TEXTE

110/2024

Fostering win-win farming practices to reduce nitrogen pollution and mitigate greenhouse gas emissions

A case study from Germany

by:

Barbara Amon

Leibniz-Institute for Agricultural Engineering and Bioeconomy (ATB), Potsdam, Germany and Faculty of Civil Engineering, Architecture and Environmental Engineering, University of Zielona Góra, Zielona Góra, Poland

Gabriele Borghardt

Umweltbundesamt, Dessau-Roßlau

Publisher:
German Environment Agency

TEXTE 110/2024

Project No. 157655
FB001485/ENG

Fostering win-win farming practices to reduce nitrogen pollution and mitigate greenhouse gas emissions

A case study from Germany

by

Barbara Amon
Leibniz-Institute for Agricultural Engineering and Bioeconomy (ATB), Potsdam, Germany and Faculty of Civil Engineering, Architecture and Environmental Engineering, University of Zielona Góra, Zielona Góra, Poland

Gabriele Borghardt
Umweltbundesamt, Dessau-Roßlau

On behalf of the German Environment Agency

Imprint

Publisher
Umweltbundesamt
Wörlitzer Platz 1
06844 Dessau-Roßlau
Tel: +49 340-2103-0
Fax: +49 340-2103-2285
buergerservice@uba.de
Internet: www.umweltbundesamt.de

Report performed by:
Leibniz-Institute for Agricultural Engineering and Bioeconomy (ATB)
Max-Eyth-Allee 100
14469 / Potsdam
Germany

Report completed in:
July 2023

Edited by:
Section II 4.3 Luftreinhaltung und terrestrische Ökosysteme
Dr. Gabriele Borghardt

Publication as pdf:
http://www.umweltbundesamt.de/publikationen

ISSN 1862-4804

Dessau-Roßlau, August 2024

Abstract: Fostering win-win farming practices to reduce nitrogen pollution and mitigate greenhouse gas emissions: A case study from Germany

This paper examines the potential synergies between German nitrogen and green-house gas (GHG) mitigation policies in the agricultural sector. Agricultural practices aimed at reducing air (ammonia) and water (nitrates) pollution (“nitrogen practices”) can have beneficial effects (co-benefits) on GHG mitigation (nitrous oxide and methane) taking into consideration the nitrogen cycle and biogeochemical pathways. This study re-views the effect of nitrogen practices on GHG emission based on the IPCC guidelines and the UNECE Guidance document on integrated sustainable nitrogen management, and identifies win-win practices.

Kurzbeschreibung: Förderung von "Win-Win"-Praktiken in der Landwirtschaft, um die Stickstoffbelastung zu verringern und die Treibhausgasemissionen zu reduzieren: Eine Fallstudie aus Deutschland

In diesem Papier werden die potenziellen Synergien zwischen der deutschen Stickstoff- und Treibhausgas (THG) - Minderungspolitik im Agrarsektor untersucht. Landwirtschaftliche Praktiken, die darauf abzielen, die Verschmutzung von Luft (Ammoniak) und Wasser (Nitrate) zu reduzieren ("Stickstoff-Praktiken"), können unter Berücksichtigung des Stickstoffkreislaufs und der biogeochemischen Pfade positive Auswirkungen (Co-Benefits) auf die THG-Minderung (Lachgas und Methan) haben. In dieser Studie werden die Auswirkungen von Stickstoffpraktiken auf die Treibhausgasemissionen auf der Grundlage der IPCC-Leitlinien und des UNECE-Leitfadens für ein integriertes nachhaltiges Stickstoffmanagement erneut untersucht und Win-Win-Praktiken ermittelt.

Table of content

List of tables

List of abbreviations

Abbreviation	Explanation
AR5	Fifth assessment report
AwSV	German Ordinance on Installations for Handling Substances Hazardous to Water
BAT	Best available Techniques
BAT AEL	BAT-associated emission level
BREF	Best Reference Techniques Document
CH_4	Methane
CO_2	Carbon dioxide
DüV	Düngeverordnung; German Fertilizer Application Ordinance
DM	Dietary measure
FM	Field measure
GHG	Green-house gas
CofGAP	Code for Good Agricultural Practice for Reducing Ammonia Emissions
HELCOM	Helsinki Commission (Baltic Marine Environment Protection Commission)
IED	Industrial-Emission Directive
HM	Housing measure
IPCC	Intergovernmental Panel on Climate Change
IRPP	Intensive Rearing of Poultry and Pigs
JGS	Jauche, Gülle, Sickersaft; liquid manure
MM	Manure measure
N_2	Nitrogen
NM	Nutrient measure
Nr	Reactive nitrogen
NEC	National Emission Ceilings
NH_3	Ammonia
N_2O	Nitrous oxide (laughing gas)
NO_3	Nitrate
OSPAR	Oslo- and Paris Commissions (Convention for the Protection of the Marine Environment of the North-East Atlantic)
PM	Particulate matter
TA Luft	Technische Anleitung zur Reinhaltung der Luft (en: TI AIR)
TI AIR	Technical Instructions on Air Quality Control (de: TA Luft)

Abbreviation	Explanation
TFRN	Task Force on Reactive Nitrogen der UNECE
StoffBilV	Stoffstrombilanzverordnung, German Ordinance on Nutrient-Flow Balances
UNECE	United Nations Economic Commission for Europe
UNECE GD	United Nations Economic Commission for Europe Guidance Document

Summary

Taking into consideration the nitrogen cycle, any agricultural practice aimed at reducing air pollution by ammonia or water pollution by nitrates ("nitrogen practices") will affect positively or negatively the emissions of nitrous oxide (N_2O). However, agricultural green-house gas (GHG) mitigation practices, and policies to encourage them, have not paid sufficient attention practices already implemented by nitrogen policies, when many practices are similar.

The European Commission and the UNECE Task Force on Reactive Nitrogen (TFRN) have initiated work to identify agricultural practices that can simultaneously reduce ammonia, nitrate and N_2O and reduce overall losses of nitrogen. The practices of applying fertilisers, both organic and inorganic, feeding and housing livestock, storing and treating manure, and using cultivable and non-cultivable land must be taken into consideration. The spatial variability of nitrogen pathways also calls for considering nitrogen practices at the landscape level.

Effective agricultural practices to reduce nitrogen in all its reactive forms have side effects (positive or negative) on methane, and the other agricultural GHGs. The mitigation of agricultural GHGs must be considered as a whole.

The report gives an overview on available mitigation measures and assessed their impact on NH_3, NO_3, N_2O and CH_4 emissions.

Zusammenfassung

Unter Berücksichtigung des Stickstoffkreislaufs wirkt sich jede landwirtschaftliche Maßnahme, die darauf abzielt, die Luftverschmutzung durch Ammoniak oder die Wasserverschmutzung durch Nitrate zu verringern ("Stickstoffmaßnahmen"), positiv oder negativ auf die Emissionen von Distickstoffoxid (N_2O) aus. Allgemeiner ausgedrückt, haben die landwirtschaftlichen Praktiken zur Verringerung der Treibhausgasemissionen und die politischen Maßnahmen zu ihrer Förderung den bereits von der Stickstoffpolitik umgesetzten Praktiken nicht genügend Aufmerksamkeit geschenkt, obwohl viele Praktiken ähnlich sind.

Die Europäische Kommission und die UNECE Task Force on Reactive Nitrogen (TFRN) haben Arbeiten zur Ermittlung landwirtschaftlicher Praktiken eingeleitet, die gleichzeitig Ammoniak, Nitrat und N_2O reduzieren und die Gesamtverluste an Stickstoff verringern können. Die Praktiken der Ausbringung von organischen und anorganischen Düngemitteln, der Fütterung und Haltung von Tieren, der Lagerung und Behandlung von Dung sowie der Nutzung von bebaubaren und nicht bebaubaren Flächen müssen dabei berücksichtigt werden. Die räumliche Variabilität der Stickstoffeinträge erfordert auch die Berücksichtigung von Stickstoffpraktiken auf Landschaftsebene.

Wirksame landwirtschaftliche Praktiken zur Verringerung von Stickstoff in all seinen reaktiven Formen haben (positive oder negative) Nebeneffekte auf Methan und die anderen landwirtschaftlichen Treibhausgase. Die Minderung der landwirtschaftlichen Treibhausgase muss als Ganzes betrachtet werden.

Der Bericht gibt einen Überblick über die verfügbaren Minderungsmaßnahmen und bewertet ihre Auswirkungen auf NH_3-, NO_3-, N_2O- und CH_4-Emissionen.

1 Farming the issue

Already the fifth assessment report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) concluded that mitigation in agriculture, forestry and land use is essential to limit climate change in the 21st century, in terms of mitigation of non-CO_2 greenhouse gases (GHGs) and land-based carbon sequestration (IPCC, 2014). Given the nitrogen cycle pathways, any agricultural practice to reduce ammonia and/or nitrates will affect nitrous oxide (N_2O) and nitrogen in the soil. The nitrogen cycle is, however, largely overlooked by environmental policy. The long-term strategy for the Convention for 2020–2030 and beyond (ECE/EB.AIR/142/Add.2, decision 2018/5) recognized the disruption of the nitrogen cycle as one of the most important challenges for environmental policy that required an integrated approach (UNECE 2021). It is essential to control pollution from agricultural sources in the context of the wider nitrogen cycle in an integrated manner harvesting multiple co-benefits of improved nitrogen management (UNECE 2021).

The purpose of this report is to assess the extent to which practices to manage ammonia and nitrate pollution from agriculture can produce co-benefits on agricultural GHG mitigation in net terms, including N_2O emissions, as well as methane emissions. Methane is not part of the nitrogen cycle but it is an agricultural GHG and, as such, it cannot be ignored in the evaluation of the effectiveness of nitrogen policy on agricultural GHGs.

This report will give a comprehensive overview of currently available measures for emission mitigation, their efficiencies and their pros and cons. While the assessment is mainly based on the UNECE guidance document on integrated sustainable nitrogen management, this report adds the aspect of methane emissions and includes their assessment into the respective tables. It also compares suggested measures with the current German legislation by detailing environmental regulations for this case study examples.

Taking into consideration the nitrogen cycle opens the way to synergies between policies aimed at improving the quality of air, water, nature and policies aimed at mitigating climate change. Agricultural practices implemented to comply with air, water and nature legislation can have positive or negative effects on GHG emissions. Identifying win-win practices for the simultaneous management of ammonia, nitrates and agricultural GHG emissions, as well as policies to encourage them as key. The effects would also extend to the protection of the ozone layer and to reduce tropospheric ozone.

The UNECE guidance document on integrated sustainable nitrogen management (UNECE 2021) clearly mentions opportunities of integrated nitrogen management:

“Integrated sustainable nitrogen management offers the opportunity to link the multiple benefits of better nitrogen (N) use from environmental, economic and health perspectives, helping to avoid policy trade-offs while maximizing synergies. By demonstrating the multiple benefits of taking actions on nitrogen, a much stronger mobilization for change is expected, catalysing progress towards many of the United Nations Sustainable Development Goals. There are multiple co-benefits of taking actions on nitrogen, especially for climate mitigation, stratospheric ozone and the protection of water resources, including groundwater, rivers, lakes, coastal zones and the wider marine environment.

Nitrogen is critical as a major nutrient to allow food, fibre and biofuel production. However, the efficiency with which nitrogen is used is very low when considering the full chain from fertilization to human consumption and waste. A distinction is made between unreactive atmospheric dinitrogen (N_2) and reactive nitrogen forms (Nr), which represent valuable resources. Around 80 % of anthropogenic Nr production is wasted as air and water pollution and through denitrification back to N_2."

It is widely recognized that integrated strategies are required to finally safe the environment. An integrated approach links air, water, climate, stratospheric ozone and other issues as a basis for the development of sound strategies. In this way, "integrated"' is here seen as an opportunity and requirement to be aware of synergies and trade-offs in order to mobilize more effective outcomes (UNECE 2021).

With regard to categorising measures, the UNECE GD (Bittman et al., 2014) states: "The UNECE approach established for the Ammonia Guidance Document (ECE/EB.AIR/120, para. 18), where each abatement/mitigation measure is assigned one of the three following categories according to expert judgement:

(a) Category 1 techniques and strategies: These are well-researched, considered to be practical or potentially practical and there are quantitative data on their abatement efficiency at least on the experimental scale;

(b) Category 2 techniques and strategies: These are promising, but research on them is at present inadequate, or it will always be difficult to generally quantify their abatement efficiency. This does not mean that they cannot be used as part of a nitrogen abatement strategy, depending on local circum-stances;

(c) Category 3 techniques and strategies: These have not yet been shown to be effective or are likely to be excluded on practical grounds."

The magnitude of effects has been classified as follows (UNECE 2021):

(a) Downward arrows indicate a reduction in losses: ↓, small to medium effect; ↓↓, medium to large effect;

(b) Upward arrows indicate an increase in losses: ↑, small to medium effect; ↑↑, medium to large effect;

(c) Little or no effect, indicated by ~;

(d) Uncertain, indicated by?

The UNECE GD (UNECE 2021) states the following "Principles of integrated sustainable nitrogen management":

"Nitrogen (N) provides substantial benefits to society by boosting crop productivity, allowing richer diets for humans, including with increased meat and dairy production and consumption. However, N losses present multifaceted problems affecting air, water, human health, climate, biodiversity and economy. To grasp the principles of sustainable nitrogen management, it is first necessary to consider the key points of nitrogen cycling.

Integrated sustainable nitrogen management in agriculture has a dual purpose: to decrease N emissions/losses, including to protect human health; the environment and climate; and to optimize the beneficial effects of N related to food production through balanced fertilization and circular economy principles.

Many environmental policies have a narrow scope concerning nitrogen management and would benefit from an integrated approach. For example, most NOx and NH_3 sources have been included in the Gothenburg Protocol, but NOx emissions from agricultural soils, (semi-)natural NOx and NH_3 sources are excluded when assessing compliance with the Gothenburg Protocol emission reduction commitments, as are N_2O and N_2 emissions to air and N leaching to waters.

Conversely, in the European Union Nitrates Directive, all N sources in agriculture must be considered for reducing NO_3^- leaching, but NH_3, NOx, N_2O and N_2 emissions to air are not explicitly addressed."

Ten Key Points of nitrogen cycling are relevant for integrated sustainable nitrogen management (cited from the UNECE 2021):

1. Nitrogen is essential for life. It is an element of chlorophyll in plants and of amino acids (protein), nucleic acids and adenosine triphosphate in living organisms (including bacteria, plants, animals and humans). Nitrogen is often a limiting factor for plant growth.

