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Draft Guidance document on integrated sustainable nitrogen management

Agriculture, Food and Environment

Submitted by the Task Force on Reactive Nitrogen

Summary

The draft Guidance document on integrated sustainable nitrogen management was prepared by the Task Force on Reactive Nitrogen in accordance with item 2.2.3 of the 2020–2021 workplan for the implementation of the Convention (ECE/EB.AIR/144/Add.2). 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 (paras. 68 and 79(d)). The purpose of the document is to mobilize Parties' efforts 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. The document is in particular aimed to support the implementation of the Protocol to Abate Acidification, Eutrophication and Ground-level Ozone.

The current document is being presented to the Working Group on Strategies and Review for consideration. It is expected that a final draft will then be forwarded to the Executive Body for adoption at its current session.

Contents

Acronyms

AE	Abatement efficiency
AN	Ammonium Nitrate
BAT	Best available technique
BMP	Best management practices
BSP	Best system practices
C	Carbon
C/N	Carbon-to-Nitrogen ratio
CAN	Calcium Ammonium Nitrate
CBA	Cost-benefit analysis
CDU	Crotonylidene diurea
CH_4	Methane
CLRTAP	UNECE Convention on Long-range Transboundary Air Pollution (informally the “Air Convention”)
CO_2	Carbon dioxide
CP	Crude protein
DCD	Dicyandiamide, a nitrification inhibitor
DM	Dry Matter
DMPP	3,4-dimethylpyrazole phosphate – a nitrification inhibitor
DOC	Dissolved Organic Carbon
DON	Dissolved Organic Nitrogen
DPSIR	Driver-Pressure-State-Impact-Response
ECE	United Nations Economic Commission for Europe
ENA	European Nitrogen Assessment
EU	European Union
EU28	The former group of 28 countries of the European Union, now EU27
FAO	Food and Agriculture Organization of the United Nations
FYM	Farmyard Manure
GEF	Global Environment Facility
GHG	Greenhouse Gas
GPS	Global Positioning System
H_2O	Water
HELCOM	Helsinki Commission for Baltic Marine Environment Protection
HNO_3	Nitric acid
IBDU	Isobutylidene diurea
INCOM	Inter-convention Nitrogen Coordination Mechanism
INMS	International Nitrogen Management System – implemented through the GEF/United Nations Environment Programme Towards INMS project
IPCC	Intergovernmental Panel on Climate Change
K	Potassium

LRTAP	UNECE Convention on Long-range Transboundary Air Pollution (informally the "Air Convention")
N	Nitrogen
N footprint	Nitrogen footprint
N_2	Dinitrogen – a colourless and odourless gas, forming about 78 per cent of the Earth's atmosphere
N_2O	Nitrous oxide – a powerful greenhouse gas
NAC	National Ammonia Code
NBPT	N-(n-butyl) thiophosphoric triamide – a urease inhibitor
NGO	Non-governmental organization
NH_3	Ammonia – an air and water pollutant and the primary nitrogen form in biological systems
NH_4^+	Ammonium – present in biological systems and soils, while forming a pollutant in atmospheric PM and aquatic systems
NH_x	Total ammoniacal nitrogen – sometimes referred to as TAN
NI	Nitrification Inhibitor
NO	Nitric oxide – a tropospheric air pollutant
NO_2	Nitrogen dioxide – a tropospheric air pollutant
NO_2^-	Nitrite
NO_3^-	Nitrate – present as a secondary pollutant in atmospheric PM and a eutrophying pollutant of aquatic systems
NO_x	Nitrogen oxides – a combination of NO and NO_2
N_{org}	Organic nitrogen
NPK	Nitrogen, Phosphorus and Potassium in combination
N_r	Reactive Nitrogen – a term used for a variety of nitrogen compounds that support growth directly or indirectly, as opposed to N_2 which is inert
NUE	Nitrogen Use Efficiency – typically defined as the ratio of N in outputs divided by the N in inputs. May be expressed for different systems such as crops, livestock, food chain and the whole economy
O_3	Ozone
OECD	Organization for Economic Cooperation and Development
P	Phosphorus
PM	Particulate Matter – includes NH_4^+ and NO_3^- as major components. PM_{10} and $PM_{2.5}$ refer to atmospheric particulate matter (PM) that has a diameter of less than 10 and 2.5 micrometres respectively
R-NH_2	Organic nitrogen compounds
S	Sulphur
SEA	Strategic environmental assessment
Si	Silicon
SO_2	Sulphur dioxide
TAN	Total Ammoniacal Nitrogen
TFIAM	Task Force on Integrated Assessment Modelling of the UNECE Air Convention

TFRN	Task Force on Reactive Nitrogen of the UNECE Air Convention
TN	Total Nitrogen
UAN	Urea Ammonium Nitrate
UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
VOCs	Volatile Organic Compounds
WGSR	Working Group on Strategies and Review of the UNECE Air Convention
WHO	World Health Organization
Zn	Zinc

I. Overview for policymakers

Nitrogen opportunities for agriculture, food and environment

Goals and context

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 action on nitrogen, a much stronger mobilization for change is expected, catalysing progress towards many of the United Nations Sustainable Development Goals.

The present document has been prepared under the lead of the United Nations Economic Commission for Europe (UNECE) Convention on Long-range Transboundary Air Pollution (Air Convention) as part of its work to reduce air pollution impacts, including from acidification, eutrophication, ground-level ozone and particulate matter (PM), as these affect human health, biodiversity and economy.

There are multiple co-benefits of taking action 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.

The present guidance is simultaneously a contribution from the International Nitrogen Management System (INMS), delivering support to the developing Inter-convention Nitrogen Coordination Mechanism (INCOM) in partnership with the United Nations Environment Programme (UNEP), the Global Environment Facility (GEF) and the International Nitrogen Initiative.

Main Points

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 (N_r), which represent valuable resources. Around 80 per cent of anthropogenic N_r production is wasted as air and water pollution and through denitrification back to N_2.

The present guidance document is focused on agriculture in the context of the food system, and includes specific information on the principles and measures that can reduce emissions to the air of ammonia (NH_3), nitrogen oxides (NO_x), nitrous oxide (N_2O) and N_2, plus nitrate (NO_3^-) and other N_r leaching to water and total N loss.

Informed by 10 keys points that underpin nitrogen cycling, the document reflects on 24 principles of integrated sustainable nitrogen management. The document then identifies 76 specific measures to improve nitrogen management, increase nitrogen use efficiency and reduce polluting losses to the environment.

The document describes: 5 livestock diet measures; 18 housing measures; 12 manure storage/processing measures; 5 nutrient recovery measures; 20 field-based measures for application of organic and inorganic fertilizers; and 16 land-use and landscape measures.

The accompanying discussion of basic principles will help strengthen the development of future strategies for pollution and sustainable development, and the establishment of coherent “packages of measures” that maximize the synergies.

A. Background

1. Ever since crops and livestock were first domesticated, the maintenance of civilization has been intrinsically linked to human alteration of the natural nitrogen cycle. The cultivation

of crops and rearing of livestock mobilize nitrogen (N) and other nutrients, which are then transported as food, feed and fibre to villages, towns and cities (Lassaletta and others, 2014). Nitrogen-fixing crops and manures have been used for millennia to help increase harvests (for example, Columella, *On Agriculture* 2.13.1, trans. Boyd Ash, 1941), while the last 200 years have seen the mobilization of additional nitrogen, including from mined resources (for example, guano, saltpetre, coal distillation) and, ultimately, in the twentieth century, from the manufacture of inorganic fertilizers directly from atmospheric dinitrogen (N_2) (Sutton and others, 2011). As the scale of human alteration of the nitrogen cycle has increased, so have the consequences. Inorganic nitrogen fertilizers (including manufactured urea) have allowed the production of surplus food and feed in many regions, permitting substantial increases in human and animal populations (Erisman and others, 2008), with consumption of animal products by humans in excess of dietary needs across much of the UNECE region (Westhoek and others, 2014, 2015; Springmann and others, 2018).

2. This transformation of the global nitrogen cycle, especially over the last century, has led to a web of pollution problems linking the human production and use of nitrogen compounds with multiple environmental threats. Together with nitrogen compounds formed during combustion processes, and those mobilized through wastewater, nitrogen pollution currently affects all environmental media across the whole of planet Earth.

3. Until recently, efforts to address nitrogen pollution had largely been fragmented. This was mainly a consequence of fragmentation in environmental policymaking, management and science between environmental media and issues such as air pollution, water pollution, greenhouse gas (GHG) emissions, stratospheric ozone depletion, biodiversity loss and soil protection. Each of these issues is affected by nitrogen pollution, which thereby acts as a linking driver between many issues related to environment, economy, health and well-being. Traditional fragmentation of policies between these issues has slowed progress in the achievement of policy goals by reducing the coherence of local, national and international actions across the nitrogen cycle, risking trade-offs that can act as barriers to change (Oenema and others, 2011a and 2011b).

4. The emerging recognition of the way that nitrogen links all these issues is now leading to a major policy opportunity to mobilize change. A joined-up approach across the nitrogen cycle can help develop the gravity of common cause between air pollution, water pollution, climate change, stratospheric ozone depletion, biodiversity loss, health and economy (Oenema and others, 2011b; Sutton and others, 2013, 2019; Zhang and others, 2015; Leip and others, 2015; Kanter and others, 2020).

5. UNECE has long been a pioneer in developing such joined-up approaches. These include the Protocol to Abate Acidification, Eutrophication and Ground-level Ozone (Gothenburg Protocol, signed in 1999 and amended in 2012) to the Convention on Long-range Transboundary Air Pollution (Air Convention) (UNECE, 1999). The amended Protocol came into force on 7 October 2019. The Gothenburg Protocol includes ceilings to limit emissions of sulphur dioxide (SO_2), nitrogen oxides (NO_x) and ammonia (NH_3) up to 2020, together with national commitments to reduce emissions of SO_2, volatile organic compounds (VOCs), particulate matter (PM), NO_2 and NH_3 as from 2020 and onwards, as these contribute to acidification, eutrophication, ground-level ozone and PM. This multi-pollutant, multi-effect approach has encouraged further efforts to understand the many air pollution impacts and interactions of nitrogen. Following the establishment of the Task Force on Reactive Nitrogen (TFRN) in 2007 (ECE/EB.AIR/91/Add.1, decision 2007/1), the *European Nitrogen Assessment: Sources, effects and policy perspectives* (Sutton and others, 2011) extended the approach to consider the full range of nitrogen interactions linking air, water, climate, ecosystems and soils, including identification of abatement options.

6. Concerning agricultural sources of air pollution, most effort under the Gothenburg Protocol has focused on NH_3, which, in the UNECE region, is mainly emitted from animal excreta and nitrogen-containing fertilizers. This led to the establishment of the *Guidance document on preventing and abating ammonia emissions from agricultural sources* (Ammonia Guidance Document) as a comprehensive reference manual, as revised in 2012 (ECE/EB.AIR/120) (published as Bittman and others, 2014). This document is complemented by the *UNECE Framework Code for Good Agricultural Practice for Reducing Ammonia Emissions* ((ECE/EB.AIR/129), a shorter document describing

voluntary approaches, which can also form the starting point for Parties to establish, publish and disseminate their own national ammonia codes, as required under annex IX to the Gothenburg Protocol.

7. With the improved understanding emerging from the European Nitrogen Assessment (Sutton and others, 2011), it was agreed by the Air Convention that there was a need for guidance on mitigating all forms of nitrogen, with the priority in the first instance being to focus on agricultural sources relevant across the UNECE region. This was deemed necessary to support the objectives of the Gothenburg Protocol (twenty-second preambular para.; art. 4 (1); art. 6 (1) (g); annex IX, para. 2) and the revised Gothenburg Protocol (tenth preambular para.; art. 7 (3) (d); art. 10 (4)). As part of the 2016–2017 work plan for the implementation of the Convention agreed by the Executive Body at its thirty-fourth session (Geneva, 18 December 2015), the Task Force on Reactive Nitrogen undertook to "Initiate the development of an ECE guidance document that describes an integrated approach, addressing multiple compounds and their synergies, with regard to nitrogen management in agriculture and illustrates its co-benefits" (ECE/EB.AIR/133/Add.1, item 2.3.4).

8. Progress in the development of this guidance document was facilitated by assistance from the European Commission Directorate-General for Environment and from the International Nitrogen Management System (INMS). INMS provides global and regional scientific support for international nitrogen policy development, practice and awareness-raising, with financial support through the United Nations Environment Programme (UNEP) and the Global Environment Facility (GEF), while building partnerships, including through the International Nitrogen Initiative and the Global Partnership on Nutrient Management.

9. The present guidance document simultaneously provides a contribution to the developing activity of the Inter-convention Nitrogen Coordination Mechanism (INCOM), currently being established through the Nitrogen Working Group under the auspices of the UNEP Committee of Permanent Representatives. This forms a central part of the Road map for Action on Sustainable Nitrogen Management 2020–2022 (UNEP, 2019a and 2019b) in implementing United Nations Environment Assembly resolution 4/14 on sustainable nitrogen management (see UNEP/EA.4/Res.14).

10. The financial support from UNEP/GEF and the European Commission, together with the Global Challenges Research Fund South Asian Nitrogen Hub – a regional contribution to INMS – has allowed the work to be developed through two dedicated workshops (Brussels, 11–12 October 2016 and 30 September–1 October 2019), including contributions from Eastern Europe, the Caucasus and Central Asia.

11. The importance of the activities has been emphasized as part of the revised mandate of TFRN (ECE/EB.AIR/142/Add.2, decision 2018/6, annex, para. 3 (g) and (h)), including its functions to:

> 3 (g) Explore the relationships between emission mitigation of ammonia and other nitrogen compounds in the context of nitrogen benefits for food and energy production, considering the opportunities to share experiences on tools for improved nitrogen management and approaches to improve the uptake of the most promising options;
>
> (h) Initiate work on the potential for mitigation strategies that simultaneously reduce ammonia and nitrogen oxide emissions from soils considering the increasing share of NO_x from agriculture and the potential relationships with mitigation of nitrous oxides and dinitrogen.

12. The present Guidance document is a result of this process. It is anticipated that the document will help mobilize efforts to control air pollution from agricultural sources in the context of the wider nitrogen cycle. In particular, the Guidance document aims to foster change by clearly identifying the multiple co-benefits of reducing nitrogen emissions, as relevant for air quality, climate change, water quality, human health, ecosystems and economy. By aiming to harvest the multiple co-benefits of better nitrogen management, a more coherent and effective response may be expected that maximizes synergies, minimizes trade-offs and accelerates progress towards achievement of the United Nations Sustainable Development Goals.

B. Approach of the Guidance document

1. Scope and target groups

13. The present Guidance document on integrated sustainable nitrogen management focuses on the agricultural sector, including both cropping and livestock systems. While humans have implicitly engaged in managing nitrogen over many millennia, this has not always been sustainable or integrated. The use of the word "sustainable" in the title emphasizes the importance of considering the full set of environmental, social and economic consequences of nitrogen use in agriculture. It is consistent with the adoption, in March 2019, of United Nations Environment Assembly resolution 4/14 on sustainable nitrogen management and the follow-up Colombo Declaration on Sustainable Nitrogen Management (UNEP, 2019c), and reflects the fact that sustainable nitrogen management is a prerequisite for achieving most of the Sustainable Development Goals.

14. The word "integrated" also features in the title of the present guidance document. This reflects recognition by experts and stakeholders of the fact that an integrated approach is needed to link 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. The approach is also fully consistent with ongoing developments, coordinated through UNEP and INMS, towards the establishment of an Inter-convention Nitrogen Coordination Mechanism (INCOM) (Sutton and others, 2019). This activity aims to promote synergies through cooperation between the Air Convention and other intergovernmental conventions and programmes, thereby accelerating progress in nitrogen-related challenges in implementing United Nations Environment Assembly resolution 4/14.

