Nordic Council
of Ministers

Integrated strategies for air and climate measures

Reducing emissions of Ammonia Nitrogen and Methane from the agricultural sector in the Nordic countries

Contents

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Summary

Emissions of ammonia (NH_3), reactive nitrogen (Nr) compounds, and methane (CH_4) from agriculture are recognized as significant contributors to both air pollution and climate change. This project focuses on identifying integrated solutions that address these challenges together. The primary goal of this project to identify effective measures and develop science-based policies aimed at reducing emissions of the targeted pollutants through integrated strategies. By doing so, the report highlights how both climate change and air quality issues can be addressed simultaneously, as well as what steps the Nordic countries can take to meet their obligations under international agreements.

In this project, we have compiled a database with over 300 mitigation measures that can be used to reduce emissions of NH_3, Nr and CH_4 in the agricultural sector, based on data and information from the Nordic countries and beyond. We have also mapped and created a database with the Nordic countries' national and international commitments and obligations to reduce these emissions. The databases serve as valuable tools for Nordic policymakers at the national, regional, and local levels, in their work of reducing emissions. The databases support decision-making, by helping to prioritize and identify effective measures that can be used to reduce air pollution and the impact on climate change, either individually or in combination.

The synergies among the identified mitigation measures, were analysed to find integrated strategies for simultaneously addressing climate change and air pollution in positive ways. The potentials for these measures to reduce emissions, were quantified through literature reviews and the GAINS model, resulting in a short-list of 17 key integrated mitigation measures holding the highest potential to reduce emissions which negatively affect both air pollution and climate change. The majority of the selected measures target the handling of manure and fertiliser applications, demonstrating a significant potential to simultaneously reduce emissions of NH_3 and CH_4, thereby contributing to improved air quality and a lower impact on climate change.

The conclusion of this project is that the Nordic countries should prioritise integrated measures to tackle both air pollution and climate change, particularly through improved manure storage and fertiliser application practices. To do so, it is essential to implement strengthened policy frameworks with financial incentives and educational programs, as well as addressing organisational challenges within governmental structures that often separate the sectors agriculture, environment, and climate. A common platform for coordination can help design effective policies

that maximise co-benefits relating to various environmental goals. Additionally, developing streamlined monitoring and evaluation systems, along with promoting farm-level climate gas measurement and planning, will contribute to the sustainability of agricultural practices and to successful emissions reductions.

Sammanfattning

Utsläpp av ammoniak (NH_3), reaktiva kväveföreningar (Nr) och metan (CH_4) från jordbrukssektorn är bidragande faktorer till både luftföroreningar och klimatförändringar. I det här projektet har vi fokuserat på att identifiera integrerade lösningar i de nordiska länderna som kan hantera både luftföroreningar och klimatutsläpp. Genom att adressera båda dessa miljöutmaningar samtidigt, utgör de integrerade åtgärderna inom jordbruket ett viktigt verktyg för att effektivt uppnå satta nationella och internationella mål och åtaganden för de nordiska länderna. Ett övergripande mål med arbetet har varit att fastställa effektiva åtgärder och utveckla vetenskapligt baserade strategier för att minska utsläppen av dessa föroreningar.

Inom ramen för projektet har vi sammanställt en databas med över 300 åtgärder från de nordiska länderna och andra delar av världen för att minska utsläppen av CH_4, NH_3 och Nr inom jordbrukssektorn. Vi har även kartlagt och etablerat en databas över de nordiska ländernas nationella och internationella åtaganden för att reducera dessa utsläpp. Dessa databaser utgör verktyg som kan användas av beslutsfattare på nationell, regional och lokal nivå, för att stödja prioritering och identifiering av effektiva åtgärder som kan minska luftföroreningar och klimatpåverkan, antingen individuellt eller i kombination.

Som en del av arbetet analyserades synergier mellan de identifierade åtgärderna för att ta fram integrerade strategier för utsläpp av NO_x, NH_3, CH_4 and N_2O. Dessa åtgärdsstrategier syftar till att minska klimat- och luftföroreningsutsläppen från jordbruket samtidigt. Åtgärdernas potential för utsläppsminskning har sedan kvantifierats genom en litteraturstudie och analyser med hjälp av GAINS-modellen. Resultatet utgör en lista med 17 centrala åtgärder med störst potential för att minska utsläpp av de aktuella ämnena. Majoriteten av dessa åtgärder är inriktade på hantering av gödsel och gödningsmedel, och visar på stor potential att reducera både NH_3- och CH_4-utsläpp, vilket kan bidra till förbättrad luftkvalitet och minskad klimatpåverkan.

Sammanfattningsvis har projektet visat att det finns stora fördelar med att de nordiska länderna prioriterar integrerade åtgärder för att samtidigt minska luftföroreningar och klimatutsläpp, särskilt genom förbättrad hantering av gödsel och gödningsmedel. För att uppnå detta krävs ett stärkt ramverk genom lagstiftning, föreskrifter och rekommendationer med ekonomiska incitament och utbildningsinsatser, samt en bättre samordning mellan de olika sektorerna för jordbruk, miljö och klimat. En gemensam plattform för samordning skulle underlätta utvecklingen av policys som maximerar synergierna mellan olika mål.

Vidare är det viktigt att utveckla effektiva system för övervakning och utvärdering av utsläppen, bland annat genom att uppmuntra mätning och planering av utsläpp på gårdsnivå. Detta kan bidra till hållbara jordbruksmetoder och en långsiktig minskning av utsläppen.

1. Introduction

The emissions of ammonia (NH_3), other reactive nitrogen (Nr) species and methane (CH_4) from the agricultural sector have been identified as significant contributors to both air pollution and climate change.[1] Reactive nitrogen refers to all nitrogen compounds that are chemically active, with the exception of inert nitrogen gas (N_2), which makes up 78 percent of the Earth's atmosphere but is largely unreactive. Agricultural emissions primarily contribute to global warming through the release of nitrous oxide (N_2O) and CH_4,[2] while air pollution is mainly driven by the emission of nitrogen oxides (NO_x) and NH_3.[3] CH_4 also contributes to air pollution by the forming of ground-level ozone.[4] The emission of pollutants from the agricultural sector is compiled each year by UNFCCC and CLRTAP. Emissions of CH_4, NO_x, NH_3 and N_2O from each Nordic country are shown in table 1.

Environmental issues are complex, ranging from climate change and biodiversity loss to resource depletion and pollution. These issues link to sustainable development; biodiversity; food systems; international environmental cooperation; environmental impact assessment and public participation; implementation, enforcement and monitoring.[5] Unsustainable production and consumption patterns drive both climate change and environmental pollution in a negative direction.[6]

The policies and measures adopted to mitigate climate change and reduce pollution are inevitably characterised by synergies and trade-offs.[7] This study focusses on co-benefits and trade-offs between mitigation of NH_3, N_2O, CH_4 and NO_x on the basis of effects on both air pollution and climate. Agriculture is a main polluting sector for emissions of NH_3, N_2O, and CH_4, while NO_x emissions are primarily linked to the energy and transportation sectors. However, agricultural practices also contribute to NO_x emissions, although to a lesser extent. It is expected that mitigation of agricultural air pollution would offer the opportunity to improve human and ecosystem health alongside the co-benefits for climate, water quality and the economy.[8]

1. Sutton, Howard, Mason, Brownlie, & Cordovil, 2022
2. Naturvårdsverket, 2024
3. European Commission, 2024e
4. European Commission, 2024a
5. European Parliament, 2024
6. EEA, 2024
7. EEA, 2024
8. Leip, et al., 2023

Table 1. Emissions of NH_3, N_2O, CH_4 and NO_x from the agricultural sector 2022 (tones)[9].* Values marked with (*) from the year 2021.

	Sweden	Norway	Finland	Denmark	Iceland
NH_3	45 982	28 000	28 000	71 000	4 320
N_2O	10 751	6 400	12 038	17 321*	796
CH_4	130 179	100 600	93 929	257 464*	17 321
NO_X	13 320	7 414	9 750	19 000	940

The Nordic countries have committed to reducing their emissions in line with international conventions and agreements. In addition, there are national and international commitments to reduce nitrate (NO_3^-) leaching that effect ground-, fresh- and coastal waters. Figure 1 illustrates the nitrogen cascade and losses of CH_4 from agriculture.

The existing national action strategies predominantly focus on mitigating negative environmental impacts in isolation, without considering the interconnected or holistic effects on several areas. Consequently, mitigation measures being targeted to reduce climate change can have negative effects on air pollution, by increasing emissions and vice versa. Looking at several areas at the same time would bring a greater overall environmental benefit and reduce the risk of implementing measures that solve one problem but worsen another. It is common to describe the complex interactions of nitrogen as the nitrogen cascade[10]. In brief terms, the nitrogen cascade refers to the series of environmental changes and impacts that occur as reactive nitrogen (from sources like fertilisers and fossil fuel combustion) moves through ecosystems. It begins with nitrogen deposition, leading to soil and water contamination, to shifts in plant communities, and disruptions in biodiversity. As nitrogen compounds cycle through air, land, and water, they contribute to consequences like climate change and eutrophication, ultimately affecting ecosystem health and functioning.

9. UNFCCC & LRTAP
10. Galloway, et al., 2003

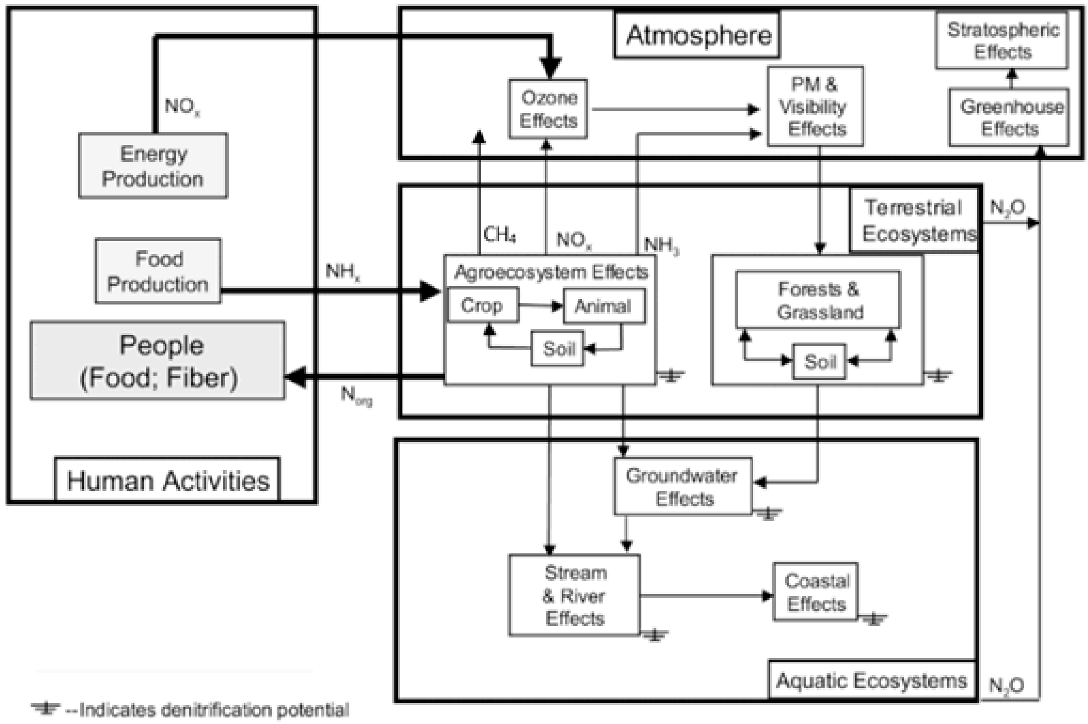

Figure 1. The nitrogen cascade and CH_4 emissions from agriculture. Modified from [11].

Developing integrated strategies for climate and air pollution in the agricultural sector focusing on measures reducing NH_3, CH_4, and N_2O and considering NO_3^- leaching and N use efficiency would help the Nordic countries to work for multiple national goals as well as towards their commitments under several international conventions and agreements. An integrated strategy in this context is a comprehensive plan containing a mix of measures designed to simultaneously reduce more pollutants without increasing other environmental problems.

1.1 Background

For air pollution, all Nordic countries are Parties to the UNECE Convention on Long Range Transboundary Air Pollution (CLRTAP)[12]. The eight protocols in this convention set national binding emission reduction targets on many air pollutants, including the metals mercury, leads, cadmium as well as many Persistent Organic Pollutants (POP). In the most recent protocol, the so-called Gothenburg Protocol, from 1999, with the objective to abate acidification, eutrophication and

11. Galloway, et al., 2003
12. Directive (EU) 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

ground-level ozone, emission targets, cover the pollutants: sulfur dioxide (SO_2), NOx, volatile organic compounds (NMVOC), NH_3, fine particulate matter ($PM_{2,5}$) (including black carbon) are covered. The Gothenburg Protocol was amended in 2012 to include updated national emission reduction commitments set as percentage emission reductions between the base year 2005 and the target year 2020 and beyond. The Gothenburg Protocol has entered a revision phase in 2024, which is anticipated to enhance efforts to further reduce air pollution across Europe and North America.[13]

The EU directive on National Emissions Ceilings (NEC) (2016/2284/EU) is another key legislation for air pollution and is closely aligned with the Gothenburg Protocol. It sets national Emissions Reduction Commitments (ERCs) for the same air pollutants (NOx, NMVOCs, SO_2, NH_3 and $PM_{2.5}$). The ERCs agreed for the year of 2030, are designed to reduce the health impacts of air pollution by half compared with 2005 levels. In addition, air pollutants are also regulated under the Ambient Air Quality Directives (AAQD), which set air quality standards for 12 pollutants including NOx, based on recommendations from the World Health Organisation (WHO). The standards in the AAQD were under revision, and in October 2024 the amended directive was adopted, with updated air quality standards for pollutants to be reached by 2030.[14] Furthermore, there are also several sector specific legislations that covers air pollutants, for example for the energy, industry, transport and agricultural sector.[15]

The Paris Agreement, adopted in 2015, is an international binding agreement aimed at mitigating climate change. All Nordic countries have committed to the Paris agreement. On an EU level the Effort Sharing Regulation (ESR) sector is designed to manage greenhouse gas emissions from agriculture as well as other sectors not included in the EU Emissions Trading System (EU ETS) or the Land Use, Land Use Change, and Forestry (LULUCF) Regulation. The ESR sector thus includes the agricultural sector as well as domestic transport (excluding aviation), buildings, small industry and waste. Together the ESR sector stand for almost 60 percent of the total domestic EU emissions.[16] The ESR sector establishes a national target for each member state for the reduction of greenhouse gas emissions by 2030. EU Member States, have new emission reduction targets ranging from 10 to 50 percent in 2030 compared to 2005 levels. In addition to establishing targets for the reduction of emissions by 2030, the ESR also defines annual emission limits for the years 2021 to 2030. The EU Climate Law also requires the European Commission to make a legislative proposal for a 2040 climate target, which was put forward in the beginning of February 2024. The European Commission recommended a 90 percent cut on 1990 levels by 2040 to complement the existing targets to reduce net

13. Decision 2023/5, 2023
14. European Council, 2024
15. European Commission, 2024c
16. European Commission, 2024d

emissions with 55 percent by 2030 and 100 percent by 2050. Although agriculture accounts for around 10 percent of the EU's greenhouse gas emissions, there was no specific target for the agricultural sector to reduce their emissions in the final proposal. It will be up to a new EU Commission and Parliament, formed after the European Parliament elections in June 2024, to pass the final target.

The Global Methane Pledge (GMP) commits members to a collective goal of reducing CH_4 emissions by at least 30 per cent by 2030, compared with 2020 levels. All Nordic countries are participating in the GMP and have submitted an EU Methane Action Plan, and developed national action plans.

Efficient incentives mechanisms will be needed for the agriculture to contribute to the decided goals on air pollution and climate. The Nordic countries use different policy measures today and have somewhat different plans for the way forward. For the counties that are members in the EU, a large common incentive structure is EU's common agricultural policy (CAP). The current program period is 2023–2027 and the next will start from year 2028.

1.2 Purpose

This project's main goal is to present and evaluate existing mitigation measures of NH_3, other forms of Nr and CH_4 in the agricultural sector for the Nordic countries. The report primarily focuses on emissions affecting air quality and climate; however, other aspects of reactive nitrogen are also considered. The project will identify and propose measures and science-based policies of integrated strategies for emission reductions for the above-mentioned pollutants. By doing so, this project demonstrates how to simultaneously mitigate negative impacts on both climate change and air quality, and what measures can help the Nordic countries to meet targets under international agreements and commitments.

1.2.1 Delimitation

This project addresses the current state of knowledge through literature review on measure effectiveness on CH_4, NH_3 and Nr in the Nordic countries and mainly the European Union. The project has not performed new measurements or analysis on measure effectiveness beyond the literature review. Another restriction is that this report does not address metrics related to dietary change and consumption patterns because there have been numerous studies on this topic and the applicability of those measures are difficult to apply, although they are efficient in theory.

