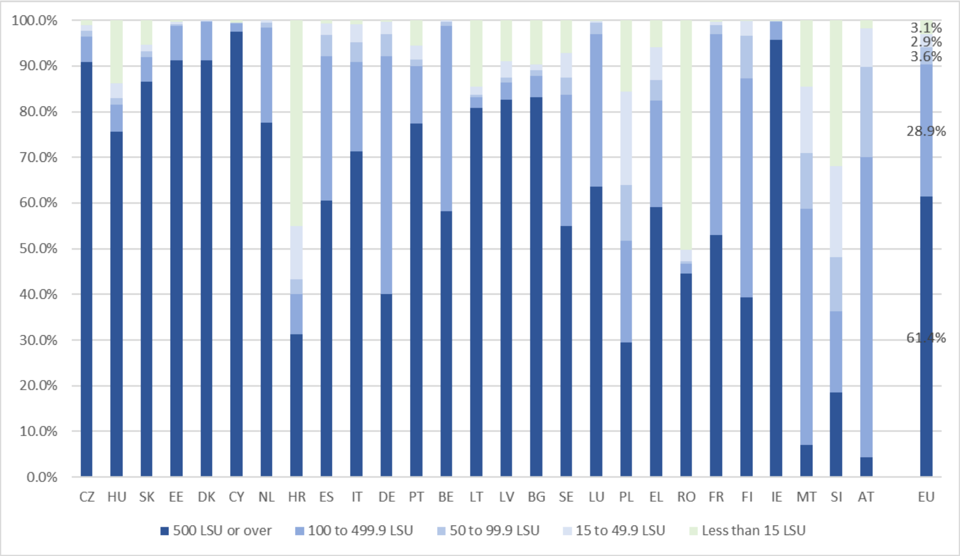


Figure A4.2: Distribution of CH₄ emissions by farm size in 2019 (only emissions from poultry)

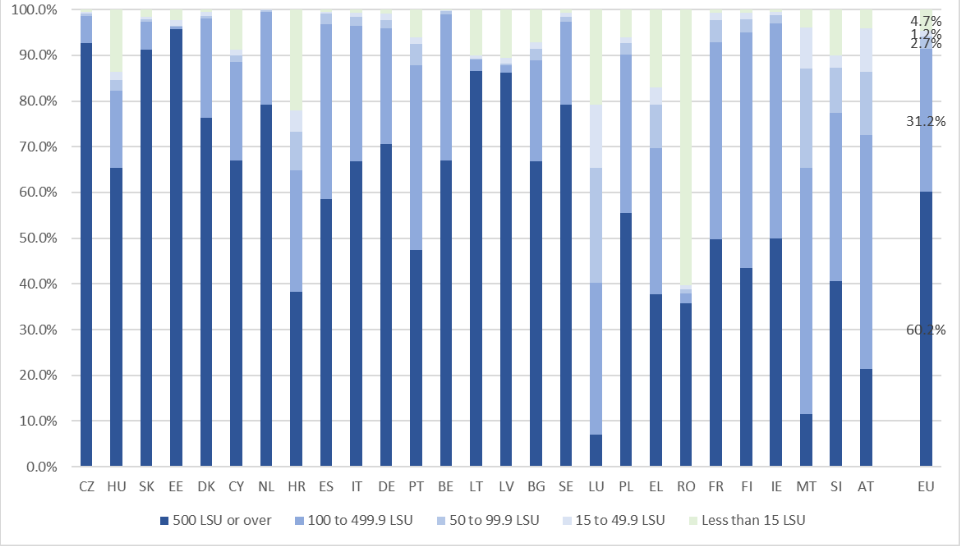


Figure A4.3: Distribution of CH_4 emissions by farm size in 2019 (only emissions from sheep)

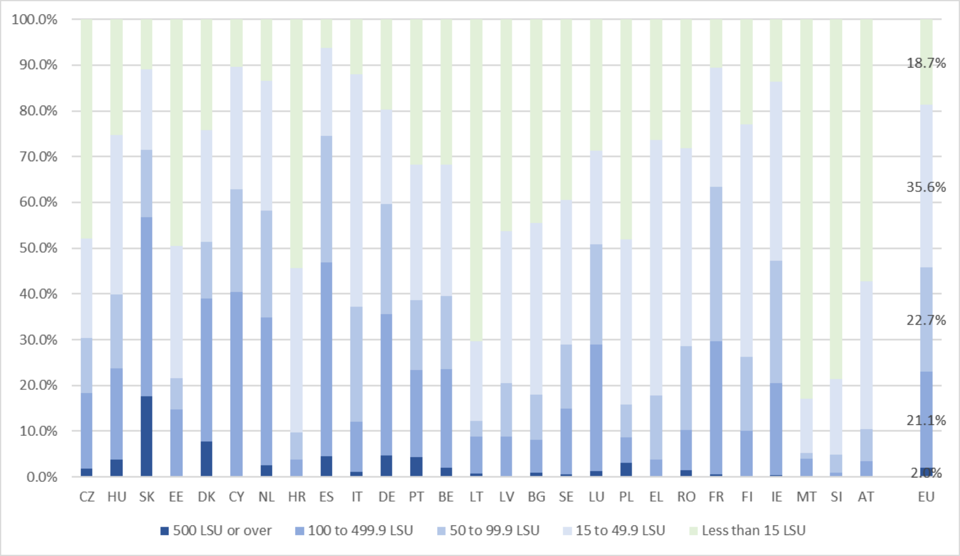
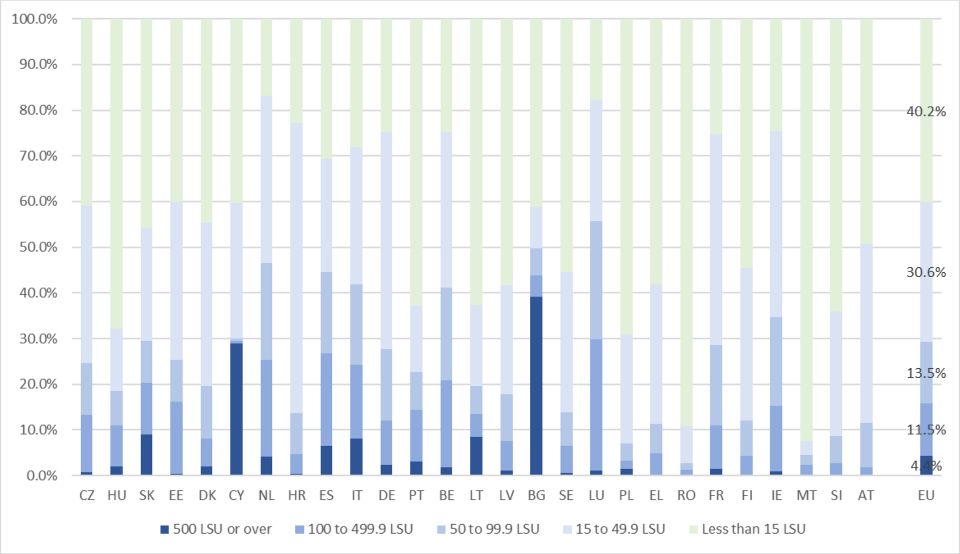
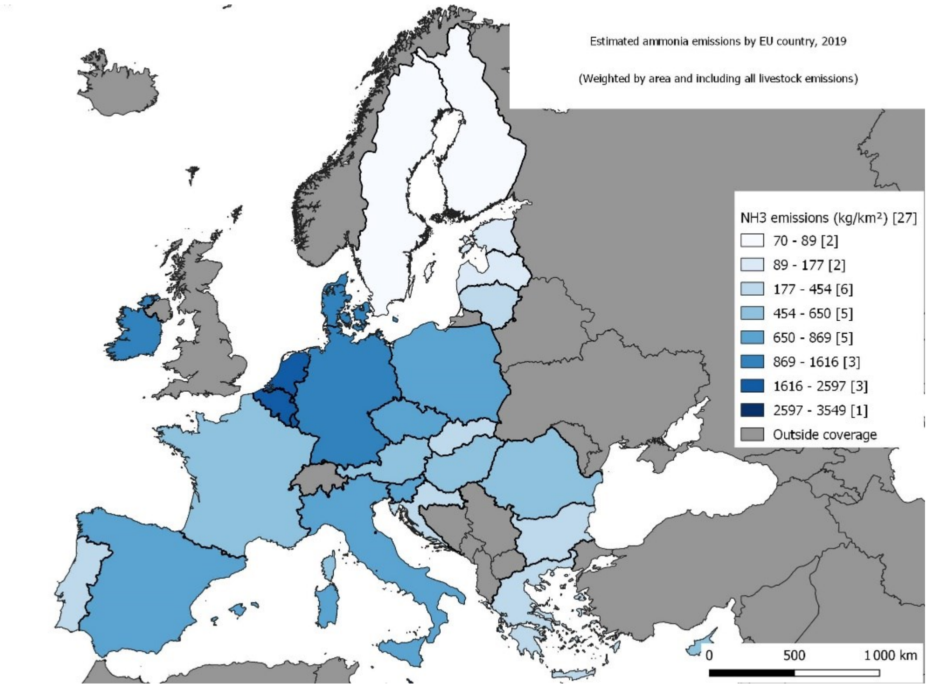


Figure A4.4: Distribution of CH_4 emissions by farm size in 2019 (only emissions from equidae)

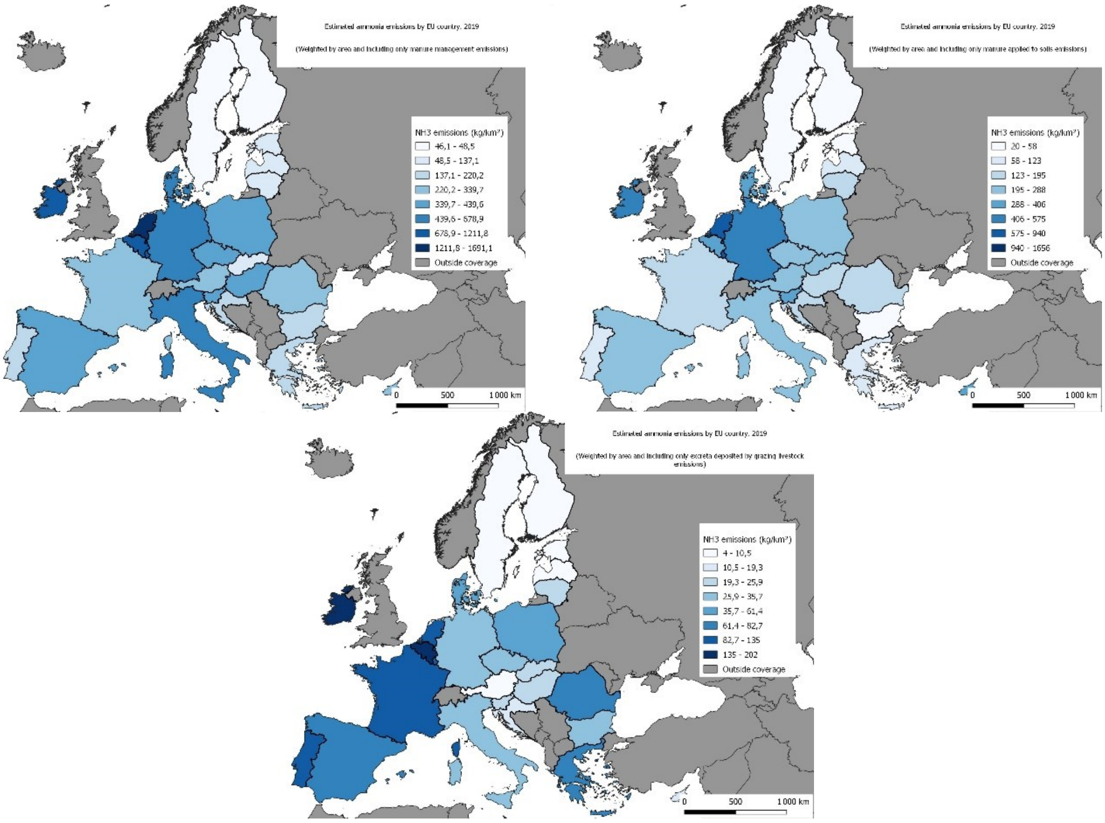


Annex 5 Maps of estimated ammonia emissions by EU country from livestock - Weighted by area