2. Excess nitrogen has a range of negative effects, especially on human health, ecosystem services, biodiversity, through air, water and climate change. The total amounts of N introduced into the global biosphere by human activities have significantly increased during the last century (more than doubled) and have now exceeded critical limits for the so-called safe operating space for humanity.

3. Nitrogen exists in multiple forms. Most N forms are "reactive" (Nr) because they are easily transformed from one form to another through biochemical processes mediated by microorganisms, plants and animals and chemical processes affected by climate. Dinitrogen (N_2) is unreactive, forming the main constituent of air (78 per cent). Nitrogen is "double mobile" because it is easily transported by both air and water in the environment.

4. The same atom of N can cause multiple effects in the atmosphere, in terrestrial ecosystems, in freshwater and marine systems and on human health. This phenomenon is termed the "nitrogen cascade", which has been defined as the sequential transfer of Nr through environmental systems.

5. Nitrogen moves from soil to plants and animals, to air and water bodies, and back again, with international transboundary pollution transport of most nitrogen forms. These flows are a result of natural drivers and human activities, which have to be understood for effective N management.

6. Human activities have greatly altered the natural N cycle and have made the N cycle more leaky. Main factors include: creation of synthetic inorganic N fertilizer; land-use change; urbanization; combustion processes; and transport of food and feed across the world. These have resulted in nitrogen depletion in crop food/feed exporting areas and regional nitrogen enrichment in urban areas and those areas with intensive livestock farming. Regional segregation of food and feed production and consumption is also one of the main factors why N use efficiency at whole food system level has decreased in the world during the last decades.

7. The nature and human alterations of the N cycle challenge the realization of both a circular economy and integrated sustainable nitrogen management. Sustainable nitrogen management provides the foundation to strengthen an emerging "nitrogen circular economy", reducing N losses and promoting recovery and reuse.

8. Nitrogen forms need to be near plant roots to be effective for plant growth. Nitrogen uptake depends on the N demand by the crop, the root length and density, and the availability of NO_3^- and NH_4^+ in the soil solution.

9. Some crop types are able to convert non-reactive N_2 into reactive N forms (NH_3, amine, protein) by using specialist bacteria in plant root nodules. This process of biological nitrogen

fixation is an important source of reactive N in the biosphere including agriculture, which can also result in N pollution.

10. Humans and animals require small amounts of protein N and amino acids for growth, development and functioning, but only a minor fraction of the N intake is retained in the body weight and/or milk and egg. The remainder is excreted, mainly via urine and faeces, and this N can be recycled and reused.

The UNECE GD (UNECE 2021) identifies 24 Principles of integrated sustainable nitrogen management (cited from the UNECE 2021):

Principle 1: The purpose of integrated sustainable nitrogen management in agriculture is to decrease nitrogen losses to the environment to protect human health, climate and ecosystems, while ensuring sufficient food production and nitrogen use efficiency, including through appropriately balanced nitro-gen inputs;

Principle 2: There are various actors in agriculture and the food chain, and all have a role in N management. There is a joint responsibility for all actors in the food chain, including for policymakers at several levels, to support a decrease of N losses and to share the cost and benefits of N abatement/mitigation measures;

Principle 3: Specific measures are required to decrease pathway-specific N losses. This is because the loss mechanisms differ between NH_3 volatilization, NO_3^- leaching, erosion of all Nr forms to surface waters, and gaseous emissions of NOx, N_2O and N_2 related to nitrification-denitrification processes. Pathway-specific measures relate to pathway-specific controlling factors;

Principle 4: Possible trade-offs in the effects of N loss abatement/mitigation measures may require priorities to be set, for example, which adverse effects should be addressed first. Policy guidance is necessary to inform such priorities and properly weigh the options according to local to global context and impacts;

Principle 5: Nitrogen input control measures influence all N loss pathways. These are attractive measures because reductions in N input (for example, by avoidance of excess fertilizer, of excess protein in animal diets, and of human foods with a high nitrogen footprint), lead to less nitrogen flow throughout the soil-feed-food system;

Principle 6: A measure to reduce one form of pollution leaves more N available in the farming system, so that more is available to meet crop and animal needs. In order to realize the benefit of a measure to reduce N loss and to avoid pollution swapping, the nitrogen saved by the measure needs to be matched by either reduced N inputs, increased storage, or increased N in harvested outputs. Reduced N inputs or increased harvested outputs are thus an essential part of integrated nitrogen management while providing opportunities for increased economic performance;

Principle 7: The nitrogen input-output balance encapsulates the principle that what goes in must come out, and that N input control and maximization of N storage pools (in manure, soil and plants) are main mechanisms to reduce N losses.

Principle 8: Matching nitrogen inputs to crop needs (also termed "balanced fertilization") and to live-stock needs offers opportunities to reduce all forms of N loss simultaneously, which can help to improve economic performance at the same time. Natural differences between crop and animal systems similarly imply opportunities from integrating animal and crop production and optimizing the balance of food types;

Principle 9: Spatial variations in the vulnerability of agricultural land to N losses require spatially explicit N management measures in a field and/or landscape. This principle is applicable to field application of both organic and inorganic fertilizer resources;

Principle 10: Spatial variations in the sensitivity of natural habitats to N loadings originating from agriculture highlight the need for site- and region-specific N management measures. A source-pathway-receptor approach at landscape scale may help to target specific hot spots, specific N loss pathways, and specific sensitive or resilient areas;

Principle 11: The structure of landscape elements affects the capacity to store and buffer nitrogen flows. This means that ecosystems with high N storage capacity (for example, woodlands and unfertilized agricultural land) tend to buffer the effects of N compounds emitted to the atmosphere, so that less N is transferred to other locations. In this way, woodlands, extensive agricultural land and other landscape features help absorb and utilize N inputs from atmospheric N deposition or N that would otherwise be lost through lateral water flow. This principle is the basis of planning to increase overall landscape resilience, where, for example, planting of new woodland (with the designated function of capturing N) may be used as part of a package of measures to help protect other habitats (including other woodland and ecosystems, where nature conservation objectives are an agreed priority);

Principle 12: In order to minimize pollution associated with N losses, all factors that define, limit and reduce crop growth have to be addressed simultaneously and in balance to optimize crop yield and N use efficiency. Elements include: selecting crop varieties adapted to local climatic and environmental conditions; preparing an appropriate seedbed; ensuring adequate levels of all essential nutrient elements and water; and ensuring proper weed control, pest and disease management and pollution control.

Principle 13: In order to minimize pollution associated with N losses, all factors that define, limit or reduce animal growth and welfare have to be addressed simultaneously and in balance to optimize animal production and N use efficiency, also to decrease N excretion per unit of animal produce. Elements include: selecting breeds adapted to the local climatic and environmental conditions; ensuring availability of high-quality feed and water; and ensuring proper disease, health, fertility and pollution control, including animal welfare;

Principle 14: Slowing down hydrolysis of urea and uric acid containing resources reduces NH_3 emissions. Hydrolysis of these resources produces NH_3 in solution and locally increases soil pH, so slowing hydrolysis helps avoid the highest ammonium concentrations and pH, which can also reduce other N losses by avoiding short-term N surplus;

Principle 15: Reducing the exposure of ammonium-rich resources to the air is fundamental to reducing NH_3 emissions. Hence, reducing the surface area, lowering the pH, temperature and wind speed above the emitting surface, and promoting rapid infiltration by dilution of slurries all reduce NH_3 emissions;

Principle 16: Slowing down nitrification (the biological oxidation of NH_4^+ to NO_3^-) may contribute to decreasing N losses and to increasing N use efficiency. This is because NH_4^+ can be held in soil more effectively than NO_3^-, making it less vulnerable to losses via leaching and nitrification-denitrification processes than NO_3^-.

Principle 17: Some measures aimed at reducing N_2O emissions may also reduce losses of N_2 (and vice versa) since both are related to denitrification processes. Measures aimed at jointly reducing N_2O and N_2 losses from nitrification-denitrification may therefore contribute to saving N resources within the system and reducing climate effects at the same time;

Principle 18: Achieving major N_2O reductions from agriculture necessitates a focus on improving N use efficiency across the entire agrifood system using all available measures. The requirement for wider system change is because of the modest potential of specific technical measures to reduce N_2O emissions from agricultural sources compared with the scale of ambitious reduction targets for climate and stratospheric ozone. It implies a requirement to consider system-wide changes in all aspects of the agrifood system, including human and livestock diets and management of fertilizer, biological and recycled N resources;

Principle 19: Strategies aimed at decreasing N, P and other nutrient losses from agriculture are expected to offer added mitigation benefits compared with single nutrient emission-abatement strategies, because of coupling between nutrient cycles. A nitrogen focus provides a pragmatic approach that encourages links between multiple threats and element cycles, thereby accelerating progress;

Principle 20: Strategies aimed at optimizing N and water use jointly are more effective than single N fertilization and irrigation strategies, especially in semi-arid and arid conditions. This underlines the need for an integrated approach in which the availability of both N and water are considered jointly, especially in those regions of the world where food production is limited by the availability of both water and N. The joint coupling of N and water management also underlies the safe storage of solid manures to avoid run-off and leaching;

Principle 21: Strategies aimed at enhancing N use efficiency in crop production and at decreasing N losses from agricultural land have to consider possible changes in soil organic carbon (C) and soil quality over time and the impacts of soil carbon-sequestration strategies. Carbon sequestration is associated with N sequestration in soil due to reasonably conservative ratios of C:N in soils. Protection of soil organic matter against degradation ("nitrogen mining") is vital to sustain agricultural productivity in regions with low N input;

Principle 22: Strategies aimed at reducing N emissions from animal manures through low-protein animal feeding have to consider the possible impacts of diet manipulations on enteric methane (CH_4) emissions from ruminants. Low-protein diets in ruminants are conducive to low N excretion and NH_3 volatilization, but tend to increase fibre content and CH_4 emissions, pointing to the need for dietary optimization for N and C;

Principle 23: The cost and effectiveness of measures to reduce losses of N need to take account of the practical constraints and opportunities available to farmers in the region where implementation is intended. The effectiveness and costs must be examined as much as possible under practical farm conditions and, in particular, taking account of farm size and basic environmental limitations. Cost-effectiveness analysis should consider implementation barriers, as well as the side effects of practices on other forms of N and greenhouse gases in order to promote co-benefits;

Principle 24: The whole farm-level is often a main integration level for emission-abatement/mitigation decisions, and the overall effects of emission-abatement/mitigation measures will have to be assessed at this level, including consideration of wider landscape, regional and transboundary interactions.

2 Win-win agricultural practices to reduce nitrogen pollution and GHG emissions

The UNECE GD (UNECE 2021) has identified a wide range of measures to mitigate emissions in livestock feeding, housing, manure management and manure and fertiliser application. The measures were described and rated with regard to their effect on various N and GHG emissions. This report concentrates on the most relevant measured from housed livestock, manure storage and manure processing and from field application of organic and inorganic fertilizers, including manures, urine and other organic materials. Data given here are taken from the UNECE GD (UNECE 2021). More measures and a more detailed description of each of these measures can be found in the UNECE GD. We added an assessment of the measures´ implications on CH_4 emissions to the tables we took from the UNECE GD.

2.1 Housed Livestock

The following priorities are identified to reduce nitrogen losses from livestock housing:

(a) Reduction of indoor temperature, including by optimized ventilation;

(b) Reduction of emitting surfaces and soiled areas;

(c) Reduction of air-flow over soiled surfaces;

(d) Use of additives (for example, urease inhibitors, acidification); and

(e) Regular removal of manure to an outside store.

The following priorities are identified to reduce N losses and to mobilize N recovery/reuse from manure storage, treatment and processing:

(a) Storing outside the barn in a dry location;

(b) Covering slurry stores;

(c) Manure treatment/processing to reduce slurry dry matter content, increase slurry NH_4^+ content and lower pH;

(d) Anaerobic digestion, solid/liquid separation and slurry acidification;

(e) Ensuring that all available nutrient resources are used effectively for crop growth;

(f) Improving nutrient recapture and recovery; and

(g) Production of value-added nutrient products from recycled manure N resources.

Dietary Measure 1: Adapt protein intake in diet (dairy and beef cattle)

Adaptation of crude protein in the diet to match the needs of animals is the first and most efficient measure to mitigate N emissions. This measure decreases the excretion of excess N and thus reduces emissions along the whole manure management chain. Increasing the energy/protein ratio in the diet is a well-proven strategy to reduce levels of crude protein. For grassland-based ruminant production systems, the feasibility of this strategy may be limited, as older grass may reduce feeding quality.

Table 1: Dietary Measure 1: Adapt protein intake in diet (dairy and beef cattle)

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of adapted protein intake

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
UNECE category	1	1	3 [a]	1	2	1-2		1
Magnitude of effect	↓↓	~ ↓↓	? [a]	↓↓	↓↓	↓↓ [b]		~

[a] The measure would be expected to reduce NOx emissions, though experimental data to demonstrate this are needed. [b] As this measure reduces total N inputs, it can help to increase system efficiency and circularity, reducing wider Nr and N_2 losses.

Dietary Measure 2: Increase productivity (dairy and beef cattle)

Increasing the productivity of dairy and beef cattle through an increase in milk yield or daily weight gain reduces CH_4 (and potentially N_2O) emissions per kg of product. A balance must be found be-tween emission reduction through productivity increase and the limited capacity of cattle to deal with concentrates. The ability of cattle to convert protein from roughage, which is inedible for humans, to high-value protein is valuable from a resource and biodiversity perspective.

Table 2: Dietary Measure 2: Increase productivity (dairy and beef cattle)

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of increased productivity

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
UNECE category	2	2	3 [a]	2	2	2		1
Magnitude of effect	↓	~ - ↓	? [a]	-	↓	↓ [b]		↓↓

[a] The measure would be expected to reduce NOx emissions, though experimental data to demonstrate this are needed. [b] As this measure reduces total N inputs, it can help to increase system efficiency and circularity, reducing wider Nr and N_2 losses.

Dietary Measure 3: Increase longevity (dairy cattle)

Productivity can be increased though increasing milk production per year and through increasing the amount of milk production cycles. Optimized diet and housing conditions enable a higher longevity of dairy cattle, and therefore fewer replacement animals are needed, thereby reducing N losses per product.