1.3 Earlier studies

There have been earlier studies on co-benefits and trade-offs between mitigation measures for air pollution and climate in agriculture, also earlier studies funded by the Nordic Council of Ministers.[17]

The project 'Nordic agriculture air and climate, Baseline and system analysis report' [18] constituted one of the main outputs of the project "Pathways to a Nordic food system that contributes to reduced emissions of greenhouse gases and air pollutants".[19] The focus of the project was to describe the greenhouse gas emissions N_2O, CH_4 and CO_2, and other pollution sources such as NH_3 from the agricultural sector. The presence of measures in each country was mapped either as commonplace (C), on trial basis (T), non-existent (N) or uncertain (U). The mapping was done for 13 measures to reduce emissions from manure and fertilisers; 9 measures on feeding, 10 measures on land use, 6 measures on energy efficiency, 5 measures on energy production, and 5 measures on production and consumption.[20]

A subsequent project on 'Nordic nitrogen and agriculture, policy, measures and recommendations to reduce environmental impact'[21] stressed the importance of exchanging experiences on practices and knowledge between the Nordic countries to provide solutions to reduce harmful environmental impacts from agriculture.

It was concluded that Nr, if not taken up by crops, may contribute to several environmental problems, affecting ecosystems, climate and human health. It was further concluded that the Nordic countries have, during the last 20 years (prior to 2017), introduced efficient measures to reduce N losses to the environment. But still, N losses are relatively high as compared to the policy targets set, despite the regulatory framework applicable to the agricultural sector at EU and national levels. It was further concluded that the Nordic countries are at very different stages regarding N abatement. The project gave no firm conclusions on climate interactions.

The considered environmental effects included:

- N leaching in soil and groundwater.
- Eutrophication and acidification of terrestrial ecosystems.
- Eutrophication of marine ecosystems.
- Global warming (N_2O emissions and other effects of Nr).

17. Antman, et al., 2015; Hellsten, et al., 2017
18. Antman, et al., 2015
19. The Nordic Council and the Nordic Council of Ministers, 2024
20. Antman, et al., 2015
21. Hellsten, et al., 2017

- Effects of N on human health (particulate matter and tropospheric ozone formation).
- Nr effects on the carbon cycle, and on global-scale effects on atmospheric fluxes of carbon dioxide (CO_2) and CH_4.

A later study from the Norwegian Research Institution NIVIO (Rivedal et al., 2019) estimated the potential for NH_3 reduction of measures linked to livestock manure and mineral fertiliser, and the social and private economic costs of introducing the measures.

Reduction of N_2O and CH_4 emissions, as a result of NH_3-reducing measures, was also estimated. It was found that various measures linked to the spreading of livestock manure on meadows have the greatest potential for NH_3 reduction.

The effect of livestock manure measures on emissions of NH_3 and N_2O (N_2O) was estimated using the "nitrogen model for livestock manure" used in the national emissions calculation. Changes in CH_4 emissions as a result of NH_3-reducing measures were estimated using the "*Methane Model for Livestock Manure*". Although these earlier studies address the issue of co-mitigation, the starting point has been from one side, looking at co-benefits on air or climate.

2. Methodology

2.1 Long list of international directives, strategies, goals and obligations

A review of the Nordic countries commitment to international directives, strategies, goals and obligations was undertaken by identifying different levels of policy instruments that the Nordic countries have committed to. The analysis was divided into four categories:

- Level 1: international
- Level 2: national
- Level 3: regional
- Level 4: local/municipal

Based on the four levels, a systematic review of the Nordic countries commitments was undertaken. The systematic review analysed the policy instruments and divided them into multiple categories to clearly identify what type of policy instruments the Nordic countries have committed to; what societal challenges, ecosystems and pollutants the policy instruments cover. A database, *policy overview*, in Microsoft excel was created to systematically present the relevant international and national commitments the Nordic countries have committed to that addresses emissions of NH_3, NO_X, N_2O and CH_4 from agriculture. The full database can be viewed in appendix 1 – Mapping policy overview.

Based on the policy overview a database with quantified goals was created with the international and national obligations the Nordic countries have committed to. The database was divided into four different categories with international goals and obligations:

- Air – NO_x and NH_3
- Climate – CH_4 and N_2O
- Water – NO_3
- Health – NO_X, NH_3 and CH_4

The database provides the Nordic countries a quick systematic overview of which international goals and obligations, with quantified measures, can be connected to emissions from the agricultural sector. It can be found in appendix 2 – Mapping Nordic countries commitments and obligations.

2.2 Inventory of measures to mitigate ammonia, methane and nitrogen emissions

A comprehensive literature review on measures related to CH_4, NH_3 and Nr was conducted to create a database (in Microsoft excel) of relevant measures to abate NH_3, Nr and CH_4 from the agricultural sector in the Nordic countries and beyond. This database, *measures to mitigate ANM*, includes descriptions of the measures, their areas of application and their potential environmental impact and is available in appendix 3 – Mapping measures to mitigate ANM. The review involved gathering compilations of mitigation measures from various Nordic government bodies, agricultural agencies, and relevant institutions. These were further supplemented by research from European and international sources to provide a broader perspective of measures to reduce emissions from the agricultural sector. The aim of the literature review was to provide a thorough overview of emission reduction strategies, combining national-level reports with scientific literature. To achieve this, we opted to find literature reviews from each Nordic country that compile and summarise data and research from multiple sources. This approach provided a more comprehensive overview of the existing research. While the database does not claim to be fully exhaustive, it presents a wide range of measures in use or under consideration in the Nordic countries.

For each identified measure, the primary pollutants were identified, although for Nr, we opted to include the speciation of different N sources to pinpoint the effectiveness of the measure towards a specific form of N, while the release of dinitrogen (N_2) itself does not directly cause pollution it signifies a loss of valuable Nr, which lowers the N use efficiency. Consequently, additional inputs of Nr, such as fertilisers and biologically fixed N, become necessary, ultimately leading to an increase in N pollution. The following speciation was used for the inventory:

- Ammonia (NH_3)
- Nitrogen oxide (NO_2)
- Nitrous oxide (N_2O)
- Nitrate (NO_3^-)
- Dinitrogen (N_2)

The impact of each measure on CH_4, and Nr emissions has been classified as *positive*, *negative*, *not effective* or *unknown*. If the measure has positive or negative effect on multiple pollutants, they have been classified accordingly. Note that this classification in the database is derived from a single source for each measure, which may not encompass all the potential effects. Therefore, there could be additional positive or negative impacts not addressed in the specific literature. This can however be addressed by comparing measures from different sources using the filtering function *Measure Type* described below.

The database is structured in a systematic manner and encompasses a wide range of different mitigation measures implemented in the Nordic countries and beyond. These measures were categorised under two main classifications:

- Measure type
- Measure category

The category *measure type* is a first classification of the individual measures reported in the literature. Some individual measures appear multiple times in the database, as they are reported across various sources or from different countries. To address this, the database employs a filtering function within the measure type classification. This classification helps manage the occurrence of similar or repeated measures across different literature sources or countries by grouping them under a single type, regardless of their origin. The classification measure type covers all the different measures identified in the database and has been divided into approximately 150 different measure types that cover measures for CH_4, NH_3 and Nr. For instance, the measures are classified as *cooling of slurry, biogas production* and *precision farming.* This allows the end user to narrow down the measure to a more specific interest and compare results from different literature sources and countries.

The second classification, *Measure Category*, was designed to group the mitigation measures from the literature into broader categories of different agricultural practices. These categories allow for an assessment of measures across different sources and countries within the same area of practice. This allows users to easily navigate, group and compare strategies and to compare how different strategies address emissions within the various agricultural sectors. In total, six categories were identified:

- **Manure storage and processing:** This category includes measures such as slurry cooling, acidification of manure, and the use of slurry covers, all of which target multiple types of emissions.
- **Field application of manure and/or fertilisers:** Measures in this category focus on optimising nutrient use efficiency and minimising emissions during field application. Examples include rapid incorporation of manure, band spreading and the reduction of fertiliser doses.
- **Crop production and crop rotation:** This category encompasses strategies aimed at enhancing soil health and crop productivity while mitigating emissions. Key measures include the use of cover crops, precision farming techniques, and adjustments in crop rotation.
- **Livestock production, housing, and diet:** Measures in this category focus on modifying livestock diets, improving housing conditions, and managing waste within animal production systems.

- **Land use and landscape management:** This category includes a variety of strategies to optimise land use for environmental benefits. For example, implementation of agroforestry, permanent fallow and perennial crops.
- **Energy and nutrient recovery:** Measures in this category focuses on capturing energy and nutrients from waste streams to reduce emissions and enhance resource efficiency. Key examples include biogas production from manure and other organic residues.

Furthermore, the literature used in the study has been classified on the scale of the measure and what societal challenge and ecosystem it encompasses.

2.3 Quantification of measures and synergies

To identify synergies from measures affecting both air quality and climate, identified measures in the long list were prioritised based on the classification *positive, not effective or unknown.* Measures classified as *positive* for reducing NO_x or NH_3 and at the same time being classified as *positive* for reducing CH_4 or N_2O were considered as measures having a synergy effect on air quality as well as on climate.

The magnitude of the effect from the measures considered having desired synergy effects was then quantified through two methods. The first method included an extensive literature review of primarily Nordic literature on emission control from agriculture. The second method included comparison of emission scenarios for the Nordic countries where the scenarios differed with respect to measures being implemented.

The Nordic countries do not consistently report emission projections and alternative scenarios for the pollutants and greenhouse gases studied in this work. Therefore, to estimate emission reduction potentials for the Nordic countries we have used the ECLIPSE version 6b emission scenarios as developed by IIASA.[22][23] The ECLIPSE scenarios presents technologically and economically consistent scenarios of emissions until 2050 for all countries in the world. For the air pollutants, CH_4, and N_2O considered in this report, the emission scenarios are calculated with the GAINS model[24][25] which is commonly used as decision support to the European Commission and to the Air Convention. Sector- and pollutant-specific GAINS model documentation is found at the IIASA web page.[26] For the Nordic countries, there are two scenarios of interest for this study, the ECLIPSE 6b CLE and the ECLIPSE 6b MTFR. CLE stands for 'current legislation', and the CLE scenario correspondingly illustrates current and future emissions as a function of existing and decided emission control legislation. MTFR stands for 'maximum feasible reduction' and the emissions in the MTFR scenario are a function of a maximised implementation of

22. IIASA, 2021
23. Höglund-Isaksson, Gomez-Sanabria, Klimont, Rafaj, & Schöpp, 2020
24. Amann, et al., 2011
25. Kiesewetter, Schöpp, Heyes, & Amann, 2015
26. GAINS Model

all emission control technologies represented in the GAINS model (given vintage-specific constraints on the rate of possible implementation). The CLE and the MTFR scenarios give future emission trajectories from agricultural sources (excl. non-road mobile machinery) as in figure 2.

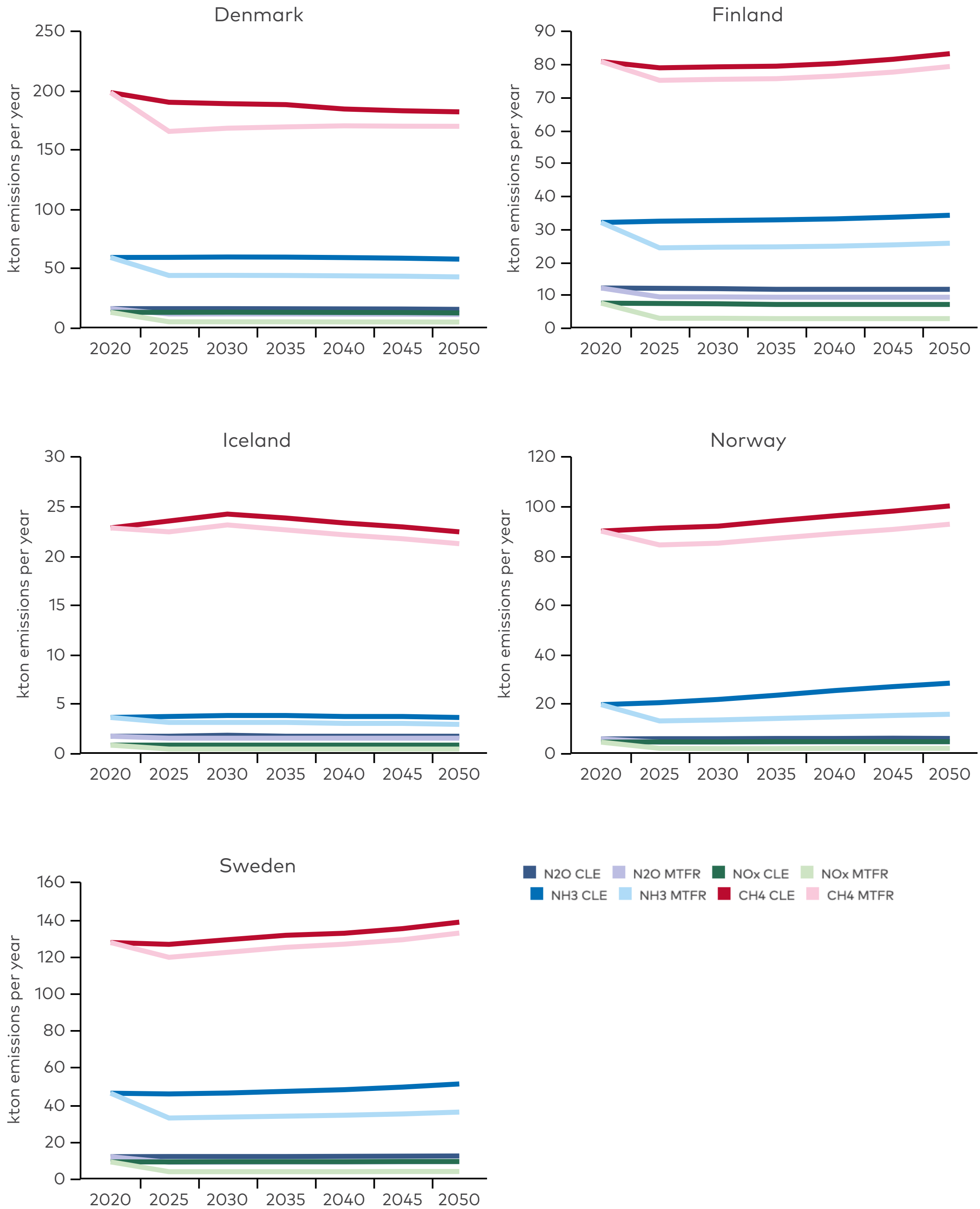

Figure 2. ECLIPSE v. 6b current legislation (CLE) and maximum feasible reduction (MTFR) emission scenarios for the Nordic countries and the pollutants N_2O, NO_x, NH_3, and CH_4.

Even though future emissions are inherently uncertain, it is still interesting to compare the emission trajectories for the ECLIPSE v.6b scenarios with the corresponding national emission projections (Nat.) as reported to the EU, CLRTAP and UNFCCC by national experts in the respective countries. Unfortunately, the national emission projections include emissions from non-road mobile machinery used in the agricultural sector, so the comparison is most valid with respect to direction of the emissions, figure 3.