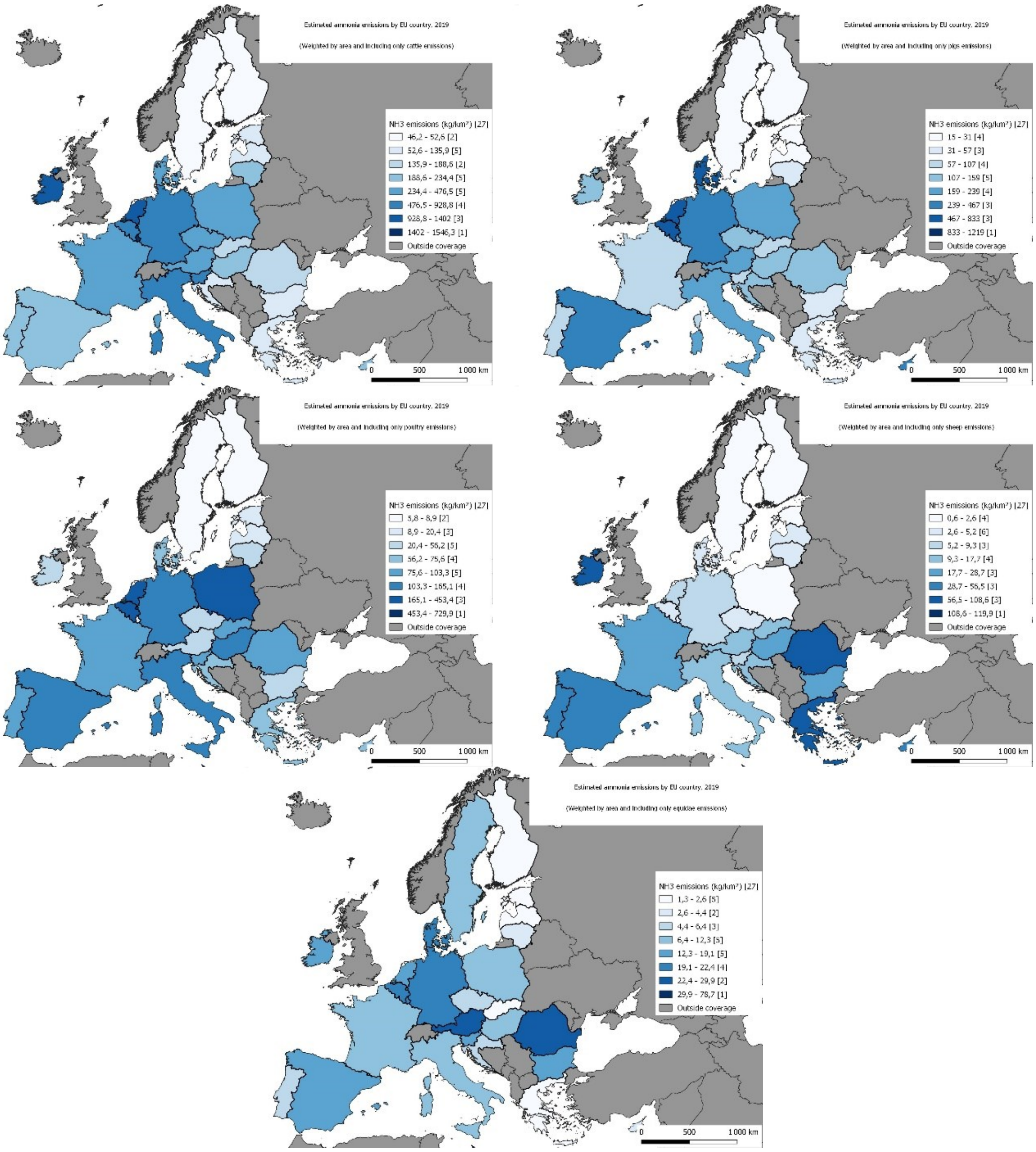
Map A5.1: Map of estimated ammonia emissions by EU country from all livestock in 2019 – weighted by area (kg/km²)



Map A5.2: Map of estimated ammonia emissions by EU country from respectively manure management activities, manure applied to soils and excreta deposited by grazing livestock in 2019 – weighted by area (kg/km²)

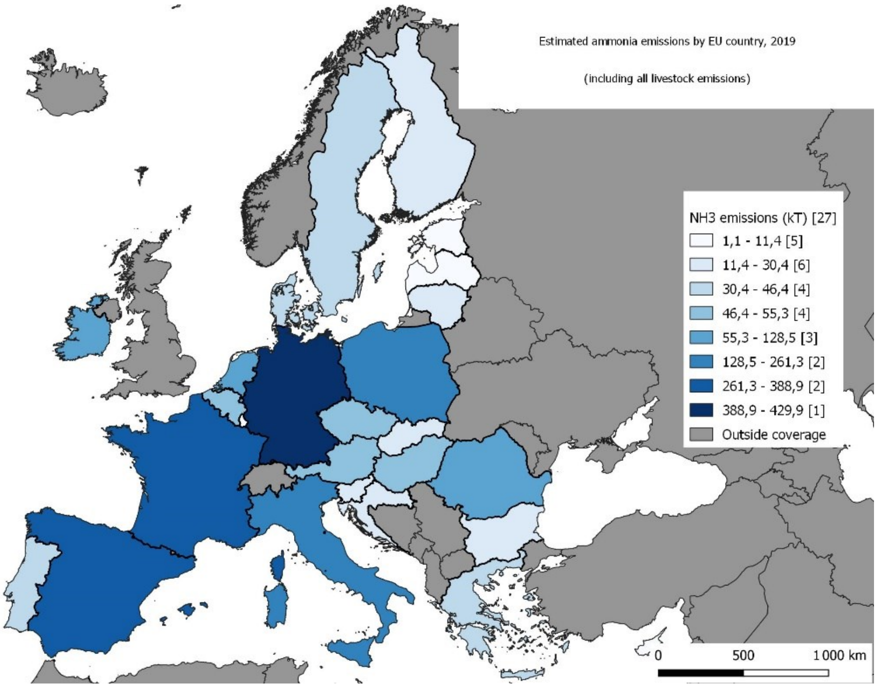


Map A5.3: Map of estimated ammonia emissions by EU country from respectively cattle, pigs, poultry, sheep and equidae activities in 2019 – weighted by area (kg/km²)

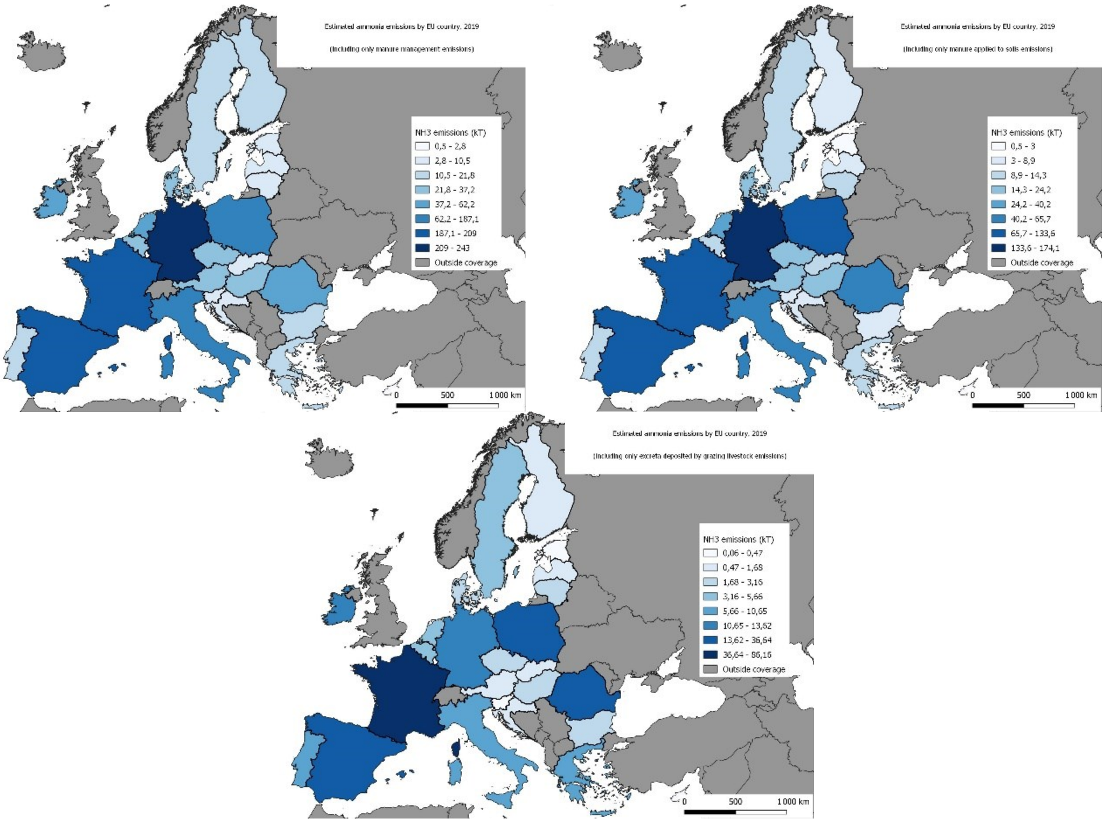


Annex 6 Maps of estimated ammonia emissions by EU country from livestock

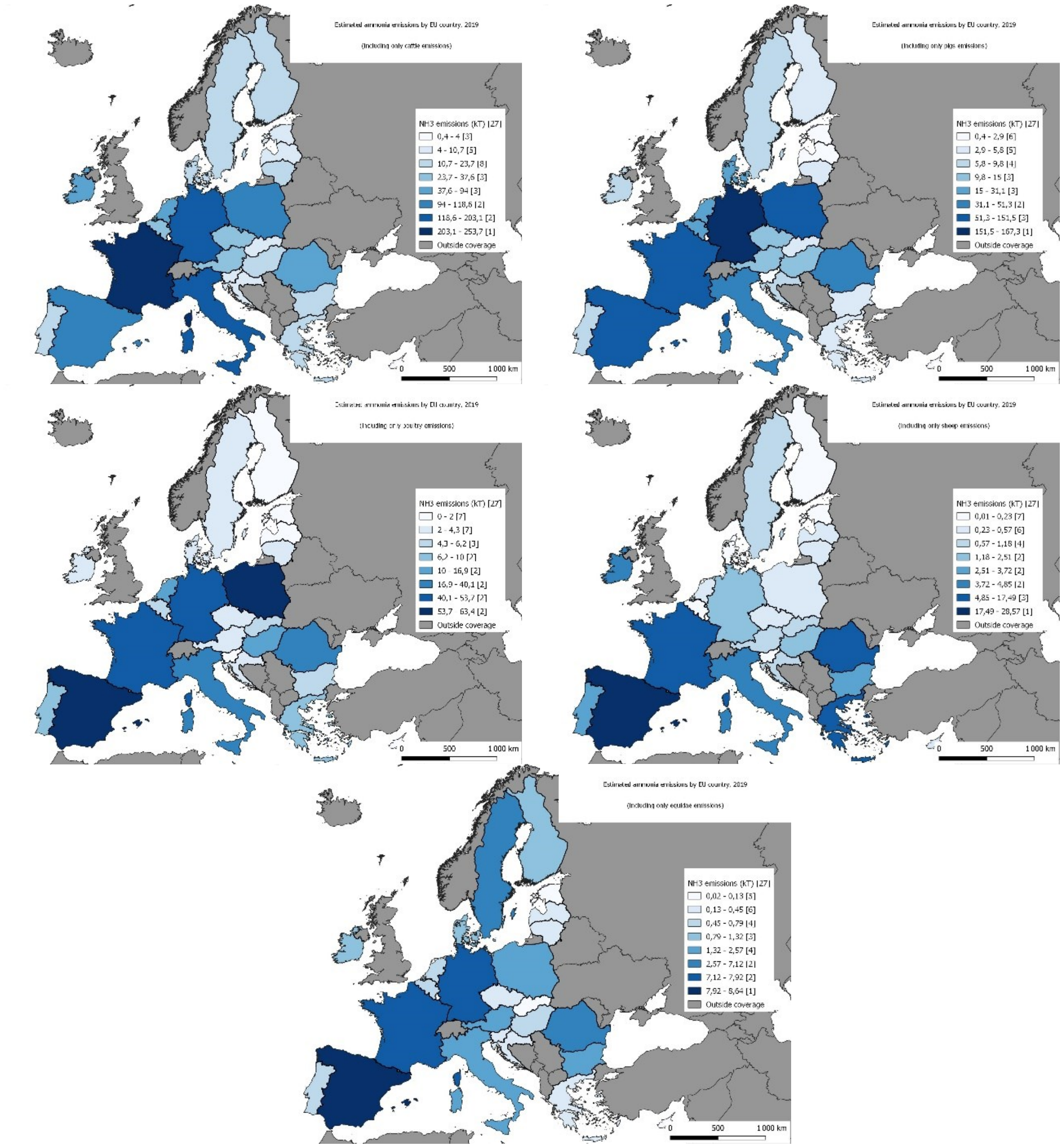
Map A6.1: Map of estimated ammonia emissions by EU country from all livestock in 2019 – (kT)



Map A6.2: Map of estimated ammonia emissions by EU country from respectively manure management activities, manure applied to soils and excreta deposited by grazing livestock activities in 2019 – (kT)