Table 3: Dietary Measure 3: Increase longevity (dairy cattle)

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of increased longevity

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
UNECE category	2	2	3 [a]	2	2	2		1
Magnitude of effect	↓	~ - ↓	? [a]	-	↓	↓ [b]		↓↓

[a] The measure would be expected to reduce NOx emissions, though experimental data to demonstrate this are needed. [b] As this measure reduces total N inputs, it can help to increase system efficiency and circularity, reducing wider Nr and N_2 losses.

Dietary Measure 4: Adapt protein intake in diet (pigs)

Feeding measures in pig production include phase feeding, formulating diets based on digestible/available nutrients, using low-protein amino acid-supplemented diets, and feed additives/supplements. The crude protein content of the pig ration can be reduced if the amino acid supply is optimized through the addition of synthetic amino acids. It is not yet fully known to which extent a lower protein content in the pig diet influences CH_4 emissions from stored manure. A major effect is not to be expected and can be further avoided by anaerobic digestion.

Table 4: Dietary Measure 4: Adapt protein intake in diet (pigs)

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of adapted protein intake in pig diets

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
UNECE category	1	1	3[a]	1	2	1		3
Magnitude of effect	↓↓	↓↓	?[a]	↓↓	↓↓	↓↓[b]		~ - ↑

[a] The measure would be expected to reduce NOx emissions, though experimental data to demonstrate this are needed. [b] As this measure reduces total N inputs, it can help to increase system efficiency and circularity, reducing wider Nr and N_2 losses.

Dietary Measure 5: Adapt protein intake in diet (poultry)

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

Table 5: Dietary Measure 5: Adapt protein intake in diet (poultry)

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of adapted protein intake in poultry diets

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
UNECE category	1	1	3[a]	1	2	1		3
Magnitude of effect	↓↓	↓↓	?[a]	↓↓	↓↓	↓↓[b]		?

[a] The measure would be expected to reduce NOx emissions, though experimental data to demonstrate this are needed. [b] As this measure reduces total N inputs, it can help to increase system efficiency and circularity, reducing wider Nr and N_2 losses.

Housing Measure 1: Immediate segregation of urine and faeces (cattle)

A physical separation of faeces (which contain urease) and urine in the housing system reduces hydrolysis of urea, resulting in reduced NH_3 emissions from both housing and manure spreading. Solid-liquid separation will also reduce emissions during land-application, where urine infiltrates soil more easily than mixed slurry.

Table 6: Housing Measure 1: Immediate segregation of urine and faeces (cattle)

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of immediate segregation of urine and faeces

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
UNECE category	1[a]	3	3	3	3	2		3
Magnitude of effect	↓↓	?	?	?	?	↓		~

[a] Immediate segregation of urine and faeces will reduce NH_3 emissions substantially, in the same way as increased grazing period. However, subsequent separation of previously mixed slurry is considered less effective (category 2).

Housing Measure 2: Regular cleaning of floors in cattle houses by toothed scrapers (cattle)

The emitting surface may be reduced by using "toothed" scrapers running over a grooved floor, thereby reducing NH_3 emissions. This also results in a cleaner floor surface with good traction for cattle to prevent slipping. It can also reduce CH_4 emissions as scraped slurry is moved to an outside storage and stored under cooler conditions than inside the barn.

Table 7: Housing Measure 2: Regular cleaning of floors in cattle houses by toothed scrapers (cattle)

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of regular cleaning of floors in cattle houses by toothed scrapers

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
UNECE category	1	3 [a]	3 [a]	3 [a]	3 [a]	1		1
Magnitude of effect	↓↓	- [a]	- [a]	- [a]	- [a]	↓		↓

[a] Although this measure does not directly reduce other Nr and N_2 losses, where the NH_3-saving contributes to replace inorganic fertilizer inputs from newly fixed N, it can help to increase system efficiency and circularity, reducing wider Nr and N_2 losses.

Housing Measure 3: Regular cleaning of floors in cattle houses

Thorough cleaning of walking areas in dairy cattle houses by mechanical scrapers or robots has the potential to substantially reduce NH_3 emissions. It can also reduce CH_4 emissions as scraped slurry is moved to an outside storage and stored under collar conditions than inside the barn.

Table 8: Housing Measure 3: Regular cleaning of floors in cattle houses

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of regular cleaning of floors in cattle houses

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
UNECE category	1	3	3	3	3	1		1
Magnitude of effect	↓	-	-	-	-	↓		↓

Housing Measure 4: Frequent slurry removal (cattle)

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

Table 9: Housing Measure 4: Frequent slurry removal (cattle)

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of frequent slurry removal (cattle)

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
UNECE category	½	3	3	3	3	½		1
Magnitude of effect	↓	-	-	-	-	↓		↓↓

Housing Measure 5: Increase bedding material (cattle with solid manure)

Use of bedding material that absorbs urine in cattle housing can reduce NH_3 emissions by immobilizing nitrogen and may also reduce N_2O emissions. The approach can have a positive interaction with animal welfare measures. It can also reduce CH_4 emissions as more oxygen enters the solid manure which as a consequence prevents CH_4 formation.

Table 10: Housing Measure 5: Increase bedding material (cattle with solid manure)

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of increase bedding material (cattle with solid manure)

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
UNECE category	1	2	3	3	3	1		2
Magnitude of effect	~ /↓	~ / ↓	?	?	?	~ / ↓		↓

Housing Measure 6: Barn climatization to reduce indoor temperature and air flow (cattle)

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

Table 11: Housing Measure 6: Barn climatization to reduce indoor temperature and air flow (cattle)

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of barn climatization to reduce indoor temperature and air flow (cattle)

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
UNECE category[a]	1	2-3	2-3	2-3	2-3	1		2
Magnitude of effect	↓↓	?	-	-	-	↓		↓

[a] Where two numbers are shown in this table separated by a forward slash, the first number is for the effect of reducing indoor temperature and the second number is for the effect of reducing airflow over manure-covered surfaces.

Housing Measure 7: Slurry acidification (pig and cattle housing)

Emissions of NH_3 can be reduced by acidifying slurry to shift the balance from NH_3 to NH_4^+. Acidification in the livestock house will reduce NH_3 emissions throughout the manure management chain. Slurry acidified with sulphuric acid is not suitable as the sole feedstock for biogas production, only as a smaller proportion.

Table 12: Housing Measure 7: Slurry acidification (pig and cattle housing)

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of slurry acidification (pig and cattle housing)

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
UNECE category[a]	1	2	2	3[a]	3	1[a]		1
Magnitude of effect	↓↓	↓	~ / ↓?	~ [a]	↓	↓↓[a]		↓

[a] Although this measure is not known to reduce $NO3^-$ directly, where NH_3-saving contributes to replace inorganic fertilizer inputs from newly fixed N (for example, when fertilizer regulations require the improved fertilizer value to be taken into account), it can contribute to increased system efficiency and circularity, reducing wider Nr and N_2 losses.

Housing Measure 8: Reduce emitting surface (pigs)

Ammonia emission can be reduced by limiting the emitting surface area through frequent and complete vacuum-assisted drainage of slurry from the floor of the pit. Other floor designs can be used, including partially slatted floors, use of inclined smoothly finished surfaces and use of V-shaped gutters.

Table 13: Housing Measure 8: Reduce emitting surface (pigs)

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of regular cleaning of reduced emitting surface

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
UNECE category	1	3 [a]	3 [a]	3 [a]	3 [a]	1		2
Magnitude of effect	↓↓	- [a]	? [a]	? [a]	? [a]	↓↓[a]		-

[a] Although this measure does not directly reduce other Nr and N_2 losses, where the NH_3-saving contributes to replace inorganic fertilizer inputs from newly fixed N, it can help to increase system efficiency and circularity, reducing wider Nr and N_2 losses.

Housing Measure 9: Regular cleaning of floors (pigs)

Thorough and regular cleaning of floors in pig houses by mechanical scrapers or robots has the potential to reduce NH_3 emissions substantially.

Table 14: Housing Measure 9: Regular cleaning of floors (pigs)

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of regular cleaning of floors

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
UNECE category	1	3	3	3	3	1		2
Magnitude of effect	↓	-	-	-	-	↓		-

Housing Measure 10: Frequent slurry removal (pigs)

Regular removal of slurry from under the slats in the pig house to an outside store can reduce NH_3 emissions by reducing the emitting surface and the slurry storage temperature. It also reduces CH_4 emissions as manure is stored outside, under cooler conditions.

Table 15: Housing Measure 10: Frequent slurry removal (pigs)

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of frequent slurry removal

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
UNECE category	1	3	3	3	3	1-2		1
Magnitude of effect	↓	-	-	-	-	↓		↓↓

Housing Measure 11: Increase bedding material (pigs with solid manure)

Use of bedding material that absorbs urine in pig housing can reduce NH_3 emissions by immobilizing nitrogen and may also reduce N_2O emissions. The approach can have a positive interaction with animal welfare measures. Regular changes of bedding may be needed to avoid N_2O and N_2 emissions associated with deep-litter systems. It can also reduce CH_4 emissions as more oxygen enters the solid manure which as a consequence prevents CH_4 formation.

Table 16: Housing Measure 11: Increase bedding material (pigs with solid manure)

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of increased bedding material

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
UNECE category	1	2	3	3	3	1		2

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
Magnitude of effect	~ /↓	~ / ↓	-	-	-	~ / ↓		↓

Housing Measure 12: Barn climatization to reduce indoor temperature and air flow (pigs)

In houses with traditional slatted floors, barn climatization with slurry cooling, roof insulation and/or automatically controlled natural ventilation can reduce NH_3 emissions due to reduced temperature and air velocities and can also help reduce CH_4 emissions. Surface cooling of manure with fans using a closed heat exchange system can substantially reduce NH_3 emissions. In slurry systems, this technique can often be retrofitted into existing buildings.

Table 17: Housing Measure 12: Barn climatization to reduce indoor temperature and air flow (pigs)

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of barn climatization to reduce indoor temperature and air flow

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
UNECE category[a]	1	2-3	2-3	2-3	2-3	1		2
Magnitude of effect	↓↓	-	-	-	-	↓		↓

[a] Where two numbers are shown in this table separated by a forward slash, the first number is for the effect of reducing indoor temperature and the second number is for the effect of reducing air flow over manure-covered surfaces.

Housing Measure 13: Use of acid air-scrubbers (pigs)

Treatment of exhaust air by acid scrubbers has proven to be practical and effective at least for large-scale operations. This is most economical when installed in new houses. The approach also helps reduce odour and PM emission and may also contribute to reducing N_2O and NOx emissions if the N recovered is used to replace fresh fertilizer N inputs.

Table 18: Housing Measure 13: Use of acid air-scrubbers (pigs)

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of use of acid air-scrubbers (pigs)

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
UNECE category[a]	1	2	2	3[a]	3[a]	1		1
Magnitude of effect	↓↓	↓	↓	-[a]	-[a]	↓↓[a]		-

[a] Although this measure does not directly reduce other NO_3^- and N_2 losses, where the recovered Nr contributes to replace inorganic fertilizer inputs from newly fixed N, it can contribute to increased system efficiency and circularity, reducing wider Nr and N_2 losses.

Housing Measure 14: Rapid drying of poultry litter

NH_3 emissions from battery deep-pit or channel systems can be lowered by ventilating the manure pit or by use of manure removal belts to dry manure. Keeping excreted N in the form of uric acid can also be expected to reduce N_2O, NOx and N_2, since this will also reduce nitrification and denitrification. Dries manure will also emit substantially less CH_4.

Table 19: Housing Measure 14: Rapid drying of poultry litter

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of rapid drying of poultry litter

Nitrogen form	NH_3	N_2O	NO_x	NO_3^-	N_2	Overall N Loss		CH_4
UNECE category	1	2 [a]	2 [a]	3 [a]	2 [a]	1		1
Magnitude of effect	↓↓	~/ ↓[a]	~/ ↓[a]	~/ ↓[a]	~/ ↓[a]	↓↓		↓↓

[a] Although this measure primarily focuses on NH_3 abatement, the stability of uric acid in dried poultry litter can help to increase system efficiency and circularity, decreasing wider Nr and N_2 losses, and reducing the need for fresh Nr production.

Housing Measure 15: Use of acid air-scrubbers (poultry)

Treatment of exhaust air by acid scrubber has been successfully employed to reduce NH_3 emissions in several countries. The main difference from pig systems is that poultry houses typically emit a much larger amount of dust. To deal with dust loads, multistage air-scrubbers with pre-filtering of coarse particles have been developed.

Table 20: Housing Measure 15: Use of acid air-scrubbers (poultry)

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Use of acid air-scrubbers

Nitrogen form	NH_3	N_2O	NO_x	NO_3^-	N_2	Overall N Loss		CH_4
UNECE category	1	2	2	3 [a]	3 [a]	1		1
Magnitude of effect	↓↓	↓	↓	- [a]	- [a]	↓↓ [a]		-

[a] Although this measure does not directly reduce other $NO3^-$ and N_2 losses, where the recovered Nr contributes to replace inorganic fertilizer inputs from newly fixed N, it can contribute to increased system efficiency and circularity, reducing wider Nr and N_2 losses.

2.2 Manure storage and manure processing

Manure Measure 1: Covered storage of manure (solid cover and impermeable base)

Many options are available for covered storage of manure and biogas digestates, including use of metal or concrete tanks with solid lids, floating covers on lagoons and use of slurry bags, most of which are associated with negligible NH_3 emission if well operated. The impermeable base avoids nitrate leaching and must be maintained to avoid leakage. Solid covers can reduce CH_4 emissions as the shield the natural crust that forms on the slurry surface from rain. The natural crust stays dry and is well aerated. The oxygen in the crust oxidises CH_4 formed inside the slurry and thus reduces CH_4 emissions (Petersen et al. 2005).

Table 21: Manure Measure 1: Covered storage of manure (solid cover and impermeable base)

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of covered storage of manure solid cover

Nitrogen form	NH_3	N_2O	NO_x	NO_3^-	N_2	Overall N Loss		CH_4
UNECE category	1	3	3	1	3	1		2

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
Magnitude of effect	↓↓	~	?	↓↓	↓↓	↓↓		↓

Manure Measure 2: Covered storage of slurry (natural crust and impermeable base)

Where slurries have a high dry matter content, and stirring is minimized, these may form a natural crust during storage, which is associated with substantially reduced NH_3 emission, although N_2O production may be enhanced. The effect of a natural crust on CH_4 emissions depends on the amount or rainfall. In areas with little rainfall, where the natural crust stays dry and well aerated, CH_4 emissions will be reduced by a natural crust. The impermeable base avoids nitrate leaching and must be maintained to avoid leakage.