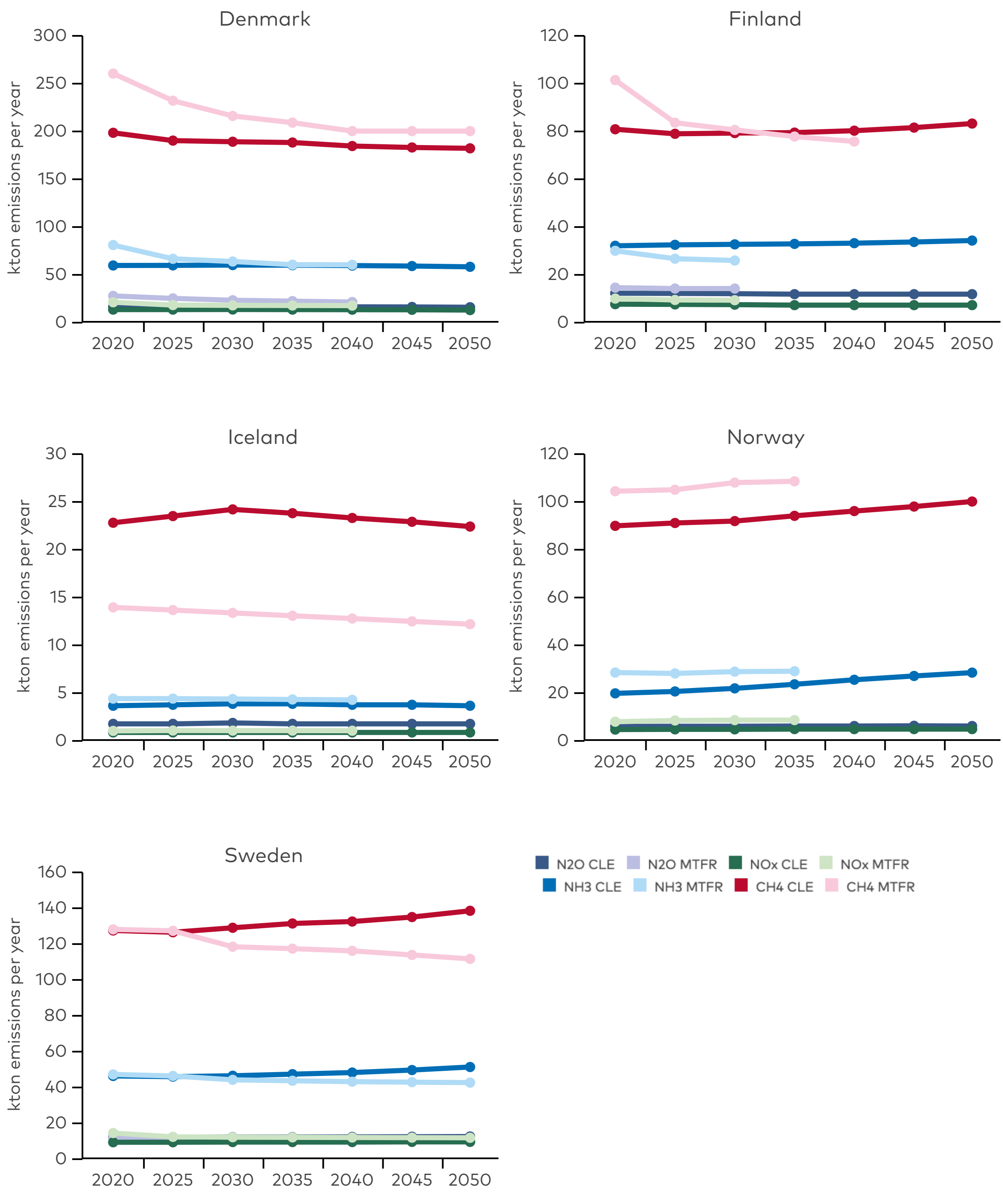

Figure 3. Comparison of nationally reported emission projections (Nat.) and the current legislation (CLE) emission scenario for the five Nordic countries and N_2O, NO_x, NH_3, and CH_4.

The comparison shows that the nationally reported emission projections assume faster emission reductions than in the CLE scenario for almost all emissions. Most problematic for this study is the large difference in absolute levels of Icelandic CH_4 emissions and the fact that emission projections for Swedish CH_4 and NH_3 diverge. The differences are presumably caused by differences in assumptions on future sizes of livestock numbers.

2.4 Calculation and assessment of effect size

To further quantify the reduction potential for the prioritised measures on the four pollutants $NO_{x,}$ $NH_{3,}$ CH_4 and N_2O, the measure categories and types identified in this work were matched with defined sectors, activities, and control measures in the GAINS model. Based on the matching, scenario-specific emissions from specific measure categories and types were identified for the year 2040. Those measures representing the highest emission reduction potential between CLE and MTFR were prioritised into a short-list. The national CLE implementation rate of the measures might however differ. The matching was made as aggregations over categories and types since the measures identified in this work aren't identical to the measures in the GAINS model. Furthermore, the effect of the measures on specifically NH3 emissions depend on whether one measure is implemented in isolation or if several measures are implemented together. There is a cascade effect that needs to be considered. Correspondingly, the emission reduction potential identified includes possible joint implementation of several measures within the same measure type.

Some measures had no clear match to a GAINS measure. These were thereby prioritised based on an extensive literature search and added to the shortlist.

By combining the method of prioritising and quantifying estimated effects from literature reviews with the approach of estimating potential effects, based on the CLE and MTFR scenario comparisons, it was possible to estimate emission reduction potentials for the synergy measures. Due to project constraints, the final shortlist of synergy measures contains up to five of the most effective measures for each of the actual pollutants.

The ECLIPSE scenarios also enable an estimate of the costs associated with some of these synergy measure types. Due to some imprecision induced by the measure matching, the costs are approximations, just as the emission reduction potential estimates. The GAINS model cost calculations present annual costs associated with scenario-specific technology investments and maintenance, as well as potential profits from, for example, utilisation of products from the technology. Furthermore, the annual costs are calculated based on the technical lifetime of an investment, and a four percent interest rate is used. The costs of emission reductions presented in this report corresponds to the additional costs of shifting technologies from the technologies assumed in the CLE scenario into the technologies assumed in the MTFR scenario.

3. Results

3.1 International goals and obligations for the Nordic countries

In this part of the project two databases were compiled. The first database focuses on policies that aim to reduce pollutants from the agricultural sector. The database aims to give an overview of policies that regulates and addresses emission of NH_3, Nr and CH_4 in the Nordic countries. The database is shown in appendix 1 – *Mapping policy overview*. The study then compiled a database with commitments and obligations that the Nordic countries have committed to, this database is shown in appendix 2 – *Mapping Nordic countries commitments and obligations*.

The study identified 71 policies and around 100 commitments of obligations and goals that addresses emissions from the agricultural sector in the Nordic countries, which are shown in appendix 1 and 2. In this chapter examples of policies, commitments and obligations will be addressed, the full list of policies, commitments and obligations can be found in appendix 1 and 2.

Many of the policies that affect Sweden, Finland and Denmark come from the EU and are implemented through national laws and regulations. Norway and Iceland are not members of the EU but are members of the EFTA (the European Free Trade Association)[27]. Through the EEA (European Economic Area) agreement, Norway and Iceland are bound by most of the EU environmental legislation with some exceptions[28]. Agriculture and fisheries are not included in the EEA agreement, nor are the two EU nature conservations directives: the Birds Directive (2009/147/EC [29]) and the Habitats Directive (92/43/EEC[30]).

Pollutants from agriculture are partly regulated on an international level through different policies and conventions, for example, polices from the United Nations and the UNECE Convention on Long-range transboundary air pollution (CLRTAP). There are also binding protocols and agreements that address the problem with these pollutants from the agricultural sector, such as the Gothenburg protocol. This study identified one research networking program, Nitrogen In Europe, that addresses pollutants from agriculture[31].

27. EFTA, 2024
28. Norwegian Ministry of Foreign Affairs, na
29. Directive 2009/147/EC of the European Parliament and of the Council of 30 November 2009 on the conservation of wild birds.
30. Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora.
31. LRTAP, 2024

The Paris agreement is an example of a commitment which all Nordic countries have committed to. The Paris agreement has set the obligation "[t]o hold the increase in the global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels" and "[a]chieving climate neutrality by 2050". To be able to achieve the goals, a wide range of measures must be actioned within each country.

Many of the Nordic countries commitments are goals set by the EU. For example, EU's initiative Farm to fork, includes the goal to reduce the use of fertilisers by 20 percent and reduce nutrient depletion by at least 50 percent by 2030[32]. Other initiatives are CAP (Common Agricultural Policy) 2023-2027 which sets the goal to foster sustainable development and efficient management of natural resources such as water, soil, nutrients and air[33]. This policy framework is built around ten key objectives linked to the EU goals for social, environmental, and economic sustainability in agriculture and rural areas, for example: *climate change action*, *environmental care* and *to protect food and health quality*. Each member state develops its own national CAP Strategic Plan with the ambition to address the common objectives. There are 28 national Strategic Plans approved by the European Commission. The CAP strategic plans cover the CAP-related and CAP-funded instruments that each Member State implements over 2023–2027 by different support schemes and policy instruments to contribute to the common goals. The Strategic Plans provides support, that aims at reducing emissions during different stages of the nutrient cycle and contributes to mitigate climate change by, for example, addressing emissions from mineral fertilisers and livestock[34]. Furthermore, the CAP Strategic Plans incorporate Good Agricultural and Environmental Conditions (GAEC), which are a set of standards that farmers must follow to receive full funding from the CAP. GAEC standards are designed to promote sustainable farming practices and protect the environment, focusing on areas such as soil management, water quality, biodiversity, and climate resilience. For example, one standard addresses run off and pollution to rivers. To meet this, farmers receiving financial support to create buffer strips along water courses[35]. Nineteen Member States has set a minimum width of 3 meters for the buffer strips in their CAP strategic Plans, while nine specify widths greater than 3 meters, such as 5 to 10 meters.

Other international goals the Nordic countries have committed to, are to improve the agricultural sector and lower the emissions. The Gothenburg protocol (annex II 2017) has for example set goals to reduce emissions from NO_X and NH_3. The National Emission Reduction Commitments Directive (2016/2284/EU) is another international legally binding commitment that sets national emission reduction commitments for Member States and the EU regarding NOx and NH_3[36].

32. EFTA, 2021
33. European Commission, 2023
34. European Commission, 2022
35. European Commission, 2022
36. European Union, 2016

3.1.1 Sweden

Sweden regulates pollutants from the agricultural sector on national, regional and local level. The Swedish Parliament issues laws and the government issues regulations[37]. As an EU member state, Sweden is obligated to implement EU directives in its national laws and regulations. A law or regulation, may mandate an authority a right to issue regulations on a subject or an issue that needs to be regulated in more detail. Regulations are legally binding. In Sweden, the responsible authorities that administrate the regulations addressing pollutants from agriculture are the Swedish board of Agriculture Agency, the Swedish Agency for Marine and Water Management and the Swedish Environmental Protection Agency.

The study found eight different policies, see appendix 1, that addresses emissions of pollutants from the agricultural sector. They work on different levels to address different social challenges and improve the environment in several different ecosystems. They cover pollutants such as CH_4, N_2O, NO_X and NH_3 from agriculture. For a full list of policies that address CH_4, N_2O, NO_X and NH_3 from agriculture, see appendix 1. There are also national environmental goals such as "no eutrophication" and "only natural acidification" that addresses pollutants from the agricultural sector, see appendix 1.

In Sweden, the environmental law is regulated through Miljöbalken (the Environmental Code), which harmonises the general rules and principles within the environmental area. The law is applicable to all activities that may harm the environment and the human health in any way. The law also contains the environmental principles and provisions providing for environmental quality norms as well as environmental impact assessments. The Environmental Code also regulates environmentally hazardous activities, as well as water operations subject to permit or notification requirements, and stipulates provisions regarding chemicals and waste. EU regulations and directives that acts within the environmental area are all implemented in the Environmental Code.

Greppa Näringen is a Swedish advisory program focused on reducing the environmental impact of agriculture, particularly concerning nutrient management [38]. The program provides farmers with advice on how to optimise the use of fertilisers and other nutrients, with the aim of reducing nutrient runoff into water bodies, thereby minimising pollution and promoting sustainable agricultural practices. Greppa Näringen is a collaboration between the Swedish Agency for Agriculture, LRF (the Swedish Farmers Confederation), the county administration boards and several different advisory organisations in Sweden.

37. European Commission, 2024b
38. Greppa Näringen, 2024

Swedish obligations and commitments to goals addressing pollutants from agriculture are presented in a database, see appendix 2. Below is a list of examples of Sweden's commitments:

- Reduce emissions of Green House Gases (GHG) by 63 percent to 2030 compared to 1990 and Reduce emissions of GHG by 75 percent to 2040 compared to 1990 (does not include emissions and uptake from land use) (Swedish climate policy)
- Reduction of NO_2 by 36 percent compared to 2005 (Gothenburg protocol annex II 2017)
- Reduction of NO_x by 66 percent and NH_3 by 17 percent to 2030 (2016/2284/EU)
- Reduce nutrient loss by at least 50 percent to 2030 (EU: Farm to fork)
- Reduce health impacts (premature mortality due to particulate matter and ozone) of air pollution by 52 percent to 2030 compared to 2005 levels (A Clean Air Programme for Europe)

3.1.2 Denmark

Laws, statutory orders, and agreements work together to reduce the environmental impact of the agricultural sector, covering different aspects of the management of Nr, CH_4, and NH_3 in Denmark.

EU directives are implemented in the Danish laws and statutory orders. The Danish laws are issued by the Danish Parliament. Laws provides the overarching legal framework in areas such as environment. Statutory orders are issued by the government or ministries as a means to implement and specify the laws, and guidelines are issued as guidance on how laws and statutory orders should be applied, primarily directed at farmers and farmers consultants. Statutory orders and guidelines regulating pollutants from the agricultural sector is mainly issued by the Danish Agricultural Agency and the Danish Environmental Protection Agency.

The study found ten different policies that address emissions of pollutants from agriculture. For the full list of policies that address CH_4, N_2O, NO_X and NH_3 from agriculture see appendix 1. The policies work on different levels to address different social challenges and to improve the environment in several different ecosystems. They cover pollutants such as CH_4, N_2O, NO_X and NH_3 from the agricultural sector. There are also national environmental goals. For example, Denmark's CAP strategic plan sets the goal and aims to double the area for organic farming by 2030 by providing support to around 403 000 ha.

The Danish Climate Law includes measures to manage N emissions, particularly from agriculture, through improved practices and technologies that enhance efficiency and reduce environmental pollution. The Minister for Climate, Energy and Utilities annually prepares a climate program for the Danish Parliament. The program is integrated into Denmark's overall goal of achieving a 70 percent reduction in greenhouse gas emissions by 2030 and climate neutrality by 2050. There are also political initiatives such as Green Growth (Grøn Vækst) which aims at combining economic growth and development in agriculture and food production with environmental and climate sustainability[39]. The initiative seeks to reduce environmental impact, particularly concerning N and phosphorus (P) emissions, while promoting innovation and competitiveness in the green sector.

Denmark has also developed and implemented an agreement on green restructuring of Danish agriculture, which sets goals to reduce greenhouse gases and discharge of N to the aquatic water.

The Danish government and parties from leading industry, agriculture, and environmental organisations presented in July 2024 the foundation for a long-term transition of Danish food and agriculture production, including land use. The agreement set out a revised framework for reducing carbon emissions ensuring compliance with the Danish climate emission reduction target in 2030. The agreement, which is not implemented yet, nor passed as a law in the Parliament, introduces a tax on carbon emissions from livestock. The carbon tax will be introduced in 2030 starting at DKK 300 pr. ton CO_2e, increasing to 750 DKK pr. ton CO_2e in 2035. However, a base deduction of 60 pct. will be added, which results in an efficient rate of DKK 120 pr. ton CO2e in 2030, increasing to DKK 300 pr. ton CO_2e in 2035[40].

On a local level, there are statutory orders such as Environmental Control of Agriculture, which aims to reduce the environmental impact from the agriculture by imposing standards for manure storage and emission monitoring. Larger farms and high-emission activities are subject to stricter rules, including mandatory emission-reducing technologies like air filters or manure acidification systems.

Denmark has many obligations and commitments to goals addressing pollutants from agriculture. They are presented in a database, see appendix 2. Below is a list of examples of Denmark's commitments:

- Denmark is to be climate neutral by 2045 (Government platform 2015)
- Reduction of N emissions to water from agriculture and forestry in Denmark by 10.800 tonne (Agreement regarding the green transition of Danish agriculture (Aftale om grøn omstilling af dansk landbrug))
- Reduction of NO_2 by 56 percent from 2005 levels (Gothenburg protocol annex II 2017)
- Reduce health impacts (premature mortality due to particulate matter and ozone) of air pollution by 52 percent to 2030 compared to 2005 levels. (A Clean Air Programme for Europe)

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39. Grøn Vækst , 2024
40. The Ministry for Climate, Energy and Utilities, 2024

3.1.3 Finland

In Finland, the legal framework operates under a hierarchical structure that incorporates laws, regulations, and guidelines. Laws are enacted by the Finnish Parliament and form the core of the legal framework. The EU directives are implemented in the Finnish laws and regulations. Laws set out the fundamental rules and principles governing various aspects of society for example environmental protection.

Regulations are issued by the government or relevant ministries to provide detailed rules for implementing laws. They address more specific issues and technicalities, ensuring that laws are applied uniformly.

The study found eight different policies that addresses emissions of pollutants from agriculture, they work on different levels to address different social challenges and improve the environment in several different ecosystems. They cover pollutants such as CH_4, N_2O, NO_X and NH_3 from the agricultural sector. For the full list of policies that address CH_4, N_2O, NO_X and NH_3 from agriculture, see appendix 1.
 Finland also has national environmental goals. One of the goals stipulated in Finland's climate policy states that Finland must be carbon neutral by 2035 at the latest.

Important directives that address various emissions from agriculture is Nitrates directive (91/676/EEG), the water framework directive (200/60/EG) and the EU legislation on fertiliser products ((EU) 2019/1009). The nitrates directive is important to limit the emissions of NH_3 because it has rules covering manure houses, spreading manure and fertilisation restrictions regarding nitrogen as well as protective distances to water bodies. Through the Water Framework Directive, Finland has water management plans, in which necessary water management measures have been identified, that, among other objectives, aim to reduce emissions of N to water bodies.