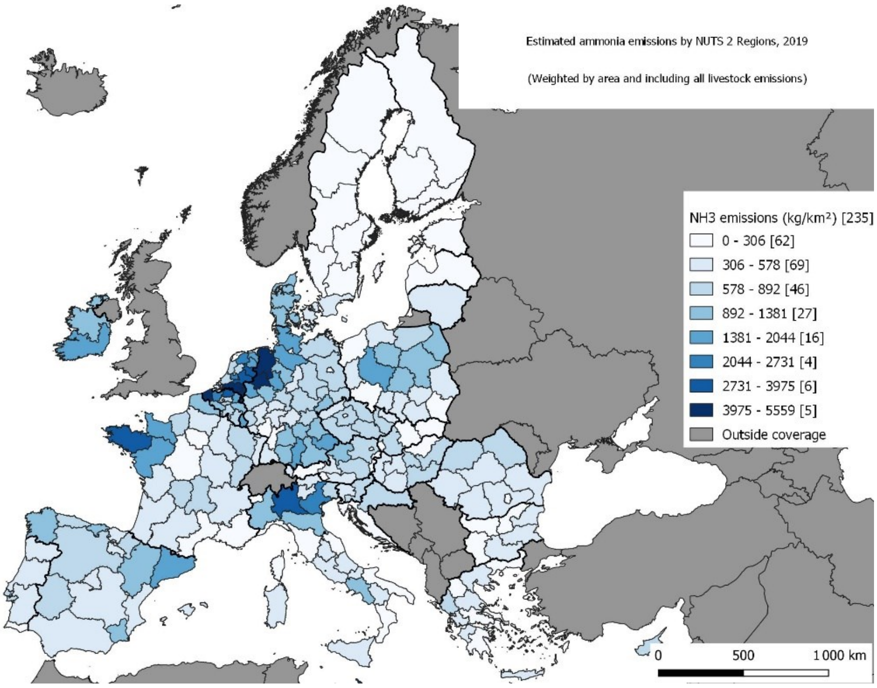


Map A6.4: Map of estimated ammonia emissions by EU country from respectively cattle, pigs, poultry, sheep and equidae activities in 2019 – (kT)

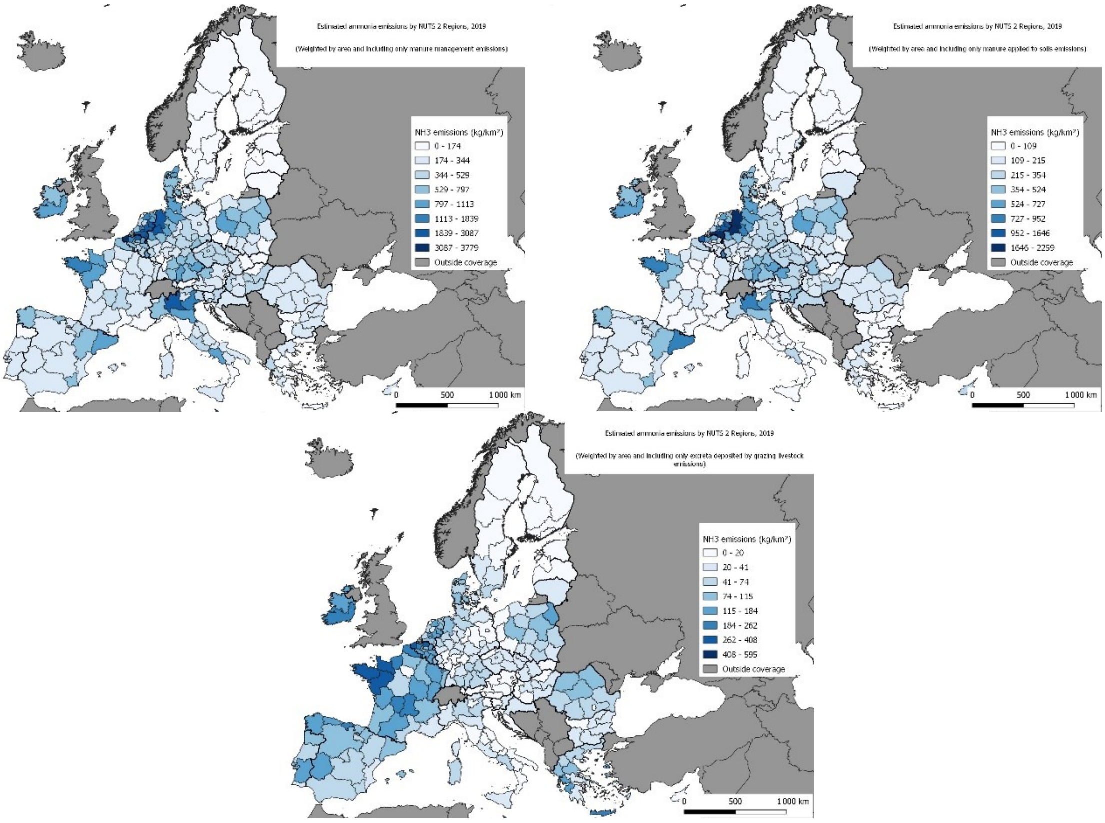


Annex 7 Maps of estimated ammonia emissions by NUTS 2 region from livestock - Weighted by area

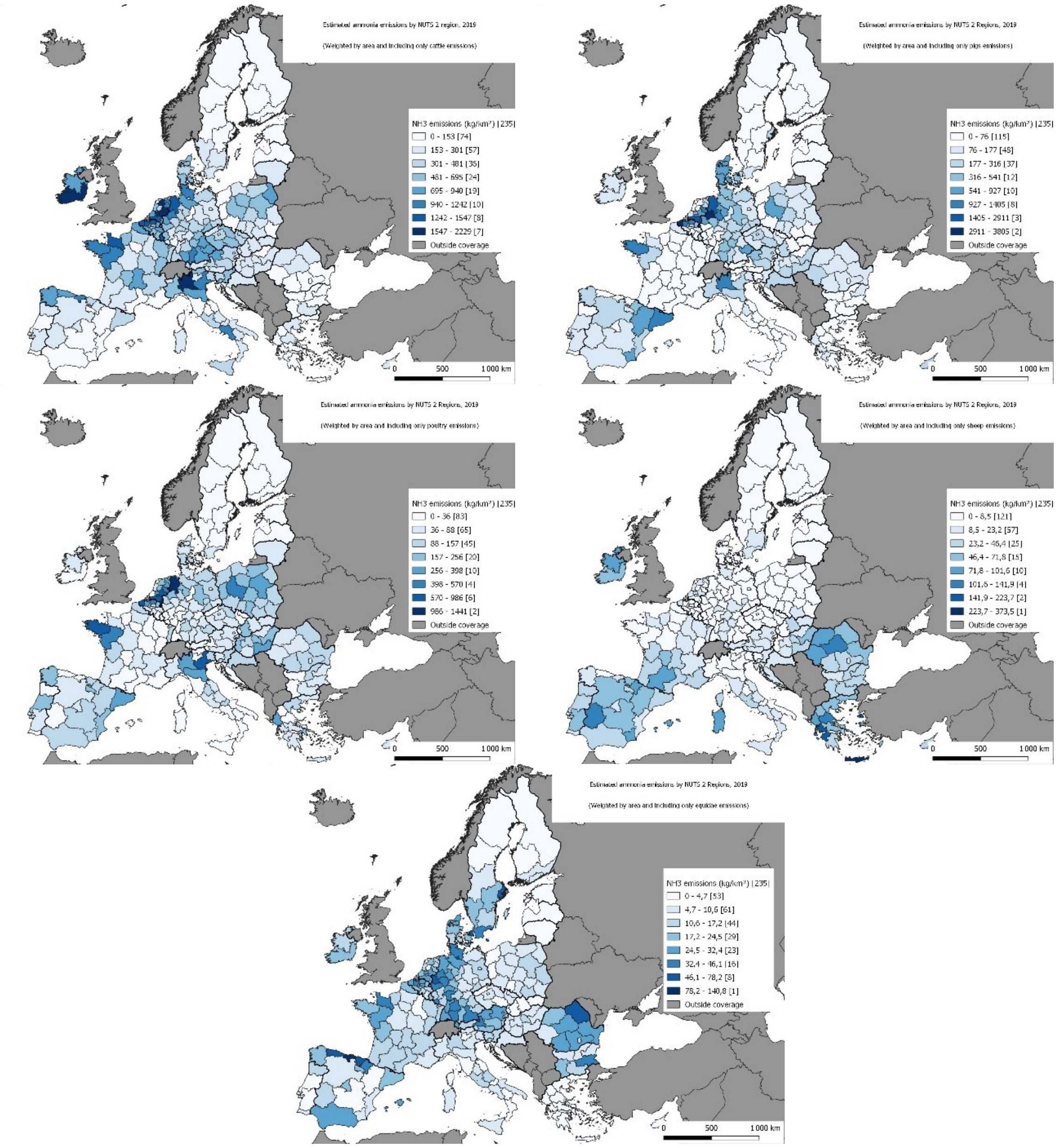
Map A7.1: Map of estimated ammonia emissions by NUTS 2 region from all livestock in 2019 – weighted by area (kg/km²)



Map A7.2: Map of estimated ammonia emissions by NUTS 2 region from respectively manure management activities, manure applied to soils and excreta deposited by grazing livestock activities in 2019 – weighted by area (kg/km²)

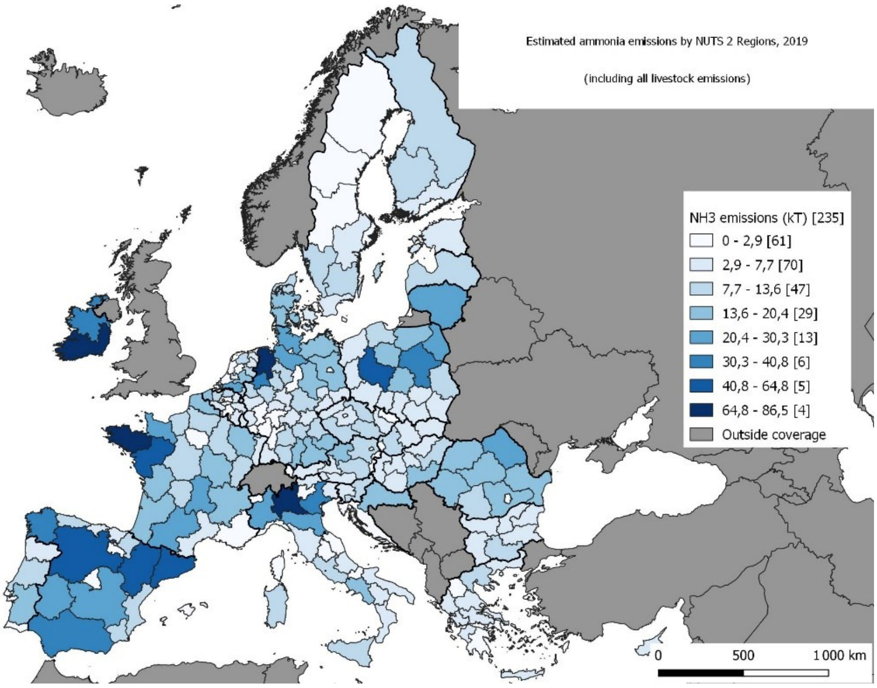


Map A7.4: Map of estimated ammonia emissions by NUTS 2 region from cattle, pigs, poultry, sheep and equidae activities in 2019 – weighted by area (kg/km^2)