15. The present document, prepared under the lead of the Air Convention, can also be seen as providing input to the wider coordination of INCOM, with benefits for many other multilateral environmental agreements. The present guidance document is aimed at policymakers, regulators and agricultural advisors, who will benefit from the overview of principles and measures presented when formulating integrated sustainable nitrogen management strategies and policies. It is anticipated that future materials may be prepared that more specifically target the needs of different farmer groups across the UNECE region and globally.

2. United Nations Economic Commission for Europe categories and magnitude of effect

(a) United Nations Economic Commission for Europe categories

16. The present guidance document adopts 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[1]:

(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 circumstances;

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

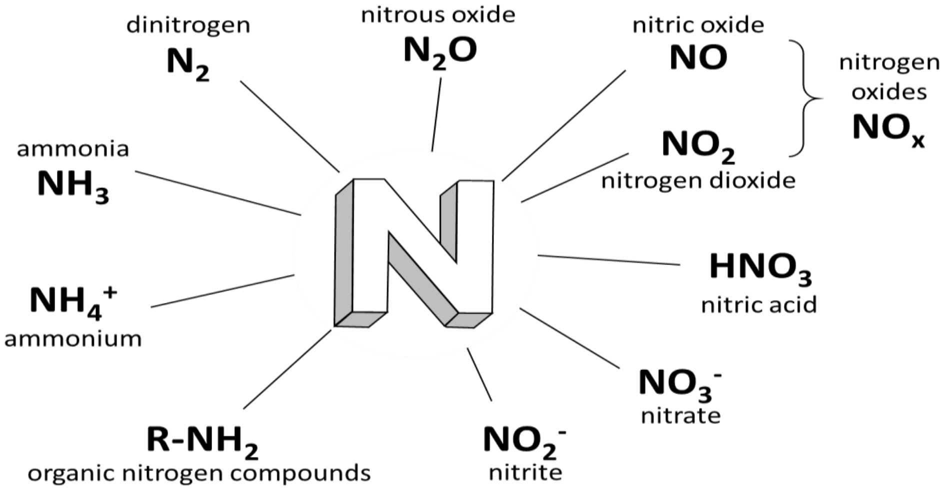
17. Under this UNECE approach, no connection is made to the profitability or otherwise of the measures in assigning these categories, which are purely based on technical criteria. It is therefore quite feasible for a measure to be listed as category 1, while not yet being

[1] The UNECE categories and system for representing magnitude of effect described in chapter I, para. 16, of the present document apply throughout the present document.

considered economical from a sector viewpoint in the absence of appropriate support. This approach can be considered distinct from and complementary to definitions of best available techniques (BATs), which typically incorporate criteria about not entailing excessive costs. In this way, it becomes much easier for experts to assign the UNECE categories (with costs of measures specified separately where available), as compared with the technical-political negotiations that are needed to agree what constitutes relevant standards for BATs. In the Technical overview below, each of the measures is assigned a UNECE category for each nitrogen form according to the following colour code: green (category 1); amber (category 2); and red (category 3). It should be emphasized that the red colour code for category 3 does not indicate any adverse effect, but simply signals that the measure has not yet been demonstrated to be effective. This may mean that further research and development is needed.

18. The UNECE approach is here extended to allow each measure to be assigned a category according to its suitability for each major nitrogen form: NH_3; NO_x[2]; nitrous oxide (N_2O); nitrate (NO_3^-), including other water-based losses of nitrogen compounds; dinitrogen (N_2); and overall nitrogen loss. The document also includes the term "reactive nitrogen" (N_r), which refers to all nitrogen compounds with the exception of N_2, which is unreactive (see figure I.1 below).

Figure I.1
Major forms of nitrogen occurring in the environment



Source: The figure was created for the present document.
Note: The sum of all forms except N_2 is often termed fixed or reactive nitrogen (N_r).

(b) Magnitude of effect

19. The present guidance document does not replace the UNECE Ammonia Guidance Document (ECE/EB.AIR.120), which provides much more detailed information on quantitative abatement efficiency and the costs of measures for NH_3. By contrast, it is not feasible to provide quantitative details for all the nitrogen components listed for all measures. To address this situation, a qualitative indication is provided in this document for each measure concerning its effectiveness in reducing losses of each nitrogen form. The following system is used:

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

[2] Nitrogen oxides (NO_x) represent a mix of nitric oxide (NO) and nitrogen dioxide (NO_2). Emissions of NO_x from agricultural soils occur mainly in the form of NO, although emissions as NO_2 may also be possible. Reactions of NO with ozone (O_3) within the air space of plant canopies can mean that a substantial fraction of emission occurs as NO_2 at the canopy scale. Although the research community has mainly referred in the past to NO emissions from soils, for these reasons, and in the interests of consistency with the Convention on Long-range Transboundary Air Pollution (Air Convention) nomenclature, this document refers primarily to NO_x emissions from soils.

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

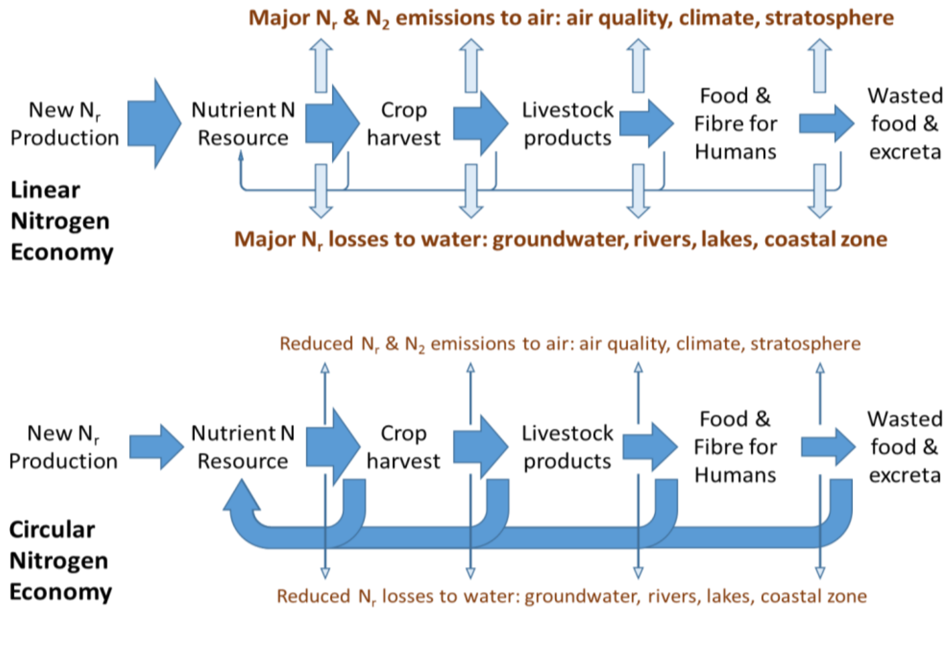
(c) Little or no effect, indicated by ~ ;

(d) Uncertain, indicated by ?.

20. The magnitude of effect can be considered as an indication of “effectiveness” of the measure as distinct from the extent to which the measure is “applicable” in different contexts. Arrows indicate outcomes at the scale of the measure described (for example, animal housing, fertilizer application), but wider system consequences also need to be considered. Where a measure is considered to increase losses of a specific nitrogen form, it is, by definition, assigned to category 3 for that nitrogen form. Where clarification is necessary, magnitude of effect of a measure is described in comparison to a specified reference system.

21. Some measures targeted to benefit one form of nitrogen pollution can increase the risk of losses in other nitrogen forms. Such trade-offs (or “pollution swapping”) are not inevitable and may often be avoided by appropriate actions that are not easy to summarize in tabular form. For this reason, the text describing each measure will typically mention main interactions, while chapter III is dedicated to the principles of good nitrogen management, helping to minimize trade-offs and maximize synergies. This highlights the opportunity to develop coherent “packages of measures”. For example, while many of the measures are applicable to both conventional and organic systems (as well as to other agroecological farming systems), overall packages of measures would be expected to differ according to climate and farming system.

Figure I.2
Simplified comparison of linear and circular economies for nitrogen in the agrifood system



Source: The figure was created for the present document.

22. Some nitrogen loss terms tend to be much larger than others in terms of the overall mass of nitrogen involved. The largest losses often occur as NH_3 emission, nitrate and other nitrogen leaching/run-off, and as denitrification to N_2. By contrast, emissions of nitrous oxide (N_2O) and NO_x tend to represent a small fraction of nitrogen flows (often ~1 per cent of inputs). Although N_2O and NO_x losses from agricultural systems therefore only make a minor contribution to total nitrogen loss, they are relevant because of their specific impacts on air quality, climate and stratospheric ozone depletion. Conversely, although dinitrogen (N_2) emissions through denitrification are environmentally benign, they represent a potentially large fraction of available nitrogen resources. This means that abatement of N_2 emissions is important because it can help improve overall system efficiency, decreasing the need for

fresh production of nitrogen compounds and therefore helping to reduce all nitrogen loss pathways and impacts. The philosophy of the present guidance document is to promote transformation towards a “circular economy” for nitrogen, as illustrated in figure I.2 above.

C. Main messages of the Guidance document

23. The core of present Guidance document report consists of a set of principles for sustainable nitrogen management followed by detailed consideration measures to reduce N losses from major parts of the agrifood system.

24. The description of sustainable nitrogen management is underpinned by ten key points of nitrogen cycling, as summarized in figure I.3 below. The fundamental reflections of biogeochemistry must be recognized if human management of the nitrogen cycle is to move from a system emphasizing new production of N compounds and wasteful losses to a more circular system, which maximizes the recovery and reuse of available N resources.

25. Twenty-four principles of integrated sustainable nitrogen management are identified and summarized in the Technical overview. The first listed principle encapsulates the overall philosophy of the approach:

> 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 nitrogen inputs.

26. All of the principles are important, with the wide diversity of principles reflecting the diversity of N forms, issues, and impacts. By considering these principles, a sound foundation is provided to inform the selection of suitable measures.

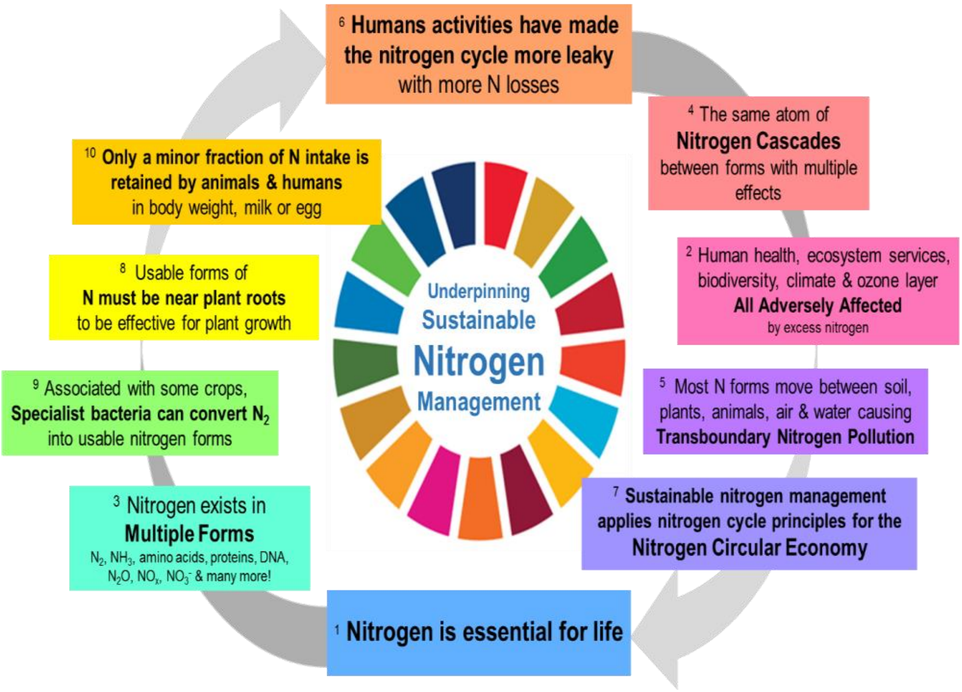
27. At the heart of nitrogen management is the idea that taking a nitrogen cycle perspective allows synergies to be identified and trade-offs minimized. This can be illustrated by the comparison of principles 4, 5 and 6 of sustainable nitrogen management:

(a) 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;

(b) Principle 5: Nitrogen input control measures influence all N loss pathways;

(c) 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.

Figure I.3
Ten key points of nitrogen cycling



Source: The figure was created for the present document.

Note: These key points underpin the principles of integrated sustainable nitrogen management. The numbers reflect the ordering as described in chapter III of the present document. Humans introduce huge amounts of additional reactive nitrogen into the nitrogen cycle, meaning that the system is now out of balance.

28. Principle 7 highlights that "The nitrogen input-output balance encapsulates the principle that what goes in must come out". This can be translated to ensure that inputs match crop and livestock needs, allowing opportunities to reduce all N losses simultaneously (principle 8), as well to reflect spatial variations between vulnerability of agricultural and semi-natural land (principles 9 and 10). The focus on land-use and landscape management is reflected in the principle whereby unfertilized agricultural land and woodlands are recognized as being able to provide buffers that can strengthen landscape resilience to decrease adverse effects in the local environment (principle 11), so long as this does not contravene any specific habitat conservation objectives for the identified buffer ecosystems themselves.

29. It is recognized that nitrogen management must be seen in relation to other limiting factors, which need to be optimized to have the largest possible reduction in nitrogen pollution, both for crop and livestock systems (principles 12 and 13). This is extended by principles that recognize the need to consider nitrogen management in relation to wider management of all nutrients and biogeochemical cycles (including carbon (C), phosphorus (P), sulphur (S), silica (Si), micronutrients, etc.) and water resources (principles 19, 20 and 21).

30. Principles 14, 15, 16 and 17 reflect the physicochemical basis for reducing emissions, including slowing urea hydrolysis, avoiding exposure of ammonium-rich resources to air and the heat of the sun and slowing nitrification and denitrification, which simultaneously maximize the potential to usefully manage nitrogen resources.

> "Manure once it is spread, should be ploughed in immediately and covered over, that it may not lose its strength from the heat of the sun…"
>
> *Columella, circa 50 AD*

31. It is recognized that nitrogen management in agriculture is intimately linked to the entire food system. This means that both dietary measures in livestock and human dietary choices, as well as waste management, will be essential if ambitious sustainability goals are

to be achieved (principle 18). At the same time, ruminant dietary strategies need to consider the possible impact on methane emissions (principle 22), where certain measures will be contraindicated for sustainable nitrogen and methane management.

32. Further principles recognize the social and economic dimension, including local aspects among the various actors in agriculture and the food chain, where these actors have a shared responsibility in N management (principle 2), including food supply, food processing, retail and consumers. As a part of these principles, it is acknowledged that "the farm-level is often a main integration level for emission-abatement/mitigation decisions" (principle 24), in addition to the wider actions of citizens and other actors in the food system. In the case of farmers, principle 23 recognizes that the cost and effectiveness of measures to reduce N losses need to take account of the regional opportunities and constraints of farmers, including effects of farm size, farm structure and economic context. Altogether, the principles show that integrated sustainable nitrogen management is an opportunity for different actors in the agrifood system to work together, where efficiency, waste reduction, environmental stewardship and investment for profitable food production all go hand-in-hand.

33. The Technical overview and chapters IV–VI provide a detailed listing of the measures identified, indicating the opportunity for abatement and mitigation of different nitrogen forms relevant for air pollution, water pollution, climate change, biodiversity, human health, stratospheric ozone, etc. Lastly, chapter VII reflects briefly on how the different measures may fit together, giving examples of possible "packages of measures" that can provide a coherent approach to sustainable nitrogen management according to the levels of ambition needed to meet different local, national and international goals.