The Finnish Climate Law[41] contains provisions on the goals and framework for Finland's climate policy. Although the law does not directly regulate individual sectors like agriculture, it impacts farmers and agriculture through national climate policies and targets.

On a local level there are regulations such as Government regulation on environmental compensation[42]. This regulation is a part of Finland's rural development program and offers financial support to farmers to implement environmentally friendly measures, including improved manure management and precision farming. The system encourages the use of environmental protection measures that reduce Nr emissions.

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41. Finish parliament, 2022
42. miljöersättning, 2023/78

Finnish obligations and commitments to goals addressing pollutants from agriculture are presented in a database, see appendix 2. Below is a list of examples of Finland's commitments:

- Reduce GHG-emissions by 90–95 percent compared to 1990 to 2050 (Finland Climate policy)
- Achieve good status in all bodies of surface and groundwater by 2027. (Good status is comprised of four assessments: Ecological status of surface waters, Chemical status of surface waters, Chemical status of groundwaters and Quantitative status of groundwaters) (Water framework agreement)
- Reduction of NO_2 by 20 percent from 2005 (Gothenburg protocol annex II 2017)
- Reduce health impacts (premature mortality due to particulate matter and ozone) of air pollution by 52 percent to 2030 compared to 2005 (A Clean Air Programme for Europe)

3.1.4 Iceland

In Iceland, the legal and regulatory framework operates under a hierarchical system that combines laws, regulations, and directives. Iceland operates under its Constitution, which provides the foundation for all laws and legal systems. Laws are passed by the parliament. Laws serve as the primary legal instruments that regulate various aspects of the Icelandic society, including environmental protection. Regulations are issued by the government. Specific ministries may get the task to implement a certain law. Ministries or government agencies have the authority to issue regulations as per the laws enacted by the parliament. Many of the environmental laws issued by the EU has through the EEA mechanism, been implemented into the Icelandic legal system. Therefore, the EU has a large influence on the Icelandic environmental laws that aims to prevent pollutions and environmental quality.

The agricultural sector in Iceland is regulated through a couple of policies. For the full list of policies that address CH_4, N_2O, NO_x and NH_3 from agriculture, see appendix 1. The environmental impact assessment establishes a framework for evaluating the environmental impact and with a focus on sustainable development [43]. The law states that projects or activities likely to have significant environmental effects must undergo an environmental impact assessment before they can proceed.

Iceland also has an Icelandic Climate Action Plan, which is a part of Iceland's climate goals. The 2020 Climate Action Plan addresses CH_4 and N_2O emissions from livestock, manure management and fertilisation use. The 2024 Climate Action

43. Environmental Impact Assessment 106/2000

Plan was published in June and is currently undergoing public consultation and address similar issues within the agricultural sector.

The Water Management Law regulates the protection of water bodies from nutrient pollution, such as N runoff from agriculture, which can lead to eutrophication of rivers, lakes, and coastal areas[44].

Iceland is in the process of transposing into national law the international directive (EU) 2016/2284 which sets emission ceilings on certain atmospheric pollutants, including NO_x and NH_3.

The study found five policies that regulates pollutants from agricultural sector in Iceland. They work on different levels to address different social challenges and improve the environment in several different ecosystems. They cover pollutants such as CH_4, N_2O, NO_x and NH_3 from the agricultural sector.

Islandic obligations and commitments to goals addressing pollutants from agriculture are presented in a database, see appendix 2. Below is a list of examples of Iceland's commitments:

- Greenhouse gas emissions should be reduced by 40 percent by 2030 under the Paris Agreement, compared to 1990 level, in a joint effort with the EU (Icelandic climate policy).
- Tackle eutrophication, through limiting inputs of nutrients and organic matter to levels that do not give rise to adverse effects on the marine environment (OSPAR, North-East Atlantic environment strategy).

3.1.5 Norway

Norway is part of the EEA, which means Norway must adopt certain EU regulations and directives in areas like environmental protection, however, common agriculture and fisheries policies are not covered by the EEA. EU directives set common standards, while Norwegian laws and regulations details how to implement these standards nationally. An example of a directive that is implemented in Norway through national legislation is the EU Nitrates Directive (91/676/EEC) to control N pollution from fertilisers.

Laws are passed by the Norwegian Parliament and form the primary legal framework. Regulations are more detailed rules issued by the government ministries to implement the provisions of laws. Regulations specify technical and administrative requirements for sectors like agriculture and environmental management.

Guidelines and directives are issued by ministries or agencies to explain how laws and regulations should be applied. The parliament can issue instructions through

44. Lög um stjórn vatnamála - Act No. 36/2011

political guidelines. Norway's local municipalities have some regulatory mandate, especially in environmental and land-use issues. Municipal councils can issue regulations that complement national laws and regulations, often focusing on local environmental management and land-use planning.

The study found twelve policies that regulates pollutants from the agricultural sector in Norway. For the full list of policies addressing CH_4, N_2O, NO_x and NH_3 from agriculture, see appendix 1. The policies work on different levels to address different social challenges and to improve the environment in several different ecosystems. They cover pollutants from agriculture such as CH_4, N_2O, NO_x and NH_3. The national environmental and climate program aims to improve the environment and mitigate the climate change and have goals such as "[t]he ecosystems should have good status and deliver ecosystem services" and that "[p]ollutants should not harm health and environment".

Pollutant from the agricultural sector is regulated in different policies. For example, the Pollution Law (Forureningsloven, 1981) aims to protect the external environment against pollution and to reduce the existing pollutions. The law aims to establish a legal framework for preventing and limiting pollution, including emissions to air, water, and soil, while promoting sustainable management of natural resources. This law plays a key role in controlling pollutants such as Nr and CH_4, from the agricultural sector.

The Climate Law sets long-term goals for reducing greenhouse gas emissions. It aligns with Norway's commitment to becoming a low-emission society by 2050, which means that Norway should, by 2050, have reduced their greenhouse emissions by 90–95 percent compared to the reference year of 1990[45].

In June 2019, Norway's two main agricultural organisations and the Government signed a letter of intent, setting out a climate target for the agricultural sector; to reduce emissions and enhance removals by a total of five million tonnes CO_2eq over the period of 2021–2030[46]. The letter of intent applies to all mitigation measures for agricultural activities whose effects can be accounted for in the sectors agriculture, transport, heating of buildings and LULUCF (with the exception of forestry) in Norway's official greenhouse gas inventory. According to the letter of intent, responsibility for reducing emissions is shared between the agricultural sector and the Government. The agricultural sector is expected to achieve a substantial share of the emission reductions, for example through breeding programs, better fertiliser management and a switch to fossil-free energy use. The Government's efforts to promote changes in consumption patterns may indirectly reduce greenhouse gas emissions that are accounted for in the agricultural sector. These efforts include initiatives to achieve the goal of reducing food waste by 50

45. Klimaloven LOV 2017-06-16-60
46. Government of Norway, 2019

percent by 2030 and to persuade people to follow the dietary recommendations from the Directorate of Health.

To follow up the 2019 letter of intent, the agricultural organisations drew up a climate action plan for the sector, published in 2020. This sets out how the agricultural sector intends to achieve the target of the letter of intent through action in defined focus areas, with the individual farm and what farmers can do themselves as a starting point.

Norway's obligations and commitments to goals addressing pollutants from agriculture are presented in a database, see appendix 2. Below is a list of examples of Norway's commitments:

- Norway's new target is to reduce emissions by at least 55 percent by 2030 compared to the reference year 1990 (The Climate Law).
- Reduction of NO_2 by 23 percent from 2005 levels (Gothenburg protocol annex II 2017)
- No waterbodies should have bad status (National environmental program 2023–2026 (Mål i Nasjonalt miljøprogram 2023–2026) – Runoff to water

3.2 Measures to mitigate ammonia, methane and nitrogen emissions

The database of mitigation measures compiled in this project has resulted in a comprehensive number of measures that catalogues mitigation strategies within the agricultural sector across the Nordic countries. These measures are designed to mitigate negative impacts on climate and/or air pollution, targeting emissions of NH_3, Nr and CH_4 across various agricultural practices and contexts. This chapter provides an overview of the database, highlighting identified integrated mitigation measures that address both climate and air pollution. The full database is available in appendix 3 – *Mapping measures to mitigate ANM*.

The database includes approximately 360 mitigation measures in total, though some measures appear multiple times in the database due to reporting from various sources or countries, see table 2 for a summary of the different categorisations used in this project. The measures are primarily reported from the Nordic countries, with additional contributions from European and international literature. About 70 of these measures are classified as integrated mitigation strategies, addressing both air and climate emissions simultaneously.

The classification, *Measure Type*, was applied to categorise the individual measures in the database into a single category if they represent the same type of mitigation action. In total, approximately 160 different measure types were identified in the literature. This approach enabled the grouping of measures with similar or the same characteristics and objectives, facilitating easier comparison between the literature sources and countries.

Approximately 30 measure types from the database were classified as integrated mitigation strategies, addressing both air and climate emissions simultaneously. These integrated measures are central for developing holistic approaches to emission reduction in agriculture. The key measure types identified in this project as the most effective in mitigating both types of emissions are presented in chapter 3.3.

Table 2. Summary of the categorisation used in this project for measures found in the literature.

Name	Description	Number identified in this project
Measure	Mitigation measures aimed at reducing NH_3, Nr and CH_4 emissions. These may appear multiple times due to reporting by different sources	360
Measure Type	Classification that groups similar or identical mitigation measures in the database, i.e. measures without duplicates	160
Measure Category	Classification that organises the measures in the database into broad categories based on agricultural practices	6
Integrated Measures	The "*Measures*" in the database addressing both air and climate emissions simultaneously	70
Integrated Measure Types	The identified "*Measure Types*" that are addressing both air and climate emissions simultaneously	30

For each measure in the literature, the primary targeted pollutants were identified, with N speciation used to more precisely assess effectiveness against different Nr species, as outlined in the methodology. In table 3, the summarised findings from the literature review are presented, showing the number of measures identified based on their effects on the emissions. A total of 152 measures were identified as having a positive effect on NH_3 emissions, while an additional 31 were categorised as having an *unknown* effect due to unknown abatement efficiency/quantification or lack of follow up studies. These measures generally show potential for positive impact, but may also have no effect or, in some cases, even a negative effect on the emissions. Similarly, 61 measures were found to reduce CH_4 emissions, with 15 measures categorised as unknown. For N_2O emissions, 99 measures were found to have positive effects, while 68 remain classified as unknown for similar reasons. Regarding NO_3^- leaching, 91 measures had a positive effect, and 36 were categorised as unknown. Additionally, 9 measures were identified as having a positive impact on N_2 emissions, with 24 classified as unknown (although N_2 release does not directly cause pollution, it reduces the N use efficiency by Nr loss, requiring more inputs such as fertilisers). While some of the measures are less well-documented, they may still play a valuable role in emission reduction strategies, especially when adapted to specific local conditions. It is also worth mentioning that some of the measures were only evaluated based on their effects on CO_2e and mainly have an impact on climate through carbon sequestration. The measures were quantified when literature was available, those are presented under chapter 3.4.

Additionally, it is important that potential trade-offs and synergies between different pollutants are considered. For example, there are 4, 12 and 29 measures in the database identified with potential negative effects on emissions of CH_4, NH_3, and N_2O respectively. This emphasises the importance of carefully considering the full range of impacts when selecting mitigation strategies to ensure that reductions in one area do not lead to unintended increases in another.

Table 3. The table summarises the number of measures identified in the literature, categorised based on their effects on emissions of CH_4 and Nr species.

	Ammonia, NH_3	Nitrogen oxide, NO_X	Methane, CH_4	Nitrous oxide, N_2O	Nitrate, NO^{3-}	Dinitrogen, N_2
Positive	152	9	61	99	91	9
Unknown	31	20	15	68	36	24
Negative	12	6	4	29	3	8
Not effective	35	44	63	69	38	35

3.3 Assessment of effectiveness and size of selected measures

The measures identified in this study were arranged into measure categories, measure types, and individual measures. The linking of these groups, between this study and the GAINS model database, was possible to do on a 'measure type' level of aggregation. Out of the 360 identified individual measures, some 30 measure types were identified as integrated measures. Eleven out of these measures were identified as key *integrated mitigation measure types* by reviewing the combined result from ECLIPSE scenarios and the literature review. To account for measures that were identified in the literature review but not covered by any ECLIPSE scenario, a second review phase was carried out, focusing exclusively on the result of the literature review. As a result, 6 additional measures were identified as key *integrated mitigation measure types* (marked with a star in table 4). In total, 17 measure types were therefore identified. The 17 measure types along with their corresponding measure category and overall effect on the pollutants NH_3, NOx, CH_4 and N_2O are presented in table 4.

Table 4. Key identified integrated mitigation measure types. Emission reductions associated with the measure type are indicated with 'positive'. Measure types indicated by star are from the literature review and not part of the ECLIPSE model.

Measure Type	Measure Category	Ammonia, NH_3	Nitrogen oxide, NO_x	Methane, CH_4	Nitrous oxide, N_2O
Biogas production	Energy/nutrient recovery and carbon sequestration	Positive		Positive	Positive
Improved productivity	Livestock production, housing and diet	Positive		Positive	Positive
Nitrification inhibitors	Manure storage and processing	Not effective	Positive		Positive
Precision farming	Crop production and crop rotation	Positive			Positive
	Field application of manure and/or fertilisers	Positive	Positive		Positive

Reduction of fertilisers	Crop production and crop rotation	Positive		Not effective	Positive
	Field application of manure and/or fertilisers	Positive	Unknown	Positive	Positive
Acidification of manure	Manure storage and processing	Positive		Positive	Unknown
Covered storage of manure/slurry	Manure storage and processing	Positive		Positive	Unknown
Rapid incorporation of manure after application	Field application of manure and/or fertilisers	Positive		Not effective	Positive
Low protein diet	Livestock production, housing and diet	Positive	Not effective		Positive
Cooling of slurry/manure	Manure storage and processing	Positive		Positive	Not effective
Slurry dilution for field application	Field application of manure and/or fertilisers	Positive		Not effective	Positive
Agroforestry*	Land use and landscape management	Positive		Not effective	Positive
Increase land cover with perennial crops*	Land use and landscape management	Positive		Not effective	Positive
Increased grazing*	Land use and landscape management	Positive		Positive	Negative
Avoid soil compaction*	Crop production and crop rotation	Positive		Not effective	Positive
Fallow in crop rotation*	Crop production and crop rotation	Positive		Not effective	Positive
Biochar production*	Manure storage and processing	Positive		Unknown	Positive

3.4 Size of effects

In table 5, a quantification of potential effects of the prioritised measure-types in kiloton (kt) is presented. In contrast to other studies, the effects on emissions of CH_4 and N_2O are not expressed as CO_2e, but as kt of the gas itself. The estimations are a sum of identified potentials for all Nordic countries separated over the four emissions NH_3, NO_x, CH_4 and N_2O. The first ten measure-types are estimated potentials from ECLIPSE scenarios for the sector and fuel-activity connected to the identified measure-type. For these measure-types the difference between a MTFR scenario and a CLE scenario are considered a potential reduction. For the six last measure-types, where the ECLIPSE scenarios do not enable a quantification, estimations are made based on the literature review. Where nothing else is noted, the potentials are in kt Nordic emission reduction potential year 2040, and all numbers are approximate estimates, affected by the future development of Nordic agricultural production. The measure-type *biogas production* has a potential to reduce CH_4 with an annual reduction 9 kt for the Nordic countries combined, and it also has a potential of reducing NH_3. As for all measures and measure types, the potential might vary between the Nordic countries dependent on local circumstances. The potential in reduction for the measure-type *improved productivity* is highest for CH_4 with a potential of 23 kt/year while reducing emissions of NH_3 by 4 kt. The measure type *precision framing* has potential in reducing NO_x with 20 kt/year and at the same time the potential of reducing N_2O by 11 kt/year. Similar double effects we observe on the measure-type *reduction of fertilisers*, but a quantification based on ECLIPSE was not possible. For reducing NH_3, we see a potential in reducing the emissions by 45 kt/year for the measure type *covered storage* in combination with *rapid incorporation of manure after application*, a low protein diet, cooling the slurry/manure and slurry dilution for field application. These combinations also have the potential of reducing CH_4 emissions. Agroforestry indicates a potential in reducing N_2O (327 kt N/year) as well as a potential in reducing NH_3 (52 kt N/Year). However, these two potentials are based on the assumption that trees are being planted of 15 percent of the agricultural area.

Table 5. Quantified estimate of the shortlisted measure types of agricultural emission reduction potential for all Nordic countries in 2040, including potential of measure combinations within a measure type. Red text indicate and increase in emission.