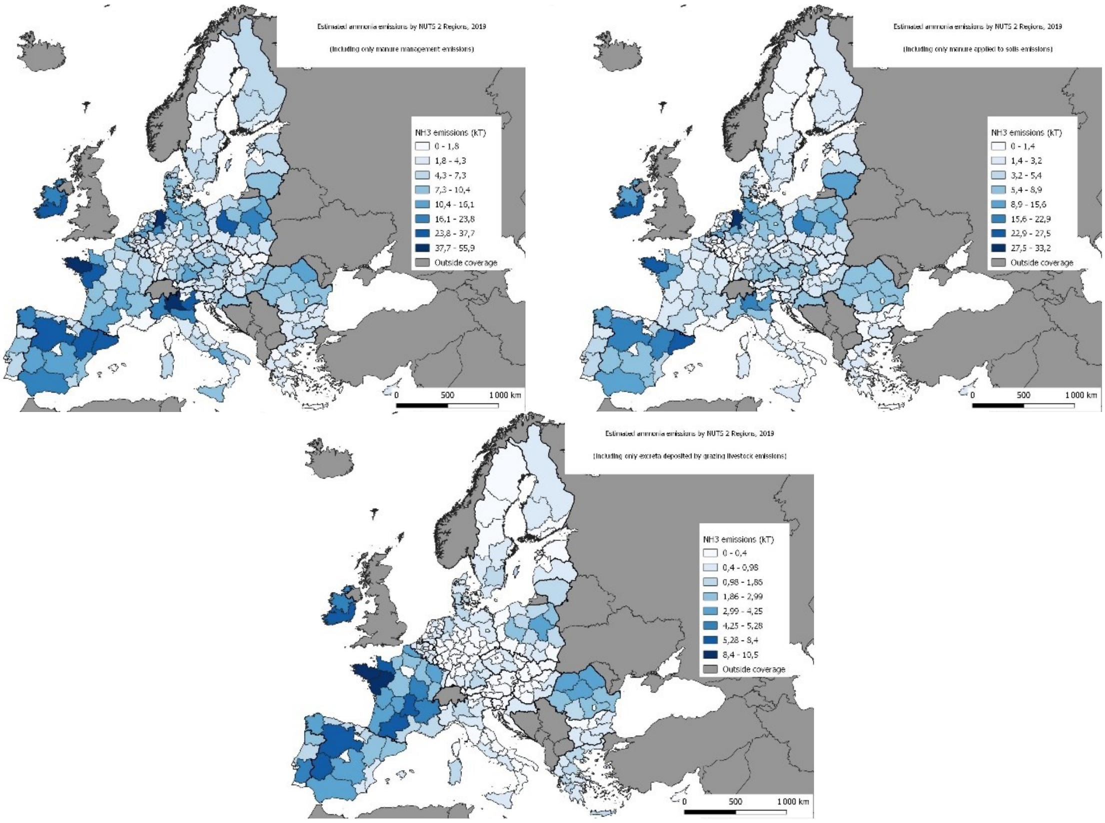


Annex 8 Maps of estimated ammonia emissions by NUTS 2 region from livestock

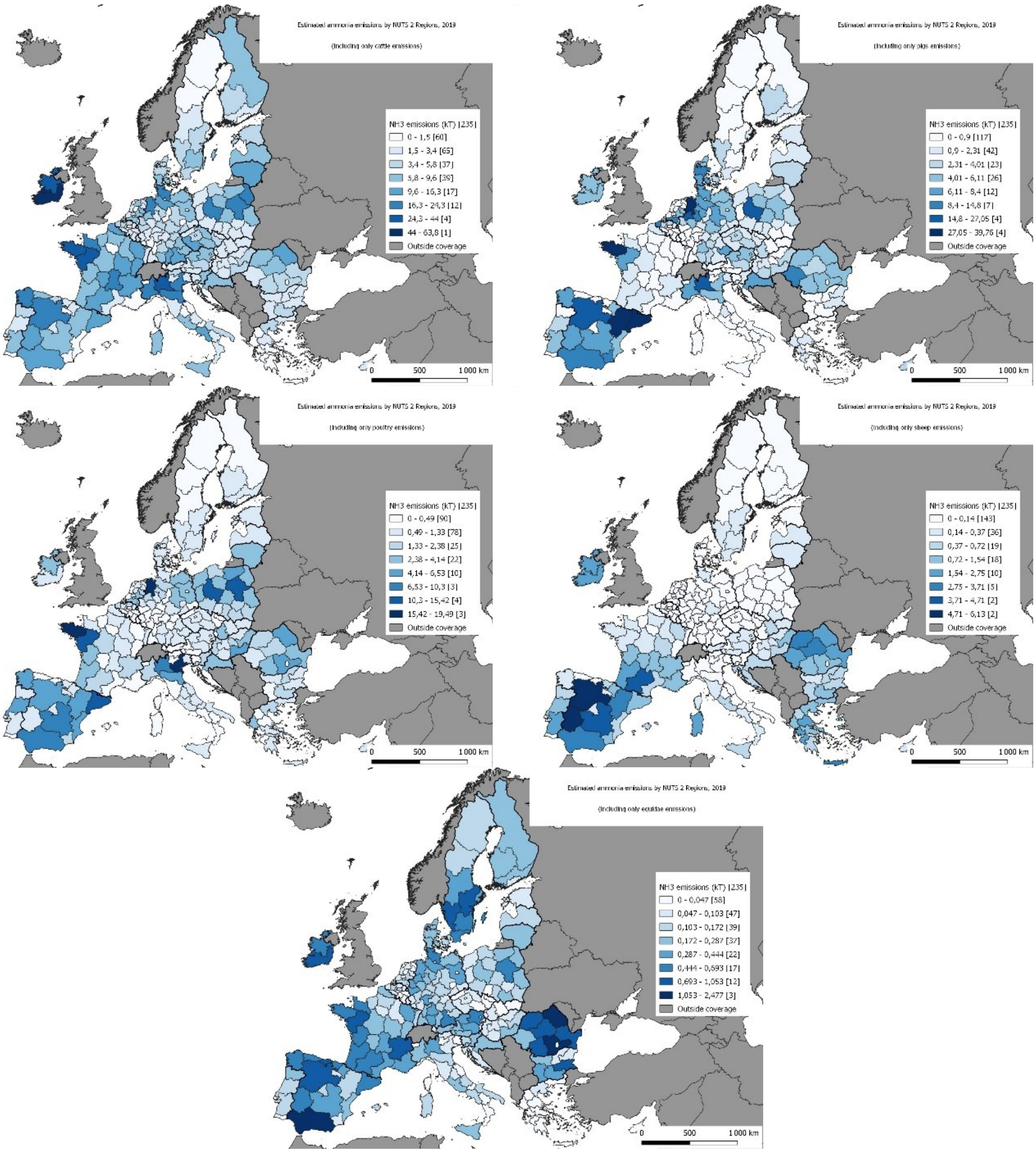
Map A8.1: Map of estimated ammonia emissions by NUTS2 region from livestock in 2019 – (kT)



Map A8.2: Map of estimated ammonia emissions by NUTS2 region from respectively manure management activities, manure applied to soils and excreta deposited by grazing livestock activities in 2019 – (kT)

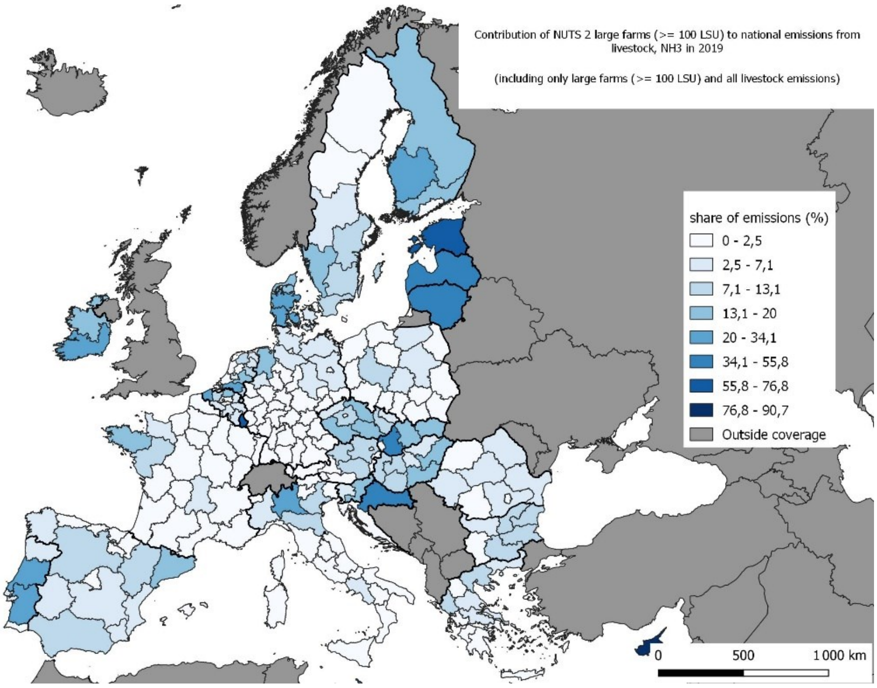


Map A8.3: Map of estimated ammonia emissions by NUTS2 region from respectively cattle, pigs, poultry, sheep and equidae activities in 2019 – (kT)

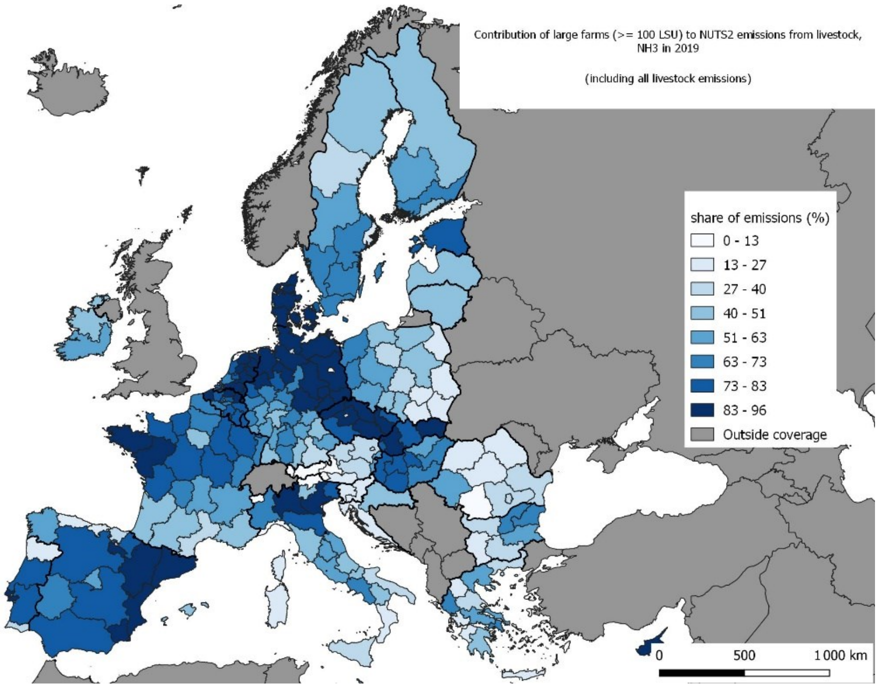


Annex 9 Maps of contribution of large farms to ammonia emissions

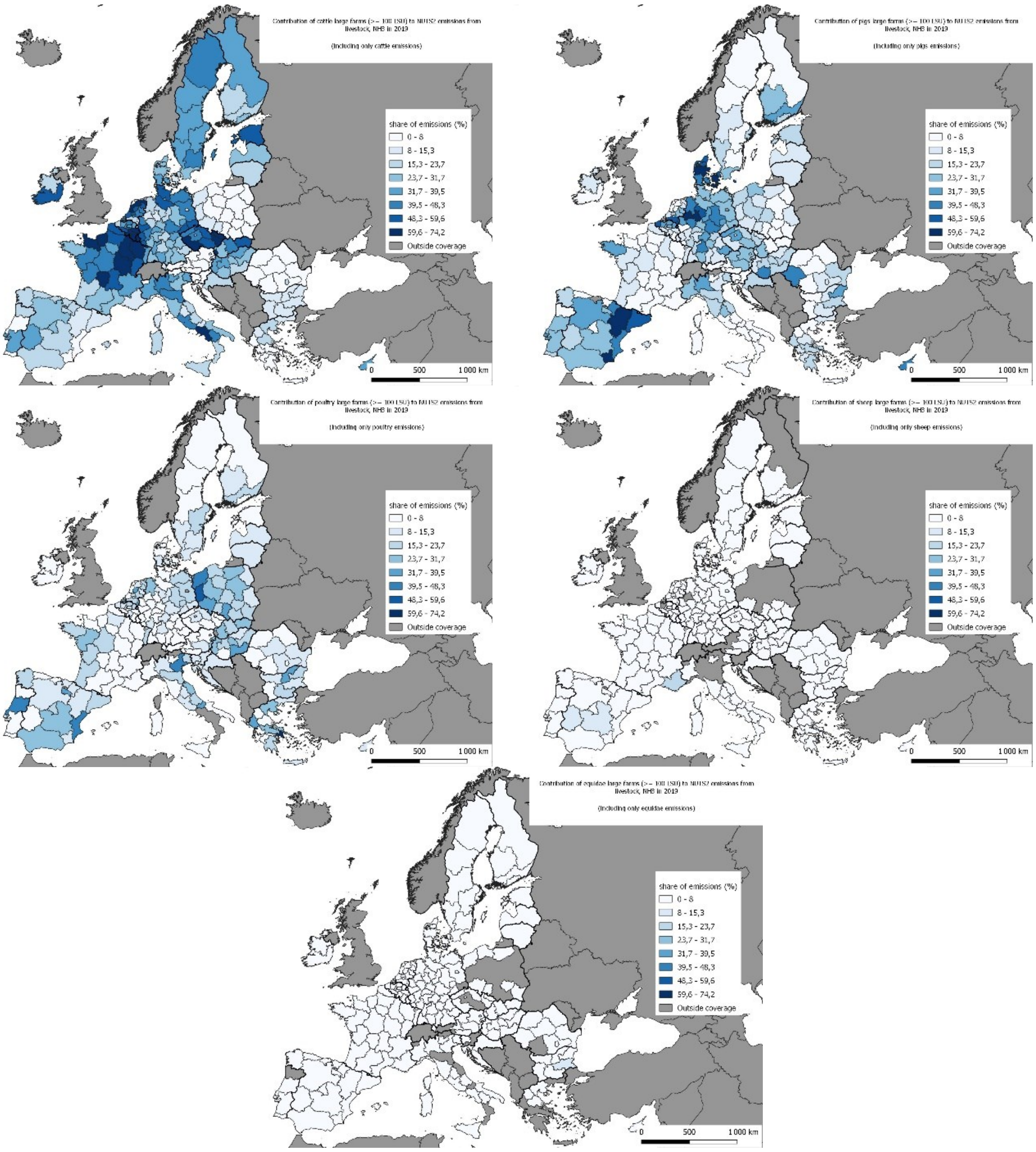
Map A9.1: Contribution of NUTS 2 large farms (>= 100 LSU) to national emissions from livestock, NH_3 in 2019 – (%)