Table 22: Manure Measure 2: Covered storage of slurry (natural crust and impermeable base)

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of covered storage of manure natural crust

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
UNECE category	1-2	3	3	1	3	2		2
Magnitude of effect	↓	↑?	?	↓↓	~	↓		~↓

Manure Measure 3: Slurry acidification (manure storage)

Ammonia emissions from stored slurry can be reduced by addition of acids. This is most commonly done just prior to spreading. The reduction in pH also reduces CH_4 and is expected to decrease N_2O and N_2 emissions. Acid may be added or produced in situ during storage (for example, by oxidation of atmospheric N_2 augmented using locally produced renewable energy). While feedstock for biogas production can only contain limited amounts of acidified slurry, acidification after anaerobic digestion can help to reduce subsequent NH_3 emissions.

Table 23: Manure Measure 3: Slurry acidification (manure storage)

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of slurry acidification

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
UNECE category	1	2	2	3	2	1		1
Magnitude of effect	↓↓	↓	~/↓?	~ [a]	↓	↓↓[a]		↓↓

[a] Although this measure is not known to reduce NO_3^- directly, where NH_3-saving contributes to replace inorganic fertilizer inputs from newly fixed N (for example, when fertilizer regulations require the improved fertilizer value to be taken into account), it can contribute to increased system efficiency and circularity, reducing wider Nr and N_2 losses.

Manure Measure 4: Mechanical solid-liquid separation of slurry fractions

Mechanical separation of solid and liquid fractions of slurry produces an ammonium-rich liquid that degrades more slowly and infiltrates more effectively into soil, reducing NH_3 emissions, with more predictable fertilization benefits increasing crop yields and allowing reduction of mineral N fertilizer. Care is needed to avoid NH_3 and CH_4 losses from the solid fraction, which may serve as a slow-release fertilizer or feedstock for biogas production.

Table 24: Manure Measure 4: Mechanical solid-liquid separation of slurry fractions

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of mechanical solid-liquid separation of slurry fractions

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
UNECE category	½	2	3	3	2	2[b]		2
Magnitude of effect	↓↓	↓	?[a]	?[a]	↓	↓[a]		~↓

[a] Although this measure is not known to reduce NOx and NO_3^- directly, where NH_3-saving contributes to replace inorganic fertilizer inputs from newly fixed N, it can contribute to increased system efficiency and circularity, reducing wider Nr and N2 losses. [b] The main emphasis of this approach is on reducing emissions from the liquid fraction, which contains most of the ammoniacal nitrogen, therefore implying: (a) the need to cover or acidify the liquid fraction during storage; and (b) the opportunity to reduce NH_3 emissions during spreading of the liquid fraction (chapter V). Maximum effectiveness of this approach also requires appropriate storage and use of the solid fraction (for example, by covered storage, direct incorporation into soil, or anaerobic digestion).

Manure Measure 5: Anaerobic digestion

Anaerobic digestion associated with production of CH_4 biogas reduces emissions of CH_4 from subsequent storage of the digestate, while substituting consumption of fossil energy. Ammonium content and pH in digested slurry are higher than in untreated slurry, increasing the potential for NH_3 emissions, requiring the use of covered stores and low-emission manure spreading. As part of an integrated package of measures, anaerobic digestion can reduce NH_3, N_2O and N_2 losses, while providing an opportunity for advanced forms of nutrient recovery. The requirement for an impermeable base avoids nitrate leaching compared with storage of manure on permeable surfaces.

Table 25: Manure Measure 5: Anaerobic digestion

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of anaerobic digestion

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
UNECE category	1[a]	2[a]	3	1[a]	2[a]	1		1
Magnitude of effect	↓↓[a]	↓[a]	?[b]	↓↓[b]	↓[a]	↓↓		↓↓↓

[a] UNECE category and magnitude are given on the basis of anaerobic digestion being implemented in combination with low-emission land application of the digestate (for example, band-spreading, injection, chapter V). Due to the high pH of anaerobic digestate, ammonia emissions may otherwise increase (↑↑). [b] Although this measure is not known to reduce NOx directly, where NH_3 and N_2 saving contribute to replace inorganic fertilizer inputs from newly fixed N, it can contribute to increased system efficiency and circularity, reducing wider Nr losses. The requirement for an impermeable base implies less nitrate leaching than storage/treatment of manure on a permeable surface.

Nutrient Recovery Measure 1: Drying and pelletizing of manure solids

Drying and pelleting of solid manures, slurry or digestate solids can be done to create a more stable and odourless bio-based fertilizer product. Drying is energy intensive, while NH_3 emissions increase, unless exhaust air filtering or scrubbing and N recovery is applied, or the solids are acidified prior to drying. CH_4 emissions from dries manure will be lower than from liquid manure.

Table 26: Recovery Measure 1: Drying and pelletizing of manure solids

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of drying and pelletizing of manure solids

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
UNECE category	3(1[a])	3	3	2	3	2		1
Magnitude of effect	↑ (↓[a])	~?	~?	~?	~?	~↑ (↓[a])		↓↓

[a] The method increases NH_3 emissions unless combined with acidification of slurry or scrubbing/stripping (Nutrient Recovery Measures 4 and 5) of the exhaust air.

Nutrient Recovery Measure 2: Combustion, gasification or pyrolysis

Combustion, thermal gasification or pyrolysis of manure and digestate solids can be used to generate a net energy output for heat and/or electricity production. However, the method wastes manure N, which is converted into gaseous N_2 and NOx (category 3). Systems under development to minimize N_2 formation and recover the Nr gases can be considered as category 2 for abating overall N loss. It is likely that this measure will strongly decrease CH_4 emissions from stored manure.

Table 27: Recovery Measure 2: Combustion, gasification or pyrolysis

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of combustion, gasification or pyrolysis

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
UNECE category	3(2[a])	3	2-3	3	3	3(2[a])		2
Magnitude of effect	↑(↓[a])	↑(↓[a])	↑(↓[a])	-	↑↑	↑↑		↓↓

[a] Values in brackets reflect the benefit of additional process controls (for example, selective (non-) catalytic reduction), which work to minimize the NOx and NH_3 emissions. However, current methods still increase N_2 emission, so that the Nr resource is effectively wasted. This approach therefore tends to reduce system-wide nitrogen use efficiency and contributes to preventing progress towards a nitrogen circular economy. Further development is required to couple minimization of N_2 formation with effective recovery of Nr gases (Sutton and others, 2013).

Nutrient Recovery Measure 3: Precipitation of nitrogen salts

Struvite ($MgNH_4PO_4 \cdot 6H_2O$) (as well as other phosphorus salts such as hydroxy apatite) can be precipitated from liquid manures, including anaerobically digested slurries and the liquid fraction from digestate separation. The main advantage of struvite compared with other approaches is its high concentration and similarity in physical-chemical properties to conventional mineral N fertilizer. The setting of UNECE category 2 reflects the need for further assessment of efficiencies. The effect of this measure on CH_4 emissions has yet to be investigated.

Table 28: Recovery Measure 3: Precipitation of nitrogen salts

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of precipitation of nitrogen salts

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
UNECE category	2	3	3	2	2	2		3
Magnitude of effect	↓[a]	?[a]	?[a]	↓[a]	↓[a]	↓[a]		?

[a] The table refers to precipitation of struvite only. As the approach recaptures Nr for reuse, system-wide reductions in the main losses of NH_3, NO_3^- and N_2 can be expected. However, the actual efficiencies remain to be demonstrated. This can be considered as an enabling measure to reduce overall Nr and N_2 losses, by mobilizing recovery and reuse of available Nr resources.

Nutrient Recovery Measure 4: Ammonia stripping and recovery

In this method, the liquid fraction after manure separation is brought into contact with air, upon which NH_3 evaporates and is collected by a carrier gas. Use of membrane systems allows use of lower temperatures, if membrane fouling can be avoided. Ammonia released from an NH_3 stripping column or from a manure drying facility can be collected using wet scrubbing with an acid solution, such as sulphuric or nitric acid. The ammonium sulphate and nitrate produced can serve as raw materials for mineral fertilizers, providing the opportunity for circular economy development. The effect of this measure on CH_4 emissions has yet to be investigated.

Table 29: Recovery Measure 4: Ammonia stripping and recovery

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of ammonia stripping and recovery

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
UNECE category	1[a]	1[a]	1[a]	1[a]	1[a]	1[a]		3
Magnitude of effect	↓[a]	↓[a]	↓[a]	↓[a]	↓[a]	↓↓[a]		?

[a] This can be considered as an enabling measure to reduce overall Nr and N_2 losses, by mobilizing recovery and reuse of available Nr resources. In this way, recovered Nr contributes to replace inorganic fertilizer inputs from newly fixed N, thereby increasing system efficiency and circularity.

2.3 Field application of manure and inorganic fertilisers

The UNECE GD summarises the benefits and objectives of reduced emissions after manure and fertiliser application: “Measures to reduce nitrogen loss from field application of nitrogen resources are especially important as the benefits of improved nutrient use can be seen by farmers. Measures to reduce overall nitrogen losses thus have a dual aim: to improve resource efficiency (allowing a reduction in bought-in fertilizers and other nutrient resources); and to reduce pollution of air and water, with multiple environmental benefits. The nitrogen savings resulting from measures during housing and storage of manure must be accounted for. These actions increase the amounts of nitrogen resources available for field spreading, enabling reductions in newly produced nitrogen resources. The most effective measures are listed below according to applicability:

(a) Measures applicable to both organic and inorganic fertilizers;
(b) Measures applicable to manures and other organic materials;
(c) Measures applicable to inorganic fertilizers;
(d) Measures applicable to livestock grazing; and their cropping-related measures."

Field Measure 1: Integrated nutrient management plan

The approach focuses on integrating all the nutrient requirements of arable and forage crops on the farm, through use of all available organic and inorganic nutrient sources. Priority should be given to utilization of available organic nutrient sources first (for example, livestock manure), with the remainder to be supplied by inorganic fertilizers. Recommendation systems can provide robust estimates of the amounts of N (and other nutrients) supplied by organic manure applications. Supported by soil nutrient testing and decision-support tools to assess crop needs (for example, leaf colour sensing), this information can be used to determine the amount and timing of any additional inorganic fertilizers, while allowing for further input reductions as a result of saved nitrogen from decreased pollution losses. This measure may have an indirect effect on CH_4 emissions. The capacity of soils to uptake atmospheric CH_4 (i.e. act as CH_4 sinks) and to oxidise it to CO_2 and H_2O strongly depends on the NH_4^+ content of the soils. Over-fertilised soils have a lower CH_4 oxidising capacity.

Table 30: Field Measure 1: Integrated nutrient management plan

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of integrated nutrient management plan

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
UNECE category	1[a]	1[a]	1[a]	1[a]	1[a]	1[a]		2
Magnitude of effect	↓	↓	↓	↓	↓	↓↓		~↓

[a] The reference for performance assessment would be N loss in the absence of an integrated nutrient management plan. While it is agreed by experts that such a plan will help reduce N losses, further work is needed to demonstrate statistical comparisons of farm performance for N losses.

Field Measure 2: Apply nutrients at the appropriate rate

Under application of N will result in reduced crop yields and can lead to mining of soil N and organic matter. Over application of N can also result in reduced crop yields and profits, and surplus available soil N, increasing the risk of losses to air and water. Applying N to match crop requirement at an environmentally and economically sustainable level requires knowledge of the N content of the organic manure or fertilizer product and crop N demand. In-crop soil testing or leaf colour sensing may help with split applications. This measure may have an indirect effect on CH_4 emissions. The capacity of soils to uptake atmospheric CH_4 (i.e. act as CH_4 sinks) and to oxidise it to CO_2 and H_2O strongly depends on the NH_4^+ content of the soils. Overfertilised soils have a lower CH_4 oxidising capacity.

Table 31: Field Measure 2: Apply nutrients at the appropriate rate

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of the measure "apply nutrients at the appropriate rate"

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
UNECE category	1[a]	1[a]	1[a]	1[a]	1[a]	1[a]		2
Magnitude of effect	↓-↓↓	↓-↓↓	↓-↓↓	↓-↓↓	↓-↓↓	↓-↓↓		~↓

[a] It is hard to define a reference for this measure, which, in UNECE conditions, would mainly be associated with too much nutrient application leading to increased Nr and N_2 losses. Repeated removal of nutrients in harvests without returning nutrients to the soil can also lead to soil degradation and risk of erosion, indicating that the risk of insufficient nutrient supply may be an issue in a few parts of the UNECE region.

Field Measure 3: Apply nutrients at the appropriate time

Targeting N to the soil at times when it is required by an actively growing crop reduces the risks of nitrogen losses to air and water. Multiple (or split) applications reduce the risk of large leaching events and enable later additions to be fine-tuned according to adjustment of yield expectations. Appropriate timing should take account of climatic differences, as well as weather forecasts (for example, to favour manure spreading during cool weather). Combined application of organic slurries and inorganic fertilizer should be avoided where co-occurrence of water and carbon increases N_2O emissions. This measure may have an indirect effect on CH_4 emissions. The capacity of soils to uptake atmospheric CH_4 (i.e. act as CH_4 sinks) and to oxidise it to CO_2 and H_2O strongly depends on the NH4+ content of the soils. Overfertilised soils have a lower CH_4 oxidising capacity.

Table 32: Field Measure 3: Apply nutrients at the appropriate time

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of the measure "apply nutrients at the appropriate time"

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
UNECE category	1[a]	1[a]	1[a]	1[a]	1[a]	1[a]		2
Magnitude of effect	↓	↓	↓	↓	↓	↓		~↓

[a] It is hard to define a reference for this measure, which, in UNECE conditions, would mainly be associated with application of nutrients outside of the main growing periods, such as application of manure to agricultural land in winter due to insufficient manure storage capacity.

Field Measure 4: Apply nutrients in the appropriate form

This measure mainly targets NH_3 emissions, which are much lower from ammonium nitrate than from urea fertilizer. There is a risk of increased losses through denitrification and/or leaching and run-off because the N saved by decreasing NH_3 emission, unless N application rate is reduced to match the amounts saved (chapter III, principle 6). With organic materials, such as livestock manure, account should be taken of the relative content of inorganic forms of N (such as ammonium) compared with organic compounds, as this affects the N replacement value.

Table 33: Field Measure 4: Apply nutrients at the appropriate form

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of the measure "apply nutrients at the appropriate form"

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
UNECE category	1-2[a]	1-2[a]	1-2[a]	1-2[a]	1-2[a]	1-2[a]		2
Magnitude of effect	↓	↓	↓	↓	↓	↓		~

[a] Performance of this aggregate measure will differ according to each specific measure selected.