Measure Type	Ammonia, NH_3	Nitrogen oxide, NOx	Methane, CH_4	Nitrous oxide, N_2O
Biogas production	Positive		around 9 kt	Positive
Improved productivity	around 4 kt		around 23 kt	
Nitrification inhibitors		around 0.7 kt		around 0.7 kt
Precision farming	Positive	around 20 kt		around 11 kt
Reduction of fertilisers	Positive	Positive		Positive
Covered storage of manure/ slurry in combination with:	around 45 kt		Positive	
• *Rapid incorporation of manure after application*				Positive
• *Low protein diet*				Positive
• *Cooling of slurry/manure*			Positive	
• *Slurry dilution for field application*				Positive
Agroforestry[47]	-52 kt N			-327 kt N
Increase land cover with perennial crops[48]				-13 kt
Increased grazing[49]	-5 kt		-3 kt	+0,15 kt
Avoid soil compaction[50]				5 – 10 kt
Fallow in crop rotation[51]	Positive			-1 kt
Biochar production[52]	-8 kt			

47. Estimations based on trees on 15 percent of crop areas and an arable land use of 7.6 MHa in the Nordics with reductions for NH_3 of 6.8 kg N/ha and for N_2O 43 kg N / ha.
48. Estimation based on a reduction of 461 kg CO_{2e}/ha and a total arable land use of 7,6 MHa in the Nordic countries.
49. Estimation based on numbers for Norway extrapolated to the whole Nordics, where Norway is assumed to represent 15 percent of grazing animals in the Nordics.
50. Estimation based on 30 – 60 percent reduction from CLE scenario of 17 kt N_2O due to NPK fertilization.
51. Estimation based on fallow on 4 percent of the Nordic countries total of 7,6 MHa and a reduction of 3,5 kg N_2O/ha.
52. Estimation based on a 60 percent reduction in NH_3 for the CLE scenario on poultry litter.

As can be seen, our interpretation of the ECLIPSE scenarios suggests that the largest NH_3 emission reduction potential is through an increased use of covered storage of manure and slurry, whilst biogas production has largest potential for CH_4 emissions. As mentioned above, the potential is affected by the assumed future development of Nordic agricultural production, which might differ between national estimates and ECLIPSE scenario estimates. Overall, table 5 suggest that most of the synergy measure types relates to manure/fertiliser application to soils. It is important to consider that the measures are being analysed on a Nordic level as local conditions can vary and affect the interpretation of the ECLIPSE model results.

The costs approximated per measure type are given in table 6 below. As is previously known, increased biogas production implies cost savings with the gas prices assumed in the cost calculations. Furthermore, most emission sources in the Nordic countries require joint solutions, so the costs for combinations of covered storage, low protein feed, cooling of slurry/manure and application practices. Costs are not available for several measures.

Table 6. Estimated costs for the prioritised measure-types.

Measure Type	Annual emission control cost [million € per year]
Biogas production	-5 (cost saving)
Improved productivity	17
Nitrification inhibitors	n.a.
Precision farming	n.a.
Reduction of fertilisers	n.a.
Covered storage of manure/slurry in combination with: • *Rapid incorporation of manure after application* • *Low protein diet* • *Cooling of slurry/manure* • *Slurry dilution for field application*	~280
Agroforestry	n.a.
Increase land cover with perennial crops	n.a.
Increased grazing	n.a.
Avoid soil compaction	n.a.
Fallow in crop rotation	n.a.
Biochar production	n.a.

4. Discussion and policy options

The primary aim of this project was to determine appropriate actions and develop a policy based on science that would reduce emissions of the pollutants through integrated strategies. In doing so, this project sheds light on how to simultaneously mitigate the negative effects of climate change and air quality, as well as what steps the Nordic countries can take to meet their obligations under international agreements. With reference to both mitigation measures and Nordic policy instrument examples, we have examined the political climate and the implementation of policies to reduce emissions from CH_4, NH_3 and other Nr from the agricultural sector in the Nordic countries.

4.1 International goals and obligations for the Nordic countries

The policies work on different levels to address different social challenges and improve the environment in different ecosystems. Often, the legislation focuses on solving a certain problem, without considering that a measure may affect another pollutant in a negative or positive way.

To have efficient policies that address the pollutants they need to act on different levels, with an overall legislation and then concrete measures on how to fulfil the commitments/goals in the overall policy. A good example of this is CAP, where an overall goal to reduce pollution from fertilisers is stipulated, with concreate measures on local levels that will lead to reduce pollutions of fertilisers. In many legislations, this connection can be hard to find, and sometimes there are no suggested measures or regulations on how to comply with the legislation. If there are no suggested measures on how to reduce a certain pollutant and at the same time affecting other pollutants positive, the risk of missing the indirect positive or in worst case increase emissions of other pollutants will increase.

Many of the policies that affects Sweden, Finland and Denmark comes from the EU and are implemented in the national laws and regulations. Norway and Iceland are not members of the EU but are members of the EFTA (the European Free Trade Association). Through the EEA agreement, Norway and Iceland are bound to most of the EUs environmental legislation with some exceptions, for example agriculture. This means that all the Nordic countries work towards reaching the same goal set by the EU. The EU is therefore an important actor with big potential to affect the work towards reducing emissions of Nr and CH_4 from agriculture.

Other important actors on the international area that sets goals for a better air quality is for example the United Nations and the UNECE Convention on Long-range transboundary air pollution (CLRTAP). Through international agreements the Nordic countries are bound to work towards goals that will generate a better air quality. The Nordic countries have often committed to the same goals. An example of this is the Gothenburg protocol annex 17, that all Nordic countries except Iceland have committed to.

The study did not find any webpage within each Nordic country with a combined overview of the commitments and goals that the county has agreed to work with or are bound by. It is also difficult to find information on how they perform on different goals. Therefore, it is hard to get an overall overview of which commitments and goals each country has agreed to work with and how they perform in the area, as well as if there are any conflicts between different goals to reduce emissions of NH_3 and CH_4 or other Nr. To get a better understanding of which goals/commitments that the individual country work with, and how they perform in the area, an overview of all goals and commitments as well as how the country preforms would be a good tool to increase the transparency and understanding of a country's commitments.

4.2 Integrated measures to reduce ammonia, methane and nitrogen

In this project, we have developed a database with over 300 measures to mitigate emissions of NH_3, Nr and CH_4 (appendix 3). The mitigation measures identified, might have a positive effect on air pollution, but a negative impact on climate, or vice versa. Based on the results of this report, we have identified 17 integrated measures that are effective for both air and climate, table 4.

By using published scenario analysis, comparing the technologies expected to be used for emission reductions according to current and planned legislation with technology solutions available in 2040, we have estimated the emission reduction potential for most of these 17 measures. The scenarios are, to a reasonable degree, comparable with the national emission projections for the agricultural sector, with the main deviations for Icelandic CH_4 emissions and Swedish NH_3 and CH_4 emissions. The estimation of future potentials is naturally uncertain, but serves as informative estimates nevertheless, especially for estimating the size of co-benefits between the pollutants considered in this report. It should be remembered, that much of the potential is associated with implementation of several solutions together, since most agricultural activities already, according to current legislation, will have at least one technology implemented. The cascade effect from implementing several solutions is non-additive, so identification of the emission reduction potential of all measures individually would exaggerate the potential emission reduction.

Table 4 indicates that there are big potentials for reducing NH_3 and CH_4 emissions for the Nordic countries, and that the greatest potential for these emissions seems to be to implement developed measures regarding the storage and use of manure. To reduce NOx emissions focus should be on reducing the use of fertilisers. N_2O can be reduced with several measures focusing on the soil quality, such as avoiding soil-compaction as well as increasing land cover with perennial crops and agroforestry. The latter has a high potential in reducing N_2O for all Nordic countries if assuming tree plantations on 15 percent of the area used for crops and cereal.

Table 5 indicates costs associated with the joint implementation of measures to reduce emissions. As expected, increased production of biogas would imply cost savings with the gas prices assumed in the scenarios. For the combined implementation of increased use of covered storage, low N feed, low emission housing, and low NH_3 application, the combined cost for the Nordic countries would be around 6 € per kilogram NH_3 emissions avoided.

4.2.1 Literature review of integrated measures and its effectiveness

Biogas production

According to Andersen et al.[53] nearly all types of livestock manure can potentially be utilised for biogas production, with some exceptions like cattle manure contaminated with sand. This is far from the current utilisation rate today. Figures from 2021 indicate that only 18 percent of pig manure and 29 percent of cattle manure in Denmark were processed in biogas plants.

Andersen et al.[54] calculated the potential reduction of CH_4 emissions to 76 kg CO_2e per tonne of pig manure and 54 kg CO_2e per tonne of cattle manure utilised for biogas production[55]. Additionally, the authors indicate that N_2O emissions could be reduced by 9 kg CO_2e per tonne of pig manure and 10 kg CO_2e per tonne of cattle manure by producing biogas. The reduction is compared to the manure not being utilised for biogas production and is processed according to standard agricultural practises in Denmark.

According to Byers et al.[56] less than two percent of Norway's livestock manure in year 2022 was utilised for biogas production. Their calculations suggest that increasing this proportion to 25 percent could result in annual emissions reductions of 78,000–80,000 tonnes CO_2e by 2030, accounting for CH_4, NH_3, and N_2O[57].

53. Andersen, et al., 2024
54. Andersen, et al., 2024
55. Assuming Danish agriculture conditions, practises and emissions as baseline
56. Byers, Rivedal, Budai, & Øygarden, 2024
57. Assuming Norwegian agriculture conditions, practises and emissions in year 2022 as baseline

However, Berglund & Mjöfors (2024) highlights the need to further specify regional/ national circumstances when assessing effects on CH_4 emissions from biogas production[58]. The authors highlight the importance of clarifying manure removal technologies and speed, as well as rest product temperature during storage after biogas production. In other words, the net effect on emissions might be lower in Sweden than what is quantified by models.

Improved Productivity

Rivedal et al.[59] estimates that by 2030, NH_3 emissions in Norway can annually be reduced with 810 tonnes and N_2O emissions with 68 tonnes by optimising the feed ration for dairy cows. The authors specifically mention lowering the protein content from 17 percent to 15.5 percent, calving age for heifers from 25.5 to 24 months, and feeding time for bulls from 17.9 to 16.5 months.

Nitrification inhibitors (addition to slurry)

A N_2O emission reduction of 50 percent can be achieved by adding nitrification inhibitors (NI) to cattle slurries before application[60]. In a field experiment conducted in a maize field, Recio et al.[61] evaluated the effects of two NI: 3,4 dimethylpyrazole succinic acid (DMPSA) and 3,4 dimethilpyrazol phosphate (DMPP). 30 percent less of cumulatively N_2O was lost because of the measure. However, no appreciable NH_3 loss reduction was observed over time. The measures effect on NO_X emissions have not been studied by the authors.

Nitrification inhibitors (with inorganic fertilisers)

The rate at which ammonium turns into nitrate can be slowed by adding nitrification inhibitors, such as DCD and DMPP, to fertiliser products that are urea- or ammonium-based.[62] As a result, crops have more access to NO_3^-, which raises yield levels and, depending on soil and climate conditions, lowers N_2O emissions by 35 to 70 percent[63]. A recent Swedish report does, however, indicate that more research is needed to estimate effects on NH_3, and that cost effectiveness appears low[64]. Decreases in NO_x and N_2 emissions are also anticipated, but there isn't enough information available to determine the precise impact.

Precision farming (Crop production and crop rotation)

Several international studies reviewed in Andersen et al.report concluded that precision farming can be an effective tool for emission

58. Berglund & Mjöfors, 2024
59. Rivedal, Aune, Hansen, & Prestvik, 2019
60. Sutton, Howard, Mason, Brownlie, & Cordovil, 2022; Recio, et al., 2018
61. Recio, et al., 2018
62. Sutton, Howard, Mason, Brownlie, & Cordovil, 2022
63. According to 'Akiyama, H., Yan, X., Yagi, K. (2010). Evaluation of effectiveness of enhanced-efficiency fertilisers as mitigation options for N2O and NO emissions from agricultural soils: meta-analysis. Global Change Biology, vol. 16, pp. 1837–1846.' meta-analysis using field experiment data (113 datasets from 35 studies) published in peer-reviewed journals through 2008.
64. AgriFood economic centre, 2022

reductions.[65] According to one of the studies result[66], an increased N application from 150 kg N/ha to 175 kg N/ha reduce N_2O emissions by 34 percent in areas with low yield potential, whereas areas with high yield potential were unaffected.[67] Overall, the report by Andersen et al. estimated that the measure could potentially reduce N_2O emissions from Danish agriculture with 130 kg CO_2e/ha/year. The measures effect on NH_3 emissions have not been studied by the authors. However, according to a report by the Nordic Council of Ministers[68] NH_3 and N_2O emissions will decrease through precision farming, however it has not been studied further.

Example of applicability of mitigation measure

"***Steering assistance****: The 2019 report (Korsæth et al., 2019) examined the impact of using visual guidance systems on 189,000 hectares of grassland which accounted for 40% of all fully cultivated grassland in 2019. It found a climate benefit of 1.4 kg* CO_2*-eq./daa*[69]*, or 2,646 tons* CO_2*-eq. annually. Additionally, the report indicated a potential economic gain of 15 million NOK. If autosteering had been used on the same area, it could have saved 3.7 kg* CO_2*-eq./daa, or 6,993 tons* CO_2*-eq. annually (Korsæth et al., 2019, Table 10).*

For grain production, the use of visual guidance on 1,110,000 daa, representing 40% of the grain area in 2019, was estimated to save 0.2 kg CO_2*-eq./daa, or 222 tons* CO_2*-eq. annually (Korsæth et al., 2019, Table 19). Advanced autosteering in wheat was estimated to save 1.45 kg* CO_2*-eq./daa, with barley savings being 10% lower due to lower fertilization levels. Although not calculated in detail, the average savings across wheat and barley areas was 1.3 kg* CO_2*-eq./daa, leading to a total reduction of 1,443 tons* CO_2*-eq. annually for 40% of the grain area (based on a global warming factor of 298).*

For potatoes, it was assessed that 80% of the potato area was suitable for steering assistance. Steering assistance allows for denser planting of potato rows, increasing both yield and inputs per decare. Therefore, the climate benefit primarily comes from reduced diesel consumption, although this was not calculated. It was further noted that autosteering, the most advanced form of steering assistance, provided an economic gain of 47 million NOK due to denser potato planting." [70]

65. Andersen, et al., 2024
66. Sehy, Ruser, & Munch, 2003
67. Andersen, et al., 2024
68. Nordic Council of Ministers, 2015
69. *Dekar/daa is a Norwegian unit used in agricultre, 1 daa equals 0,1 hectares*
70. Byers, Rivedal, Budai, & Øygarden, 2024

Precision farming (Field application of manure and/or fertilisers)

Precision fertilisation technology makes it possible to adapt to plants site-specific needs.[71] Studies on the precise effect on different pollutants has been limited in available literature. One report, Korsæth et al.[72], did, however, conclude that NO_3^- leaching could be reduced by 0.33 kg NO_3-N/daa, corresponding to a 3.4 kg CO_2e/daa reduction of greenhouse gas for precision fertilisation in potato fields.[73] Korsæth et al.[74] estimated the total emission reduction potential to be 8 800 tonnes of CO_2e, if applied on meadows, barley, spring, wheat and potato fields.

According to a report by Potter et al.[75] field-specific N fertilisation reduces hectare-based climate impact with about six percent for field N_2O emissions, which corresponds to a two percent reduction of total climate impact. Quantified, the authors reference (200 kg N/ha) N_2O emissions were 432 kg CO_2e/ha and the field-specific N rate was 409 kg CO_2e/ha, resulting in a reduction of N_2O emissions of 23 kg CO_2e/ha.

Reduction of fertilisers (Crop production and crop rotation)

According to a study by Andersen et al.[76] a reduction of 1 kg N fertiliser per hectare will reduce N_2O emissions, from Danish agriculture, with 6.69 kg CO_2e per hectare. However, reducing the amount of fertiliser will also reduce the soils carbon storage capacity. This trade-off effect is estimated to be 2 kg CO_2e/kg less N per hectare, resulting in a cumulative reduction of N_2O emissions of 4.7 kg CO_2e/kg less N per hectare.[77] The total potential reduction of N_2O emission is estimated to 94–298 million CO_2e/year, depending on the reduced amount of fertiliser (5–15 percent less N). The measures effect on NH_3 emissions have not been studied by the authors.

Reduction of fertilisers (Field application of manure and/or fertilisers)

Rivedal et al.[78] state that it is possible to reduce fertilisation, whilst maintaining yield levels in Norway. Assuming a reduction of 10 percent, total emission from Norwegian agriculture will be reduced with 162 tonnes of NH_3 and 2.1 tonnes of N_2O (if the measure is implemented by year 2030).[79] The authors of that study concluded that the measure was not effective in mitigating CH_4 emissions.