34. The present document takes a significant step forward in supporting international policy development by applying understanding of the nitrogen cycle to catalyse sustainable development across multiple challenges. In this way, the document breaks new ground by providing guidance on reducing losses of all main nitrogen forms: NH_3, N_2O, NO_x, NO_3^- and N_2. While the integration is new and draws on the latest research, it also depends on long-established experience. This point was made by a Roman farmer writing nearly 2,000 years ago:

> Manure once it is spread, should be ploughed in immediately and covered over, that it may not lose its strength from the heat of the sun and that the soil, being mixed with it, may grow fat on the aforesaid nourishment. And so, when piles of manure are distributed in a field, the number of those so scattered should not exceed what the ploughmen can dig in on the same day
>
> Columella, *On Agriculture* 2.5.2 (trans. Boyd Ash, 1941)

35. This measure and its principles, as explained by Columella, are still relevant today and represented in the present guidance document. The example shows how measures to reduce nutrient losses have been recognized for centuries. The challenge is to put them into practice.

D. References

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II. Technical overview

Integrating principles and measures for sustainable nitrogen management in the agrifood system

36. The guidance provided in this document is structured around four main themes:

(a) **Principles of integrated sustainable nitrogen management.** Chapter III provides the background to help understand the integrated approach, including key points of nitrogen (N) cycling, dimensions of integration and principles of the measures;

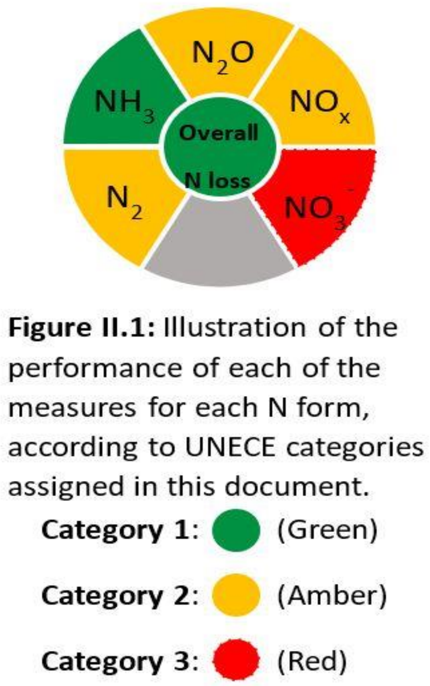
(b) **Housed livestock, manure storage and manure processing.** Chapter IV explains the rationale for an integrated approach to manure management from excretion to storage, including opportunities for processing that treat manure as a valuable nitrogen and nutrient resource to be recycled. The core of the chapter is a summary of the main dietary, housing, manure and nutrient recovery measures;

(c) **Field application of organic and inorganic fertilizers.** Chapter V considers the field use of manure, setting this in relation to opportunities for improved management of manufactured inorganic fertilizers. Following established norms, the term "inorganic fertilizers" includes manufactured urea fertilizer. The core of the chapter is a summary of the main measures associated with field application;

(d) **Land-use and landscape management.** Chapter VI explains how opportunities for integrated nitrogen management are provided by decisions at the land-use and landscape scale. While the main focus is on mitigation of adverse effects, measures may also contribute to abatement of nitrogen emissions. The core of the chapter is a summary of the most important measures.

37. This Technical overview includes an indication of the performance of each measure for each nitrogen form (see figure II.1 below), according to the UNECE categories:[3]

Figure II.1
Illustration of the performance of each of the measures for each N form, according to UNECE categories assigned in this document



[3] See chapter I, para. 16, of the present document for a description of the UNECE categories and system for representing the magnitude of effect.

38. Further details on the performance of each measure, including a qualitative indication of the magnitude of effects, are provided in chapters IV, V and VI. A reduction in "Overall N loss" indicates potential for indirect reduction of all other N losses.

A. Principles of integrated sustainable nitrogen management

39. 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 (see box II.1 below).

Box II.1

Ten Key Points of nitrogen cycling relevant for integrated sustainable nitrogen management

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” (N_r) 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 N_r 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, and 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.

40. 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.

41. Many environmental policies have a narrow scope concerning nitrogen management and would benefit from an integrated approach. For example, most NO_x and NH_3 sources

have been included in the Gothenburg Protocol, but NO_x emissions from agricultural soils, (semi-)natural NO_x 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,[4] all N sources in agriculture must be considered for reducing NO_3^- leaching, but NH_3, NO_x, N_2O and N_2 emissions to air are not explicitly addressed.

1. Different dimensions of integration in nitrogen management

42. **Dimension 1: Cause and effect** are the basis for current N policies, as the effects on human health and the environment, caused by N emissions, drive policy measures to decrease these emissions.

43. **Dimension 2: Spatial and temporal integration** of all N forms and sources affecting a certain area and time scale in management plans are critical to ensure that multiple co-benefits of action are achieved, maximizing synergies while minimizing nitrogen trade-offs.

44. **Dimension 3: Multiple nutrients and pollutants** are brought together by nitrogen. As an element, N is unique in the diversity of its environment and sustainability relevance. Sustainable nitrogen management therefore encourages integration with other elements and compounds:

(a) Between NH_3 and NO_x, SO_2, VOCs and PM in air pollution;

(b) Between N and carbon, including CO_2 and CH_4 when considering climate effects;

(c) Between N, phosphorus (P), potassium (K) and silicon (Si) when considering freshwater and coastal eutrophication;

(d) Between N and all other essential plant nutrients (either macronutrients or micronutrients) when considering crop, livestock and human nutrition;

(e) Between N and irrigation water, when considering sustainable water management.

45. **Dimension 4: Integrating stakeholders' views** is an additional dimension and has to be done as early as possible during the design phase of nitrogen management plans and measures. Multiple stakeholder types ensure that policy measures are:

(a) Policy relevant by addressing the main issues;

(b) Scientifically and analytically sound;

(c) Cost-effective, with costs proportional to the objective to be achieved; and

(d) Fair to all actors/users.

46. **Dimension 5: Regional integration** aims at enhanced cooperation between regions and countries, incorporating the landscape scale. Arguments for regional integration are:

(a) Enhancement of markets;

(b) Creation of a "'level playing field" for policy measures

(c) The transboundary nature of environmental pollution;

(d) Consideration of indirect pollution affects; and

(e) The increased effectiveness and efficiency of regional policies and related management measures.

47. The Gothenburg Protocol has demonstrated the benefits of developing an approach that integrates multiple pollutants and multiple effects. In the case of nitrogen, most NO_x and NH_3 sources are included when defining the emissions ceilings, while further efforts are

[4] Council Directive of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources (91/676/EEC), *Official Journal of the European Communities*, L 375 (1991), pp. 1–8.

needed to integrate NO_x emissions from agricultural soils, (semi-)natural NO_x and NH_3 sources, and the relationships to N_2O and N_2 emissions and NO_3^- leaching. The need to bring these issues together was recently recognized in United Nations Environment Assembly resolution 4/14 on sustainable nitrogen management and its follow-up in the Colombo Declaration. These texts emphasize the win-win opportunities for environment, health and economy, including air quality, water quality, climate, stratospheric ozone and biodiversity protection, together with the provision of sustainable food and energy.

2. Principles of integrated sustainable nitrogen management

48. Twenty-four principles of integrated sustainable nitrogen management are identified below:

(a) **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 nitrogen inputs;**

(b) **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;

(c) **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 N_r forms to surface waters, and gaseous emissions of NO_x, N_2O and N_2 related to nitrification-denitrification processes. Pathway-specific measures relate to pathway-specific controlling factors;

> "Reduced N inputs or increased harvested outputs are thus an essential part of integrated nitrogen management while providing opportunities for increased economic performance."
> *From principle 6*

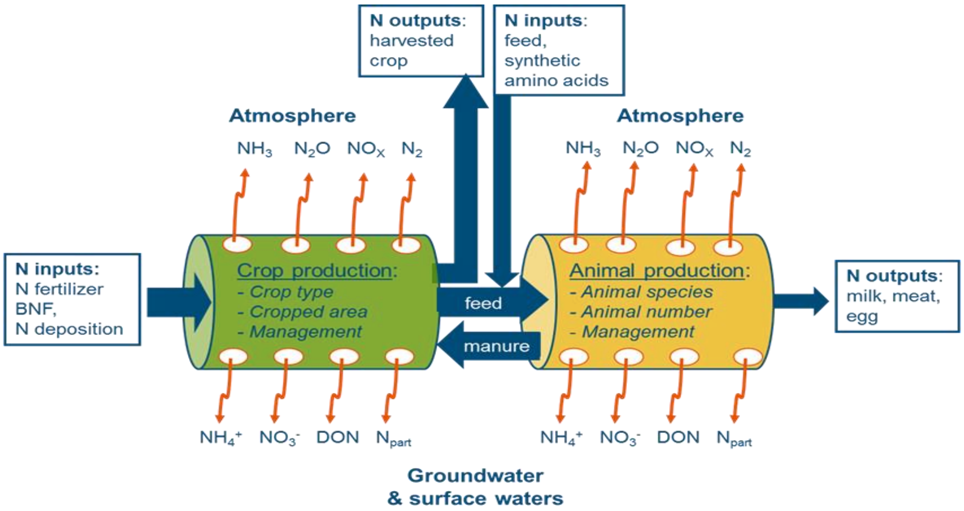
(d) **Principle 4: Possible trade-offs in the effects of N loss abatement/mitigation measures may require priorities to be set, for example, which adverse effects should be addressed first.** Policy guidance is necessary to inform such priorities and properly weigh the options according to local to global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

(e) **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;

(f) **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;

(g) **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 (see figure II.2 below).

Figure II.2:
Concept of the nitrogen input – output mass balance of mixed crop – livestock production systems



Source: Modified from Oenema and others (2009).

Note: Total inputs must balance total outputs, following corrections for possible changes in storage within the system. The concept is applicable at field, farm, regional and global scales for all farm types (chapter III).

(h) **Principle 8: Matching nitrogen inputs to crop needs (also termed "balanced fertilization") and to livestock 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;

(i) **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;

(j) **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;

(k) **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);

(l) **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.

(m) **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;

(n) 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;

(o) 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;

(p) **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^-.

(q) **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;

(r) **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;

(s) **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;

(t) **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;

(u) **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;

(v) **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;

(w) **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;

(x) **Principle 24: The 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.

3. Tools for integrated nitrogen management approaches

49. The toolbox for developing integrated approaches to N management contains both tools that are uniformly applicable and more specific tools, suitable for just one dimension of integration. Important common tools are:

(a) Systems analysis, used especially by the science-policy-practice interface;

(b) Nitrogen input-output budgeting tools to integrate N sources and N species for well-defined areas at various scales (from farms to continents) and that are easy for farmers and policymakers to understand (as well as being compatible with data privacy regulations);

(c) Integrated assessment modelling and cost-benefit analyses. The “Driver-Pressure-State-Impact-Response” (DPSIR) framework can be used as a starting point for analysing cause-effect relationships conceptually and cost-benefit analysis (CBA) goes a step further by expressing costs and benefits of policy measures in monetary terms;

(d) Food-chain assessment and management relates to the planning and management of activities and information between actors in the whole food production–consumption chain, including suppliers, processors, retail, waste-recycling companies and citizens;

(e) Stakeholder dialogue and communication are essential for exchanging views of actors on N management issues, which can help make the concepts transparent and facilitate adoption of targets and the implementation of measures in practice;

(f) Abatement/mitigation measures, including best management practices, which have been shown to reduce emissions and impacts, as described in chapters IV-VI of the present document.

B. Housed livestock, manure storage and manure processing

50. Measures to reduce N loss from housed livestock, manure storage and processing influence manure composition and the storage environment, with the result that conditions are unfavourable for emissions. The first crucial step is to adapt the N content in the livestock diet as closely as possible to the requirements of animals, for which five measures are identified.

51. NH_3 emissions will be small at low temperatures and low pH values if the contact of manure with ambient air is limited. Emissions of N_2O, NO_x and N_2 will be reduced by low organic C content, sufficient oxygen availability and low nitrate concentrations. Concepts for best practices to reduce adverse environmental impacts require integrated approaches, detailed understanding of emissions at the process level, and the development of flexible solutions that match regional needs.

52. 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. Overall, 18 Housing Measures are identified (see table II.1 below).

53 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. In total, 12 Manure Measures related to storage/processing and 5 Nutrient Recovery Measures are identified (see table II.1 below).

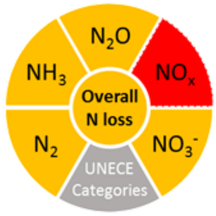
54. Overall, measures related to livestock diets, housing, manure storage and manure reprocessing should be seen in relation to the flow of nitrogen and other nutrients, with significant synergy between the different stages. For example, N saved through optimized diets and low-emission stables provides an opportunity to increase N resources for manure recycling or direct application to fields (chapter V). It is important to remember the principles by which each measure works (chapter III) to maximize the synergies and avoid trade-offs. For example, in order to achieve the full benefit of reducing NH_3 emissions during animal housing, corresponding measures are needed during manure storage and manure spreading to avoid NH_3 emissions later in the system. The manure management chain provides a key example of an opportunity for circular economy thinking where reduced losses to the environment translate into increased resource availability (see figure I.2 above).

Table II.1
Measures related to livestock diets, livestock housing, manure storage and processing and nutrient recovery

Measures related to livestock diets		
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.	

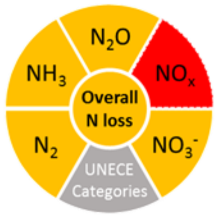
Dietary Measure 2: Increase productivity (dairy and beef cattle)

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.[5] A balance must be found between 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.



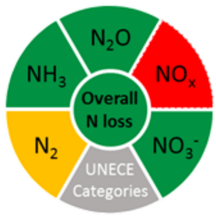
Dietary Measure 3: Increase longevity (dairy cattle)

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.



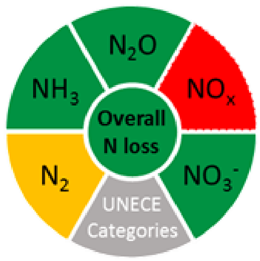
Dietary Measure 4: Adapt protein intake in diet (pigs)

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.



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.



Measures related to livestock housing

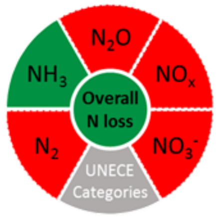
[5] This effect is noted without prejudice to any current or future agricultural policy (for example, the European Union Common Agricultural Policy) and other state aid measures oriented to conserving local traditional animal races, which emphasizes the need to consider the balance between issues.

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.

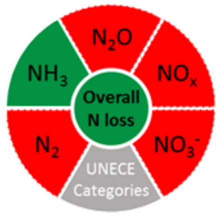
Housing Measure 2: Regular cleaning of floors in cattle houses by toothed scrapers (cattle)

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.



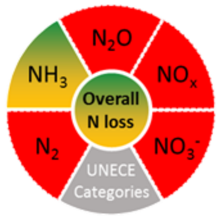
Housing Measure 3: Regular cleaning of floors in cattle houses

Thorough cleaning of walking areas in dairy cattle houses by mechanical scrapers or robots has the potential to substantially reduce NH_3 emissions.



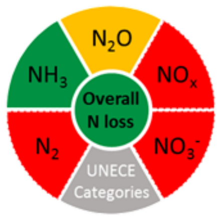
Housing Measure 4: Frequent slurry removal (cattle)

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.



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.