Map A9.2: Contribution of large farms (>= 100 LSU) to NUTS2 emissions from livestock, NH_3 in 2019– (%)

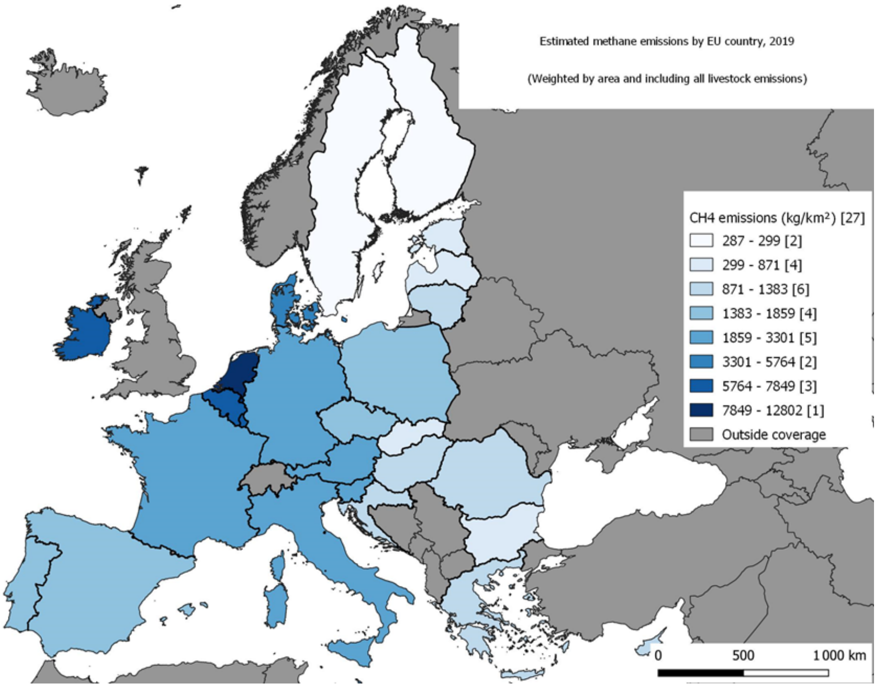


Maps A9.3: Contribution of large farms (>= 100 LSU) to NUTS2 emissions from livestock, NH_3 in 2019– (%) - Detailed by species: cattle, pigs, poultry, sheep, equidae

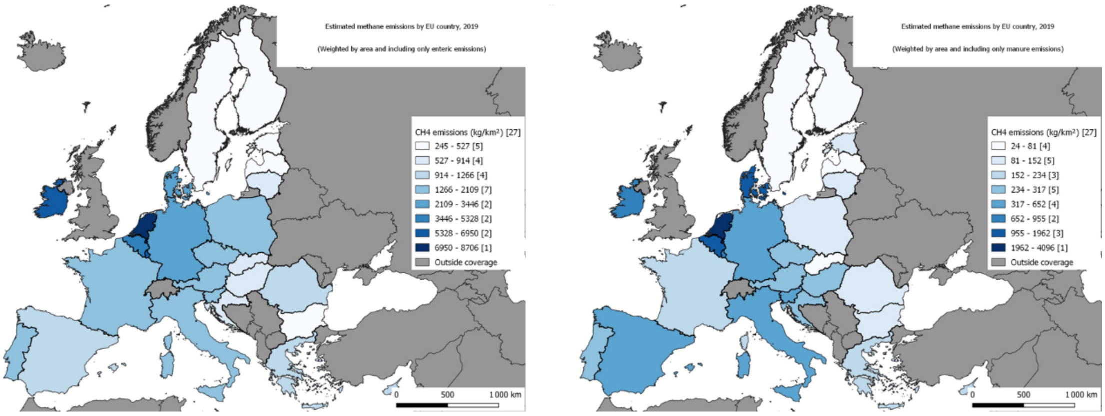


Annex 10 Maps of estimated methane emissions by EU country from livestock - Weighted by area

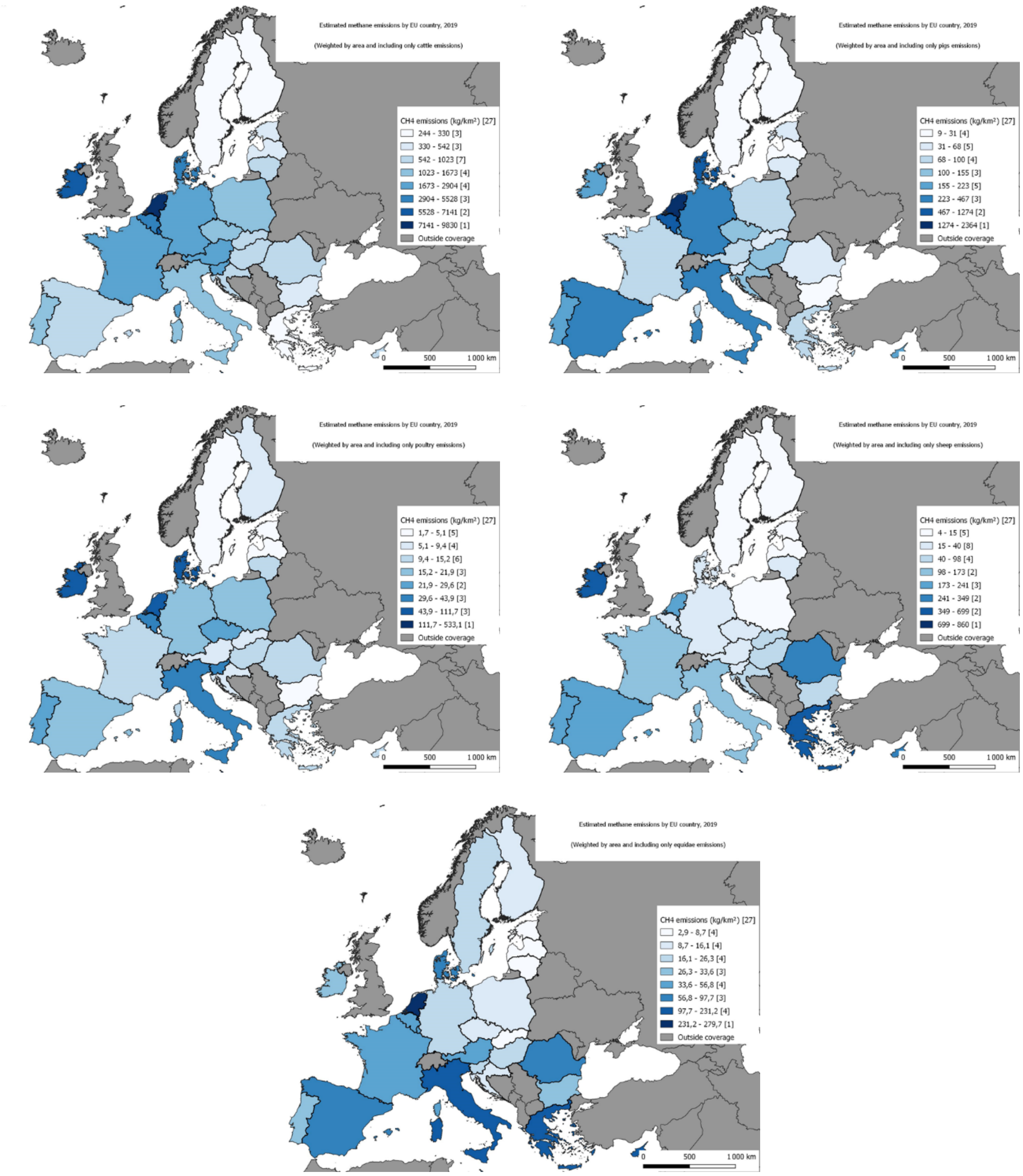
Map A10.1: Map of estimated methane emissions by EU country from all livestock in 2019 – weighted by area (kg/km²)



Map A10.2: Map of estimated methane emissions by EU country from respectively enteric and manure management activities in 2019 – weighted by area (kg/km²)

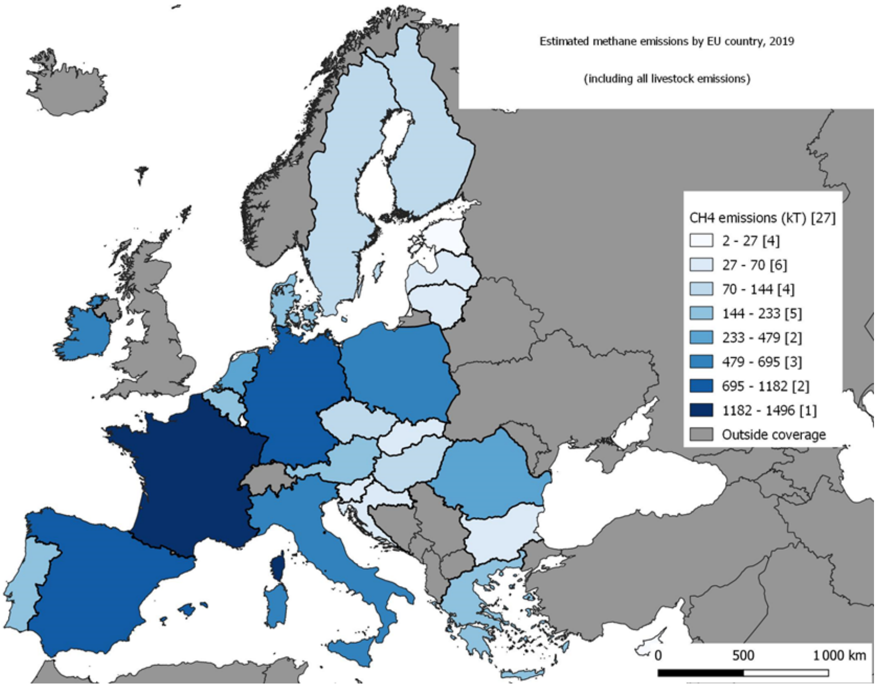


Map A10.3: Map of estimated methane emissions by EU country from respectively cattle, pigs, poultry, sheep and equidae activities in 2019 – weighted by area (kg/km²)