71. Bechmann, et al., 2023
72. Korsæth, A., Lindgaard, H. J., Veidal, A., & Asheim, L. J.
73. Bechmann, et al., 2023
74. Korsæth, A., Lindgaard, H. J., Veidal, A., & Asheim, L. J.
75. Potter, Delin, Engström, Stenberg, & Hansson, 2022
76. Andersen, et al., 2024
77. Andersen, et al., 2024
78. "Reduced fertilization should be seen in conjunction with measures in livestock husbandry, better utilization of the nitrogen in livestock manure and better agronomy." Rivedal, Aune, Hansen, & Prestvik, 2019
79. "In addition, there will be a reduction in indirect emissions from runoff and NOx and direct nitrous oxide emissions, which together are estimated at ~194 tonnes of N2O" Rivedal, Aune, Hansen, & Prestvik, 2019

According to a report from the Nordic Council of Ministers[80] the proposed measure to 'reduce fertiliser dose to below today's recommended levels', aligned with the economical optimum, impacts NH_3, N_2O and CH_4 emissions. The effect has however not been studied further. In the report, the authors emphasise the risk associated with the measure, such as reduced fertiliser will lead to reduced yield. This could in turn potentially result in forest clearing for more agriculture land, which would increase carbon emissions. However, the magnitude of these trade-offs has not been studied further.

Acidification of manure

Several methods of acidifying manure are being tested and some are already in use, according to a report by Rivedal et al.[81] An established widespread practise in Denmark is to use acids such as sulfuric acid (H_2SO_4) to stabilise N in livestock manure.[82]

A report by Rivedal et al.[83] assessed the effect of adding acid to open basins containing pig manure by increasing the proportion of artificial floating cover from 1 to 34 percent and simultaneously reducing the number of uncovered basins from 33 to 0 percent. This resulted in a reduction of 109 tonnes NH_3 emissions. However, the reduction is limited to 64 tonnes without implementing additional spreading measures. The authors also studied the effect of adding acid to wet manure spread on meadows and concluded a potential annual emission reduction of 4 700 tonnes of NH_3 emissions and 61 tonnes of N_2O emission (if measure is implemented by year 2030).[84]

Hellsten et al.[85] estimated the NH_3 emission reduction potential of acidifying slurry to 80 percent during storage, and 70 percent during spreading.[86] The authors Bechmann et al. estimated that the potential reduction of NH_3 emissions could be 70–90 percent using strong acids compared to current practise.[87] The authors did also highlight potential negative trade-offs, such as damage to stock and equipment and mentions bio-acidification as a gentler option although its effects are uncertain.

Rivedal et al. did not asses the measures effect on CH_4 emissions, they did however state its likely to result in a reduction.[88] Bechmann et al. estimated that CH_4 emissions can be reduced upwards 60 percent compared to current practise in year 2019 in Norway, although, more studies are needed to determine the effect.[89] A

80. Nordic Council of Ministers, 2015
81. Rivedal, Aune, Hansen, & Prestvik, 2019
82. Bokashi Norge AS/NIBIO, 2020; Bokashi Norge AS/NIBIO, 2020
83. Rivedal, Aune, Hansen, & Prestvik, 2019
84. Assuming Norwegian agriculture conditions, practises and emissions in year 2019 as baseline
85. Hellsten, et al., 2017
86. Hellsten, et al., 2017
87. Bechmann, et al., 2023
88. Rivedal, Aune, Hansen, & Prestvik, 2019
89. Bechmann, et al., 2023

report by Naturvårdsverket & Jordbruksverket[90] summarises results from other studies and presents a reduction in CH_4 emissions from manure according to guideline estimates of 25–90 percent, depending on where in the process the acidification occurs.

Covered storage of manure/slurry

Reduced contact between the stored manure and the surrounding air reduces both NH_3 and CH_4 emissions.[91] A floating crust coverage for slurry, which is often formed naturally or can be induced with straws or LECA balls, is estimated to reduce NH_3 emissions with 40–65 percent.[92] Floating covers, like plastic sheets, can reduce NH_3 emissions by 60–90 percent and solid covers like roofs or lids can reduce NH_3 emissions by 80–90 percent.[93]

Hellsten et al.[94] estimates the potential reduction of NH_3 emissions to 50–95 percent, depending on the type of cover.[95] This is in similar range as Bechmann et al.[96][97] and Rivedal et al.[98][99] result of 40–80 percent reduction, depending on cover (dense and solid cover, artificial floating covers in e.g. plastic and natural cover/crust). According to the report by Bechmann et al.[100], the measure will also reduce CH_4 emissions, although, the effect has not been studied further. Rivedal et al.[101] suggest that this measure could potentially lead to an annual CH_4 emission reduction of over 300 tonnes from Norway's agricultural sector by year 2030. However, the authors caution that this estimate may not be realistic, as CH_4 emissions can only be significantly reduced through the use of porous covers.

Example of applicability of mitigation measure

*"**Slurry:** JTI measured emissions over one year of storage (on a trial scale) of cattle and pig slurry, where large-scale conditions were simulated in terms of manure temperature, climate, emptying, and filling (Rodhe, Baky, Olsson, & Nordberg, 2012).*

90. Naturvårdsverket & Jordbruksverket, 2022
91. Nordic Council of Ministers, 2015
92. Assuming agriculture conditions, practises and emissions in Denmark, Finland, Norway and Sweden during year 2015 as baseline
93. Assuming agriculture conditions, practises and emissions in Denmark, Finland, Norway and Sweden during year 2015 as baseline
94. Hellsten, et al., 2017
95. Assuming Swedish agriculture conditions, practises and emissions as baseline
96. Bechmann, et al., 2023
97. Based of EMEP / EEA (2019) data
98. Rivedal, Aune, Hansen, & Prestvik, 2019
99. Assuming Norwegian agriculture conditions, practises and emissions in 2019 as baseline
100. Bechmann, et al., 2023
101. Rivedal, Aune, Hansen, & Prestvik, 2019

Measurements were taken on uncovered slurry, slurry with a floating cover, and slurry with a plastic cover. The results showed about twice as much methane emission during the warm part of the year (5 months) compared to the cold part (7 months), expressed in grams of methane per kg of volatile solids (VS). During the warm part of the year, methane emissions were significantly higher from uncovered cattle slurry and slurry with a floating cover than from cattle slurry with a plastic cover. According to JTI's summary of the trial results, there were no other significant differences between the other cover alternatives or time periods (ibid.). One explanation for the lower methane emissions with a plastic cover in the summer was that the cover may have contributed to a higher concentration of gases that inhibit methane formation. The difference could also be due to measurement uncertainties, as gas bubbles collected under the cover and the gas may have escaped too quickly to be recorded in the measurements.

The results from measurements in other countries suggest that covering (floating cover, membrane/roof) could reduce methane emissions from slurry, but the effect of cover alternatives varies between studies, and the differences in methane emissions between cover types within a study are not always significant (Petersen et al., 2013; Berg, Brunsch, & Pazsiczki, 2006; Rodhe, Baky, Olsson, & Nordberg, 2012; VanderZaag et al., 2010). According to a literature review by Petersen et al. (2013), floating covers or roofs in some cases reduced methane emissions by about 20–40% compared to uncovered slurry, but in some cases also increased methane emissions. However, it is unclear from their review whether the differences are statistically significant." [102] (machine translated to English)

"***Solid and deep litter manure:*** *Methane is produced in oxygen-free environments, but oxygen availability is generally better in deep litter and solid manure compared to slurry, resulting in relatively low methane emissions from solid manure types. However, oxygen-free zones can form in solid manure due to compaction or high oxygen consumption during composting. The composting process also increases the temperature in the manure, which can lead to more methane production, as microbial methane formation is highly temperature-dependent. Covering the manure (with a tarp) can reduce methane production because the cover limits oxygen supply, which inhibits composting and thus prevents temperature rise in the pile (Rodhe, Baky, Olsson, & Nordberg, 2012).*" [103] (machine translated to English)

102. Berglund, 2017. E*missionsfaktorer för utvärdering av klimateffekter av vissa insatser i landsbygdsprogrammet.* Hushållningssällskapet Halland, uppdrag för Jordbruksverket.
103. Berglund, 2017

Rapid incorporation of manure after application

If solid manure is incorporated into the soil within four hours, NH_3 emissions can potentially be reduced by 60–90 percent, whereas the potential emission reduction decreases to 30 percent if it is done within 24 hours.[104][105] According to the authors, this effect has no mitigating effect on N_2O emissions.

According to Rivedal et al.[106] 11 percent of the manure is decomposed within one hour. However, if the manure is broken down the share of decomposed manure increases to 34 percent. The authors estimate that by 2030, this technique could lead to an annual reduction of 560 tonnes of NH_3 emissions and 7.2 tonnes of N_2O emissions from emissions associated to animal manure in Norway.

Reducing the exposed slurry area by placing slurry in narrow surface slots can reduce NH_3 emissions with 70–90 percent[107] according to Sutton et al.[108] However, the authors state that this measure can lead to an increase of N_2O emissions as well as NO_X and N_2 emissions.

13 percent of livestock manure is decomposed within one hour and 29 percent within 24 hours.[109] If instead 25 percent is decomposed within an hour, and 50 percent within four hours, the maximum potential annual reduction of NH_3 emission is 12 000 tonnes CO_2e in year 2035.[110]

Low protein diet

By adapting crude protein in dairy and beef cattle's diet, N emissions can be mitigated.[111] A 1 percent reduction of crude protein in cattle's feed can potentially reduce NH_3 emissions with 5–15 percent[112], as well as reducing N_2O and CH_4 emissions and increase N efficiency in livestock production.[113] The authors have not done any further study of the measures effect on N_2O and CH_4 emissions.

Cooling of slurry/manure

The measure reduces NH_3 which in turn reduce indirect N_2O emissions.[114] CH_4 emissions are also reduced since cooling inhibits the slurry's biological turnover. However, if parts of the slurry contain unreacted organic matter CH_4 emissions can increase during the slurry's transfer. Andersen et al.[115] therefore concludes that the optimal effect is achieved if the slurry is degassed in a biogas plant after discharge,

104. Figures are applicable in Sweden, Denmark, Finland and Norway
105. Nordic Council of Ministers, 2015
106. Rivedal, Aune, Hansen, & Prestvik, 2019
107. Bittman, Dedina, Howard, Oenema, & Sutton, 2014)"Average emission reductions agreed to be achievable across the ECE region"
108. Sutton, Howard, Mason, Brownlie, & Cordovil, 2022
109. Byers, Rivedal, Budai, & Øygarden, 2024
110. Assuming Norwegian agriculture conditions, practises and emissions as baseline
111. Sutton, Howard, Mason, Brownlie, & Cordovil, 2022
112. Assuming Norwegian agriculture conditions, practises and emissions as baseline
113. Bechmann, et al., 2023
114. Andersen, et al., 2024
115. Andersen, et al., 2024

as this simultaneously reduces CH_4 emissions and increases bioenergy production. In total the authors calculated the potential reduction of CH_4 to 3 kg CO_2e/tonne manure and N_2O to 2 kg CO_2e/tonne.[116] Similar calculations were not made for NH_3 emissions. However, in one of the authors calculation examples[117] they concluded that NH_3 emissions will potentially decrease with 13.2 percent in barns with pipe discharge if there is a constant cooling effect of 16.8 W/m^2. If the barn instead has frequent mechanical removals (like line winch) the reduction is closer to 22.2 percent.

Andersen et. al.[118] states there are examples of cattle barns who have installed cooling hoses in manure channels to recover heat energy as an alternative to geothermal heating. However, the authors state there is a lack of studies effect of NH_3 and other emissions in relation to this in modern barns.

Slurry dilution for field application

According to the report by Rivedal et al.[119] Norway's NH_3 emissions from agriculture could potentially be reduced by 3 490 tonnes and N_2O by 45 tonnes by diluting slurry with water to a 1:1 ratio compared to not diluting at all (study from 2019). The authors also state that if wet manure is diluted with acid, NH_3 discharge can be reduced by 50 percent, resulting in a reduction of Norway's NH_3 emissions from agriculture with 4 700 tonnes and N_2O emissions with 61 tonnes (study from 2019).

Today, 85 percent of all livestock manure spread on fields in Norway are mixed with water according to the Norwegian statistics bureau (SSB's) manure survey from 2018.[120] The survey states that 75 percent of livestock manure is mixed with less than one part water to one part fertiliser, and the remaining 25 percent is specifically one part water and one part fertiliser.

Agroforestry

Agroforestry integrates the cultivation of trees and shrubs with other crops and is sometimes paired with livestock production.[121] Transfer from regular farming to agroforestry can, according to a report cited by Naturvårdsverket & Jordbruksverket, increase levels of organic carbon in soil by 34 percent.[122] Other mentioned trade-off benefits are increased biodiversity, more ecosystem services like pollination and improve the soils water retention (which reduces the loss of nutrient).

116. Assuming Danish agriculture conditions, practises and emissions as baseline
117. Assuming Danish agriculture conditions, practises and emissions as baseline
118. Andersen, et al., 2024
119. Rivedal, Aune, Hansen, & Prestvik, 2019
120. Rivedal, Aune, Hansen, & Prestvik, 2019
121. Naturvårdsverket & Jordbruksverket, 2022
122. De Stefano & Jacobson, 2017

According to the report by Andersen et al.[123] N_2O emissions can be reduced by 170 kg CO2e/ha/year if the trees are harvested in a 5- or 10-year interval, where trees make up 15 percent of the entire area.[124] However, the net climate effect differs depending on the harvest interval, spanning from 781 to 1 056 kg CO_2e/ha/year.

NH_3 emission from commercial fertilisers is assumed by Andersen et al.[125] to be four percent of the N content in the applied fertiliser. Therefore, NH_3 emissions are expected to decrease by 6.8 kg N/ha/year with the shift to agroforestry in their working example.[126]

Example of applicability of mitigation measure

"A Danish experiment with willow over 6 years (12,000 plants/ha) showed an annual yield of 4.9, 6.6 and 8.0 tonnes of dry matter per ha per year at harvest intervals of 1, 2 and 3 years, i.e. with a reduction of 18 and 38% by reducing the harvest interval from 3 to respectively 2 and 1 year (Larsen et al., 2019)

A Polish study in willow over 12 years showed similar reductions in yield by reducing the harvest interval from 3 to 2 or 1 year, but the study also showed that the effect was very dependent on plant numbers with yield reductions of respectively 25 and 55% at 12,000 plants per ha against 11 and 15% reduction at 24,000 plants per ha (Stolarski et al., 2019).

An older Swedish study in willow showed that optimal yields were obtained at 4–5 year harvest intervals but also with interaction between plant numbers (10,000-40,000 plants/ha) and harvest interval (Willebrand et al., 1993)." [127] (machine translated to English)

Increase land cover with perennial crops

Perennial crops like willow, poplar and elephant grass can affect the field's N and C balance, magnitude depending on factors such as length of growing seasons and the size of the root network.[128] In recent years, interest in growing perennial crops, specifically for energy purposes, has declined in Denmark according to Andersen et al.[129] The authors state that this is largely due to the ample availability of alternative biomass sources up until 2022, which kept prices low. Additionally, they state that Denmark's cogeneration sector has primarily relied on wood pellets, limiting the role of perennial crops. However, over the past year, prices for biomass,

123. Andersen, et al., 2024
124. Assuming current Danish agriculture conditions, practises and emissions in year 2024 as baseline
125. Andersen, et al., 2024
126. Assuming Danish agriculture conditions, practises and emissions as baseline
127. Jensen, Larsen, Strandberg, & Jørgensen, 2024
128. Andersen, et al., 2024
129. Andersen, et al., 2024

food, and key inputs like fertiliser have shifted, making future developments uncertain. Andersen et al.[130] quantified the potential reduction of N_2O emissions by having multi-year perennial crops in rotation to 461 kg CO_2e/ha/year, with a net climate effect (accounting for CO_2/LULUCF and CO_2/energy consumption effect on emissions) to 1 340 kg CO_2e/ha/year[131]. The measures effect on NH_3 emissions were not included in those calculations. However, in one of Andersen et al.[132] worked examples, the authors concluded that cultivating the perennial crop willow instead of standard crop seeds, a fertiliser saving of 51 kg N/h is achieved. Applying an NH_3 evaporation rate of four percent results in a reduction of 2 kg N/ha.

Increased grazing

If livestock are outside for more than 18 hours a day, grazing can reduce NH_3 emissions with 30 to 50 percent and if the animals are outside for 12 hours a day the reduction is estimated to 10 percent.[133][134] In the report Rivedal et al.[135] estimates that if grazing is increased to 25 percent in 2030, total NH_3 emissions can be reduced with 799 tonnes, N_2O emissions increased with 23 tonnes and CH_4 emission decreased with 467 tonnes. If animal density is high and grazing is extensive, the expected reduction may not be as significant.