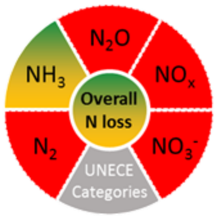


Housing Measure 6: Barn climatization to reduce indoor temperature and air flow (cattle)

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.

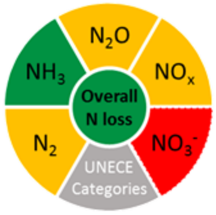
Housing Measure 7: Use of acid air-scrubbers (cattle)

In the few situations where cattle are housed with forced ventilation, this measure can be considered as category 1 to reduce NH_3 emissions. However, most cattle are housed in naturally ventilated buildings across the ECE region. Recent developments explore the use of air-scrubbers with naturally ventilated buildings (for example, by directly extracting and scrubbing air from the slurry pit).



Housing Measure 8: 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.



Housing Measure 9: 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.

Housing Measure 10: Regular cleaning of floors (pigs)

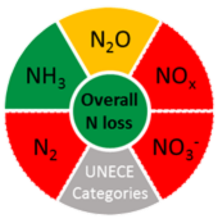
Thorough and regular cleaning of floors in pig houses by mechanical scrapers or robots has the potential to reduce NH_3 emissions substantially.

Housing Measure 11: 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.

Housing Measure 12: 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



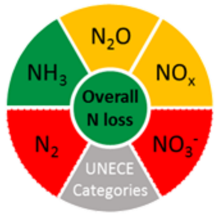
bedding may be needed to avoid N_2O and N_2 emissions associated with deep-litter systems.

Housing Measure 13: Barn climatization to reduce indoor temperature and air flow (pigs)

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.

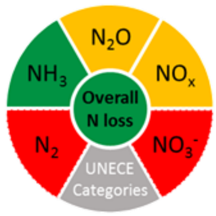
Housing Measure 14: Use of acid air-scrubbers (pigs)

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 NO_x emissions if the N recovered is used to replace fresh fertilizer N inputs.



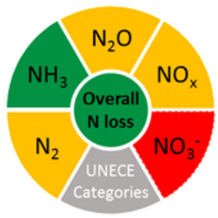
Housing Measure 15: Use of biological air-scrubbers (pigs)

Biological air-scrubbers operate with bacteria that remove NH_3 and odours from the exhaust air. Careful management is needed to ensure that NH_3 captured in biological air-scrubbers (for example, organic biofilters) is not nitrified/denitrified, leading to increased emissions of N_2O, NO_x and N_2. Recovery of the collected N_r in bioscrubbers may help offset any increase, with opportunities to recover N_r through use of biotrickling systems.



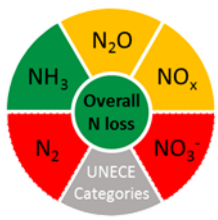
Housing Measure 16: Rapid drying of poultry litter

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, NO_x and N_2, since this will also reduce nitrification and denitrification.



Housing Measure 17: 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.

Housing Measure 18: Use of biological air-scrubbers (poultry)

Treatment of exhaust air by use of biotrickling filters (biological air-scrubbers) has been successfully employed in several countries to reduce NH_3 emissions, fine dust and odour. Multistage scrubbers have been developed to deal with high dust loads, although use of biofilters may increase other N losses as N_2O, NO and N_2.

Measures related to manure storage and 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.

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

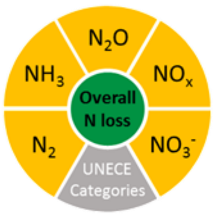
Where slurries have a high dry matter content, these may form a natural crust during storage, which is associated with substantially reduced NH_3 emission, although N_2O production may be enhanced. The impermeable base avoids nitrate leaching and must be maintained to avoid leakage.

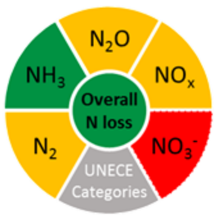
Manure Measure 3: Covered storage of solid manure (dispersed coverings)

Covering solid manures with dispersed coverings, such as peat, clay, zeolite and phosphogypsum or clay, can substantially reduce NH_3 emissions. The approach works by protecting manure surfaces from the air, while these materials also have a high affinity for ammonium. Sufficient thickness of the covering is required.

Manure Measure 4: Storage of solid manure under dry conditions

Simply storing solid manure in a dry place, out of the rain, can also reduce N emissions from a range of N_r compounds and N_2. This is even more important for poultry litter, where keeping manure dry limits hydrolysis of uric acid to form NH_3.



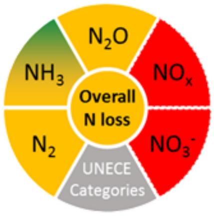
Manure Measure 5: Storage of solid manure on a solid concrete base with walls	Storage of manure on a walled solid base helps reduce nitrate leaching and other N_r leaching by avoiding run-off and infiltration into the soil. The approach costs less than installing a solid cover, but risks substantial NH_3, N_2O, NO_x and N_2 emissions.	
Manure Measure 6: Slurry mixing (during storage)	Slurry mixing of stored manure prior to field application helps ensure a homogenous distribution of nutrients. There are no additional benefits to reduce emissions of N_2O, NO_x or N_2. The method may even increase NH_3 losses (for example, if mixing increases pH by promoting CO_2 loss from slurry), so mixing should only be done shortly before field application.	
Manure Measure 7: Adsorption of slurry ammonium	Certain additives to slurry can be used to adsorb ammonium on a chemical, physical or biological basis. Mineral additives such as clay/zeolite require a high amount of additives, which can result in the measure being costly (for example, 25 kg of zeolite per m^3 slurry to adsorb 55 per cent of ammonium). However, experiments have shown only a small effect in reducing NH_3 emission. Addition of biochar may also reduce NH_3 emissions from stored manure.	
Manure Measure 8: 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.	

Manure Measure 9: Slurry aeration

Slurry aeration introduces oxygen into the slurry in order to allow aerobic microbes to develop, so reducing odour. However, CO_2 and NH_3 emissions are increased. Emissions of NO_x are also expected to increase, while greater NO_3^- availability risks a subsequent increase in denitrification-related loss of N_2O and N_2. Therefore, slurry aeration is not recommended.

Manure Measure 10: 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.

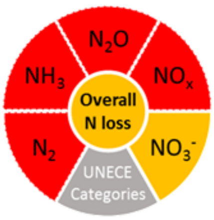


Manure Measure 11: Anaerobic digestion of manure

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 (Nutrient Recovery Measures 3–5). The requirement for an impermeable base avoids nitrate leaching compared with storage of manure on permeable surfaces.

Manure Measure 12: Manure composting

Composting of manure creates a stable and odourless biobased fertilizer product, with lower moisture content, while containing most of the initial nutrients, free of pathogens and seeds. However, losses of NH_3, N_2O, NO_x, N_2, CO_2 and CH_4 tend to increase, also



reducing N fertilizer value, while composting on porous substrates risks increasing N leaching. Use of covered composting can mitigate some of these effects. The UNECE categories shown assume open composting on an impermeable surface.

Measures related to nutrient recovery

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 biobased 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.

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, as well as NO and NO_2 (for example, NO_x). Until systems are implemented to minimize N_2 formation and recover the N_r gases, this measure cannot therefore be considered appropriate for abating overall N loss.

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.

<table>
<tr>
<td>Nutrient Recovery Measure 4: Concentration of nitrogen salts and solutions</td>
<td>Mineral concentrates are highly nutrient-rich solutions that may be obtained via ultrafiltration, evaporation or reverse osmosis of the liquid fraction from separation of slurry or digestate. Provided that losses can be kept to a minimum (for example, use of acidification, soil injection), the mineral fertilizer replacement value of the mineral concentrates can be relatively high, as they resemble commercial liquid fertilizers. As these technologies are still under investigation, they are set as UNECE category 3, pending further assessment.</td>
<td>
</td>
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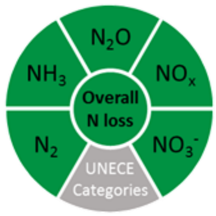
<tr>
<td>Nutrient Recovery Measure 5: Ammonia stripping and recovery</td>
<td>In this method, the liquid fraction after manure separation is brought into contact with air, upon which NH_3 evaporates and is collected by a carrier gas. Use of membrane systems allows use of lower temperatures, if membrane 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.</td>
<td>
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Note: See figure II.1 above and accompanying text for explanation of colour code system employed in graphics contained in table II.1

C. Field application of organic and inorganic fertilizers, including manures, urine and other organic materials

55. 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.

56. According to principle 6, 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.

57. The most effective measures are listed below according to applicability:

(a) Measures applicable to both organic and inorganic fertilizers;

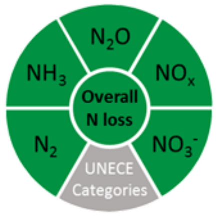
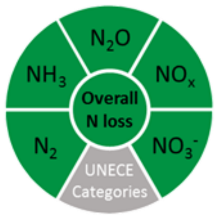
(b) Measures applicable to manures and other organic materials;

(c) Measures applicable to inorganic fertilizers;

(d) Measures applicable to livestock grazing; and

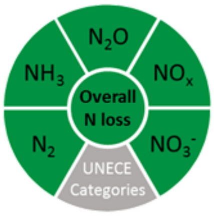
(e) Other cropping-related measures. Overall, 20 field measures are identified (see table II.2 below).

Table II.2
Measures applicable to organic and inorganic fertilizers, manures and other organic materials and grazing livestock

Measures applicable to both organic and inorganic fertilizers		
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, in accordance with Field Measure 3. 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.	
Field Measure 2: Apply nutrients at the appropriate rate	Under application of N will result in reduced crop yields, soil organic matter and can lead to N mining of the soil. Overapplication 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.	

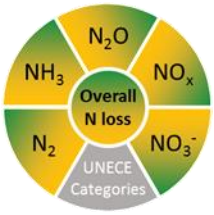
Field Measure 3:
Apply nutrients at the appropriate time

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.



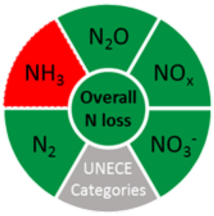
Field Measure 4:
Apply nutrients in the appropriate form

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.



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).



Measures specific to the application of manures and other organic materials

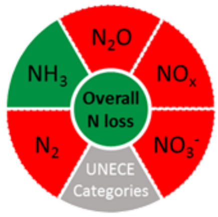
Field Measure 6:
Band spreading and trailing shoe application of livestock slurry

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).

Field Measure 7: Slurry injection

Placing slurry in narrow surface slots, via shallow or deep injection, greatly reduces the exposed slurry surface area, greatly reducing NH_3 emissions (by 70–90 per cent). Emissions of N_2O (as well as NO_x 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.

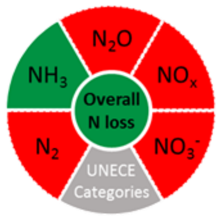


Field Measure 8: Slurry dilution for field application

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 (c. 30 per cent emission reduction for 1:1 dilution of slurry in water).

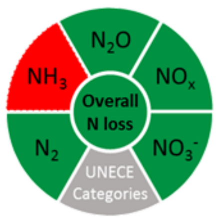
Field Measure 9: Slurry acidification (during field application)

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.



Field Measure 10: Nitrification inhibitors (addition to slurry)

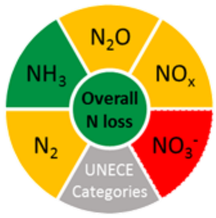
While more usually associated with mineral fertilizers, nitrification inhibitors can also be added to livestock slurries just prior to application to land with the aim of delaying the conversion of the slurry ammonium content to nitrate, which is more susceptible to N_r losses through denitrification, run-off and leaching.[6]



[6] No benefit is expected from using urease inhibitors in spreading cattle and pig manure, as most of the

Field Measure 11: 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.	

Measures specific to the application of inorganic fertilizers

Field Measure 12: 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 NO_x, though the opposite can happen in other situations.	
Field Measure 13: Urease inhibitors	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 NO_x emissions.[7]	
Field Measure 14: 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 NO_x and N_2, and	

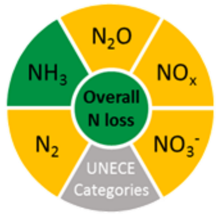
excreted urea will have already hydrolysed to form ammonium during livestock housing and manure storage. Potential long-term effect of nitrification inhibitors on non-target organisms should be considered.

7 See footnote 6.

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. Field Measures 13 and 14 are complementary and can be combined.

Field Measure 15: Controlled release fertilizers

Special coatings on fertilizers slow the release of nutrients to the soil over a period of several months (for example, sulphur or polymer coating). The gradual release of nutrients is associated with lower leaching and gaseous N losses. Organic N products with low water solubility, such as isobutylidene diurea (IBDU), crotonylidene diurea (CDU) and methylene-urea polymers, are also considered as slow- release fertilizers. Potential effects from the degradation of polymer coatings to form microplastics remain to be demonstrated.

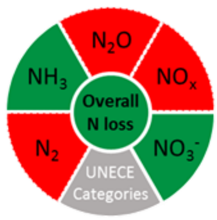


Field Measure 16: Fertigation

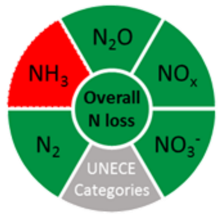
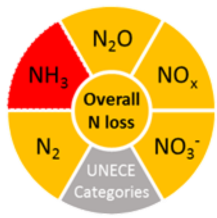
In areas subject to drought or limited soil water availability, the efficiency of water and N use should be managed in tandem. Drip irrigation combined with split application of fertilizer N dissolved in the irrigation water (for example, drip fertigation) provides precision application (in space and time), minimizing evaporative losses of water and losses of N to air and water, thereby greatly enhancing the N use efficiency.

Field Measure 17: 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.



Measures for grazing livestock

Field Measure 18: 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.	
Field Measure 19: Avoid grazing in high-risk areas	High-risk areas include those with high connectivity to vulnerable surface waters and/or groundwaters, 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.	
Field Measure 20: Nitrification inhibitors: addition to urine patches	Nitrification inhibitors, more commonly associated with mineral fertilizers, may also have an application in reducing leaching and denitrification from urine patches in grazed pastures. Risks of increased NH_3 emissions from urine patches associated with delays in nitrification are likely to be minimal because of the rapid urine infiltration.	

D. Land-use and landscape management

58. Landscape management enables N_r pollution problems to be addressed where they occur, both in space and time, helping to achieve the desired N mitigation effect.

59. Landscape measures can be economically favourable compared with other types of measures, especially as they can be placed outside agricultural areas, for example, retaining agricultural production, while creating new nature and recreational resources in the form of hedgerows, forests and extensive buffer-zones around fields, streams or wetlands.

60. For land-use and landscape-scale measures, the primary focus is on mitigation of adverse impacts, though there can also be benefits for emissions abatement. This means that measures focus on increasing overall landscape resilience so that there are fewer adverse impacts per unit of emission, in addition to a contribution to reducing emissions (for example, by local recapture within landscapes).

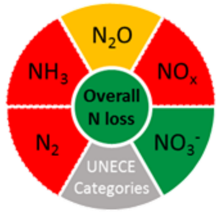
61. The most effective measures are listed in table II.3 below according to their applicability. Overall, 16 Landscape Measures are identified.

Table II.3
Landscape Measures

Land-use measures for crops and crop rotations, including agroforestry

Landscape Measure 1: Increasing land cover with perennial crops

Introducing perennial crops, such as grasslands, predominately grass or grass-clover mixtures, can reduce the risk of environmental N_r losses due to N_r immobilization in plant biomass and litter. They typically have a higher capacity for storage in biomass/litter and have a longer N uptake period than annual plants. This approach also increases soil N (and C) stocks, with higher soil organic carbon contents providing increased N_r retention capacities.