Field Measure 5: Limit or avoid fertilizer application in high-risk areas

Certain areas on the farm can be classified as higher risk in terms of N losses to water, by direct run-off or leaching, or to air through denitrification. Pollution can be reduced by avoiding or limiting fertilizer application to these locations (for example, in the vicinity of ditches and streams and on steeply sloping areas.

Table 34: Field Measure 5: Limit or avoid fertilizer application in high-risk areas

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of limit or avoid fertilizer application in high-risk areas

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
UNECE category	3[a]	1[a]	1[a]	1[a]	1[a]	1[a]		2
Magnitude of effect	~[b]	↓	↓	↓	↓	↓		~

[a] It is hard to define a general reference for this measure, as each situation must be judged in context. [b] Landscape measures related to mitigation of NH_3 impacts.

Field Measure 6: Band spreading and trailing shoe application of livestock slurry

Reducing the overall surface area of slurry, by application in narrow bands, will lead to a reduction in ammonia emissions of 30–35 per cent compared with surface broadcast application, particularly during the daytime when conditions are generally more favourable for volatilization. In addition, if slurry is placed beneath the crop canopy, the canopy will also provide a physical structure to reduce further the rate of ammonia loss (by 60 per cent).

Table 35: Field Measure 6: Band spreading and trailing shoe application of livestock slurry

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of band spreading and trailing shoe application of livestock slurry

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
UNECE category	1[a]	3[a]	3[a]	3[a]	3[a]	1[a]		2
Magnitude of effect	↓-↓↓	~↑↓[b]	~↑↓[b]	~↑↓[b]	~↑↓[b]	↓[b]		~

[a] The reference for this method is surface spreading of stored liquid manure (slurry) without any special treatment. [b] While there is some risk of trade-off between ammonia and other forms of N loss from the applied slurry, when considering the farm and landscape scale, there is the opportunity to decrease these N losses, as the increased N use efficiency, as a result of the measure, allows a reduction of fresh N inputs. Indirect N_2O and NOx emissions resulting from atmospheric ammonia deposition to forest and other land are also reduced.

Field Measure 7: Slurry injection

Placing slurry in narrow surface slots, via shallow or deep injection greatly reduces the exposed slurry surface area, thereby reducing NH_3 emissions (by 70–90 per cent). Emissions of N_2O (as well as NOx and N_2 emissions) may be increased, though this risk can be reduced by compensating for the amount of nitrogen saved through NH_3 emission reductions by using reduced slurry applications rates. In addition to the UNECE GD, we would like to state that deep injection increases N_2O emissions and CO_2 emissions (the latter through the increased fuel consumption). Therefore, shallow injection would be the preferred option.

Table 36: Field Measure 7: Slurry injection

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of slurry injection

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
UNECE category	1[a]	3[a]	3[a]	3[a]	3[a]	1[a]		2
Magnitude of effect	↓↓	~↑↓[b]	~↑↓[b]	~↑↓[b]	~↑↓[b]	↓↓		~

[a] The reference for this method is surface spreading of stored liquid manure (slurry) without any special treatment.

[b] While there is some risk of trade-off between ammonia and other forms of N loss from the applied slurry, when considering the farm and landscape scale, there is the opportunity to decrease these N losses, as the increased N use efficiency, as a result of the measure, allows a reduction of fresh N inputs. Indirect N2O and NOx emissions resulting from atmospheric ammonia deposition to forest and other land are also reduced.

Field Measure 8: Slurry dilution for field application

Ammonia losses following surface broadcast slurry application are less for slurries with lower dry matter, because of the more rapid infiltration into the soil. The reduction in ammonia emission will depend on the characteristics of the undiluted slurry and the soil and weather conditions at the time of application (ca 30 per cent emission reduction for 1:1 dilution of slurry in water).

Table 37: Field Measure 8: Slurry dilution for field application

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of slurry dilution for field application

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
UNECE category	1[a]	3[a]	3[a]	3[a]	3[a]	2[a]		2
Magnitude of effect	↓↓	~↑	~↑	~↑	~↑	↓		~

[a] The reference method for comparison with this measure is field application of undiluted slurry.

Field Measure 9: Slurry acidification (during field application)

A lower pH favours ammoniacal N in solution to be in the form of ammonium rather than ammonia, thereby reducing ammonia volatilization. Typically, sulphuric acid is used to lower the pH, though other acids may be used. Acid addition during field application of slurry requires appropriate safety procedures.

Table 38: Field Measure 9: Slurry acidification (during field application)

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of the measure "Slurry acidification during field application"

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
UNECE category	1[a]	3[a]	3[a]	3[a]	3[a]	1[a]		2
Magnitude of effect	↓↓	~↓	~↓	~	~↓	↓↓		~

[a] The reference method for comparison with this measure is field application of slurry without addition of acid.

Field Measure 10: Rapid incorporation of manures into the soil

Rapid soil incorporation of applied manure (within a few hours after application) reduces the exposed surface area of manure from which NH_3 volatilization occurs and can also reduce N and P losses in run-off. The measure is only applicable to land that is being tilled and to which manure is being applied prior to crop establishment.

Table 39: Field Measure 10: Rapid incorporation of manures into the soil

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of rapid incorporation of manures into the soil

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
UNECE category	1[a]	3[a]	3[a]	3[a]	3[a]	1[a]		2
Magnitude of effect	↓↓	~↑↓[b]	~↑↓[b]	~↑↓[b]	~↑↓[b]	↓-↓↓		~

[a] The reference method for this measure is the surface field application of slurry and solid manure. [b] While there is some risk of trade-off between ammonia and other forms of N loss from the applied slurry, when considering the farm and landscape scale, there is the opportunity to decrease these N losses, as the increased N use efficiency, as a result of the measure, allows a reduction of fresh N inputs. Indirect N_2O and NOx emissions resulting from atmospheric ammonia deposition to forest and other land are also reduced.

Field Measure 11: Replace urea with an alternative N fertilizer

Following land application, urea will undergo hydrolysis to form ammonium carbonate, locally increasing pH and favouring NH_3 emission. By contrast, for fertilizer forms such as ammonium nitrate, ammonium will be in equilibrium at a much lower pH, greatly reducing the potential for ammonia volatilization. In calcareous and semi-arid soils, the replacement of urea by ammonium nitrate or calcium ammonium nitrate usually also leads to the abatement of N_2O and NOx, though the opposite can happen in other situations.

Table 40: Field Measure 11: Replace urea with an alternative N fertilizer

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of replaced urea with an alternative N fertilizer

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
UNECE category	1[a]	3[a]	3[a]	3[a]	3[a]	1[a]		2
Magnitude of effect	↓↓	~↑↓	~↑↓	~	~?	↓-↓↓		~

[a] The reference method for this measure is the surface application of prilled urea (or of urea containing solutions in water).

Field Measure 12: Urease inhibitors with inorganic fertilizers

Urease inhibitors slow the hydrolysis of urea by inhibiting the urease enzyme in the soil. This allows more time for urea to be incorporated in the soil and for plant uptake, thereby reducing the potential for NH_3 emissions. In some studies (for example, under nitrifying conditions), urease inhibitors have also been found to decrease soil N_2O and NOx emissions.

Table 41: Field Measure 12: Urease inhibitors with inorganic fertilizers

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of urease inhibitors with inorganic fertilizers

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
UNECE category	1[a]	2[a]	2[a]	3[a]	2[a]	1[a]		2

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
Magnitude of effect	↓↓	~↓	~↓	~	~↓	↓↓		~

[a] The reference method for this measure is the surface application of prilled urea (or of urea containing solutions in water) without urease inhibitors.

Field Measure 13: Nitrification inhibitors with inorganic fertilizers

Nitrification inhibitors are chemicals (manufactured or natural) that can be incorporated into NH_3 or urea-based fertilizer products, to slow the rate of conversion of ammonium to nitrate. These have been shown to reduce emissions of N_2O and can also be expected to reduce emissions of NOx and N_2, and leaching losses of nitrate, as they arise from the same process pathways. Potential long-term effects of nitrification inhibitors on non-target organisms should be considered.

Table 42: Field Measure 13: Nitrification inhibitors with inorganic fertilizers

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of nitrification inhibitors with inorganic fertilizers

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
UNECE category	3[a]	1[a]	1[a]	1[a]	1[a]	1-2[a]		2
Magnitude of effect	↑~	↓↓	↓↓	↓-↓↓	↓↓	↓↓		~

[a] The reference method for this measure is the surface application of a nitrogen-containing fertilizer without nitrification inhibitors.

Field Measure 14: Precision placement of fertilizers, including deep placement

Placement of N and P fertilizer directly into the soil close to the rooting zone of the crop can be associated with enhanced N and P uptake, lower losses of N to air and N and P to water and a lower overall N and P requirement compared with broadcast spreading. Placement within the soil reduces losses by NH_3 volatilization.

Table 43: Field Measure 14: Precision placement of fertilizers, including deep placement

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of precision placement of fertilizers, including deep placement

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
UNECE category	1[a]	3[a]	3[a]	1[a]	3[a]	1[a]		2
Magnitude of effect	↓↓	~↑↓	~↑↓	~↓	~↑↓	↓		~

Note: The reference method for this measure is the surface application of a nitrogen-containing fertilizer. [a] When considering the farm and landscape scale, there is the opportunity to decrease these nitrogen losses, where increased nitrogen use efficiency allows a reduction of fresh nitrogen inputs. Indirect N_2O and NOx emissions resulting from atmospheric ammonia deposition to forest and other land are also reduced.

Field Measure 15: Extend the grazing season

Ammonia emissions arising from grazing livestock are much smaller than for managed manure (for example, from housed animals) because of the rapid infiltration of urine into the soil. Where climate and soil conditions allow, extending the grazing season will result in a higher proportion of excreta being returned via dung and urine during grazing, thereby reducing NH_3 emissions. Risks of nitrate leaching and denitrification losses (as N_2O and N_2) may be increased unless additional actions are taken. This measure will also reduce CH_4 emissions are manure is excreted during grazing rather than in the barn and therefore CH_4 emissions during manure storage are avoided.

Table 44: Field Measure 15: Extend the grazing season

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of extend the grazing season

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
UNECE category	1[a]	3[a]	3[a]	3[a]	3[a]	2[a]		1
Magnitude of effect	↓↓	~↑	~↑	~↑	~↑	~↓		↓↓

[a] The reference method for this measure is the traditional grazing season of a particular region during the late twentieth century. In North-Western Europe, a standard situation for cattle would be half a year (182.5 days) grazing per year, with 365 days grazing for sheep and zero days outdoors for pigs or poultry, though local variations will apply.

Field Measure 16: Avoid grazing in high-risk areas

High-risk areas include those with high connectivity to vulnerable surface waters and/or ground waters, and those subject to waterlogging, poaching and compaction. These include cases with both greatly enhanced potential for N, P and pathogen losses from dung and urine via run-off and denitrification. Such areas should be fenced, or carefully managed, to exclude livestock grazing.

Table 45: Field Measure 16: Avoid grazing in high-risk areas

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of the measure "Avoid grazing in high-risk areas"

Nitrogen form	NH_3	N_2O	NO_x	NO_3-	N_2	Overall N Loss		CH_4
UNECE category	3[a]	1[a]	1[a]	1[a]	1[a]	1[a]		2
Magnitude of effect	~	↓	↓	↓↓	↓	↓		~

[a] The reference method for this measure is grazing the full extent of available land, up to the edges of fields, irrespective of the occurrence of high-risk features.

2.4 Conclusions and research questions

It is clear that manure management has an impact on quantities of Nr emissions (NH_3, direct and indirect N_2O emissions, NOx emissions, NO_3^- leaching) and N_2 emissions, as well as emissions of CH_4 and CO_2. This applies at each stage of the manure management continuum (Chadwick and others, 2011). Since production of these gases, as well as of leachable Nr, is of microbial origin, the dry matter (DM) content and temperature of manure and soil are key factors for farm manure management decisions that influence the magnitude of N and greenhouse gas losses. There remains a degree of uncertainty in emission rates of N and greenhouse gases from different stages of manure management, and researchers continue to investigate interactions of the management and environmental factors that control emissions. Some specific approaches to reducing N and greenhouse gas emissions from live-stock housing and manure storage include: optimizing diet formulation; low-emission housing technologies; manure processing; and nutrient recovery. The technologies include: air-scrubbers; covered manure storage; slurry separation and anaerobic digestion; nitrogen concentration; and stripping methods.

Existing legislation across the UNECE region offers opportunities to find “win–win” scenarios, with benefits in reducing multiple forms of pollution. One example is the European Nitrates Directive, which has led to development of Nitrate Vulnerable Zone action plans to prevent application of animal manure, slurry and poultry manure (with high available N content) in autumn, a practice that reduces N losses, as well as direct and indirect N_2O losses. Care is needed to ensure that legislation does not lead to potential “pollution swapping” (for example, unadjusted use of slurry injection to reduce NH_3 emissions at the expense of an increase in N_2O emissions, with no modification of N inputs. A core principle is that measures that reduce one form of N loss need to be accompanied by either a reduction of fresh nitrogen inputs, or an increase in harvested products, to maintain mass consistency. In this way, what may at first seem a trade-off at the field scale, can be seen at the landscape and regional scales as an opportunity to move towards a more circular system with lower overall N losses.

The nature of the N cycle and its interaction with the C, P and other nutrient cycles demands a holistic approach to addressing N and greenhouse gas emissions and mitigation research at a process level of understanding. Systems-based modelling must play a key role in integrating the complexity of management and environmental controls on emissions. Progress has been made to this end (Sommer and others, 2009), with some studies producing whole farm models encompassing livestock production (del Prado and others, 2010).

The UNECE Guidance Document on Sustainable Nitrogen Management identifies the following requirements when addressing environmental needs:

Concepts for best practices to reduce adverse environmental impacts depend on the following integrated concepts:

- Relationship between nitrogen and greenhouse gas emissions;
- Influence of climate change on nitrogen emissions;
- Interaction between abatement/mitigation and adaptation measures;
- Interaction between nitrogen emissions and animal welfare;
- Integrated assessment of the whole manure management continuum;
- Integrated assessment considering the three pillars of sustainability: economy; environment; society;
- Interaction between consumer demand and nitrogen emissions;
- Development of region-specific concepts for sustainable intensification;
- Modelling of livestock production at the regional, national and global scales;

- Economic impact of both the cost of the techniques and the benefit to the farmer of reducing emissions and retaining nitrogen as a fertilizer.