Avoid soil compaction

Soil compaction could potentially cause damages to the soils structure, resulting in lower yield levels up to 20 percent.[136] By avoiding and/or minimising soil compaction these yield losses can be reduced. According to the report by Bechmann et al.[137] this measure will reduce NH_3 and N_2O emissions, however the magnitude of that effect was not studied by the authors. According to a study by Sitaula et al.[138] N_2O emissions could potentially be lowered 30 to 60 percent by avoiding and/or minimising soil compaction.[139]

Fallow in crop rotation

In crop rotation, fallow refers to leaving a field uncultivated for at least one growing season/harvest period.[140] Therefore, less fertiliser is required which reduces greenhouse gas emissions. Farms in Denmark with more than 15 hectares must allocate 4 percent of their cultivated land with non-productive elements, like for example fallow, in order to receive agricultural support.[141]

130. Andersen, et al., 2024
131. Assuming Danish agriculture conditions, practises and emissions in year 2024 as baseline
132. Andersen, et al., 2024
133. Assuming Norwegian agriculture conditions, practises and emissions as baseline, study from 2019
134. Rivedal, Aune, Hansen, & Prestvik, 2019
135. Rivedal, Aune, Hansen, & Prestvik, 2019
136. Bechmann, et al., 2023
137. Bechmann, et al., 2023
138. Sitaula, Hansen, Sitaula, & Bakken, 2000
139. Reduction potential calculated based of Norwegian agriculture conditions, practises and emissions in year 2000 as baseline
140. Andersen, et al., 2024
141. Andersen, et al., 2024

According to a report by Andersen et al.[142] fallow in crop rotation results in a reduction of N leaching by 39–55 N/ha.[143] The effect largely depends on whether the set-aside area was a turnover area or part of environmental schemes, permanent grassland, or uncultivated land.

In Andersen et al.[144] worked examples, they calculated what effect the measure will have on N_2O emissions. Assuming no fertilisation is needed in fallow areas, and 171 kg N/ha is needed in a regular crop rotation, N_2O emissions would be reduced with 930 kg CO_2e/ha/year, and the net climate effect 1 385 kg CO_2e/ha/year (when taking savings of fossil energy into account).[145] The measure would also reduce NH_3 emissions, although the reduction has not been quantified by the authors. They do however state that NH_3 volatilization is abated and/or reduced because of the reduction of N fertiliser usage, compared to the reference case (171 kg N/ha).

Biochar production

Andersen et al.[146] proposes producing biochar through pyrolysis of the fibre fraction from digested biomass. In the authors working example, its assumed that pyrolysis occurs in temperatures where the ratio between hydrogen and organic carbon is 0.5 and that that pyrolysis preserves 50 percent of the carbon in biochar. In their report the authors quantified the potential reduction of N_2O emissions by producing biochar through pyrolysis of the fibre fraction from digested biomass to 6 kg CO_2e/tonne manure[147], with a net climate reduction effect (accounting for CO_2/LULUCF and CO_2/energy consumption effect on emissions) of 18 kg CO_2e/tonne manure.[148] The measure would also reduce NH_3 emissions, it has however not been quantified by the authors.

4.3 Policy Areas

Although the focus here is on of NH_3, Nr and CH_4, it is in a policy context necessary to acknowledge that the agricultural sector is important for many reasons, e.g. the importance for food security, economy, land use and landscape, culture, rural communities etc. Agriculture also affects health and environment, both through emissions to air, and through leaching of NO_3^- to ground- and surface waters, pollution with pesticides and heavy metals, soil degradation from agricultural practices etc. There can be linkages between overall N use efficiency, and losses of N as NH_4, NO_3, NO_X and other forms of Nr. This is, however, not dealt with in detail in this report. For all these reasons, regulation and control of the agricultural sector

142. Andersen, et al., 2024
143. Reference leaching of 59 kg N/ha. Figures based of Danish agriculture conditions and practises in year 2023
144. Andersen, et al., 2024
145. Assuming Danish agriculture conditions, practises and emissions as baseline
146. Andersen, et al., 2024
147. 20 percent deep litter in the manure, the rest cattle and pig manure.
148. 20 percen deep litter in the manure, the rest cattle and pig manure. Assuming Danish agriculture conditions, practises and emissions as baseline

is quite complex with measures ranging from legislation over permits and control for individual farms to tax and subsidies promoting or inhibiting certain practices or encouraging special farming practices like organic farming.

Table 7 summarises some of the tasks and policy areas connected to regulation of the agricultural sector and links to ministerial areas and other authorities, as well as to international regulations. For EU member states, there are policies on many areas affecting agricultural regulations, and other international obligations are typical implemented in EU regulations, that can act directly as law for the member states, or be directives, which need to be implemented in national legislation. The Common Agricultural Policy (CAP) is also an important tool in regulating agriculture. For the non-EU countries, there are still international obligations through Conventions and bilateral agreements that need to be implemented in national law.

Table 7. Policy areas, international obligations and authorities.

Authority	Task/policy area	International obligations
Ministries	**Policy area**	Air emission ceilings
Environment, nature	Air emissions	Air quality
Agriculture, food	Environment, pollution	Water quality
Climate, energy	Climate	Soil quality
Health	Nature, forests, biodiversity	Pollution, air, water, soil
Planning, rural development	Air quality, health	Nitrate
Green transition	Surface- and ground water	Methane
Regions	Soil quality	Nature protection and restoration
Municipalities	**Permit and control**	Integrated pollution prevention
	Agricultural approvals	and control, Industrial emissions
	Agricultural operation	Environmental impact assessment
	Environmental approval	Agricultural policy (for EU: CAP)
	International obligations	

Ministerial areas changes with governments depending on political focus and priorities. Because of the complex interactions between agriculture and environment, agricultural regulation is normally divided between different ministerial areas. In many cases, the most important split will be between ministries for agriculture/food and environment, where the division can shift with governments. In some cases, there can be a split for environment between a pollution-oriented area and a ministry/ministerial area dealing with nature. In this case, the responsibility for agricultural approvals can also be split.

For the substances in question here, the deposition of NH_3 can have a negative effect on sensitive terrestrial nature types and add to the N pollution of marine areas. However, NH_3 is also a precursor of fine particles ($PM_{2.5}$) in the air, which is important for health. CH_4 is an important climate gas, but at the same time a precursor for ozone and therefore important for health. This means that these pollutants and their regulation can also be important for ministries of health and climate, which has a boundary to energy. Planning and rural development also have boundaries to agricultural regulation, and with the latest government reshuffle in Denmark, a new ministry for green transition of agriculture was constructed, which will integrate most of the ministerial areas connected to agriculture.

The organisation of different policy areas in different ministries may appear to be of less importance but can be important for the possibilities of developing policies for co-mitigation of different pollutants. Different ministries and agencies have different traditions for getting science-based advice and different traditions for stakeholder involvement. Established cooperation between knowledge institutions and ministries and agencies can be important, both for national regulation and for cooperation with international entities. As an example, NH_3 emissions are reported to UNECE/TFRN, whereas CH_4 and NO_2 emissions are reported to UNFCCC, often by different groups in the countries.

Finally, the political and administrative level of a certain regulation can be important; both in how international obligations and regulations are incorporated in national regulations, and at which administrative level a given regulation is implemented, be at national/regional/municipality level.

The organisation of ministerial areas, where agriculture, environment and climate are rarely under the same ministerial area can be a potential barrier for the implementation of integrated measures. This does not mean that effective measures cannot be implemented, but it can lead to a suboptimal prioritisation when measures are implemented to address a single problem like water pollution, emissions to air, or climate mitigation, and the co-benefits of measures might not be fully achieved.

4.4 Policy instruments

A general basis for environment policy and implementation of instruments could follow the principles of precaution, prevention, rectifying pollution at source, and the 'polluter pays' principle.[149] Policy instrument can be i) information, ii) direct environmental regulation (command-and control) iii) pricing instruments (taxes, emissions trading systems) and iv) financing instruments (public financial support, payments for ecosystem services).[150]

In general, measures aimed at increasing animal ***productivity*** and profitability are implemented continuously and do also have a positive side effect for the environment since they reduce climate impact per kilogram produced food.[151]

A large contribution to CH_4 emissions from the agricultural sector is drained organic soils, mainly originating from waterbodies that have been created by excavation (ditches) on forest land and cropland.[152] Policies aimed at ***restoring natural hydrology and extensive farming practises*** on these areas can give some, but limited effect.

It is generally acknowledged that ***knowledge dissemination and education of farmers*** can help to improve their understanding of how best to use fertilisers, and that a fertiliser plan and bookkeeping of actual fertiliser use is an important tool for this purpose.[153] Reporting of this information to the authorities can be a part of control of existing regulation and the development of new measures. A similar accounting and reporting is, however, not in place for climate gasses.

Since 2001, there has been a free advisory service in Sweden for farmers called "Focus on nutrients" (in Swedish: Greppa Näringen), which is financed by the current rural development programme. The initial focus was on advice for higher nutrient efficiency to reduce nutrient leaching but today, the service also provides advice specifically targeting greenhouse gas emission reductions and energy efficiency.[154]

Mineral fertilisers are associated with emissions of CO_2 and N_2O in the production phase as well as in the cultivation phase (including transport). A ***tax*** on N surplus at farm level can play a vital role in limiting the excess use of N fertilisers and improving efficiency in the use of manure-N. Levies or taxes on mineral fertilisers can further underpin efforts to reduce N and GHG emissions.[155]

149. European Parliament, 2024
150. Andersen & Bonnis, 2021
151. Government Offices of Sweden, 2022
152. Government Offices of Sweden, 2022
153. Andersen & Bonnis, 2021
154. Government Offices of Sweden, 2022
155. Andersen & Bonnis, 2021

This can be combined with ***quotas*** on the use of mineral fertilisers.[156] This can be combined with limits to the use of total fertiliser (N and/or P) and manure per hectare, potentially differentiated by crop.

Targeted ***subsidy*** can be given as direct support as well as tax credits to farmers and used to encourage farmers to adopt best practices for manure management, including appropriate storage containers and spreading machinery and possible win-win practices.[157]

As described earlier, results show that effective integrated measures mainly are related to manure/fertiliser application to soils, which can have positive impact for emission reduction for at least two of the pollutants. Measures including information, tax, quotas and targeted subsidy can be relevant in this context.

There can be a significant difference in the price and incentives needed for the implementation of measures in ***new compared with existing*** production systems. For example, retrofitting slurry cooling in existing pig farms is estimated to be significantly more expensive than in the case of a new establishment. For new barns, the investment and operation costs of slurry cooling are a barrier to expansion, while the need to meet environmental requirements is a significant incentive.[158]

Nature-based solutions in European farming systems and in cities can simultaneously contribute to nature restoration, climate mitigation and adaptation, and reduce nutrient and pesticide pollution.[159] Measures listed by EEA (2021) with potential impact on nutrients include improvement of soil and water management, as well as mixed crop-livestock systems.

There are many different possible drivers for changes in the agricultural system, that will also affect emissions, including ***dietary changes***. A broader shift towards healthier diets in Europe could yield significant co-benefits in terms of nutrient pollution and GHG emissions.[160] In the report '*Nitrogen on the Table: The influence of food choices on nitrogen emissions and the European environment*' Leip et al.[161] analysed the consequences of a demitarian approach, halving meat and dairy intake across Europe (with a corresponding increase of other foods). This scenario at the same time estimated a 43 percent reduction in NH_3 emissions, with similar reductions in greenhouse gas emissions, as well as N losses to water and total N losses from the food system.

For conventional animal-based foods, most of the GHG emissions are associated with feed production, manure management and enteric CH_4 emissions from ruminants; while the GHG emissions of ***future foods*** are mainly linked to

156. Andersen & Bonnis, 2021
157. Andersen & Bonnis, 2021
158. Andersen, et al., 2024
159. Agency, 2021
160. EEA, 2024
161. Leip, et al., 2023

energy-intensive processes such as drying (e.g., microalgae and insects), cell cultivation, steam production and maintenance of fermentation processes. For this reason, a shift towards renewable energies could potentially bring larger GHG emission reductions related to the production of future foods than from conventional animal-based foods.[162]

4.5 Examples on stakeholder perspectives

There are potentially many stakeholders in agricultural regulation. In the political agreement, made for a green transition of Danish agriculture this year, both the Ministry of Agriculture and Environment participated along with the Danish Municipalities Organisation, The branch Organisation for Agriculture and Food, and the Danish Nature Conservation NGO, each with different perspectives.

The ministries are getting science-based advice from knowledge institutions, but although this might include feasibility and barriers for the implementation of measures, the knowledge institutions providing the advice are not stakeholders in the policy process and will generally not give political advice. In a report from 2024 providing an overview of the effects, potentials, uncertainties, and barriers of several measures that can contribute to reducing greenhouse gas emissions from Danish agriculture, DCA/Aarhus University investigated 29 reduction measures from livestock, manure, crop production, and land use. The main barriers reported, for all measures, was lack of data. Although the report also looked at side-effects on environment and biodiversity, these issues were not dealt with in detail.[163]

For the Municipalities Organisation, the main perspective was on administration, and division of work with the agencies, which is also a perspective of the agencies. The ministries will, however, also focus on realising the political goals of the government and on reaching an agreement that does not conflict with other laws and regulations, and which can pass through parliament.

For the Danish Nature Conservation NGO, the original perspective was to ensure that a CO_2e tax in agriculture 'should be introduced as early as 2025. The fee should be high and uniform, so that it creates the best starting point for the market to drive the green transition and find the best solutions itself.', and that this 'will be cheapest for society and create security around the reductions.[164]

The perspective of the branch Organisation for Agriculture and Food is reflected in a report on climate measures for Danish agriculture from their research institution SEGES Innovation[165]. Here it is stated that "taxes that impose a financial burden on farmers when a certain amount of CO_2 is emitted have the consequence that

162. Leip, et al., 2023
163. Andersen, et al., 2024
164. Danmarks naturfredningsforening, n.d.
165. Henricksen, et al., 2023

there is a liquidity drain from the individual company which means, that there is a poorer financial opportunity for the individual farmer to invest in CO_2-reducing measures." In addition, it is stated that the vast majority of possible measures has both an investment cost and an increased cost of production for farmers. It is therefore desired that a financial incentive structure is created, where consumers must pay an additional price for the food products and the food companies will pay more to their suppliers, which can contribute to financing the implementation of measures with the farmers, and investments in CO_2e-reducing measures in the processing stage.[166]

SEGES points to a voluntary scheme Arla Foods has made with the milk suppliers who implement "green initiatives" on the farms and are rewarded with an additional payment at the expense of the milk producers who do not actively implements the measures. Furthermore, it is stated that consumer driven demand for specialty products and high-value goods is well known to be well-intentioned when asked, but that it is usually the price of the item that ultimately determines the product choice.[167]

The range between these views is from the green NGO who calls for a high CO_2e tax to ensure reductions at the lowest cost to society, to agriculture who wants voluntary agreements with an incentive structure paid for by the consumers or the state.

The starting point for the negotiations of a green transition of Danish agriculture was an analysis showing that the agricultural agreement from 2021 would not give sufficient reductions for the agricultural sector. The agreement contained several initiatives which reduce the emission of greenhouse gases, including an implementation track with measures, which can already be implemented, as well as a track with additional measures which need development. A carbon tax was suggested at different levels in addition with subsidies for other measures.

At the end, an agreement was reached where improvement for nature and the aquatic environment was included by taking out agricultural land to rewetting and afforestation meaning that the climate target can be reached with a smaller carbon tax. The price of this agreement supported by both agriculture and nature conservationists was the construction of a land fund of 50 billon DKK to buy up agricultural land.

166. Henricksen, et al., 2023
167. Henricksen, et al., 2023

4.6 Synergies and trade-offs

Synergies and trade-offs between NH_3 and CH_4 abatement has been dealt with in the first part of this report. The intension of this section is not to repeat this, but to widen the scope based on literature and international policy recommendations.