Landscape Measure 2: Use of cover crops in arable rotations

Cover crops (or “catch crops”) that follow the main crop can help reduce available soil N levels during high-risk periods for nitrate leaching by taking up N originating from post-harvest decomposition and mineralization. Success in reducing emissions and in increasing N use efficiency over the whole cropping cycle depends on effective management of the cover crop residue and appropriate tuning of fertilization rates to the subsequent crop. The approach also reduces the risk of erosion and other soil/nutrient transport to streams.

Landscape Measure 3: Inclusion of N_2-fixing plants in crop rotations (including intercropping)

Inclusion of plants such (for example, legumes) that fix atmospheric N_2 to produce organic nitrogen forms reduces the requirement for applied N (as fertilizer or manure) and the N losses associated with such applications. The approach can be implemented by including legumes as part of a crop rotation or by including legumes within a mixed crop (“inter-cropping”, for example grass-clover sward). Incorporation of legumes into the soil as part of a crop rotation leads to a pulse of mineralization, which can lead to N_r emissions to air and nitrate leaching to water.

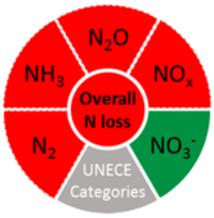
Landscape Measure 4: Introducing agroforestry and trees in the landscape

Introducing agroforestry land-uses, with alternate rows of trees and annual crops or blocks of trees in the landscape, can help remove surplus N_r from neighbouring arable fields, minimizes erosion, provides wind shelter, and supports biodiversity provision.

Landscape measures for management of riparian areas and waters

Landscape Measure 5: Constructed wetlands for stimulating N_r removal

Constructed wetlands can help remove nutrients from water bodies or for wastewater treatment. The principle of operation of constructed wetlands is to encourage conditions that favour denitrification to N_2, while other nutrients accumulate. The approach is cheap but wastes N_r as N_2 and risks increased N_2O and CH_4 emissions, as well as dissolved organic C and N loss to watercourses.



Landscape Measure 6: Planting of paludal cultures in riparian areas or constructed wetlands

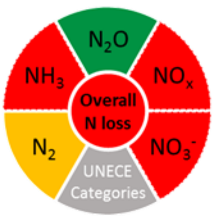
Wetland (paludal) plants are specifically planted to maximize biomass growth, thereby removing N_r from the water. The biomass can be harvested and used, for example, as source of bioenergy. Poorly managed systems may increase N_2O and N_2 emissions (as well as CH_4 emissions) if N_r is not fully used for plant growth. Performance is compared with Landscape Measure 5 as the reference.

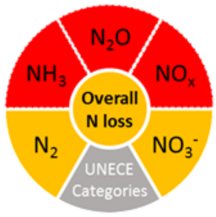
Landscape Measure 7: Use of organic layers to promote denitrification

A layer of organic matter (for example, woodchips) is placed in trenches in soil at key points in the landscape to promote denitrification, enhancing the removal of nitrates from groundwaters and surface waters. The approach can help improve water quality but wastes N_r resources as N_2 emission while risking increased N_2O and CH_4 emissions.

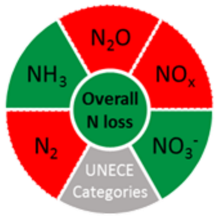
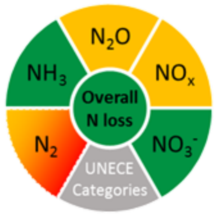
Landscape Measure 8: Drainage management

Drainage measures (such as insertion of tile drains for water-table management) promote run-off and limit waterlogging, reducing residence times of nutrients. This can help abate emissions of CH_4 and N



	compounds relating to denitrification (N_2O, N_2), while shorter residence time may increase NO_3– and carbon losses to stream waters.	
Landscape Measure 9: Stimulating N_r removal in coastal waters	It has been proposed that growing seaweed, eel grass, oyster farming or shellfish aquaculture can help remove excess nutrients from coastal waters. Nitrogen is incorporated into the biomass, which is harvested. While the principle of encouraging N_r recovery into useful products is sound, further evidence of the quantitative performance of this system is needed before it can be used with confidence to mitigate coastal water pollution.	

Afforestation, set-aside and hedgerow measures to mitigate N_r effects

Landscape Measure 10: Introducing trees for afforestation and hedgerows in the landscape	Afforestation and preservation and planting of strips of trees around agricultural fields can reduce NO_3– leaching and has very positive effects on biodiversity. The efficacy of hedgerows for N_r retention will depend on size and placement of hedgerows, on the amount of NO_3– in soil and groundwater, hydrological flow-paths and timing. With sufficient tree area, there can also be benefits for NH_3 mitigation (see Landscape Measure 12).	
Landscape Measure 11: Set-aside and other unfertilized grassland	Unfertilized grasslands (for example, "set-aside" grassland) have the potential to remove NO_3– from lateral soil water flows and can be used as buffers to protect adjacent natural land or streams. The effectiveness of the measure also depends on the extent to which overall N inputs are accordingly reduced in the landscape.	

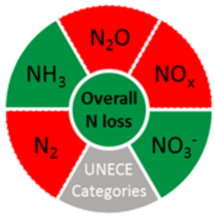
Mitigating the cascade of N_r effects from livestock hot spots

Landscape Measure 12: Shelterbelts around large point sources	Wide shelterbelts, such as woodland planted around point sources, can help mitigate landscape N_r dispersion from emission hot spots, such as manure storage areas or animal housing facilities, due to the function of trees as biofilters for NH_3 and the immobilization of N_r into plant	

biomass and soil organic N stocks. The approach may also reduce NO_3^- leaching losses but can risk increased N_2O emissions.

Landscape Measure 13: Environmentally smart placement of livestock facilities and outdoor animals

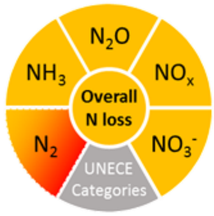
Placement of livestock facilities away from sensitive terrestrial habitats or waterbodies can reduce local N_r problems. The approach is most commonly used as part of planning procedures for new developments to expand existing farms.



Smart landscape farming in relation to mitigation of N_r effects

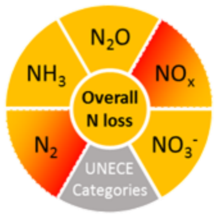
Landscape Measure 14: Digital planning of land-use on basis of a suitability assessment

Land-use and farm planning based on digital 3D precision maps of soil N retention can help to optimize fertilizer use and reduce N leaching and other losses. This can help to improve nutrient retention at landscape scale, improve water quality in surface waters and groundwaters and reduce gaseous N_r losses. The approach typically requires support through detailed modelling.



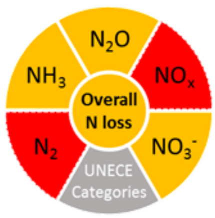
Landscape Measure 15: Towards mixed farming

Mixed farming combines livestock and cropping at farm and landscape scales. Crop and livestock integration provides opportunities to connect nitrogen inputs and surpluses so as to reduce overall levels of nitrogen pollution, while increasing farm- and landscape-scale nitrogen use efficiency. Emissions associated with long-distance feed and manure transport are reduced. Mixed cropping-livestock systems also provide the opportunity to develop free-range livestock production in combination with crops that mitigate N_r losses.



Landscape Measure 16: Landscape-level targeting of technical options to reduce N_r losses

Technical measures may be selectively applied at the landscape scale, where they are targeted to be used in specific sensitive areas. Analysis at the landscape scale can also allow for a more nuanced analysis of the potential trade-offs and synergies between emissions abatement and effects mitigation of different N compounds.



E. Overall priorities for policymakers

62. Policymakers may find it helpful to recognize that underlying every measure is one or more of the listed principles for integrated sustainable nitrogen management, as illustrated by table II.4 below.

63. The following priorities are identified linked to livestock housing and manure storage:

(a) Concepts for best practices to reduce adverse environmental impacts require integrated concepts including consideration of the interactions:

(i) Between pollutants;

(ii) With animal welfare aspects;

(iii) With climate change;

(iv) With biodiversity protection; and

(v) With region-specific characteristics.

(b) Concepts to reduce adverse environmental impacts require a detailed understanding at a process level to assess emissions, influencing factors and abatement/mitigation options;

(c) Concepts to reduce adverse environmental impacts depend on the development of flexible concepts that account for climate- and site-specific conditions, the three pillars of sustainability, potential conflicts of interest and whole-system solutions.

Table II.4

Summary of measures to support integrated sustainable nitrogen management in agriculture and their linkage to underlying principles.

Measure		*Relevant principles underlying the listed measure*	
Measure numbers	*Description of measures*	*Principle numbers*	*Description and application of the principles*
Livestock Diets, Housing, Manure Management and Nutrient Recovery			
Dietary Measures 1, 4 and 5	Adapt protein intake in diet (cattle, pigs, poultry)	Principle 5 Principle 22 Principle 4	Control of N inputs influences all N loss pathways. Dietary strategies for N consider C and CH_4 interactions. Trade-offs require policy priorities to be set.
Dietary Measure 2	Increase productivity (dairy and beef cattle)	Principle 13	Optimizing animal production requires that all factors be in balance.
Dietary Measure 3	Increase longevity (dairy cattle)	Principle 13	Optimizing animal production requires that all factors be in balance
Housing Measure 1 and Manure Measure 10	Immediate segregation of urine and faeces (cattle) Mechanical separation.	Principle 14 Principle 15	Reduce rate of urea hydrolysis. Reduce exposure of NH_4^+-containing resources to air by increasing infiltration to soil.
Housing Measures 2, 3, 9 and 10	Reduce emitting surface and regular cleaning of floors (cattle, pigs)	Principle 15	Reduce exposure of NH_4^+-containing resources to air, including by reducing temperature.
Housing Measures 4 and 11	Frequent slurry removal (cattle, pigs)	Principle 15	Reduce exposure of NH_4^+-containing resources to air, plus benefits through reducing temperature and surface area.
Housing Measures 5 and 12	Increase bedding material (cattle and pigs with solid manure)	Principle 7	Nitrogen input-output balance, with increased storage from N absorbed in bedding.
Housing Measures 6 and 13	Barn climatization (cattle, pigs)	Principle 15	Reduce exposure of NH_4^+-containing resources to air, due to reduced temperature and airflow.
Housing Measures 7, 14 and 17	Acid air-scrubbers (cattle, pigs, poultry)	Principle 7	Nitrogen input-output balance, with N captured by the scrubbers.
Housing Measure 8	Slurry acidification (pig and cattle)	Principle 15	Reduce exposure of NH_4^+-containing resources to air, due to reduced pH.
Housing Measures 15 and 18	Biological air-scrubbers (pigs and poultry)	Principle 7 contra Principle 16 Principle 4	Nitrogen input-output balance, with N captured by the scrubbers. Increasing denitrification risks other N losses and reduced NUE. Trade-offs require policy priorities to be set.
Housing Measure 16	Rapid drying of poultry litter	Principle 14 Principle 16	Reduce rate of urea hydrolysis; Reduce rate of nitrification.
Manure Measure 1	Covered storage (solid cover and impermeable base)	Principle 15 Principle 20	Reduce exposure of NH_4^+-containing resources to air. Coupling N and water cycles: avoidance of rain driven leaching and run-off from stored manure.
Manure Measure 2	Covered slurry storage (natural crust and impermeable base)	Principle 15 Principle 20 contra Principle 16 Principle 4	Reduce exposure of NH_4^+-containing resources to air. Coupling N and water cycles: avoidance of rain driven leaching and run-off from stored manure. Increasing denitrification risks other N losses and reduced NUE. Trade-offs require policy priorities to be set
Manure Measure 3	Covered storage of solid manure (dispersed coverings)	Principle 15 contra Principle 16	Reduce exposure of NH_4^+-containing resources to air. Increasing denitrification risks other N losses and reduced NUE. May be combined with Manure Measure 5.

Measure		*Relevant principles underlying the listed measure*	
Measure numbers	*Description of measures*	*Principle numbers*	*Description and application of the principles*
Livestock Diets, Housing, Manure Management and Nutrient Recovery			
Manure Measure 4	Storage of solid manure under dry conditions	Principle 16 Principle 20	Reduced rate of nitrification and denitrification. Coupling N and water cycles: avoidance of rain driven leaching and run-off from stored manure.
Manure Measure 5	Storage of manure on a concrete base with walls	Principle 20 contra Principle 15 contra Principle 16 Principle 4	Coupling N and water cycles: avoidance of rain driven leaching and run-off from stored manure. Exposure of NH_4^+ resources to air increases NH_3 emissions. Increasing denitrification risks other N losses and reduced NUE. Trade-offs require policy priorities to be set.
Manure Measure 6	Slurry mixing	Principle 9 contra Principle 15	Managing spatial variations: better mixed slurry ensures more reliable application rate. Exposure of NH_4^+ resources to air increases NH_3 emissions.
Manure Measure 7	Additives to adsorb slurry ammonium	Principle 7	Nitrogen input-output balance, with increased storage from N absorbed in bedding.
Manure Measure 8	Slurry acidification	Principle 15	Reduce exposure of NH_4^+-containing resources to air, due to reduced pH.
Manure Measure 9	Slurry aeration to reduce odour	contra Principle 15 contra Principle 16 Principle 4	Exposure of NH_4^+ resources to air increases NH_3 emissions. Increasing denitrification risks other N losses and reduced NUE. Trade-offs require policy priorities to be set.
Manure Measure 11	Anaerobic digestion of manure	Principle 6 Principle 15 Principle 16 Principle 18 Principle 19	Measures to save N pollution leave more available in the farming system, which needs to be managed accordingly. Reduce exposure of NH_4^+-containing resources to air. Reduce rate of nitrification. Can increase whole system NUE by promoting N recovery and reuse. Co-benefits from reuse of other nutrients and CH_4.
Manure Measure 12	Manure composting for odourless fertilizer supply	Principle 19 Contra Principle 15 contra Principle 16 Principle 4	Co-benefits from reuse of other nutrients Exposure of NH_4^+ resources to air increases NH_3 emissions. Increasing denitrification risks other N losses and reduced NUE. Trade-offs require policy priorities to be set.
Nutrient Recovery Measure 1	Drying and pelletizing of manure solids	Principle 19 contra Principle 15 Principle 4	Co-benefits from reuse of other nutrients. Exposure of NH_4^+ resources to air increases NH_3 emissions. Trade-offs require policy priorities to be set.
Nutrient Recovery Measure 2	Combustion, gasification or pyrolysis	Principle 4 contra Principle 6 contra Principle 16	Trade-offs require policy priorities to be set (for example, bioenergy or N pollution). Burning destroys N resources, reducing system-wide NUE (unless converted into a recoverable N_r form). Increasing denitrification risks other N losses and reduced NUE.
Nutrient Recovery Measures 3 and 4	Precipitation of N salts; Concentration of N solutions.	Principle 6 Principle 18 Principle 19	Measures to save N pollution leave more N available for the farming system, which needs to be managed accordingly. Increase whole-system NUE by promoting N recovery and reuse. Co-benefits from reuse of other nutrients

Measure		*Relevant principles underlying the listed measure*	
Measure numbers	*Description of measures*	*Principle numbers*	*Description and application of the principles*
Livestock Diets, Housing, Manure Management and Nutrient Recovery			
Nutrient Recovery Measure 5	Ammonia stripping and recovery	Principle 6 Controlled use of principle 15 Principle 18	Measures to save N pollution leave more N available in the farming system, which needs to be managed accordingly. Exposure of NH_4^+ resources to air with high pH and temperature increases emission of NH_3 (which is re-captured). Increase whole system NUE by promoting N recovery and reuse.
Field application			
Field Measure 1	Integrated nutrient management plan	All principles apply including: Principle 2 Principle 5 Principle 6 Principle 7 Principle 8 Principle 9	 Multiple actors have a role in N management: a clearly documented plan can support multi-actor agreement. Control of N inputs influences all N loss pathways. Measures to save N pollution leave more N available in the farming system, which needs to be managed accordingly. Nitrogen input-output balance provides a basis to optimize N and economics. Matching inputs to crop and livestock needs allows all N losses to be reduced. Spatially explicit management to match N needs and vulnerability within and between fields.
Field Measures 2 and 3	Apply nutrients at appropriate rate and time	Principle 5 Principle 6 Principle 7 Principle 8	Control of N inputs influences all N loss pathways. Measures to save N pollution leave more N available in the farming system, which needs to be managed accordingly. Nitrogen input-output balance provides a basis to optimize N and economics. Matching inputs to crop & livestock needs allows all N losses to be reduced.
Field Measure 4	Apply nutrients in the appropriate form	Principle 14 Principle 16 Principle 17	Reduce rate of urea hydrolysis. Reduce rate of nitrification. Nitrogen input forms reducing N_2O loss may also reduce N_2 loss, as both are controlled by denitrification.
Field Measure 5	Limit or avoid fertilizer use in high-risk areas	Principle 9 Principle 10	Spatial variations in agricultural land require spatially explicit N management. Spatial variations in natural habitat sensitivity require spatially explicit N management.
Field Measure 6	Band-spreading and trailing shoe application of slurry	Principle 15 Principle 6	Reduce exposure of NH_4^+-containing resources to air. Measures to save N pollution leave more N available in the farming system, which needs to be managed accordingly.
Field Measures 7 and 11	Slurry injection Rapid incorporation of manure	Principle 15 Principle 6	Reduce exposure of NH_4^+-containing resources to air. Measures to save N pollution leave more N available in the farming system, which needs to be managed accordingly.
Field Measure 8	Slurry dilution for field application	Principle 15 Principle 20 Principle 4	Reduce exposure of NH_4^+-containing resources to air by increasing infiltration to soil. Coupling N and water cycles: may risk increased NO_3^- leaching unless integrated with irrigation management. Trade-offs require policy priorities to be set
Field Measure 9	Slurry acidification (during spreading)	Principle 15	Reduce exposure of NH_4^+-containing resources to air by decreasing pH.