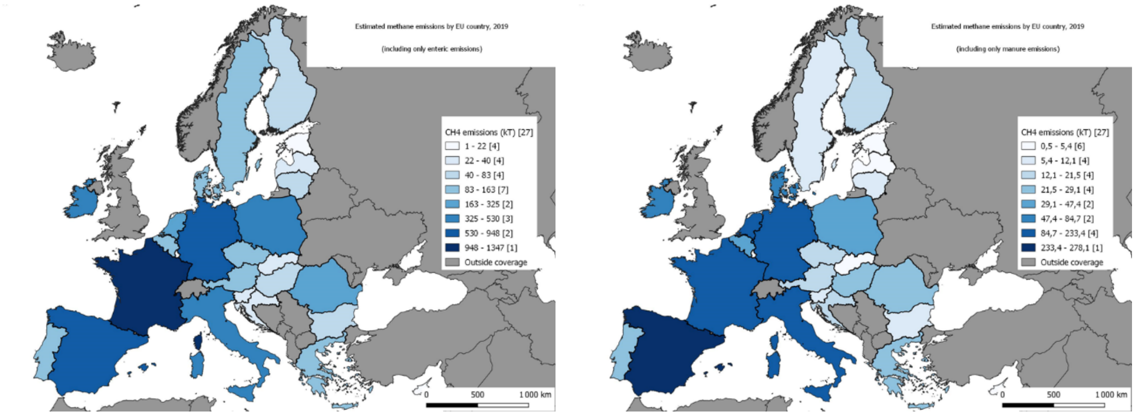


Annex 11 Maps of estimated methane emissions by EU country from livestock

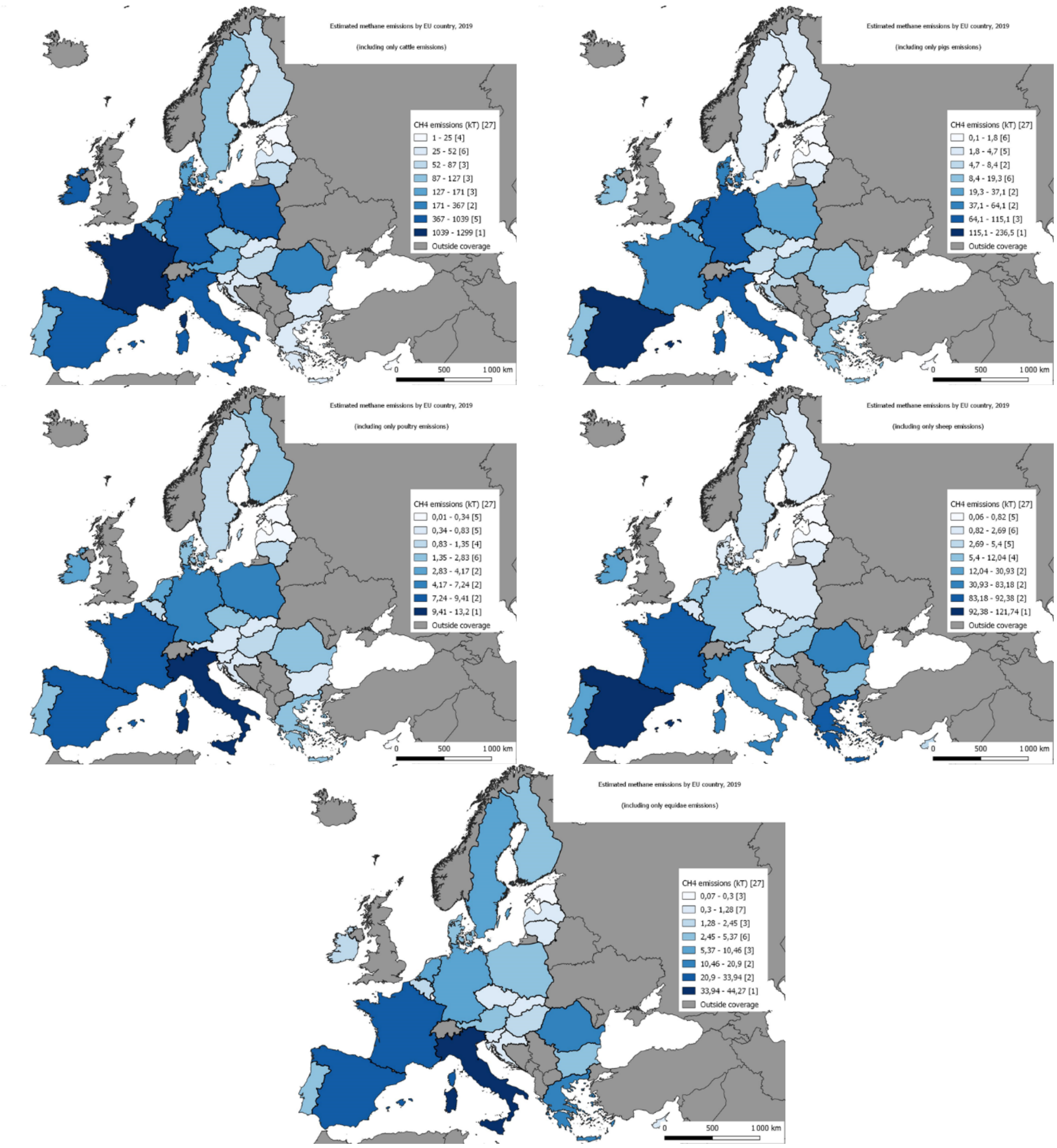
Map A11.1: Map of estimated methane emissions by EU country from all livestock in 2019 – (kT)



Map A11.2: Map of estimated methane emissions by EU country from respectively enteric and manure management activities in 2019 – (kT)

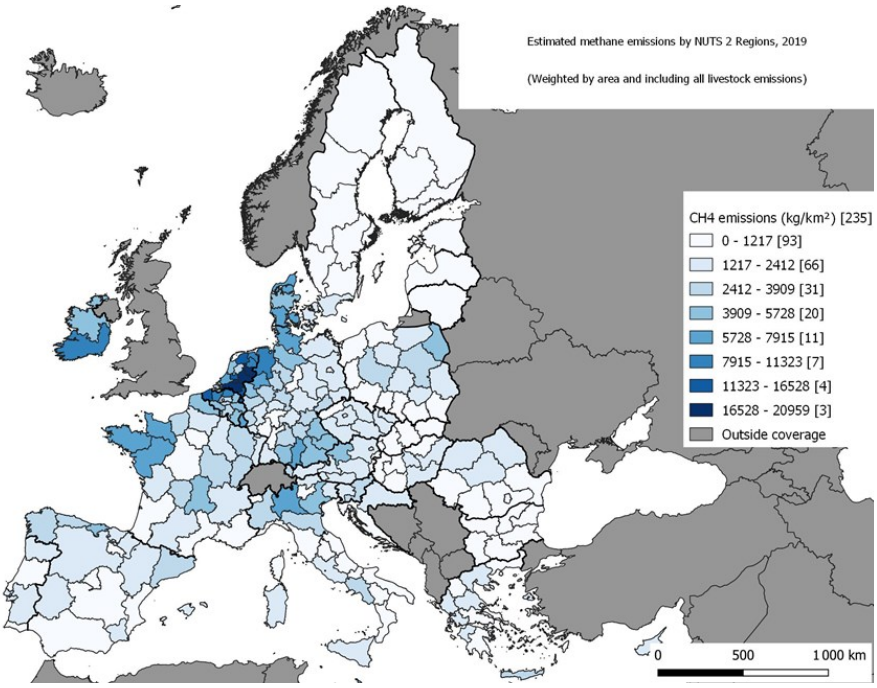


Map A11.3: Map of estimated methane emissions by EU country from respectively cattle, pigs, poultry, sheep and equidae activities in 2019 – (kT)

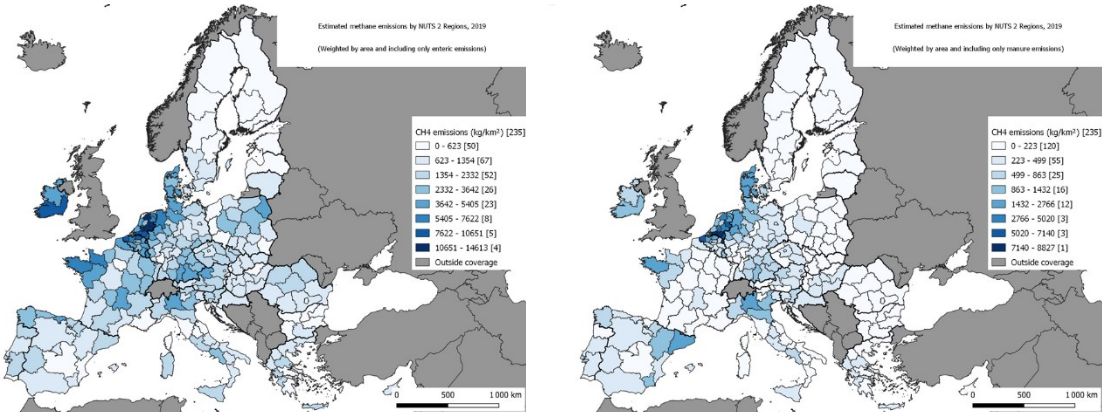


Annex 12 Maps of estimated methane emissions by NUTS 2 region from livestock - Weighted by area

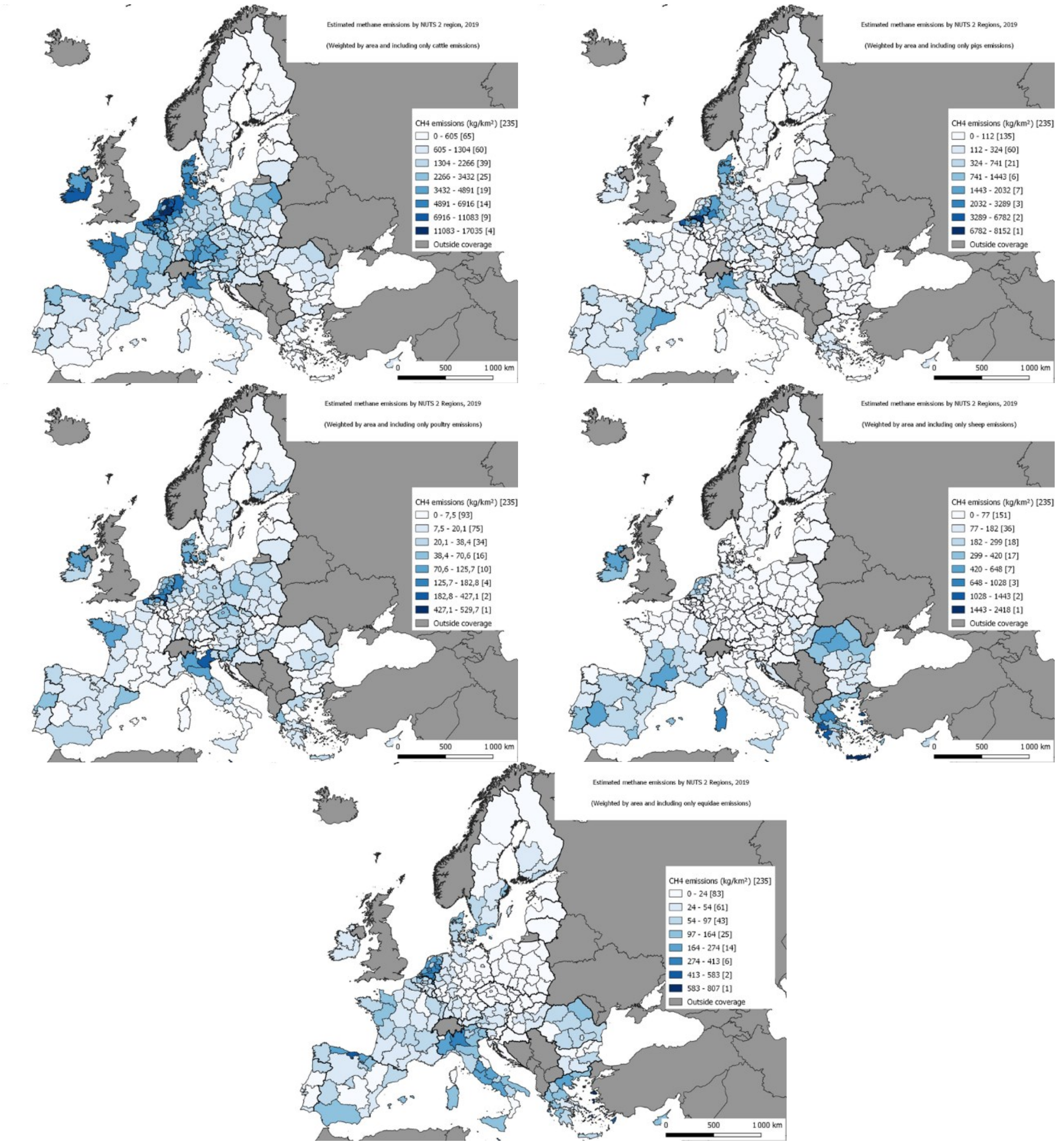
Map A12.1: Map of estimated methane emissions by NUTS 2 region from all livestock in 2019 – weighted by area (kg/km²)



Map A12.2: Map of estimated methane emissions by NUTS 2 region from respectively enteric and manure management activities in 2019 – weighted by area (kg/km²)