Concepts to reduce adverse environmental impacts depend on the understanding at a process level of the following:

- Assessment of emissions from naturally ventilated barns;
- Assessment of emissions from new, animal-friendly housing systems;
- Development of abatement/mitigation measures, especially for naturally ventilated dairy barns (for example, targeted ventilation and air-scrubbers, manure acidification);
- Interaction between climate change and heat stress/animal behaviour/emissions;
- Interaction between low-protein diets and N and greenhouse gas emissions;
- Interactions between N and greenhouse gas emissions during housing, storage and application to field;
- Life-cycle assessment: for example, grass-based dairy feeding versus low-protein dairy feeding;
- Feed and manure additives for improved N use efficiency;
- Manure treatment for higher N use efficiency (increase of nutrient availability, decrease of emissions) and potential of processing to recover manure N into biobased fertilizers in a circular economy.

Concepts to reduce adverse environmental impacts depend on the development of flexible concepts for environmental improvement:

- Climate and site-specific conditions vary across the UNECE region and globally;
- All three columns of sustainability must be considered: economic, environmental and social sustainability;
- Conflicts of interest must be addressed;
- Targeted approaches should be used according to the needs of different regions.

Concepts to reduce adverse environmental impacts depend on effective communication and interaction:

- Establishing networks to exchange manure management information, connect people, and forge partnerships;
- Launching an online knowledge hub on best practices for livestock housing and manure management;
- Establishing a roster of experts to provide targeted technical assistance and training, analysis and practical implementation and policy support, relying heavily on co-financing and in-kind re-sources from partners;
- The development of best practice concepts is challenging. Climate and site-specific conditions are highly variable. It is essential to consider the three columns of sustainability – economy, environment and society – and to address synergies and potential conflicts of

interest. This inevitably leads to the conclusion that there will be no “one-size fits all solution”. Best-practice concepts provide a basis that offers guidance on the development of flexible measures targeted for each specific region and context.

3 Case Study of Germany

Agricultural production results in ammonia (NH_3) and nitrous oxide (N_2O) emissions into the atmosphere, as well as nitrate (NO_3) pollution of the hydrosphere. Germany committed itself in international agreements and legal regulations to the protection of health and ecosystems, immission values and emission reduction obligations for air:

- Gothenburg Protocol Annex IX of the Convention on Long-Range Transboundary Air Pollution, UNECE, (1979), UNECE Framework code for Good Agricultural Practice for Reducing Ammonia Emissions
- EU NEC-Directive (2016/2284)
- EU Nitrate Directive (91/676/EWG)
- EU Water Framework Directive (2000/60/EG)
- Baltic Sea Action Plan
- EU Air Quality Directive
- EU Industrial-Emission Directive (IED)
- Common Agricultural Policy

The requirements in the international regulations have been transposed into German law in national sub-statutory regulations.

3.1 UNECE CLRTAP, UNECE Framework Code for Good Agricultural Practice for Reducing Ammonia Emissions, German CofGAP

In order to effectively combat eutrophication and the acidification of ecosystems caused by reactive nitrogen, the Gothenburg Protocol (1999), Annex IX of the Convention on Long-Range Transboundary Air Pollution, UNECE, (1979), aims to limit annual ammonia emissions by introducing national emission ceilings. Germany has also committed itself to reducing ammonia emissions. The derivation of these maximum levels is carried out according to the effect-based approach.

The Gothenburg Protocol states that each Party "shall establish, publish and disseminate an advisory code of good agricultural practice to control ammonia emissions". In 2001 the UNECE established a „Framework Code for Good Agricultural Practice for Reducing Ammonia Emissions" and revised it in 2015. Germany has published (2003) and revised (2021) the National Code for Good Agricultural Practice for Reducing Agricultural Ammonia Emissions (UBA/KTBL 2021).

3.2 EU NEC Directive and National air pollution control program

The European Union has implemented many of the requirements and recommendations of the bodies of the Geneva Convention on Air Pollution Control in European regulations. With the Directive on National Emission Ceilings as annual loads for certain air pollutants (NEC Directive 2016/2284), EU Member States are pursuing emission reduction targets of the Gothenburg Protocol. Germany committed to a 29-percent reduction in ammonia emissions by 2030 compared to 2005 emissions. Details of the implementation in Germany are regulated in the 43rd Federal-Immission-Control Ordinance (43. BImSchV, 2018). The new NEC Directive includes extensive EU reporting obligations: In addition to annual emission reporting, emission projections for the aforementioned pollutants must be reported every two years.

In national air pollution control programs, member states present their past, present and future strategies and measures for achieving the reduction commitments. These programs must be updated at least every 4 years. In accordance with Articles 6 and 10 of Directive (EU) 2016/2284 on the reduction of national emissions of certain atmospheric pollutants, a “National Air Pollution Control Program of the Federal Republic of Germany” was established for the first time in 2019. It includes all measures necessary to comply with Germany’s commitments. By reducing measures in the field of fertilization, such as low-emission application of manure, direct incorporation of manure into the soil, exhaust air purification in barn buildings and the coverage of manure storage facilities, ammonia emissions can be significantly reduced.

3.3 EU Nitrate Directive, Fertilizer Law and Fertilization Ordinance, Strategic Environmental Assessment for the Amendment of the Fertilizer Application Ordinance, Ordinance on Nutrient-Flow Balances

The EU Nitrate Directive (91/676 / EEC) was adopted in 1991 for the protection of groundwater and the surface waters from nitrate impurities from agriculture. This provides for the monitoring of the basic and surface water, the designation of endangered territories and the preparation of rules of good professional practice in agriculture. Human health should also be protected against high nitrogen loads due to water limits. For drinking water, the maximum tolerated nitrate concentration is 50 mg per liter. With the Water Protection Directive (2006/11 / EC), substances that are unfavorably affect the oxygen balance, in particular ammonium and nitrite, are limited. For assessing the success of the measures taken to reduce nitrogen measures, Member States shall assess the state of their surface waters and groundwater resources every four years and submit a nitrate report to the EU Commission. The nitrate direction is substantially implemented in national law in Germany with the Fertilizer Application Ordinance.

With the judgment of the European Court of Justice of 21 June 2018, Germany has been convicted for the second time due to insufficient implementation of the Nitrate Directive 91/676 / EEC. The European Court of Justice noted that the provisions of the Fertilizer Application Ordinance were not suitable for ensuring the protection of waters from contamination by nitrate from agricultural sources. The Nitrate Report 2020 of the Federal Government re-established that the situation of the nitrate burden of groundwater has only improved slightly. The proportion of groundwater measuring points of the EU measuring network with a nitrate concentration over 50 mg per liter decreased only 1.5-percent points to 26.7 percent compared to the previous reporting period (UBA Texts 200/2020).

Fertilizer Act, Fertilizer Application Ordinance and General Administrative Regulation for the designation of with nitrate contaminated and eutrophicated areas, Ordinance on Nutrient-Flow Balances

The Fertilizer Act (Düngegesetz) regulates the requirements for the placing on the market, application of fertilizers, soil and plant- improving substances. It contains authorizations to issue ordinances in order to lay down the detailed arrangements in this respect.

With the amendment of the Fertilizer Law in 2017, it was determined that fertilization does not serve exclusively to secure the yield formation, but must ensure sustainable and resource-efficient use of nutrients and in particular to avoid nutrient losses into the environment as much as possible.

The Fertilizer Application Ordinance (DüV, 2017, 2020) specifies the requirements for good agricultural practice in fertilization and regulates how the risks associated with fertilization – such as nutrient losses – can be reduced. In accordance with this, the nitrogen fertilizer requirements of crops for arable land and grassland must be calculated prior to application. The Fertilizer Application Ordinance contains restrictions on the application of nitrogen and phosphate fertilizers depending on the regional and soil condition, regulates periods in which the application of fertilizers is prohibited and sets requirements for the storage of organic fertilizers. The new Fertilizer Application Ordinance has been in force since 2 June 2017.

For the implementation of the judgment of the European Court of Justice against Germany 2018 due to insufficient implementation of the EU Nitrate Directive, the Fertilizer Application Ordinance had to be adjusted. Therefore, an updated version was developed and approved by the German government in 2020. Based on this Ordinance for Designation (AVV-Gebietsausweisung) all German state governments (German Laender) have to report the designated areas which are contaminated and eutrophicated, by nitrate. In these areas, additional qualitative requirements concerning the ground water measuring points and the measuring of nitrate concentration in waters have to be fulfilled ac-cording to § 13a of the amended Fertilizer Application Ordinance (2020).

The 2020 revised Fertilizer Application Ordinance also contains requirements for the application of manure. Manure must be incorporated on bare arable land immediately, at least within one hour after application. From 2020 the application of slurry on arable land and on grassland from 2025 has to be done only with low-emission application technology (trailing hose, trailing shoe, injection). From 2020 urea fertilizer may only be applied when incorporated within four hours after application or when urease inhibitor is added to urea fertilizers.

With the amendment of the Fertilizer Application Ordinance (2020) the evaluation of a nutrient comparison is not required any longer, and therefore, an instrument for limiting the operating nutrient sur-pluses of 50 kg N per hectare (in the three-year average) was lacking. Only the determination of the fertilizer requirement by the farmers remained. However, the N and P surpluses represent the causally relevant quantities for the estimation of nutrient losses into the environment. The Ordinance on Nutrient-Flow Balances (StoffBilV, 2017) shall equal this lack and shall make the nutrient flows in farms more transparent. The scope of this Ordinance will be extended in 2023 to all farms with more than 20 hectares of agricultural land or more than 50 livestock units. Operating the N and P balances as well as upper limits for the nutrient surpluses will then become mandatory for farmers. Thus, requirements of the Ordinance on Nutrient-Flow Balances replace the regulation of the former Fertilizer Application Ordinance. However, the current requirements in the new Ordinance remain behind these earlier requirements. Balance values, like the balance value for nitrogen of 175 kg N per hectare, are too high. In the opinion of German experts this is not sufficient in order to reduce the environmental impact of nitrogen. Furthermore, the Ordinance on Nutrient-Flow Balances does not include noticeable consequences, like fines, for the exceeding of the upper limit (UBA Texts 200/2020). A study by Becker and Beiser (2017) clarifies that the current design of the Ordinance on Nutrient-Flow Balances does not make progress in the limitation of nutrient surpluses of farms. In terms of phosphorus, the Ordinance it is observed currently a blatant regulatory gap: it is prescribed to determine the supplied and temporary P quantities, but there is no limitation of the permissible P-surplus of a farm.

3.4 HELCOM und OSPAR

International agreements have the goal of protecting the sea and coastal ecosystems of the North and Baltic Sea from eutrophication. As part of the Helcom-9 and the OSPAR Convention, the signing states decided to achieve a state without eutrophication until 2010 for the North East Atlantic (including North Sea) and the Baltic Sea. The share of phosphorus input from German agriculture in the North and Baltic Sea is between 50% and 63% of total entries (UBA Texts 200/2020). The national implementation of the Baltic Sea Action Plan (HELCOM 2021) for reaching the reduction targets for nitrogen is currently going on in Germany.

3.5 Water Framework Directive (2000/60/EG)

Environmental quality goals for surface waters in Germany are mainly based on the EU Water Framework Directive. The German action programs are derived from it. They are closely linked with the environmental quality destinations for marine ecosystems. The primary goal of the Water Frame-work Directive is a good ecological and chemical status of surface waters. The good chemical state is based on the specifications of the nitrate directive and limits the nitrate concentration to 50 milligrams per litter.

In German coastal waters the “good ecological status”, pursuant the Water Framework Directive, failed since the beginning of the measurements. The main reason for this is the high N load to the North Sea and Baltic Sea, more than 70% of which are caused by agriculture. The required values for nitrogen in the flowing waters (2.6 and 2.8 mg N per litter) are exceeded almost nationwide (UBA texts 200/2020). These N loads are particularly due to the drained nutrition flows from agricultural areas. Therefore, not only the groundwater loads from agricultural sources are critical, but also the loads from drained flows and the current classification in "green" and "red" regions is questionable. Would the burdens of flowing waters from agricultural sources in Germany be considered as the burdens of groundwater in the water protection ordinance (as this is done already in Denmark), then the current discussion about a so-called "differentiation in green and red regions" would be largely obsolete (Henning and Dove, 2019).

3.6 The European Industrial Emission Directive 2010/75/EU, BAT-Conclusions, German Federal Immission Control Act, Technical Instructions on Air Quality Control, Ordinance on Installations for Handling Substances Hazardous to Water Substances, Waste-water Law

The European Industrial Emission Directive and the German Federal Immission Control Act

The purpose of the Directive 2010/75/EU on industrial emissions (IED) is to achieve integrated systems for the prevention of polluting emissions to air, land and water, including measures concerning waste, in order to reach a consistent and high level of protection for the environment taken as a whole. An important sector is the intensive livestock agriculture due to its very large impact especially on the wider environment. Best available techniques are required to operate in accordance with permits is-sued by Member State competent authorities.

The European IPPC Bureau (EIPPCB) located in Seville (Spain) was set up by the European Commission to organize a European information exchange in order to establish crucial Reference Documents (known as BREFs). The IED and the Seville process provide for the BAT conclusions of the BREFs to be adopted by the Commission as implementing acts. In Germany the requirements of the IED are implemented in the Federal Immission Control Act. The general administrative regulation pertaining the Federal Immission Control Act are to be found in the 4th Ordinance which contains a list of installations needing permits and in the Technical Instructions on Air Quality Control (TI AIR). In addition, BAT requirements are included in the German regulations to protect waters (like AwSV see be-low).

For the sector of 'intensive rearing of pig and poultry' installation with 2.000 animal places for fattening pig, 750 animal places for sows, 6.000 animal places for weaners and 40.000 animal places for poultry fall under the scope of the IED (4th Ordinance – procedure type with letter G, §10 Federal Immission Control Act). Additionally, in Germany installations with 1.500 to <2.000 animal places for fattening pig, 560 to <750 animal places for sows, 4.500 to < 6.000 animal places for weaners, 600 animal places for cattle, 500 animal places for calves and 30.000 to <40.000 animal places for poultry (4th Ordinance – procedure type with letter V, §10 Federal Immission Control Act) require special measures.

Moreover, Article 15(3) of the IED gives a particular role to the BAT-associated emission levels (BAT-AELs) set out in the BAT conclusions. It requires the emissions of the installations concerned not to exceed the BAT-AELs, except in specific cases where the conditions are fulfilled to allow a derogation by the competent authority (Article 15(4) of the IED). In the development of the Reference Documents on the Best Available Techniques for Intensive Rearing of Poultry and Pigs (BREF IRPP) 2003 and 2017, BAT-AELs are defined for BAT to reduce N- and P-emissions to environment by N- and P- adapted feeding of Pigs and poultry, as well as for reducing ammonia emissions from housing and manure application to fields.