Measure		*Relevant principles underlying the listed measure*	
Measure numbers	*Description of measures*	*Principle numbers*	*Description and application of the principles*
Livestock Diets, Housing, Manure Management and Nutrient Recovery			
Field Measures 10, 14 and 20	Nitrification inhibitors (slurry, fertilizers and urine)	Principle 16 Principle 17	Reducing rate of nitrification and denitrification reduces N losses and increases NUE. Reducing N_2O loss may also reduce N_2 loss.
Field Measure 12	Replace urea with other N fertilizer	Principle 15	Reduce exposure of NH_4^+-containing resources to air by avoiding pH peaks associated with urea hydrolysis
Field Measure 13	Urease inhibitors: addition to urea-based fertilizers	Principle 14	Reduce rate of urea hydrolysis.
Field Measure 15	Slow release fertilizers	Principle 8	Matching N inputs to crop needs, through improved timing of N availability.
Field Measure 16	Fertigation	Principle 20	Co-optimization of N and water increases effective nutrient uptake reducing N losses.
Field Measure 17	Precision placement of fertilizer including deep placement.	Principle 12 Principle 15	Optimizing crop yield and NUE requires that all defining and limiting factors be addressed simultaneously. Reduce exposure of NH_4^+-containing resources to air
Field Measure 18	Extended grazing season.	Principle 15 contra Principle 16 Principle 4	Reduce exposure of NH_4^+-containing resources to air, as urine infiltrates soil more rapidly than manures and slurries. Increasing denitrification risks other N losses and reduced NUE. Trade-offs require policy priorities to be set.
Field Measure 19	Avoid grazing high- risk areas for waterlogging and run-off.	Principle 9 Principle 10	Spatial variations in agricultural land require spatially explicit N management. Spatial variations in natural habitat sensitivity require spatially explicit N management.
Land-use and landscape management			
Landscape Measure 1	Increasing land cover with perennial crops	Principle 7 Principle 16 Principle 20	Perennial crops allow more C and N to be stored in biomass and soil, reducing N losses according to the mass balance of inputs-outputs. Reduction in soil inorganic N levels can reduce losses as NO_3^-, NO_x, N_2O and N_2. Better-developed root systems of perennial crops may offer co-benefits for N and water to reduce NO_3^- leaching.
Landscape Measure 2	Use of cover crops in arable rotations	Principle 7 Principle 8 Principle 16 Principle 20	Removing N using a cover crop can reduce N loss during vulnerable periods. Matching N inputs to crop needs, offers opportunity to reduce all N losses. Cover crops remove N from the soil and can therefore reduce losses as NO_3^-, NO_x, N_2O and N_2. Co-optimizing N and water management can help reduce NO_3^- leaching.
Landscape Measure 3	Inclusion of N_2 fixing plants in crop rotations (including intercropping)	Principle 8 Principle 15 Principle 16 contra Principle 16	Matching N inputs to crop needs, offers opportunity to reduce all N losses. Reduce exposure of NH_4^+-containing resources to air, by provision of slow release biological N fixation. Decreasing denitrification reduces other N losses by a slow-release N source. Ploughing-in of N from legumes in crop-rotations manure may give N losses as NO_3^-, NO_x, N_2O and N_2
Landscape Measure 4	Introducing agroforestry and trees into the landscape	Principle 7	Perennial crops allow more C and N to be stored in biomass and soil, reducing N losses according to the mass balance of inputs-outputs.

Measure		*Relevant principles underlying the listed measure*	
Measure numbers	*Description of measures*	*Principle numbers*	*Description and application of the principles*
Livestock Diets, Housing, Manure Management and Nutrient Recovery			
		Principle 11	The structure of landscape elements affects the capacity to store and buffer nitrogen flows.
		Principle 20	Better-developed root systems of perennial crops may offer co-benefits for N and water to reduce NO_3^- leaching.
Landscape Measure 5	Constructed wetlands	Principle 11	Specially designed ecosystems may act as buffers of N pollution.
		Principle 19	Co-benefits if reuse of other nutrients.
		contra Principle 15 contra Principle 16	Exposure of NH_4^+ resources to air increases NH_3 emissions.
		Principle 4	Increasing denitrification risks other N losses and reduced NUE. Trade-offs require policy priorities to be set.
Landscape Measure 6	Planting of paludal cultures in riparian areas or constructed wetlands	Principle 11	The structure of landscape elements affects the capacity to store and buffer nitrogen flows.
		contra Principle 15 contra Principle 16	Exposure to air increases NH_3 emissions.
		Principle 4	Increasing denitrification risks other N losses and reduced NUE. Trade-offs require policy priorities to be set.
Landscape Measure 7	Use of organic layers to promote denitrification	contra Principle 16 Principle 4	Deliberately increasing denitrification reduces NO_3^- in water flows while increasing other N losses as N_2O and N_2, also reducing NUE. Trade-offs require policy priorities to be set.
Landscape Measure 8	Drainage management	Principle 16	Reduces denitrification related losses by reducing soil water residence times, but correspondingly likely to increase NO_3^- losses to stream-water.
		Principle 4	Trade-offs require policy priorities to be set.
Landscape Measure 9	Stimulating N_r removal in coastal waters.	Principle 7	Cultivation and harvesting of biomass in coastal waters allows more N removed reducing coastal N pollution according to mass balance.
Landscape Measure 10	Introducing trees for afforestation and hedgerows	Principle 11	The structure of landscape elements affects the capacity to store and buffer nitrogen flows.
		Principle 20	Better-developed root systems of perennial crops may offer co-benefits for N and water management to reduce NO_3^- leaching.
Landscape Measure 11	Set-aside and other unfertilized grassland	Principle 11	The structure of landscape elements affects the capacity to store and buffer nitrogen flows. Unfertilized land may serve as a buffer to N compounds flowing to water, and physically separate emissions and vulnerable ecosystems.
Landscape Measure 12	Shelterbelts of trees around large point sources	Principle 11	The structure of landscape elements affects the capacity to store and buffer nitrogen flows. Tree belts planted around point sources of NH_3 emission help recapture and disperse NH_3 and particles, acting as buffers to protect nearby sensitive ecosystems beyond.
Landscape Measure 13	Environmentally smart placement of livestock facilities	Principle 11	The structure of landscape elements affects the capacity to store and buffer nitrogen flows. Utilizes smart placement to maximize landscape buffering capability.
		Principle 16	Avoiding acute N inputs to semi-natural lands helps avoid local surpluses, reducing N losses.
Landscape Measure 14	Digital planning of land-use suitability	Principles 11, 12, 14, 16 and 20	Optimizing crop and livestock production according to all parameters including landscape structure and vulnerability, including interactions with water flows.

Measure		*Relevant principles underlying the listed measure*	
Measure numbers	*Description of measures*	*Principle numbers*	*Description and application of the principles*
Livestock Diets, Housing, Manure Management and Nutrient Recovery			
Landscape Measure 15	Towards mixed farming, including free range systems	Principles 5, 7 and 8	Mixed farming allows manure flows to be reused more locally in cropping systems, allowing reduced N inputs according to mass balance with a broad opportunity to reduce N losses.
Landscape Measure 16	Landscape-level targeting of technical options to reduce N_r loss	Principle 4 Principle 11	Based on agreed policy priorities, certain areas are designated as more vulnerable and requiring special protection, so more ambitious technical measures are applied in the vicinity of such sites.

Abbreviations: NUE, nitrogen use efficiency, which may be defined on a range of scales from crop and livestock scale to the full agrifood chain and across the entire economy.

64. The priority considerations for policymakers regarding integrated management of N to minimize pollution include:

(a) Integrated N planning at the farm, sectoral and regional levels (including addressing the trend towards concentration of intensive livestock and crop farms, often near cities), taking into account the fact that a healthy mix of food products is produced at low environmental burden;

(b) Minimizing nutrient applications to high-risk zones (water and N deposition-sensitive habitats, high-risk drainage basins), being aware of region-specific requirements and conditions;

(c) Integrating nutrients from recycling of organic residues to agriculture (this may require regional planning and adequate quality control of materials to be applied);

(d) Identifying cost-effective abatement measures for farmer implementation;

(e) Providing technical advice, guidance and adequate training to farm advisors and farmers relative to N use and management.

65. Priority considerations for policymakers regarding land-use and landscape actions for integrated nitrogen management include:

(a) Establishing pilots and demonstrations of sustainable land-use and landscape management to demonstrate how these approaches can utilize the nitrogen cycle to maximize overall resilience with reduced environmental impacts;

(b) Establishing evidence, scenarios and tools to demonstrate performance in reducing multiple adverse effects of nitrogen on sensitive landscapes, including analysis of costs and benefits;

(c) Demonstrating how land-use and landscape options support the development of production systems that are more resilient to climate change and with more diverse services delivered, at the same time as reducing environmental N_r footprint;

(d) Consideration of how benefits for nitrogen link to other issues; for example, woodlands in landscapes serve many functions, such as increasing landscape water retention to reduce flooding and providing wildlife habitats and shelter for livestock, in addition to their benefit as N management tools.

F. Priorities for practitioners

66. The following priorities are identified linked to livestock housing and manure storage:

(a) Match the N content of the animals' diet as closely as possible to the animals' requirements in order to avoid excess N input already at the feeding level;

(b) Keep livestock houses cool and clean and regularly remove manure to a covered outside storage;

(c) Store manure in a covered store, consider manure treatment for low emissions (for example, anaerobic digestion, separation, acidification);

(d) Recycle manure nutrients as valuable fertilizer in crop production.

67. For farmers, the main goals of implementing abatement measures are to increase the efficiency of N applied as fertilizer or manure to their 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.

68. Top land-use and landscape management measures to be implemented in practice can be divided into two groups: those related to a geographically targeted land-use change, and those related to geographically adapted management practices at landscape/regional scale.

69. Key land-use change measures identified include:

(a) Set-aside/grassland (with no addition of fertilizers);

(b) Establishment of riparian buffer strips, or of biodiversity buffer strips around or within fields (the difference being the proximity to an aquatic environment;

(c) Hedgerows and afforestation;

(d) Changed crop rotation/perennial crops (for example, permanent grasslands);

(e) Agroforestry;

(f) Wetlands and watercourse restoration and/or constructed mini-wetlands.

70. Key management options for geographically oriented measures at landscape and regional scales include:

(a) Soil tillage and conservation (for example, no tillage of organic soils);

(b) Drainage measures and controlled drainage;

(c) Grassland management;

(d) Placement of livestock production;

(e) Spatial redistribution of manure;

(f) Fertigation and installation of proper irrigation system for dry cultivated areas;

(g) Placement of biogas plants and biorefineries for biomass redistribution.

71. It is recognized that more farmers are adopting practices referred to as “regenerative agriculture”, with some practices having potential to reduce different N losses, including no-till, “organic farming” (avoiding manufactured inorganic fertilizers and focusing on biological nitrogen fixation) and activities designed to increase carbon sequestration, etc. As with other agricultural approaches, such systems provide the opportunity to design bespoke “packages of measures” to foster sustainable nitrogen management. These require further assessment to quantify their effects for all forms of N loss, including emissions of NH_3, N_2O, NO_x and N_2 and leaching of NO_3– and other N_r forms.

III. Principles of integrated sustainable nitrogen management

A. Introduction and background

72. Nitrogen provides substantial benefits to society, especially by boosting crop productivity. However, nitrogen (N) losses present multifaceted problems affecting human health and the environment. These N-related problems straddle many scientific disciplines, and many domains across policy and regulation. This means that an integrated approach is required to manage N use optimally, avoiding trade-offs and allowing multiple benefits to society and the environment (Oenema and others, 2011b). As agriculture is the one sector where N is introduced intentionally to increase crop yield and quality for financial gain, it is the clearest example of why an integrated approach is required.

73. Nitrogen management in agriculture has a dual purpose: to decrease N losses to protect human health and the environment; and to optimize the beneficial effects of N related to food production. The adjectives "integrated" and "sustainable" in the title refer to the fact that N management needs to be balanced and durable – for example, environmentally sound, socially acceptable and economically profitable – for current and future generations. The negative effects of N losses on human health, ecosystem services, biodiversity, water and climate need to be addressed fully. Integrated sustainable N management contributes to achieving most of the Sustainable Development Goals. Notably, integrated sustainable N management contributes directly or indirectly to achieving Goal 1 (no poverty), Goal 2 (zero hunger), Goal 3 (good health and well-being), Goal 6 (clean water and sanitation), Goal 12 (responsible consumption and production), Goal 13 (climate action), Goal 14 (life below water) and Goal 15 (life on land). At present, the widespread evidence of adverse effects of nitrogen pollution through air, climate, land and water (Galloway and others, 2008; Fowler and others, 2013; Sutton and others, 2011, 2019; Alcamo and others, 2013) demonstrates that further action is needed to improve the effectiveness of N abatement and mitigation measures in agriculture to reduce these effects (European Environment Agency, 2015). Integrated sustainable N management provides a basis for mobilizing more sustained and coordinated action, while taking account of agroecological principles, as a basis for achieving multiple Sustainable Development Goals.

74. The purpose of this chapter is to outline the principles of integrated sustainable N management in agriculture. Subsection 1 below considers five important dimensions that any N management needs to cover to be effective. Subsection 2 describes key points of N cycling in the biosphere, to inform the reader about the nature of the N cycle in relation to agricultural practice. Subsection 3 discusses principles of nitrogen management in agriculture. Section 1.5 then presents some general tools for integrated N management. Possible measures to decrease N losses and to increase N use efficiency in agriculture are presented in subsequent chapters.