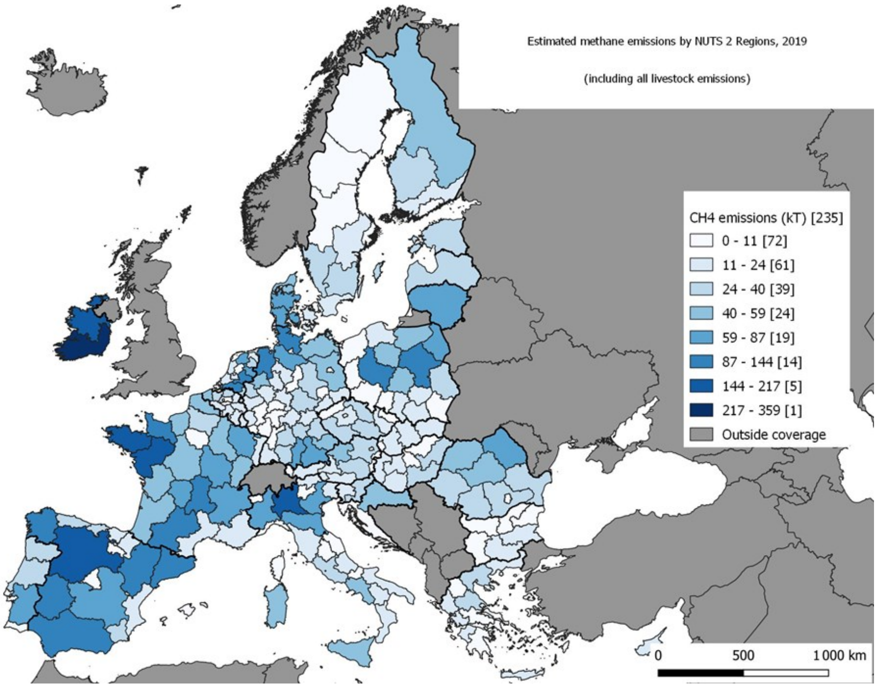


Map A12.3: Map of estimated methane emissions by NUTS 2 region from cattle, pigs, poultry, sheep and equidae activities in 2019 – weighted by area (kg/km²)

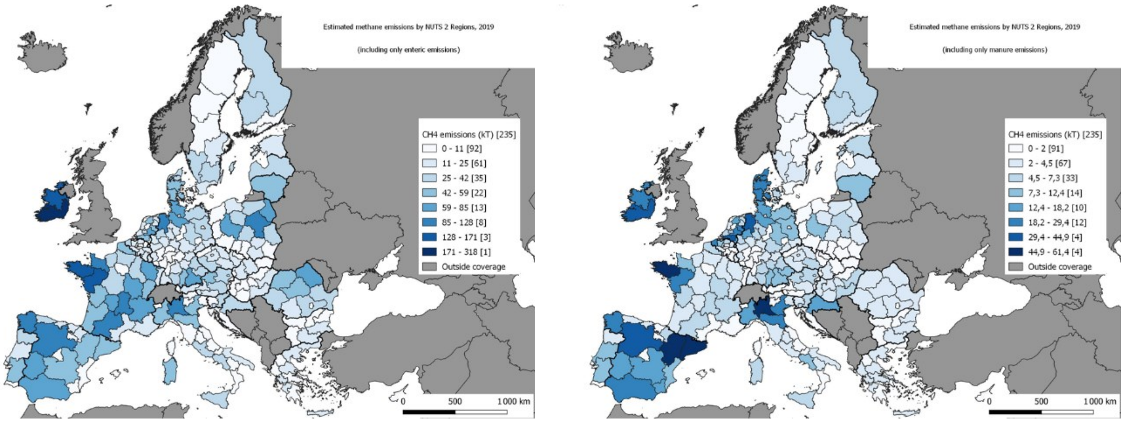


Annex 13 Maps of estimated methane emissions by NUTS 2 region from livestock

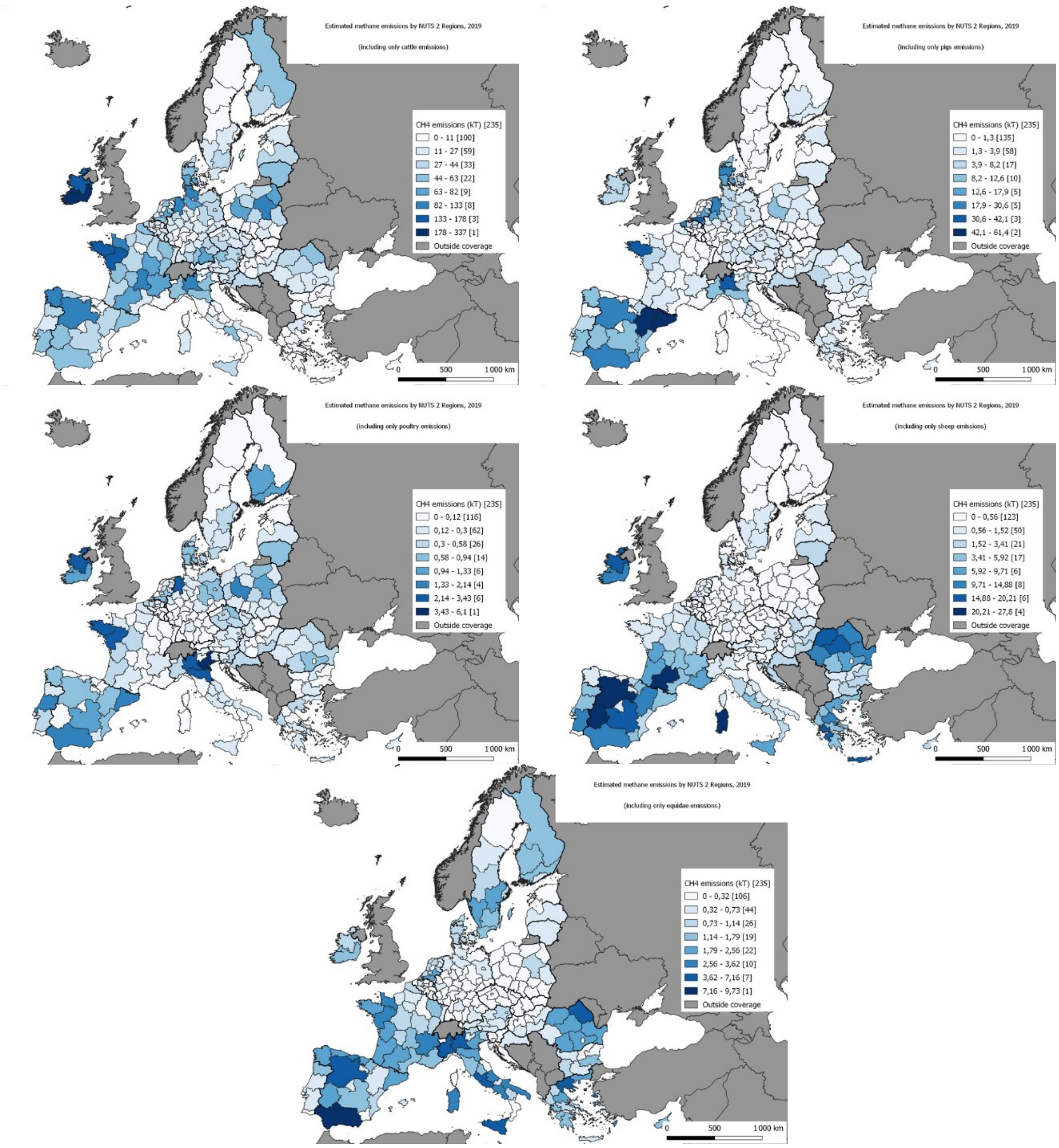
Map A13.1: Map of estimated methane emissions by NUTS2 region from livestock in 2019 – (kT)



Map A13.2: Map of estimated methane emissions by NUTS2 region from respectively enteric and manure management activities in 2019 – (kT)

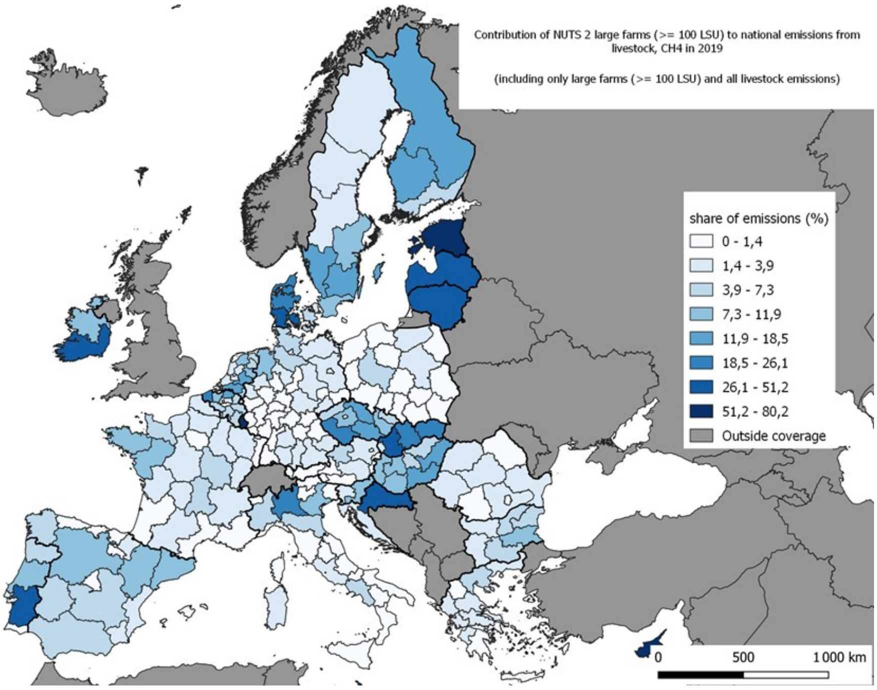


Map A13.3: Map of estimated methane emissions by NUTS2 region from respectively cattle, pigs, poultry, sheep and equidae activities in 2019 – (kT)