During the latest revision of the IRPP BREF a harmonized approach for BAT assessment was lacking. Therefore, European countries used their own system and their own criteria for the evaluation of the best available technologies. This led to differing results and to the inevitable call for consistent guide-lines for the formulation of classification methods of BAT for intensive livestock farming. In Germany the BAT for IRPP needed to be evaluated during the implementation process into the Technical Instructions on Air Quality Control, No. 5.4.7.1, see below.

Technical Instructions on Air Quality Control

The Technical Instructions on Air Quality Control (TI AIR / TA Luft), No 5.4.7.1 contain measures de-rived from the IRPP BAT conclusions for large livestock facilities (see 4.2.1).

Minimum distance: When installations are first erected on a site, a distance of 100 m from the installation or to the nearest existing residential building shall be maintained. As a rule, the distance from nitrogen-sensitive plants and ecosystems, e.g. heath, moor, forests, shall not be less than 150 m.

The following constructional and operational measures are to be applied as a rule:

- The greatest possible cleanliness and dryness in the stable, including all feed and feeding hygiene measures, and keeping the manure, walking and resting areas.
- The amount of feed shall be provided in such a way that the amount of leftover feed is kept to a minimum; leftover feed shall be removed from the stable on a regular basis. Spoiled or un-usable feed or feed residues may not be stored openly.
- Feeding adapted to the energy and nutrient requirements of the animals must be ensured. Feed mixtures or rations adapted to crude protein and phosphorus shall be used in multiphase feeding. The nitrogen and phosphorus contents in the excreta of pigs and poultry must not exceed maximum values derived from BAT AEL of BAT conclusions.
- Optimum barn climate: For barns with forced ventilation an optimal barn climate must be achieved. For new barns with forced ventilation it must be ensured that the prerequisites are met to enable the subsequent installation of an exhaust air purification system.

- To reduce emissions from the barn, manure and urine generated in slurry systems must be transferred continuously or at short intervals to the storage tank outside the barn.
- In the case of temporary storage of liquid manure in the barn using underfloor vacuuming, the maximum filling level of the slurry channel should be at least 0.5 m below the concrete grates. For new construction of barn buildings, underfloor suction is only permitted if the level of manure is automatically monitored and recorded. In the case of underfloor vacuuming, the stable air should be extracted directly under the slatted floor at a maximum speed of 3 m/s.
- For poultry and swine confinement buildings with forced ventilation and mixed flocks, the exhaust air shall be supplied to a quality-assured exhaust air purification system that meets certain criteria. The exhaust air purification system shall ensure emission reduction levels for dust, ammonia and total nitrogen of at least 70 percent each in relation to a barn without air purification. An odour concentration in the clean gas of less than 500 GEE/m^3 must be ensured.
- An electronic operating logbook must be kept for exhaust air purification systems, which must be checked for functionality during the inspection measurements. The records shall be kept for five years and presented to the competent authority upon request. A functional test of the exhaust air purification system must be carried out annually by an officially recognized body.
- Quality-assured husbandry practices that can be shown to promote animal welfare may be used. In this case, measures from a technique list or equivalent mitigation measures shall be applied as far as possible.
- In the case of new construction of livestock buildings with forced ventilation in the smaller plants of the 4th Ordinance of the Federal Immission Control Act, mitigating techniques are to be used to reduce ammonia emissions that ensure an emission reduction rate of at least 40 percent in relation to the reference values specified in a list of technologies. When exhaust air purification equipment is used, at least 60 percent of the maximum volume flow occurring shall be treated, ensuring an emission reduction level of 70 percent for ammonia.
- Liquid manure must be stored in closed containers, with cover of suitable foil, with a solid cover or with a tent roof to reduce emissions, which achieve an emission reduction of at least 90 percent of the emissions of odour and ammonia in relation to the open container without a cover. Measures using straw chopped covers, granules or fillers are not permitted. Slurry filling into tanks must be carried out as sub-level filling. The storage tanks must be covered immediately after homogenization. The openings required for the stirring devices must be kept as narrow as possible.
- Slurry generated at manure storage sites shall be discharged into a drainless container. Three-sided enclosure of the storage area and the smallest possible surface area shall be provided to reduce wind-induced emissions. Solid manure piles shall be covered or roofed.
- Dried poultry manure and poultry solid manure must be stored in such a way that rewetting, for example by rainwater, is excluded. Storage outside the barn must take place on solid surfaces. In the case of out-door housing, the facility and the associated facilities must be dimensioned and designed in such a way that the nutrient inputs from manure deposition do not lead to harmful environmental effects.

Annexes: Annex 9 deals with requirements to reduce nitrogen depositions. Annex 10 includes requirements for monitoring and mass balancing in nutrient-reduced multiphase feeding in livestock. Annex 11 provides a list with mitigation techniques in housing to reduce ammonia emissions with emission ceilings. Annex 12 includes criteria using exhaust air purification in pig and poultry installations.

Examples from the technique list in Annex 11:

Measures for pigs:

- Slanted walls in the manure channel for pigs
- Convex floor and separated manure and water channels for pigs
- Slurry cooling for pigs
- Slurry acidification in barn, storage and during manure application to the field for pigs and cattle
- Use of an air cleaning system for pigs and poultry
- Animal friendly outdoor climate stable, e.g. Kennel/hut housing for pigs
- Manure belt or scraper with forced drying of litter using indoor air for poultry

3.7 Ordinance on Installations for Handling Substances Hazardous to Water (AwSV)

The Ordinance on Installations for Handling Substances Hazardous to Water (AwSV 2017) is a nationwide ordinance on installation-related water protection. It regulates the construction and operation of facilities for the storage of liquid manure, slurry and leachate (JGS facilities).

This ordinance includes requirements and measures in the field of water policy and for the protection of waters against pollution by nitrate from agricultural sources (2014/101/EU, 1137/2008/EG).

The following substances and mixtures are considered generally hazardous to water and are not classified in water hazard classes: liquid or solid manure as defined by the German Fertilizer Act, silage leachate, silage or ensiled material that may produce silage leachate, fermentation substrates of agricultural origin for the production of biogas, as well as the liquid and solid fermentation residues produced during fermentation. Therefore, installations for the storage of liquid manure, slurry and leach-ate must comply with the ordinance on facilities for the handling of substances hazardous to water. The requirements for these storage facilities are set out in Appendix 7 of the ordinance: Requirements for slurry, manure and silage leachate storage (JGS-storage installation).

Considering the requirements of the German water law, only types of construction or kits may be used for installing of JGS-storage installations for which building inspectorate certificates of usability are available. Installations shall be designed, erected, constructed and operated in such a way that:

- Substances generally hazardous to water like liquid or solid manure, silage leachate fermentation substrates of agricultural origin for the production of biogas cannot escape,

- Leakages of all plant components that come into contact with substances water like liquid or solid manure, silage leachate fermentation substrates of agricultural origin for the production of biogas can be detected quickly and reliably,
- Leaking substances generally hazardous to water like liquid or solid manure, silage leachate fermentation substrates of agricultural origin for the production of biogas are detected quickly and reliably.

3.8 Framework Convention on Climate Change, Climate Action Plan, 10 items for action from the German Federal Ministry of Food and Agriculture

According to Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC) and its interpretation by the EU Council of Environment Ministers (COUNCIL OF THE EU, 2007), stabilising greenhouse gas concentrations in the atmosphere should help to avoid an increase in the global mean air temperature of more than 2°C compared to pre-industrial levels. Greenhouse gas emission reductions include N_2O (nitrous oxide) among other climate-relevant gases. In order to achieve the "2°C target" with a high probability, a stabilisation of greenhouse gas concentrations in the atmosphere at 400 ppm CO_2 equivalents is considered necessary.

The German government coalitions´ 2030 climate package was presented in 2019 and updated in 2021. It consists of the Climate Action Law and the Climate Action Programme 2030. The Climate Action Law enshrines the 2030 GHG reduction target of -55% into law. And it assigns – for the first time – sector specific annual emission budgets for the period 2020 – 2030. Emissions from the sector agriculture, (inclusive emissions from mobile agricultural and local burning) until 2030 to 56 Mio. t CO_2 equivalents, thus, by 11.8 Mio. t CO_2-equ., which have to decrease per year. Compared to 2020 ca. 17 %. This means that a mandatory reduction for the sector agriculture is introduced. The Climate Action Programme 2030 stipulates measures to reach 2030 targets for each sector including support programme, CO_2 pricing, and regulatory measures.

In September 2019, the German Federal Ministry for Agriculture and Food published 10 items for action to reduce GHG emissions from agriculture:

1 Reducing nitrogen surpluses

Much has already been achieved by agriculture through the legal changes in fertiliser legislation. As a result, the Ministry of Agriculture expects a further reduction in nitrogen surpluses - including the reduction of ammonia and nitrous oxide emissions. For the targeted reduction of nitrogen emissions from agricultural soils, the BMEL also wants to intensify research. This includes, for example, long-term studies at various locations on the effectiveness of nitrification inhibitors and the prevention of nitrous oxide emissions, the further development of fertilisation technologies and plant cultivation measures with regard to measuring and reducing greenhouse gas emissions, and the promotion of breeding improvements in crops with regard to nitrogen efficiency.

Reduction potential: 1.9 to 7.5 million t CO_2 equivalents

2 Energetic use of manure

The second important measure concerns the energetic use of manure of animal origin and agricultural residues in biogas plants. The increased use of manure in biogas plants and the gastight storage of fermentation residues, especially to reduce methane emissions, are to be promoted with new instruments. Here it is particularly important to find sensible ways to connect the plants that are currently being promoted under the Renewable Energy Sources Act (EEG), explains the BMEL.

Reduction potential: 2 to 2.4 million t CO_2 equivalents

3 Increase of the share of organic farming

The expansion of organically farmed areas is also a climate measure. This is primarily due to the saving of mineral fertilisers, the production of which produces greenhouse gases. Legislation in favour of particularly environmentally friendly practices such as organic farming or other particularly sustainable land management practices should be further developed, according to BMEL.

Reduction potential: 0.4 to 1.2 million tonnes of CO_2 equivalents

4 Emission reductions in animal husbandry

The BMEL wants to realise further savings potential in animal husbandry and animal nutrition. In addition to research and breeding, the future development of livestock will be important. Support measures are to be geared more towards animal welfare, taking into consideration environmental impacts and emission savings. In addition, emission-reducing housing technology is to be further developed. The dissemination, further development and establishment of precision feeding, of methods to avoid and reduce feed losses, and of methods to reduce harvest losses in feed advertising are to be researched and put into practical application (knowledge transfer).

Reduction potential: 0.3 to 1 million t CO_2 equivalents annually

5 Increasing energy efficiency

The technology used in agriculture and horticulture can be further improved in terms of its energy requirements. The federal programme for energy efficiency in agriculture and horticulture will be continued and further developed for this purpose, and the use of renewable energies will be promoted.

Reduction potential: 0.9 to 1.5 million t CO_2 equivalents annually

6 Humus build up in arable land

The carbon storage potential of soils is to be increasingly activated, the BMEL further informs. Based on the 2018 soil status survey and a second survey after about ten years, the carbon stock in agriculturally used soils and its changes will be recorded. Measures for carbon sequestration are to be taken into consideration, among other things, in the arable farming strategy that is currently being developed. The expansion of organic farming also contributes to carbon sequestration. It will also be important to include instruments in the Common Agricultural Policy that support humus enrichment - we are commit-ted to this. These include, for example: crop rotations with arable crops that do not consume humus; catch crops and non-rotational tillage; grassland conservation.

Reduction potential: 1 to 3 million tonnes of CO_2 equivalents annually

7 Conservation of permanent grassland

High carbon stocks are also stored in grassland. The conservation of permanent grassland is there-fore also an important climate protection measure, which is already promoted within the framework of the Common Agricultural Policy (CAP). The BMEL intends to continue regulations on grassland conservation and develop a grassland strategy to secure and strengthen permanent grassland use.

8 Protection of peat soils/reduction of peat use in cultivation substrates

It is also important to consider the greenhouse gas emissions resulting from drained peatland soils on which agriculture is practiced. Since the rehydration of peatland soils entails considerable restrictions on use and thus encroachment on property rights, this can only be done on a voluntary basis. Accordingly, financial incentives on a considerable scale are envisaged. This measure also includes the reduction of peat use in cultivation substrates.

Reduction potential: 3 to 8.5 million tonnes of CO_2 equivalents per year

9 Conservation and sustainable management of forests and wood use

The conservation and sustainable management of forests and the use of wood have enormous cli-mate protection potential. However, this is subject to periodic fluctuations. It is extremely important to preserve and secure forests and their sustainable management in the long term. This requires suitable measures for adaptation to climate change.

Mitigation potential: According to the Scientific Advisory Council on Forest Policy, forests, sustainable forestry and the associated use of wood sequestered around 127 million tonnes of carbon dioxide in 2014 or reduced it through substitution effects.

10 Promoting sustainable diets

Avoiding food waste

If food waste can be avoided, this will also have an indirect impact on the greenhouse gases associated with food production. To this end, the adopted National Strategy to Reduce Food Waste must be consistently implemented, the BMEL further explains. An indicator on food waste and loss in Germany would be included in the German Sustainability Strategy. This will make the results of efforts transparent and documentable. The appropriate financial and human resources will be made available for continuous reporting.

Programme to strengthen sustainability in communal catering

Strengthening the sustainability criteria (minimum standards) for the food offered in canteens of the federal administration on the basis of the already obligatory DGE quality standards, as well as developing a funding programme to strengthen a climate-friendly and healthy food offer in communal catering.

Reduction potential: 3 to 7.9 million tonnes of CO_2 equivalents annually.