B. Dimensions of integrated sustainable nitrogen management

75. Many countries aspire to develop more integrated and effective approaches to decreasing N losses from agriculture. However, current environmental policies typically have a narrow scope as regards N management. Integration is defined here as the process of combining separate elements and aspects in an organized way, so that the constituent units are linked and function cooperatively. There are five important dimensions of integration in N management, namely:

(a) Cause and effect;

(b) Spatial and temporal integration of all N forms and sources;

(c) Multiple nutrients and pollutants;

(d) Multiple stakeholder types, involvement and integration; and

(e) Regional integration. These dimensions build on earlier description (Oenema and others, 2011b) and are discussed further below.

1. Cause and effect

76. This dimension is a basis of all current N policies, as the human health effects and ecological impacts of the pollution caused by N emissions provide the justification for and underpin the policy measures to decrease such emissions.

77. The "cause and effect" or "source and impact" dimension is also related to the DPSIR framework (see European Environment Agency, 1995). This framework provides insights into cause-effect and economic-environmental relationships, as well as the possible responses of societies and Governments.

2. Spatial and temporal integration of all N forms and sources

78. Spatial and temporal integration in N management relates to combining all N forms, N sources and N emissions within a certain area and timescale in the management plan. Partial forms of this type of integration are contained in the Gothenburg Protocol; for example, most NO_x and NH_3 sources have been included, but NO_x emissions from agricultural soils, (semi-) natural NO_x and NH_3 sources, N_2O emissions to air and N leaching to waters are, as yet, not included when assessing compliance with emission reduction commitments. Similarly, in the European Union Nitrates Directive, all N sources in agriculture have to be considered for reducing NO_3 leaching to waters, but NH_3 and N_2O emissions to air are not addressed explicitly. The European Union Birds Directive[8] and Habitats Directive[9] require all N forms, N sources and N emissions to be addressed in so far as they are factors influencing the ecological requirements of protected habitats and species. The emission of gaseous N_2 through denitrification is not directly considered in any of these policies. Although emission of gaseous N_2 does not lead directly to adverse environmental effects, its release can be considered as a waste of the energy used to produce N_r, as well as a lost resource of useful nitrogen, indicating the need for N_2 emissions to also be addressed. These issues were recently raised in United Nations Environment Assembly resolution 4/14 on sustainable nitrogen management (see UNEP/EA.4/Res.14) and its follow-up in the Colombo Declaration (UNEP, 2019).

79. Conceptually, the N cascade model (Galloway and others, 2003; 2004) is a good example of spatial integration operating over different timescales, but this model has yet to be made operational for management actions. The N cascade is a conceptual model for analysing cause and effect integration, especially when cost-benefit analyses are included.

3. Multiple nutrients and pollutants

80. There are two main reasons to integrate N management with that of other specific elements (compounds) in environmental policy, namely:

(a) The other elements (compounds) may cause similar environmental effects; and

(b) Interactions between N species and these other elements and compounds may be large.

81. From a practitioner's point of view, there can be benefits when managing N and other specific elements simultaneously. This holds true, for example, for N and phosphorus (P) in agriculture and sewage waste treatment, and for NO_x and SO_2 and PM from combustion sources.

82. This type of integration is included partially in the Gothenburg Protocol and the European Union National Emission Ceiling Directive,[10] which address emissions of NO_x, NH_3 and SO_2 to air, because these emissions contribute to rather similar environmental effects (air pollution, acidification, eutrophication). Similarly, emissions of N and P to

[8] Directive 2009/147/EC of the European Parliament and of the Council of 30 November 2009 on the conservation of wild birds, *Official Journal of the European Union*, L 20 (2010), pp. 7–25.

[9] Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora, *Official Journal of the European Communities*, L 206 (1992), pp. 7–50.

[10] Directive (EU) 2016/2284 of the European Parliament and of the Council of 14 December 2016 on the reduction of national emissions of certain atmospheric pollutants, amending Directive 2003/35/EC and repealing Directive 2001/81/EC, *Official Journal of the European Union*, L 344 (2016), pp. 1–31.

surface waters both contribute to eutrophication and biodiversity loss, and thus European Union policies related to combatting eutrophication of surface waters address N and P simultaneously (for example, in the European Union Water Framework Directive).[11] Furthermore, the N and carbon (C) cycles in the biosphere are intimately linked, and perturbations of these cycles contribute to changes in the emissions of the greenhouse gases CO_2, CH_4 and N_2O, which are commonly addressed by climate change policies simultaneously. Nitrogen may also affect CO_2 and CH_4 emissions through its effect on C sequestration in the biosphere and by alteration of atmospheric chemistry (Butterbach-Bahl, Kiese and Liu, 2011a). Because of its multiple effects across all these issues, a focus on nitrogen management can serve to connect the multiple impacts and effects. Linking between the various nitrogen forms (N_2, NH_3, N_2O, NO_x, NO_3– , etc.) serves as a manageable next step in integration. In addition, it provides a framing that demonstrates the multiple linkages between the cycles of N, C, P, sulphur (S), potassium (K), silicon (Si) and many other elements, including micronutrients.

4. Multiple stakeholder types, involvement and integration

83. Any N management policy, whether integrated or not, needs to be:

(a) Policy-relevant – for example, address the key issues;

(b) Scientifically and analytically sound

(c) Cost effective – for example, costs have to be in proportion to the objective to be achieved; and

(d) Fair to users.

84. When one or more of these principles is not respected, the management policy will be less effective, either because of a delay in implementation or through poor implementation and performance, or a combination of those factors. Successful application of the above-mentioned principles requires communication between actors from policy, science and practice. The credibility and relevance of science-policy-practice interactions are, to a large extent, determined by "boundary" work at an early stage in the communication process between policy, science and practice (Tuinstra, Hordijk and Kroeze, 2006; Clark and others, 2016). Boundary work is defined here as the practice of maintaining and withdrawing boundaries between science, policy and practice, thereby shaping and reshaping the science-policy-practice interface.

85. Communication with stakeholders (for example, fertilizer manufacturers, food producers, processing and retail, society at large) is extremely important. Such stakeholders' views must be integrated as early as possible during the design phase of N management plans and measures, notably for advisors and the practitioners who, in the end, have to implement the management measures. Integration of stakeholders' views may range from public consultation procedures and hearings to participatory approaches and learning. A good example of the latter approach is the European Union Water Framework Directive, which requires full stakeholder involvement for the establishment of river basin management plans.

86. Integration of stakeholders' views does not lead to faster decision-making; on the contrary, the decision-making process often takes more time. Public consultation procedures can be time-consuming, although techniques such as multi-criteria decision-making may support decision-making effectively. This approach aims to find a way out of conflicts and solutions in a transparent process. Integration of stakeholders' views may ultimately improve acceptance of management strategies, and thereby facilitate their implementation in practice.

5. Regional integration

87. Regional integration or "integration of larger spatial scales" is considered here as the fifth dimension of integration. Regional integration aims at enhanced cooperation between

[11] Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy, *Official Journal of the European Communities*, L 327 (2000), pp. 1–72.

regions and landscapes. It relates to integration of markets and harmonization of governmental policies and institutions between regions through political agreements, covenants and treaties (Bull, Hoft and Sutton, 2011). Arguments in favour of regional integration include:

(a) Enhancement of markets;

(b) Creation of a "level playing field" for policy measures;

(c) The transboundary nature of environmental pollution;

(d) Consideration of indirect pollution effects; and

(e) The increased effectiveness and efficiency of regional policies and related management measures.

88. In terms of N management, regional integration relates, for example, to the harmonization and standardization of environmental policies across the European Union and for air pollution across the UNECE region (Bull, Hoft and Sutton, 2011). The river basin or catchment management plans developed within the framework of the European Union Water Framework Directive are also a form of regional integration. Here, water quantity and quality aspects are considered in an integrated way for a well-defined catchment. The European Union Marine Strategy Framework Directive[12] also promotes integration at the regional level by ensuring consistent determinations of good environmental status and targets under its fifth qualitative descriptor (eutrophication) (see annex I to Marine Strategy Framework Directive) and coordination of programmes of measures, supported by regional sea conventions such as the Helsinki Commission for Baltic Marine Environment Protection (HELCOM) and the Convention for the Protection of the Marine Environment of the North-East Atlantic.

89. The trend towards regional integration during recent decades does not necessarily mean that local management actions are less effective and/or efficient. Local actions can be made site-specific and, as a consequence, are often more effective than generic measures. This holds true for households, farms and businesses, especially when actors can have influence on the choice of actions. In addition, motivation for contributing to the local environment and nature protection can be greater than that for contributing to the improvement of the environment in general.

C. Key points of nitrogen cycling

90. This section describes the key points of N cycling in the biosphere that underpin the N cycle in relation to agricultural practice. These key points provide the starting point from which to consider the principles of sustainable nitrogen management described further on in this document. "Principles" are understood here as "fundamental truths" and/or "well-established scientific and practical knowledge" that should be familiar to all practitioners, N managers and policymakers. The key points of nitrogen cycling also represent informing principles.

91. Ten key points related to N cycling are distinguished below. These form a "bridge" between this section and the next section, which deals with the principles of integrated N management in agriculture:

Key point 1. Nitrogen is essential for life.

92. Nitrogen forms a key element of chlorophyll in plants, of haem in blood, and of amino acids (protein), nucleic acids and adenosine triphosphate in living organisms (including bacteria, plants, animals and humans). The natural nitrogen cycle is characterized by limited availability of nitrogen forms for living organisms; therefore the natural nitrogen cycle is a nearly closed system, with nitrogen being recycled and reused effectively. Due to this limited availability, nitrogen is often a limiting factor for plant growth. The competition between

[12] Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy, *Official Journal of the European Union*, L 164 (2008), pp. 19–40.

plant species for the limited amounts of available N (and other growth-limiting elements) is a main factor for biodiversity in natural systems.

93. In agricultural systems, significant crop-yield responses can be obtained when N is added as animal manure or fertilizer, especially when application is balanced with other key nutrients . It has been estimated that around half of the world's population is now alive because of the increased supply of fertilizer N, illustrating the massive impact that N has had in meeting human food needs, thereby allowing the world population to expand rapidly (Erisman and others, 2008; Sutton and others, 2013). Forecasts suggest that more N will be needed during the next few decades if current diets are to be matched with population increases, especially in Africa and parts of Asia (Godfray and others, 2010);

Key point 2. Excess nitrogen has a range of negative effects, especially on human health, ecosystem services, biodiversity, water and climate change.

94. The total amounts of N introduced into the global biosphere by human activities have significantly increased during the last century, more than doubling (Galloway and others, 2008), and have now exceeded critical limits for the so-called safe operating space for humanity (Steffen and others, 2015). The deleterious effects of excess N on human health and biodiversity are most apparent in regions with intensive agriculture, especially intensive animal husbandry, urban areas and in large rivers and coastal areas. Nitrogen has both warming and cooling effects on climate (Butterbach-Bahl and others, 2011b), while also contributing to stratospheric ozone depletion (Alcamo and others, 2013). The negative effects of excess N_r in the environment provide the justification for N emission-abatement policy measures;

Key point 3. Nitrogen exists in multiple forms.

95. Nitrogen is transformed from one form to another through biochemical processes, mediated by microorganisms, plants and/or animals, and through chemical processes, mediated by increased temperature and pressure, atmospheric light and possible catalysts (Smil, 2004; Hatfield and Follett, 2008; Schlesinger and Bernhardt, 2013).

96. This has a number of implications: most nitrogen forms are "reactive", because these forms are easily transformed in the biosphere into another form through biological, photochemical and radiative processes. Reactive nitrogen compounds (N_r) include:

(a) Inorganic reduced forms, such as ammonia (NH_3) and ammonium (NH_4+), collectively (NHx);

(b) Inorganic oxidized forms (for example, NO_x, nitric acid (HNO_3), nitrous acid (HONO), nitrous oxide (N_2O), nitrite (NO_2-) and nitrate (NO_3–);

(c) Organic reduced forms, such as urea, amines, proteins and nucleic acids.

97. Reduced forms are energy donors, proton donors and electron acceptors; energy is captured forms from industrial processes and biological nitrogen fixation, meaning that NH_x is an important resource. Oxidized forms are proton acceptors and electron donors. One reduced form, dinitrogen (N_2), is not reactive (it is chemically extremely stable), because a lot of energy is needed to break the bonding between the two N atoms;

98. **Nitrogen is "double mobile"**, because some forms are easily transported via air and water. All gaseous and liquid N_r forms are toxic to humans and animals (and plants) when exposure occurs to sufficiently high concentrations. The toxic concentration levels greatly differ between forms and among organisms:

(a) Nitrogen is transported in the air as gases, such as dinitrogen (N_2), nitrous oxide (N_2O), NO_x (including NO and NO_2), nitric acid (HNO_3), nitrous acid (HONO) and ammonia (NH_3), amines and other volatile organic nitrogen (VON) and as aerosols, including fine PM formed from among other things, nitrate (NO_3–), ammonium (NH_4+) and particulate organic nitrogen (PON);

(b) Nitrogen is transported dissolved in water as nitrate (NO_3–), ammonium (NH_4+), urea ($CO(NH_2)_2$), dissolved organic nitrogen (DON) and nitrous oxide (N_2O), and is transported suspended in water as particulate organic nitrogen (PON);

Key point 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.

99. This phenomenon is called the “nitrogen cascade”, which has been defined as the sequential transfer of N_r through environmental systems and which results in environmental changes as N_r moves through or is temporarily stored within each system (Galloway and others, 2003).

Key point 5. Nitrogen moves from soil to plants and animals, to air and water bodies, and back again, and from one region to another, as a result of natural drivers and human activities, which have to be understood for effective N management.

100. The natural drivers are:

(a) Solar radiation, which drives photosynthesis, the hydrological cycle, wind and temperature differences, and mass flow in air and water;

(b) Gravitation, which drives the earth movement and erosion;

(c) Earth tectonics, which drives earthquakes and volcanisms;

(d) Lightning and biological nitrogen fixation, which form reactive N;

(e) Turbulent diffusion, molecular diffusion and Brownian motion, which drive gas and particulate dispersion.

101. The cycling rate and residence times in air, water and soil differ greatly between N forms. In the atmosphere, gases such as NH_3, NO_x, and HONO have a short residence time in air (days, weeks), while N_2O remains in the atmosphere for more than a century and N_2 even longer. Residence times are related to the reactivity of the N forms. In water systems, nitrogen residence times may range from years to many centuries depending on the nature of the aquifer and groundwater storage;

Key point 6. Human activities have greatly altered the natural N cycle and have made the N cycle more leaky.

102. Land-use change, urbanization, the creation of inorganic N fertilizer, and the globalization of food systems are among the most fundamental changes created by human activities (Vitousek and others, 1997; Fowler and others, 2013). Urbanization and the globalization of food systems have resulted in increased transport of food and feed produced in rural areas (where nitrogen depletion occurs) and to areas where food and feed are being utilized, especially in urban areas and in areas with livestock (where regional nitrogen enrichment occurs). The regional spatial segregation of food and feed production and consumption is also one of the key factors why N use efficiency at whole food system level has decreased in the world during the last decades (Lassaletta and others, 2014; Oita and others, 2016).

Key point 7. The nature and human alterations of the N cycle challenge the realization of both a circular economy and integrated sustainable N management; policymakers and decision makers from both areas may learn from each other.

103. Many principles of the “circular economy” and “circular systems” also apply to the principles of integrated sustainable N management, including the principles of:

(a) Reduction of losses;

(b) Reduction, reuse and recycling of wastes;

(c) Realignment and reduction of inputs;

(d) Reconsideration of protein consumption levels (for example, minimization of excess); and

(e) Changing systems to make them less leaky and more resilient.