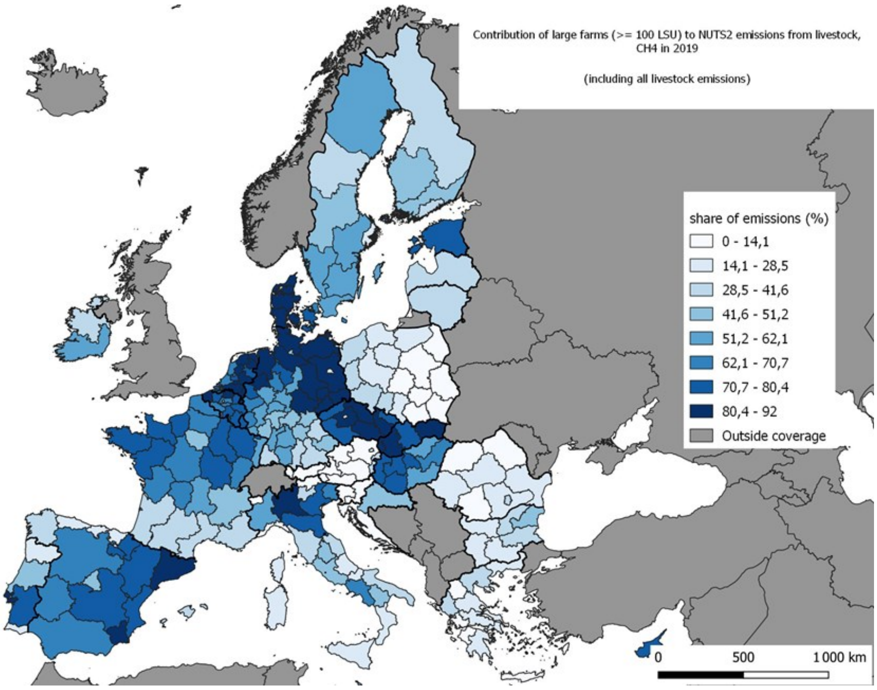


Annex 14 Maps of contribution of large farms to methane emissions

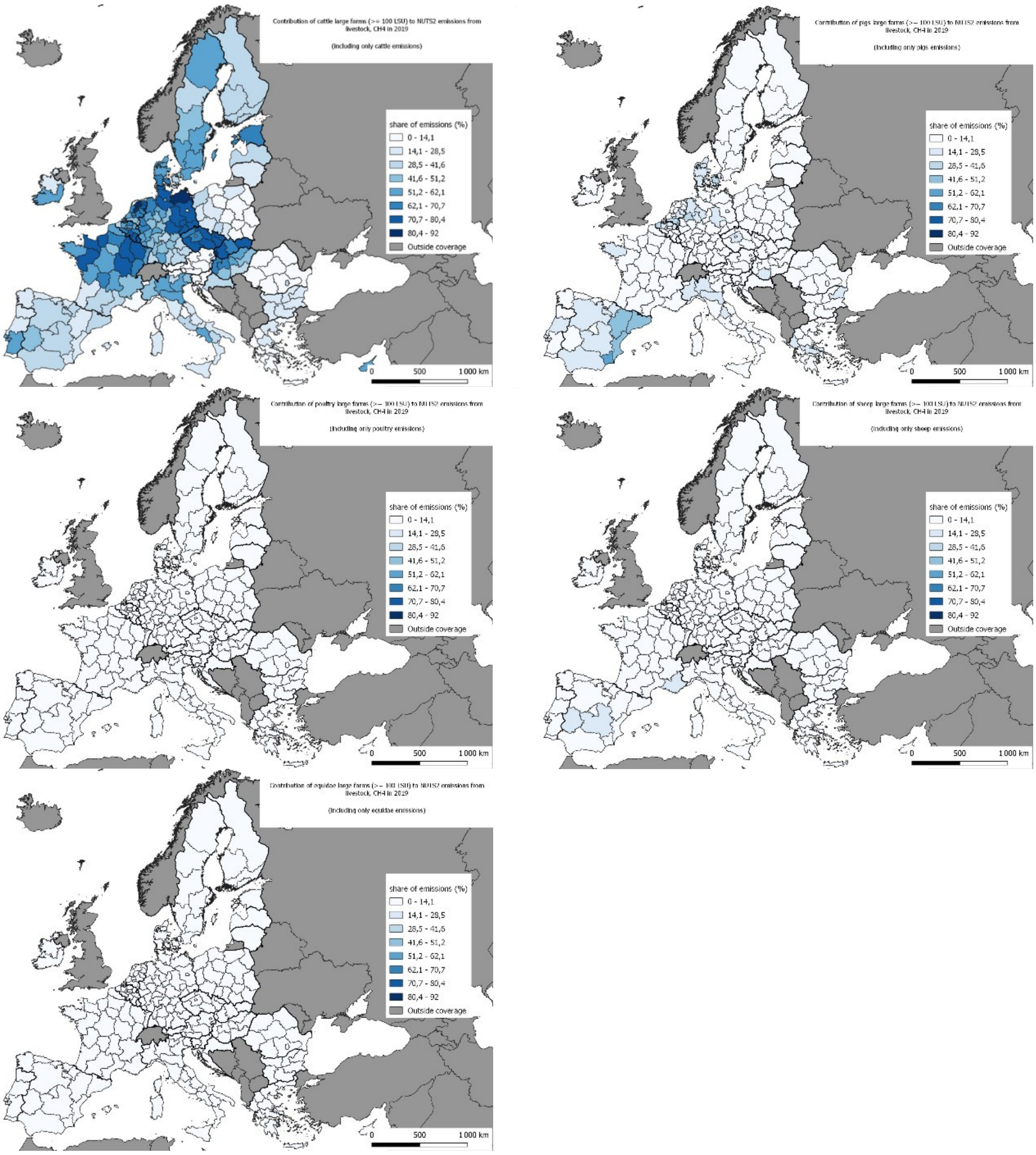
Map A14.1: Contribution of NUTS 2 large farms (>= 100 LSU) to national emissions from livestock, CH_4 in 2019 – (%)



Map A14.2: Contribution of large farms (>= 100 LSU) to NUTS2 emissions from livestock, CH_4 in 2019– (%)



Maps A14.3: Contribution of large farms (>= 100 LSU) to NUTS2 emissions from livestock, CH_4 in 2019– (%) - Detailed by species: cattle, pigs, poultry, sheep, equidae



Annex 15 Methodology developed in the MethanEmis project to assess CH_4 emissions from agricultural installations

Monitoring

Equipment for environmental measurements

The monitoring of methane levels was carried out by Ineris, using an analyser based on an optical spectroscopy method known as "Cavity Ringdown Spectroscopy" (CRDS) (Photo A15.1). This optical technique allows the continuous monitoring of methane concentrations with an accuracy of a few ppb (10-3 ppm) for acquisition frequencies of the order of Hz.

Equipment for monitoring environmental conditions

As the levels measured in the environment are linked to various meteorological phenomena (wind speed, precipitation, atmospheric stability...), a complete meteorological station was deployed and allowed the measurement of the main environmental parameters during each campaign (wind direction and speed, rainfall, temperature and pressure at a height of 10 meters). This station made it possible to monitor local meteorological conditions, which constituted input data for the numerical modeling. The measurement point was located approximately 50 to 100 meters from the first storage structure, depending on the site. The location was defined as a compromise between the most favourable wind directions for the measurements (under the winds of the methanisation activities) and the security of the equipment.

Photo A15.1: Illustration of the measurement devices deployed during the MethanEmis project

Detection and quantification of leaks

The fugitive emissions measurements were carried out by the ECS laboratory during specific campaigns lasting a few days. All equipment and pipelines were inspected using an infrared camera (FLIR GF320), a portable TDLAS detector and a flame ionization detection (FID) analyser to search for leaks and ensure that they were indeed associated with methane emissions.

The various methods make it possible to investigate all types of structures and to adapt to all possible measurement configurations, one of the difficulties residing, for example, in the detection of leaks at the level of structure covers. As an example, Photo A15.2 illustrates some of the interventions during the different measurement campaigns presented below.

Photo A15.2: Leak detection measurements; confirmation of a biogas leak by FID

Quantification of the emissions from co-generation engines

Engine emissions were monitored before and after adjustment of the combustion conditions of the

engines. These adjustments are made by the motor supplier on average every 1,600 to 2,000 hours of operation. All measurements were carried out in nominal operation of the motors.

NOx, CO2, CO, NMVOC, CH_4 and formaldehyde were measured by Ineris over a period of one day in order to better understand the share of unburned CH_4 emitted and to characterize initial engine operation.

Inverse modelling

The purpose of each campaign was to indirectly estimate CH_4 emissions associated to the identified but not quantified sources on the methanisation installation (diffuse sources and specific activities), and to correlate the detected events (point emissions of high intensity) with the site operation situations.

The inverse modelling method (successive approximation method) appeared to be a suitable approach to meet these objectives and was chosen for the first time in this context of anaerobic digestion facilities. For this purpose, the periods to be modelled had to be carefully selected (see Annex 15 on data pre-processing).

The inverse or near-field method consists in simulating the dispersion of a pollutant plume associated with a source, comparing the pollutant concentrations calculated by the model to those measured in the field and adjusting the emission flux so that the model results match the measurements. The choice of the model is mainly determined by the configuration of the site studied. In the case of a site characterized by a weak (or even non-existent) topography, elementary pollutant emission sources and far from any building, a Gaussian model can be used. For more complex sites with a significant topography, complex sources and located near buildings that can influence the flow, a Lagrangian model is preferable. This type of model allows for a realistic representation of the flow taking into account all the characteristics of the site. This method has been applied, for example, in the context of industrial discharges, for the estimation of NH_3 emissions associated with pig farms or to estimate the dispersion of particles in the case of bagasse fires in overseas territories.

The configuration of the sites to be modelled being complex, the Micro Swift Spray (MSS) Lagrangian model was used. This model allows a realistic estimation of the flow and concentrations of pollutants in the atmosphere at the local scale and indirectly a quick estimation of the emission fluxes. Details on the model and the methodology for pre-processing the data prior to the simulations are provided below.

The Lagrangian model

The Micro Swift Spray (MSS) Lagrangian model (Moussafir et al., 2004; Tinarelli et al., 2007) developed by Aria Technologiques is designed to simulate the dispersion of gaseous or particulate pollutants in a complex environment (hilly terrain, presence of obstacles, etc.) on a spatial scale covering a square of 500 m to 50 km. MSS has been developed from the SPRAY Lagrangian model; it is integrated under the name of Ariacity as a plugin of the ArcGIS platform. MSS also integrates the Micro Swift wind field diagnostic model developed from the MINERVE meteorological preprocessor (Aria Technologies, 1995). The principle of a Lagrangian dispersion model is to mathematically track elementary volumes (also called virtual particles) of the plume as they move through the atmosphere. The advective displacement of these particles is computed from the knowledge of the atmospheric wind fields, their diffusive displacement being a statistical function related to the turbulence of the medium based on Thomson's (1987) formulation of the non-linear Langevin equations. The turbulence variables can be defined as model inputs, or possibly determined using an integrated model based on the surface layer and boundary layer profiles. These profiles are generated from standard meteorological inputs at ground level and the nature of these soils. The Lagrangian model determines the pollutant concentrations by compiling all the trajectories of a large number of particles in the plume.

Pre-processing of the data prior to the modelling

A pre-processing of the data was carried out before the modelling (Figure A15.1). To do this, data from the weather station and metrology devices are collected in the format specific to the device suppliers. In order to systematize the collection and processing process, a pre-processing tool was developed.

Once the different files are gathered, the tool imports the data, checks the integrity and quality of the information and then generates two databases, one for the meteorological parameters and the other for the measured concentrations.

A report is published to give a general overview of the meteorological conditions encountered during the campaign and the concentrations measured. In addition to the classical statistics (averages, medians, quartiles...), this report is the occasion to automatically generate and record the wind roses and the associated concentrations for each site. These roses are produced using the Openair package for R software (Carslaw and Ropkins 2012).

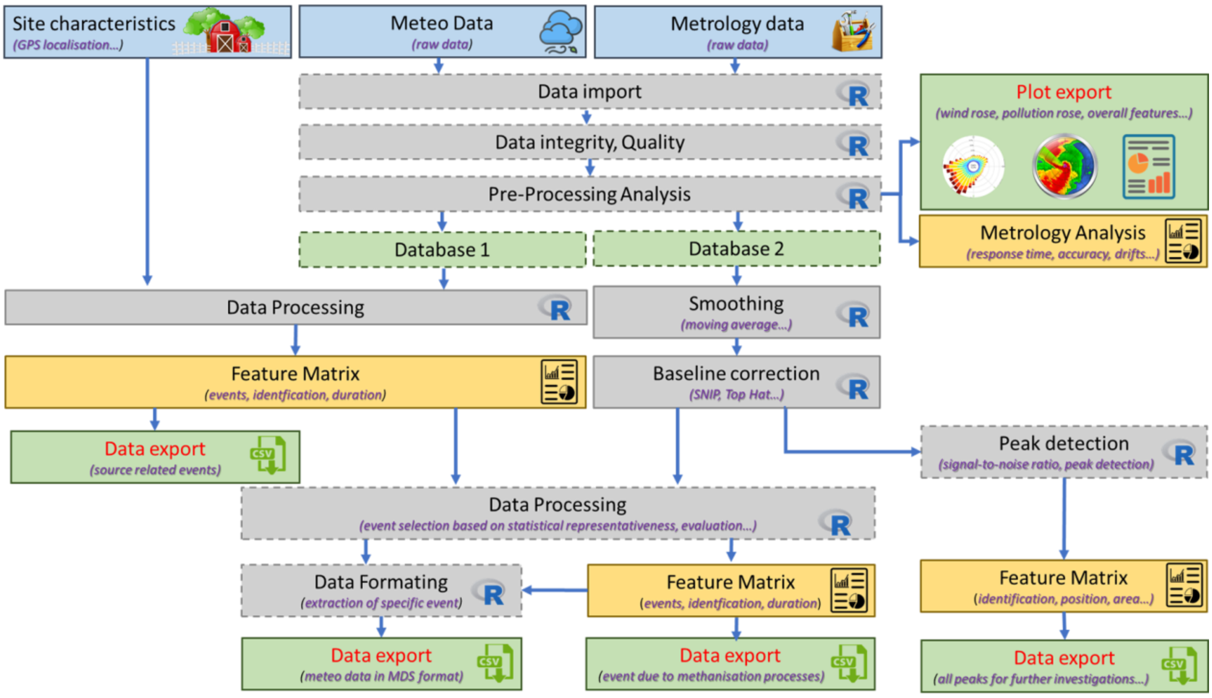
From the meteorological database and the characteristics of the methanization site, an initial analysis is performed to determine the periods during which the measurements can be associated with a specific source on the site. This analysis takes into account the position of the sources with respect to the analyzer, the transfer time between the two points and the response time of the analyzer. The list of measurement periods under the wind of each source is recorded in a report including the start and end dates, the duration of the period and the associated emission source. The statistics are also recorded to know the number of measurement periods, the average duration, the quartiles...

From the database of measured concentrations, the statistics associated with the distribution of pollutant concentrations are determined and recorded. To facilitate the exploitation, a smoothing of the data is carried out and an automatic detection of the concentration peaks is carried out. The list of peaks is then recorded in a report including the start and end dates and the meteorological conditions encountered during these peaks.

Once these first two analyses have been performed, the resulting information is cross-referenced. As the number of periods that can be modelled is generally high, an analysis of the representativeness of each period over the total duration of the campaign is performed. For this purpose, the distributions of pollutant concentrations downwind of an emission source for each period are compared to the distribution of pollutant concentrations measured for all periods downwind of the same source. The analysis of the averages, medians and variances allows to identify periods representative of the nominal operation of the anaerobic digestion site or on the contrary periods of unusual operation of the site. At the end of this identification, files exploitable by the modeling tools and including the meteorological data are then automatically generated by the developed tool. The methane contents are also extracted and exported so that they can be compared with the values obtained during the simulations. Work on the baselines is also carried out to take into account local and regional fluctuations in methane levels.

The information from these initial analyses is then cross-referenced with information on the operating conditions of the methanization site.

Figure A15.1: Illustration of the pre-processing used on the measurement data collected during the measurement campaigns



INSERT BACK COVER IMAGE HERE

European Topic Centre on
Human health and the environment
https://www.eionet.europa.eu/etcs/etc-he

The European Topic Centre on Human health and the environment (ETC HE) is a consortium of European institutes under contract of the European Environment Agency.

European Environment Agency
European Topic Centre
Human health and the environment