The study of Grethe et al. 2021 comes up with suggestions for climate neutrality in the German agricultural sector. In Germany, three main fields of action are seen as necessary to achieve climate neutrality in the agricultural sector (Grethe et al. 2021):

a) improve nitrogen use efficiency
b) reduce consumption and production of animal products
c) Rehydrating peatlands

These fields of action have particularly high reduction potentials, addressing them makes economic sense and they also make high target contributions in other sustainability dimensions. The authors calculate that these measures can lead to a reduction in GHG emissions from agriculture and agricultural land use in Germany from over 100 million tonnes per year today to under 50 million tonnes per year by 2045. Specifically, the following is recommended for this:

a) Improve nitrogen use efficiency

By 2030, N surpluses are to be reduced to 70 kg N/ha, resulting in a GHG reduction of 3.5 million t CO_2-equ. per year. At the same time, a further 1 million t CO_2-equ. from mineral fertiliser production will be saved. By 2045, N surpluses are to be reduced to 50 kg N/ha, thus saving a further 1.5 million t CO_2-eq. in agriculture and achieving additional savings in mineral fertiliser production. To achieve this goal, a reliable, transparent and verifiable material flow balance for individual farms and an N tax (50 cents/kg N) are proposed.

b) Reduce consumption and production of animal products

Animal products, especially beef, have significantly higher GHG emissions than plant products. A diet with fewer animal products and more plant products can significantly reduce CO_2 emissions (e.g. Barnsley et al. 2021). If the consumption of animal products were to be reduced by 30%, around 14 million t CO_2-equivalents could be saved in Germany. This applies under the premise that the reduction in consumption is accompanied by an equivalent reduction in animal husbandry. The study by Grethe et al. (2021) points out the considerable synergies with other sustainability goals. The authors suggest supporting the transformation towards a more plant-based diet through information, education, public communal catering, a government climate label and price incentives.

c) Rehydrating peatlands

Agriculturally used peatlands and fens cover just under 7% of the agricultural land in Germany. Drained peatland soils cause about 40% of total agricultural GHG emissions in Germany. The re-wetting of peatland soils could save more than 30 million tonnes of CO_2-equivalents per year. Whether extensive rewetting will succeed and whether this potential is achievable is currently still the subject of debate.

4 Comparison of suggested measures and national legislation

The UNECE Guidance Document on Sustainable Nitrogen Management identifies the following priorities to reduce nitrogen losses from livestock housing:

(a) Reduction of indoor temperature, including by optimized ventilation;

(b) Reduction of emitting surfaces and soiled areas;

(c) Reduction of air-flow over soiled surfaces;

(d) Use of additives (for example, urease inhibitors, acidification); and

(e) Regular removal of manure to an outside store.

The following priorities are identified to reduce N losses and to mobilize N recovery/reuse from manure storage, treatment and processing:

(a) Storing outside the barn in a dry location;

(b) Covering slurry stores;

(c) Manure treatment/processing to reduce slurry dry matter content, increase slurry NH_4^+ content and lower pH;

(d) Anaerobic digestion, solid/liquid separation and slurry acidification;

(e) Ensuring that all available nutrient resources are used effectively for crop growth;

(f) Improving nutrient recapture and recovery; and

(g) Production of value-added nutrient products from recycled manure N resources.

The main goals of implementing abatement measures are to increase the efficiency of N applied to crops, save costs on nitrogen inputs, and reduce pollution into air, water and soil. As such, the top field measures for farmers to improve N use efficiency are considered to be:

(a) Integrated farm-scale N management planning taking account of all available N sources;

(b) Precision nutrient management: appropriate rate, timing, form and placement of N;

(c) Use of the appropriate fertilizer product and form (including inhibitors, as relevant) in the appropriate context;

(d) Use of low-emission slurry-spreading technologies (accounting for the saved N in nutrient plans);

(e) Rapid soil incorporation of ammonia-rich organic amendments.

Table 46: Comparison of suggested measures with national legislation in Germany

Term	Measures suggested in the UNECE GD	German legislation
Dietary measure 1	Adapt protein intake in diet (dairy and beef cattle)	TA Luft Nr. 5.4.7.1 lit. c) no limits for N and P excretion; reduced N content in the diet according to DLG standards
Dietary measure 2	Increase productivity (dairy and beef cattle)	No incentive for farmers to reduce N excretion (they would not be allowed to keep more animals per ha); This should be adapted
Dietary measure 3	Increase longevity (dairy cattle)	No incentive for farmers to increases longevity; This should be adapted
Dietary measure 4	Adapt protein intake in diet (pigs)	TA Luft Nr. 5.4.7.1 lit. c) strongly reduced N content in the diet according to DLG standards; monitoring performed
Dietary measure 5	Adapt protein intake in diet (poultry)	TA Luft Nr. 5.4.7.1 lit. c), strongly reduced N content in the diet according to DLG standards; monitoring performed
Housing Measure 1	Immediate segregation of urine and faeces (cattle, pigs)	TA Luft Nr. 5.4.7.1 lit. h) & i) recommended to be implemented in animal friendly pig housing systems, but not mandatory
Housing Measure 2	Regular cleaning of floors in cattle houses by toothed scrapers	No regulation; some cases are subsidies, but no sufficient description and monitoring available. More frequent scraping would be a cheap and efficient mitigation measure for NH_3 and CH_4 emissions => incentive would be very helpful
Housing Measure 3	Regular cleaning of floors in cattle houses	TA Luft Nr. 5.4.7.1 lit a); no sufficient monitoring available. More frequent scraping would be a cheap and efficient mitigation measure for NH_3 and CH_4 emissions
Housing Measure 4	Frequent slurry removal (cattle)	TA Luft Nr. 5.4.7.1 lit f)
Housing Measure 5	Increase bedding material (cattle with solid manure)	TA Luft Nr. 5.4.7.1 lit e)
Housing Measure 6	Barn climatization to reduce indoor temperature and air flow (cattle)	No national regulations available
Housing Measure 7	Slurry acidification (pig and cattle housing)	TA Luft Nr. 5.4.7.1 lit h) i) (Annex 11, technique list for pigs)
Housing Measure 8	Reduce emitting surface (pigs)	TA Luft Nr. 5.4.7.1 lit a), b), h), i) (Annex 11, technique list)
Housing Measure 9	Regular cleaning of floors (pigs)	TA Luft Nr. 5.4.7.1 lit a)
Housing Measure 10	Frequent slurry removal (pigs)	TA Luft Nr. 5.4.7.1 lit f)

Term	Measures suggested in the UNECE GD	German legislation
Housing Measure 11	Increase bedding material (pigs with solid manure)	TA Luft Nr. 5.4.7.1 lit e)
Housing Measure 12	Barn climatization to reduce indoor temperature and air flow (pigs)	TA Luft Nr. 5.4.7.1 lit h) i) naturally ventilated barn (Annex 11, technique list)
Housing Measure 13	Use of acid air-scrubbers (pigs)	TA Luft Nr. 5.4.7.1 lit h) i) (Annex 11, technique list)
Housing Measure 14	Rapid drying of poultry litter	TA Luft Nr. 5.4.7.1 lit h), i) (Annex 11, technique list)
Housing Measure 15	Use of acid air-scrubbers (poultry)	TA Luft Nr. 5.4.7.1 lit h), i) (Annex 11, technique list)
Manure Measure 1	Manure Measure: Covered storage of manure (solid cover and impermeable base)	TA Luft Nr. 5.4.7.1 lit k) AwSV
Manure Measure 2	Manure Measure: Covered storage of slurry (natural crust and impermeable base)	TA Luft Nr. 5.4.7.1 lit j) solid cover or plastic foil reduce NH_3 emissions by 90% AwSV
Manure Measure 3	Manure Measure: Slurry acidification (manure storage)	No specific regulation for storage
Manure Measure 4	Manure Measure: Mechanical solid-liquid separation of slurry fractions	No national regulations available
Manure Measure 5	Manure Measure: Anaerobic digestion	Anaerobic digestion leads to lower CH_4 emissions in the national GHG emission inventory
Nutrient Recovery 1	Nutrient Recovery: Drying and pelletizing of manure solids	Nutrient recovery is generally used in areas with manure and/or nitrogen surplus; as the German DüV and the nitrate directive regulate the maximum amounts of N application per ha, it indirectly supports nutrient recovery technologies in surplus areas
Nutrient Recovery 2	Nutrient Recovery: Combustion, gasification or pyrolysis	No national regulations available
Nutrient Recovery 3	Nutrient Recovery: Precipitation of nitrogen salts	No national regulations available
Nutrient Recovery 4	Nutrient Recovery: Ammonia stripping and recovery	No national regulations available
Field Measure 1	Field Measure: Integrated nutrient management plan	Fertilizer Application Ordinance (DüV, 2017, 2020) requires a nutrient management plan, but no nutrient balance
Field Measure 2	Field Measure 2: Apply nutrients at the appropriate rate	Fertilizer Application Ordinance (DüV, 2017, 2020)
Field Measure 3	Field Measure 3: Apply nutrients at the appropriate time	Fertilizer Application Ordinance (DüV, 2017, 2020)
Field Measure 4	Field Measure 4: Apply nutrients in the appropriate form	Fertilizer Application Ordinance (DüV, 2017, 2020)

Term	Measures suggested in the UNECE GD	German legislation
Field Measure 5	Field Measure 5: Limit or avoid fertilizer application in high-risk areas	Fertilizer Application Ordinance (DüV, 2017, 2020)
Field Measure 6	Field Measure 6: Band spreading and trailing shoe application of livestock slurry	Fertilizer Application Ordinance (DüV, 2017, 2020)
Field Measure 7	Slurry injection	Fertilizer Application Ordinance (DüV, 2017, 2020)
Field Measure 8	Slurry dilution for field application	Fertilizer Application Ordinance (DüV, 2017, 2020)
Field Measure 9	Slurry acidification (during field application	Fertilizer Application Ordinance (DüV, 2017, 2020)
Field Measure 10	Nitrification inhibitors (addition to slurry	Fertilizer Application Ordinance (DüV, 2017, 2020)
Field Measure 11	Rapid incorporation of manures into the soil	Fertilizer Application Ordinance (DüV, 2017, 2020)
Field Measure 12	Replace urea with an alternative N fertilizer	No national regulations available
Field Measure 13	Urease inhibitors with inorganic fertilizers	No national regulations available
Field Measure 14	Nitrification inhibitors with inorganic fertilizers	No national regulations available
Field Measure 15	Field Measure: Precision placement of fertilizers, including deep placement	No national regulations available
Field Measure 16	Field Measure: Extend the grazing season	No national regulations available
Field Measure 17	Field Measure: Avoid grazing in high-risk areas	No national regulations available

List of references

Amon, B. and others (2007). Ammonia and greenhouse gas emissions from a straw flow system for fattening pigs: Housing and manure storage. Livestock Science, vol. 112, pp. 199–207

Bittman, S. and others, eds. (2014). Options for Ammonia Mitigation: Guidance from the UNECE Task Force on Reactive Nitrogen (Edinburgh, UK: Centre for Ecology and Hydrology).

Canh, T. T. and others (1998). Dietary protein affects nitrogen excretion and ammonia emission from slurry of growing-finishing pigs. Livestock Production Science, vol. 56, No. 5 (December), pp. 181–191

Chadwick, D. and others (2011). Manure management: Implications for greenhouse gas emissions. Animal Feed Science and Technology, vol. 166–167, pp. 514– 531.

Chowdhury, A., de Neergaard, A., Jensen, L.S. (2014). Composting of solids separated from anaerobically digested animal manure: Effect of different bulking agents and mixing ratios on emissions of greenhouse gases and ammonia. Biosystems Engineering, vol. 124, pp. 63–77.

Del Prado, A. and others (2010). Exploring systems responses to mitigation of GHG in UK dairy farms. Agriculture, Ecosystems and Environment, vol. 136, pp. 318–332.

Fangueiro, D. and others (2008a). Effect of cattle slurry separation on greenhouse gas and ammonia emissions during storage. Journal of Environmental Quality, vol. 37, No. 6 (November), pp. 2322–2331.

Fangueiro D., Hjorth M., Gioelli F. (2015). Acidification of animal slurry: a review. Journal of Environ-mental Management, vol. 149, pp. 46–56.

Grethe, Harald; Martinez, José et al. (2021): Klimaschutz im Agrar-und Ernährungssystem Deutsch-lands: Die drei zentralen Handlungsfelder auf dem Weg zur Klimaneutralität. Gutachten im Auftrag der Stiftung Klimaneutralität.

IPCC 2014: Climate Change 2014 – a Synthesis Report

IPCC 2019: 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (available at: www.ipcc-nggip.iges.or.jp/public/2019rf/index.html)

IPCC 1996: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (www.ipcc-nggip.iges.or.jp/public/gl/invs1.html)

IPCC 2000: Good practice guidance and uncertainty management in national greenhouse gas inventories

IPCC 2006: 2006 IPCC Guidelines for National Greenhouse Gas Inventories (available at: www.ipcc-nggip.iges.or.jp/public/2006gl/index.html)

Jensen, L.S. 2013. Animal Manure Residue Upgrading and Nutrient Recovery in Biofertilizers, chapter 14 in Animal Manure Recycling - Treatment and Management Sommer, S.G. and others, eds. (pp. 271-294) (John Wiley and Sons Ltd.) .

Kupper, T. and others 2020. Ammonia and greenhouse gas emissions from slurry storage - a review. Agriculture, Ecosystems and Environment

Melse, R. W., Hofschreuder, P., Ogink, N.W.M. (2012). Removal of Particulate Matter (PM10) by Air Scrubbers at Livestock Facilities: Results of an On-Farm Monitoring Program. Transactions of the American Society of Agricultural and Biological Engineers (ASABE), vol. 55, pp. 689–698.

Misselbrook, T. H. and Powell J.M. (2005). Influence of Bedding Material on Ammonia Emissions from Cattle Excreta. Journal of Dairy Science, vol. 88, pp. 4304–4312.

Petersen, S.O., Amon, B., Gattinger, A. (2005). Methane oxidation in slurry storage surface crusts. Journal of Environmental Quality, vol. 34, pp. 455–461

Petersen, S.O., Andersen, A.J., Eriksen, J. (2012). Effects of Cattle Slurry Acidification on Ammonia and Methane Evolution during Storage. Journal of Environmental Quality, vol. 41, pp. 88–94.

Sommer, S.G. and others (2009). Region-specific assessment of greenhouse gas mitigation with different manure management strategies in four agroecological zones. Global Change Biology, vol. 15, pp. 2825–2837.

Sutton, M.A. and others (2013). Our Nutrient World: The challenge to produce more food and energy with less pollution. Global Overview of Nutrient Management (Edinburgh: Centre for Ecology and Hydrology).

UNECE 2021: Guidance document on integrated sustainable nitrogen management; ECE/EB.AIR/149; https://unece.org/environment/documents/2021/04/working-documents/guidance-document-integrated-sustainable-nitrogen

Webb, J. and Misselbrook, T.H. (2004). A mass-flow model of ammonia emissions from UK livestock production. Atmospheric Environment, vol. 38, pp. 2163–2176.