There is strong scientific evidence for the existence of several climate-related co-benefits with significant economic value. This could be climate policy co-benefits, such as improved air quality, co-benefits for climate objectives from policymaking in other fields, such as taxation and land use related measures, and co-benefits from policies designed to achieve multiple objectives.[168] The number of published scientific articles on co-benefits has increased significantly, while co-benefits are seldom recognised in the preparatory stages of policymaking nor reflected in subsequent policies.[169]

It has been mentioned that NO_X emissions contribute to tropospheric O_3 formation, and NO_X and NH_3 emissions contribute to particle formation which both has effects on health. O_3, in addition has a strong, but short-term warming effect, whereas particles have a strong, but short-term cooling effect.[170]

Nitrogen management measures (including pollution mitigation) often affect air pollution, climate change, food production and biodiversity simultaneously. There are several N management measures with synergistic effects on air pollution mitigation and climate change mitigation. N management can therefore provide a contribution to meeting climate targets. The relationships between N management and climate change mitigation are, however, complex and there is still a limited understanding of the interactions between N management, air pollution mitigation and climate change mitigation at regional and global scales.[171]

There are significant interactions between NH_3 and CH_4 emissions from agriculture. Overall, measures to reduce these gases go hand-in-hand through links to sector activity, where there is a trade-off between production intensity (e.g. nitrogen use per ha) and efficiency. While some measures offer synergistic benefits, there is an ongoing need to optimise practices in order to minimise trade-offs between the two gases. These interactions highlight the opportunity to further develop synergies when including both NH_3 and CH_4 in the revised EU National Emissions Ceilings Directive (NECD).[172]

In Sweden, it is expected that with a continuous, and in accordance with the Swedish food strategy, increased food production, a large part of the greenhouse

168. Karlsson, Westling, & Lindgren, 2023
169. Karlsson, Westling, & Lindgren, 2023
170. Erisman & Bleeker, 2011
171. UNECE/WGSR, 2010
172. UNECE/WGSR, 2010

gas emissions deriving from biological processes will remain. Efficient policy packages are needed to reduce the emissions from the sector as much as possible without causing negative side effects on other environmental or societal goals.[173]

Under the EU Common Agricultural Policy (CAP), farmers can, based on certain requirements, receive support for measures aimed at producing non-profitable services delivered to the wider public such as landscapes, farmland biodiversity and certain climate change mitigation measures. Through the CAP's second pillar for rural development, member states have access to a wide range of measures to encourage higher environmental performance, including climate mitigation and adaptation.[174]

Measures specifically contributing to climate change mitigation in agriculture include those aimed at: increasing energy efficiency; production and use of renewable energy (including biogas production and establishment of perennial energy crops); conversion from fossil to renewable energy sources; improved manure handling; more efficient use of N; climate and energy advice; measures to prevent the risk of N leakage; restoration and establishment of wetlands; promotion of grass ley and catch crop production in intensive cropping areas; conservation of semi-natural pastures; and other separate projects relating to climate and energy.[175]

4.6.1 Examples of benefits, trade – offs and negative impacts

The most important measures with synergies and trade-offs for NH_3 and CH_4 are described in the first section of the report. Below is a short overview of a larger range of measures based on UNECE/TFIAM.[176]

4.6.2 Measures which reduce both ammonia and methane emissions

Examples of effective strategies for reducing both CH_4 and NH_3 emissions from animal manure include covering slurry stores (potentially with CH_4 capture), extracting biogas from slurries, and acidifying the slurry. Given the right circumstances and the use of optimal methods, each of these measures contributes to lowering emissions of both gases, though they operate through different mechanisms. Covering slurry stores is a straightforward yet impactful method for controlling emissions. The coverage prevents the release of CH_4 from the slurry's surface, as it traps the gas and either captures it for energy use or minimises its escape into the atmosphere. Additionally, covering helps to reduce NH_3 volatilization by limiting the exposure of the slurry to air, which in turn decreases the rate at which NH_3 escapes. Acidification of slurry is another effective approach

173. Government Offices of Sweden, 2022
174. Government Offices of Sweden, 2022
175. Government Offices of Sweden, 2022
176. UNECE/TFIAM, 2015

for mitigating emissions. By lowering the pH of the slurry through the addition of acids, like sulfuric acid or formic acid, NH_3 is converted into ammonium, a less volatile form that is retained in the slurry rather than being released into the air. Acidification reduces CH_4 emissions by inhibiting the activity of methanogenic bacteria during anaerobic decomposition. However, this method is only effective for CH_4 emissions when applied early in the manure management chain. The production of biogas from slurries through anaerobic digestion offers significant advantages in reducing both CH_4 and NH_3 emissions. During anaerobic digestion, CH_4 is captured and utilised as a renewable energy source. However, there is still some uncertainty regarding the overall impact of anaerobic digestion, particularly concerning CH_4 emissions during storage of the remaining digestate. Variability in emissions is influenced by factors such as manure type, pH, and storage conditions, leading to uncertainty about the methane emissions during digestate storage. Furthermore, the digestion process stabilises the slurry and can reduce its potential for NH_3 volatilization. However, the remaining digestate, particularly the liquid fraction, can have a high pH, which may increase NH_3 emissions if not managed properly. To address this, it is crucial to use low-emission land-spreading techniques.

4.6.3 Measures which reduce one pollutant but have no effect on another

For example, measures designed to mitigate NH_3 emissions from N fertiliser applications or manure applications to land generally do not impact CH_4 emissions significantly. This is because N fertilisers and manure applications are not major sources of CH_4 in the agricultural sector. Instead, CH_4 is primarily emitted from enteric fermentation in ruminants and anaerobic decomposition of organic matter in manure storage.

One strategy to reduce NH_3 emissions involve the natural crusting of slurry storage. This method works by forming a layer on the surface of the slurry, which helps to minimise NH_3 volatilization. However, its effectiveness in reducing CH_4 emissions is limited. CH_4 tends to escape through cracks in the crust rather than being effectively trapped. Although some CH_4 may be consumed and converted to carbon dioxide by microbial activity within the crust, this process does not substantially lower overall CH_4 emissions from the slurry.

Similarly, feeding ruminants a lower protein diet can lead to reduced N excretion, as less N is available for conversion into NH_3. However, if the total dry matter and fibre intake remain constant, the effect on enteric CH_4 emissions is minimal. This is because enteric CH_4 production is more closely related to the fermentation process in the rumen, which is influenced by the type and amount of fiber and carbohydrates in the diet, rather than just N content. Finally, certain novel feed additives may selectively reduce CH_4 emissions.

4.6.4 Measures which reduce one pollutant but increase the other pollutant

Some animal feeding strategies or dietary supplements aimed at reducing enteric CH_4 emissions can inadvertently lead to increased N excretion. This increase in N excretion can subsequently result in higher NH_3 emissions, as excess N in manure is more readily released into the atmosphere in the form of NH_3. Similarly, while active aeration of stored manure is an effective method for mitigating CH_4 emissions – by accelerating the decomposition of organic matter and capturing CH_4 for use as a renewable energy source – it often leads to increased NH_3 emissions. This occurs because the aeration process promotes the breakdown of N compounds, releasing NH_3 into the air.

These scenarios highlight the complex interplay between different environmental interventions and the potential for unintended consequences. The increase in one type of emission while reducing another underscore the necessity to use integrated strategies to mitigate pollution from the agricultural sector, and to minimise the trade-offs and enhance the environmental benefits.

4.7 Example of an integrated policy

The main new development on the policy side in the Nordic countries is the Danish agreement on a green transition for agriculture and the subsequent forming of a new ministry to implement the transition. The development is, from a stakeholder perspective, described in the paragraph on stakeholders. The green deal is the biggest change to the Danish landscape since the agricultural reforms from the end of the 18th century and heath cultivation from the middle of the 19th century.

In total, around 15 percent of the total agricultural area will be taken out of normal operation (9 percent of the country area of 4.3 M ha). First and foremost, 250.000 hectares of forest will be planted. In addition, 140.000 hectares of low-lying soils will be rewetted. A gradually increasing CO_2 tax will be introduced from 2030, but at the same time farmers will be given many incentives to change and be compensated.

The financing will be secured through the establishment of 'Denmark's Green Land Fund' of DKK 40 billion. The Novo Nordisk Foundation has put a further DKK 10 billion into the land fund.

The agreement can be adopted by the Danish Parliament in autumn 2024. What is new about this agreement is the consideration of different policy areas at the same time; climate, water, nature (and nature restoration), and air. It is also new that the policy has been developed in a forum that involved the main stakeholders, which reached a consensus on the deal.

In principle, this kind of policies would be applicable in all the Nordic countries. It should, however, be noticed that land use and farm structures are very different, and it might exempt certain types of (small) fares for measures like CO_2 tax. In countries which are not net exporters of agricultural products, and which already have large forested areas, it could also be less desirable to convert farmland to forest. In Denmark, it has been discussed that a CO_2 tax in the future could be replaced by an emission trading scheme if a suitable system is developed in the context of EU.[177]

177. European Commission, 2023

5. Conclusion

For the purpose of this project, we have delivered a database of over 300 mitigation measures from the Nordic countries and beyond, to use to mitigate emissions of CH_4, NH_3 and Nr from the agricultural sector. While some measures may be documented multiple times, the database incorporates a classification function called *measure type* to address these repetitions. This category effectively distinguishes unique and similar measures. In total approximately 160 measure types were identified. Moreover, we have also mapped and created a database of the Nordic countries national and international commitments and obligations to reduce emissions from the agricultural sector.

The mitigation measures database provided by this project is a useful resource for Nordic policy makers at the national, regional, and local levels. It helps to prioritise and identify measures that can reduce air pollution and address climate change, by themselves or collectively. It presents a thorough analysis of the efficacy of the various measures as well as a collective picture of the possible impacts each measure may have on NH_3, CH_4 and other forms of Nr.

This project has identified 17 measure types that can be classified as integrated measures to reduce the effects on air pollution and climate change from the agricultural sector in the Nordic countries. The results show that most integrated measures mainly are related to manure/fertiliser application to soils. One of the main conclusions of this report is that measures to reduce manure/fertiliser application can have positive impact for emission reduction for at least two of the pollutants. The potential can be large. However, it is important to recognise that emissions from biological processes can vary significantly between the Nordic countries and locally, influenced by factors such as climate, soil type, and agricultural practices

Naturally uncertain, the scenarios used for estimating potentials suggests that by 2040 combined NH_3 measures can reduce emissions with some 25 percent, to a cost around 6 €/kg NH_3. The same combination of measures would also reduce agricultural CH_4 emissions. The findings of this project underscore the critical role that integrated measures targeting manure and fertiliser application can play in mitigating both air pollution and climate change within the Nordic agricultural sector.

The identification of 17 integrated measures highlights a focused approach to address environmental challenges through integrated measures. The key conclusion drawn is that reducing emissions from manure and fertiliser application can significantly decrease at least two environmental problems, air quality and climate change. By refining application practices, such as adopting precision farming techniques and incorporating manure promptly into the soil, the project demonstrates that it is possible to achieve dual benefits: enhancing air quality and contributing to climate change mitigation. These measures not only help in reducing harmful emissions, but also offer ancillary advantages, such as improved soil health and increased agricultural productivity.

Effective implementation of these measures will require coordinated efforts among policymakers, farmers, and stakeholders to develop supportive frameworks, provide necessary incentives, and promote best practices. With targeted interventions and continued innovation in nutrient management, Nordic countries can advance towards a more sustainable agricultural sector, realising both environmental and economic gains.

The report also highlights the importance of supporting farmers through targeted policies and incentives to adopt these integrated measures. This can include financial subsidies for purchasing advanced technologies, educational programs on best practices, and regulatory frameworks that promote sustainable agricultural practices.

A potential barrier for the implementation of these measures could be organisation of ministerial areas, where agriculture, environment and climate are rarely under the same ministerial area. This will not mean that effective measures cannot be implemented but can lead to a suboptimal prioritisation when measures are implemented to address a single problem like water pollution, emissions to air, or climate, and the co-benefits of measures might not be fully realised. We argue that a common platform for between ministerial areas is an important aspect to foster measures that are addressing both air, climate, and other aspects such as food security. All countries already have many policy measures in place which addresses N and P emissions, but not so many directly targeted at reducing climate gas emissions. Both information to the farmers, direct environmental regulation, pricing instruments (carbon tax) and financing instruments (e.g. targeted use of the CAP and national subsidies to promote integrated measures) could be needed to address both air and climate pollution from the agricultural sector and to ensure that all relevant benefits are maximised.

For example, integrating policy efforts could facilitate a more holistic approach, where addressing water pollution and air quality could simultaneously support climate objectives and improve food security. By fostering coordination among different ministerial areas, it becomes possible to design and implement policies that are mutually reinforcing rather than competing. Such a platform could enable better alignment of strategies and resources, helping to identify synergies and trade-offs between different environmental and agricultural goals. It could also facilitate the sharing of best practices and innovative solutions that address multiple issues simultaneously.

For instance, practices that enhance soil health and reduce nutrient runoff can also contribute to lower greenhouse gas emissions and improved resilience to climate change. Furthermore, the implementation of integrated measures would benefit from a streamlined approach to monitoring and evaluation. Consistent and comprehensive data collection across different domains could provide valuable insights into the effectiveness of integrated policies and help refine strategies over time.

In addition, involving stakeholders from various sectors – such as farmers, environmental organisations, and industry representatives – in the development of these policies can ensure that diverse perspectives are considered and that measures are practical and effective. Engaging in collaborative policymaking can also help build broad support and facilitate smoother implementation. Ultimately, creating a common platform for coordination among ministerial areas can lead to more coherent and impactful policies, driving progress towards a sustainable and resilient agricultural sector that balances environmental protection, climate action, and food security. It is positive that agricultural advice is starting to include both Nr and climate. It is, however, not common on farm level to have plans and bookkeeping relating to climate gases, which will be important for planning of farm level measures. However, there are an increasing interest and an increasing number of farmers that are now doing climate calculations by using different tools provided by different initiative, for example the Greppa Näringen and Arla Food initiatives.

5.1 Future recommendations

Based on the conclusions of the project, Nordic countries should continue to focus on the implementation of integrated measures that target both air pollution and climate change, particularly through improving manure and fertiliser application practices. These measures have the potential to significantly reduce emissions of NH_3 and CH_4, contributing to better air quality and climate change mitigation, while also enhancing soil health and agricultural productivity. Continued innovation in precision farming and prompt manure incorporation should remain a priority, as they offer dual environmental and economic benefits.

To further support these goals, it is important that Nordic countries enhance their policy frameworks to promote the adoption of these integrated measures. This includes providing financial incentives, such as subsidies for advanced technologies, and creating educational programs that inform farmers about best practices in nutrient management. Additionally, regulatory frameworks should be refined to encourage sustainable agricultural practices that address both nitrogen Nr and greenhouse gas emissions.

Another key recommendation is to address the current organisational challenges within governmental structures. Agriculture, environment, and climate issues are often handled by separate ministries, which can lead to fragmented and suboptimal policy implementation. Nordic countries should work on creating a common platform that fosters coordination among these ministerial areas, enabling the design of policies that address multiple environmental and agricultural goals simultaneously. Such integration would help maximise the co-benefits of measures aimed at air quality, climate, water pollution, and food security.

The Nordic countries should also focus on developing streamlined monitoring, reporting, verification and evaluation systems that can consistently track the effectiveness of integrated measures. Comprehensive data collection across domains will allow for better insights into the outcomes of policies and help refine strategies over time.

Finally, Nordic countries should promote and create farm-level climate gas measuring, accounting and planning, encouraging farmers to track and plan their emissions reductions, thus contributing to the overall success of integrated measures aimed at both environmental and economic sustainability.

Based on the study, we recommend continuing working with the following aspects of integrated measures of air quality and climate change in the Nordic countries:

- to continue to work, nationally and internationally, with reducing emissions from the agricultural sector to protect the environment and human health,
- to target measures that have an integrated effect on air pollution and climate change, while avoiding the measures that have a negative impact on climate or air pollution,
- to promote and share knowledge of the adoption of integrated measures targeting manure and fertiliser application to reduce NH_3, Nr and CH_4 emissions,
- to continue the development of multi pollutant-multi effect decision support modelling. As can be seen in table 4, there are several measures identified in the literature as affecting several pollutants, but this effect is not included in important models yet. Further model development focusing on including multipollutant effect of emission control measures would assist decision makers through more complete decision support,
- to support innovation in precision farming techniques and prompt manure incorporation to achieve dual benefits for air quality and climate change mitigation,
- to enhance policy frameworks by providing financial incentives (subsidies, CAP funding) and educational programs to encourage farmers to adopt sustainable practices and pro-environmental technologies,
- to foster coordination among agriculture, environment, and climate ministries to create a common platform that facilitates holistic policymaking and maximises co-benefits. An inter-ministerial task force to set the terms of references for this type of coordination should be the first step,

- to improve monitoring and evaluation systems to track the effectiveness of integrated measures, ensuring data consistency across different sectors,
- to engage a wide range of stakeholders (farmers, environmental organisations, industry) in collaborative policymaking to ensure practical and widely supported solutions, and
- to promote farm-level climate gas accounting and planning to enhance the effectiveness of mitigation strategies at the local level.

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Appendices

Appendix 1 – Mapping policy overview

Appendix 2 – Mapping Nordic countries commitments and obligations

Appendix 3 – Mapping measures to mitigate ANM

About this publication

Integrated strategies for air and climate measures:
Reducing emissions of Ammonia Nitrogen and Methane from the agricultural sector in the Nordic countries

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