104. The concept of the “nitrogen circular economy” (Sutton and others, 2019), and circularity more generally, originate from industrial ecology (Jurgilevich and others, 2016),

which aims to reduce resource consumption and emissions to the environment by closing the loop of materials and substances, including N and other nutrients. Increasing circularity in food production requires a rethink of economic growth, human diets, agricultural policy and regulations related to fertilizers and food waste (De Boer and van Ittersum, 2018).

Key point 8. Most of the nitrogen in plants is taken from soil via roots in the form of nitrate (NO_3-) or ammonium (NH_4+), indicating that the NO_3- and NH_4+ need to be in the vicinity of plant roots and available at the right time to be effective for plant growth.

105. The N uptake depends on the N demand by the crop, the root length density and distribution and the concentrations of NO_3– and NH_4+ in the soil solution. The N demand by the crop depends on crop type and variety and climate. The uptake rate of N in plants commonly follows Michaelis–Menten kinetics. This implies that a maximum rate is achieved at a saturating substrate (NO_3–, NH_4+) concentration, so that surplus N is not used and at risk of being wasted as pollution (following the law of diminishing returns). Both the demand for N of the crop and the supply of N via the soil are influenced by soil and weather conditions and management. Dominant sources of NO_3– and NH_4+ in soil are:

(a) Mineralization of organically bound nitrogen in soil;

(b) Inputs via atmospheric deposition;

(c) Inputs via animal manure, compost and wastes; and

(d) Inputs via inorganic N fertilizers (Marschner, 2012).

106. However, some N (for example, gaseous NH_3 and NO_2 from ambient atmospheric deposition) may be taken up directly by plant leaves (Sutton, Schjørring and Wyers, 1995; Sparks, 2009). In unfertilized agroecosystems, forests and natural habitats, mycorrhizae (soil fungi living in association with plants) can play an important role in bringing nutrients to plant roots. High levels of external nitrogen input can affect the performance of such mycorrhizal symbioses.

Key point 9. Some crop types are able to convert non-reactive dinitrogen (N_2) from air into reactive N forms (amine, protein) in the plant roots through association with specialist blue green bacteria. This biological N fixation is an important source of reactive N in the biosphere, including agriculture.

107. Important crops include the legume family (Fabaceae or Leguminosae) with taxa such as (soy)beans, peas, alfalfa, clover and lupins. They contain symbiotic bacteria, especially rhizobia, within nodules in their root systems, which are able to convert N_2 into NH_3 from which amines are produced (Herridge, Peoples and Boddey, 2008). The N_2 fixation rate depends on the availability of NO_3– and NH_4+ in soil; the fixation rate is suppressed when the availability of NO_3– and NH_4+ in soil is high, and vice versa. The fixation rate also depends on the availability of substantial chemical energy (carbohydrates) and other essential nutrient elements, including phosphorus, calcium and molybdenum. Non-symbiotic N_2 fixation by free-living soil microorganisms can represent an additional input of reactive N to the ecosystems (Ladha and others, 2016).

Key point 10. Humans and animals require protein-N and amino acids for growth, development and functioning, but only a minor fraction of the N is retained in the growing body weight and/or milk and egg.

108. The remainder is excreted, mainly via urine and faeces, and this N can be recycled and reused. The protein N need (or amino acid requirements) of animals mainly depends on animal category, body weight, growth rate, milk and egg production, activity (labour, grazing) and reproduction (McDonald and others, 2010; Suttle, 2010). The N retention in animal production is strongly dependent on animal breed, feed quality, age and herd management, and commonly ranges from 5 to 15 per cent in beef production, 15 to 30 per cent in dairy production, 25 to 40 per cent in pork production and 40 to 50 per cent in poultry production (Gerber and others, 2014). The remainder is excreted as urea in urine (uric acid in poultry) and in animal manure. Typically, half of N excretion is in the form of urea (and

ammonium (NH_{4+})) and half in organically bound form, depending on the protein content of the feed. Animal manure and urine provide a valuable source of nutrient elements and organic C in natural and agricultural systems. However, animal manures and urine are also main sources of ammonia (NH_3) and nitrous oxide (N_2O) emissions to air, and of N leaching to groundwater and surface waters, depending on management and environmental conditions.

D. Principles of integrated sustainable nitrogen management in agriculture

109. Twenty-four principles of integrated sustainable nitrogen management are identified:

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 nitrogen inputs.

110. As the key input, along with water, the importance of N for food security cannot be overstated. The effectiveness of integrated sustainable N management in agriculture can be assessed through applying consistent metrics (see box III.1 below).

Principle 2: There are various actors in agriculture and the food chain, and all have a role and responsibility in N management.

111. These actors include:

(a) Suppliers of fertilizers, feed, germplasm, seed, machinery and loans;

(b) Advisors, extension services, accountancy specialists and financial organizations;

(c) Farmers;

(d) Product handling and processing industries (crop products, dairy, meat, manure);

(e) Retail organizations;

(f) Consumers;

(g) Governments and NGOs, including food testing; and

(h) Scientists.

112. Evidently, farmers have a direct role to play in N management, in enhancing N use efficiency and in minimizing N losses to the environment. Therefore, farmers reap the economic benefits and bear the burdens of the measures needed to decrease N losses. Incorporation of certain N measures offers net economic benefits that can contribute to farm business planning and circular economy development. For other measures, the costs of implementation exceed the agricultural benefits arising from the greater retention of N in the agricultural system, and may only be justifiable from an environment, health and climate perspective. The net costs are as yet difficult to transfer to (spread over) other actors in the food production – consumption chain, because farmers have little or no “market power” in a globalized food system. Farmers may be reluctant to implement costly measures to reduce N losses because they want to maximize income and fear losing competitiveness relative to farmers who do not implement measures. Providing access to funding/financing via appropriate instruments may therefore need to be considered as part of the policy to support the transition to more integrated sustainable nitrogen management. **There is thus 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. This should be done in concert with other critical policies, including mitigating climate change.**

Principle 3: Specific measures are required to decrease pathway-specific N losses.

113. The dominant N loss pathways in agriculture are:

(a) NH_3 volatilization;

(b) Downward leaching of (mainly) nitrate to groundwater and then to surface waters;

(c) Overland flow and erosion of basically all N forms to surface waters; and

(d) Nitrification-denitrification processes combined with the gaseous emissions of NO_x, N_2O and N_2.

114. These pathways are influenced by a complex of controlling factors, including the availability and form of N sources, climate, soil and geomorphological/hydrological conditions and management. **Pathway-specific measures have to consider pathway-specific controlling factors** (Hatfield and Follett, 2008; Bittman and others, 2014; UNEP, 2013).

Box III.1

Metrics for assessing the effectiveness of integrated sustainable nitrogen management.

One of the core purposes of integrated sustainable nitrogen management in agriculture is to decrease N losses to the environment to protect human health, ecosystems, climate and other aspects of economy and sustainability, while ensuring adequate crop and animal production (Principle 1).

Indicators to reflect this principle have been proposed by the European Union Nitrogen Expert Panel (Oenema and others, 2015), with a focus on Nitrogen Use Efficiency (NUE):

NUE = Sum of N outputs / Sum of N inputs (percentage, per cent)

N surplus = Sum of N inputs – Sum of N outputs (kg N /ha /yr)

N in harvested or other utilized outputs (kg N /ha /yr)

Evidently, a high NUE indicates that N input is being used efficiently. A low N surplus indicates that the potential for N loss and impacts on the environment is low, with a large part of the N input recovered in N in harvested products. The approach is relevant from multiple perspectives, for crops, livestock, agrifood system and across the economy (Bleeker and others, 2013; Sutton and others, 2013; Westhoek and others, 2015; Erisman and others, 2018).

The effects of measures aimed at the abatement of specific nitrogen loss pathways are commonly expressed in terms of abatement efficiency (AE), reduction in N loss and overall change in NUE:

AE = (Unabated N loss – Abated N loss) / Unabated N loss (percentage, per cent)

Total reduction in N loss (kg N /ha /yr)

Change NUE = (NUE revised – NUE reference) / NUE reference (percentage, per cent)

Another approach focused on reducing overall environmental impact considers global and national reduction in total "nitrogen waste", this being the sum of all nitrogen losses to the environment (including N_2 and all N_r forms). This approach is reflected in the ambition of the Colombo Declaration (UNEP, 2019; Sutton and others, 2019) to "halve nitrogen waste" from all sources, as a contribution to achieving the United Nations Sustainable Development Goals:

$$\text{Reduction in total N waste} = \frac{(\text{Reference N waste} - \text{Revised N waste})}{\text{Reference N waste}} \quad \text{(percentage, \%)}$$

Whereas AE focuses on the performance of specific measures on each form of N loss, the reduction in total N waste emphasizes the benefit of all reductions in N losses, by all approaches at national, regional and global scales. Further work is needed to agree international protocols for each of these indicators to assist countries in preparing data sets and to enable informed comparison of different indicator values and target values.

Principle 4: Possible trade-offs in the effects of N loss abatement measures may require priorities to be set, for example, which adverse effects should be addressed first.

115. In practice, the outcome will depend on a quantification – a small negative effect of one kind may be tolerated when there is a huge improvement elsewhere – and on policy guidance on how to compare the importance of issues (for example, N eutrophication versus greenhouse gas emissions through N_2O emissions versus human health effects through NH_3 emissions and associated formation of small particles $PM_{2.5}$ (Sutton and others, 2011)). There may also be non-N agricultural trade-offs, and even non-agricultural trade-offs. 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.

116. These are attractive measures to decrease N losses in an integrated manner, because reductions in nitrogen input (for example, by avoidance of excess fertilizer, of excess protein in animal diets, and of any human foods with high nitrogen footprint) lead to less nitrogen flow throughout the soil-feed-food system, reducing losses of all forms of nitrogen pollution. For example, Westhoek and others (2015) showed that halving meat and dairy intake by European citizens (which is currently in excess of health needs) would reduce nitrogen pollution by 40 per cent (for NH_3) and by 25–40 per cent (for N_2O and NO_3^- leaching) in the absence of any technical measures. The reason for the range for N_2O and NO_3^- is that substantial agricultural land would also be liberated for other purposes, allowing alternatives such as increased crop production for export (net 25 per cent abatement) or "greening measures", which deliver the maximum reduction in nitrogen pollution (net 40 per cent abatement). Further assessments are needed to consider the impact of consuming unessential, non-livestock-based foods and beverages.

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.

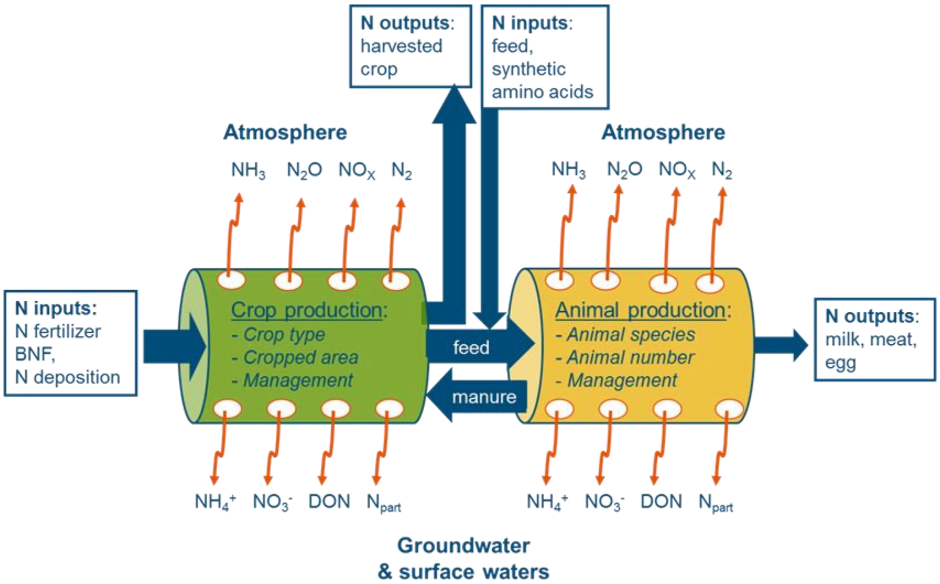
117. This means that reducing one form of N loss involves the risk of increasing other forms of N losses, sometimes termed "pollution swapping", unless inputs and outputs (including N storage in soils) are changed. In order to realize the benefit of a measure to reduce N losses (and to avoid pollution swapping), the nitrogen saved by the measure needs to be matched by either reduced N inputs or increased N in harvested outputs (including N storage in soil). Reduced N inputs or increased harvested outputs are thus an essential part of integrated nitrogen management, while providing opportunity for increased economic performance (Oenema and others, 2009; Quemada and others, 2020).

Principle 7: The N input-output balance encapsulates the principle that "what goes in must come out", making it a key indicator of N management.

118. Based on the law of mass conservation, inputs must match outputs or be temporarily stored within the farm system. Hence, N input = N output in harvested products (+ temporal N storage) – N losses (see figure III.1 below). It illustrates also that N input control is a main mechanism to reduce N losses. It also allows for strategies based on maximization of N in storage pools, including in manure, soil and plants (for example, by promoting plant uptake of N). Internationally agreed protocols are needed for making these N input-output balances; N inputs and N outputs must be recorded in a uniform manner to allow fair comparisons between farms and regions, and to circumvent bias.

Figure III.1

Concept of the nitrogen input – output mass balance of mixed crop – livestock production systems



Source: Modified from Oenema and others (2009).

Note: The "hole-in-the-pipe" model (after Firestone and Davidson, 1989) illustrates the "leaky N cycle" of crop and animal production; it shows the fate of N inputs in agriculture. Inputs and outputs in useful products and emissions to air and water show dependency in crop production and animal production; a change in the flow rate of one N flow has consequences for others, depending also on the storage capacity of the system. Total inputs must balance total outputs, following corrections for possible changes in storage within the system. The concept is applicable at field, farm, regional and global scales for all types of farms (Oenema and others, 2009).

Principle 8: Matching nitrogen inputs to crop-needs (also termed "balanced fertilization") and matching protein N inputs to livestock needs offers opportunities to reduce all forms of nitrogen losses simultaneously that can help to improve economic performance at the same time.

119. Hence, increasing "partial factor productivity" (defined as harvest output per unit of N input) increases N use efficiency and reduces all forms of N losses. This follows directly from the above-mentioned law of mass conservation. Furthermore, the law of diminishing returns must be considered when matching N inputs to crop needs; with increasing N input, crop yield and N uptake increase only marginally, while N losses tend to increase progressively. These basic principles equally hold true for crop and animal production and overall food production.

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 (including with the aid of precision farming techniques and tools).

120. The surface of land is often sloping and soils are often heterogeneous in nature, while the weather is variable and uncertain, which indicates that crop growth conditions, soil N delivery and N loss pathways are variable in space and time. Such spatially diverse conditions can only be addressed by locally fine tuning agricultural management techniques (such as "precision farming" techniques, where management actions are adjusted for each field location) and use of site-specific emission-abatement measures. This principle is applicable to field application of both organic and inorganic fertilizer resources (see chapter V).

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.

121. A source-pathway-receptor approach may help to target specific hot spots, specific N loss pathways and specific sensitive areas. This holds true especially for natural habitats that are sensitive to N loading in an agricultural landscape with intensive livestock farms; the latter are likely hot spots for NH_3 emissions, while the natural habitats are likely highly sensitive to N inputs via atmospheric deposition. The same principle applies to drinking water reservoirs, pristine lakes, streams and coastal waters; these need special protection to prevent pollution. This principle underlies added benefits from landscape-level N management (see chapter VI).

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.

122. This principle equally applies to unfertilized buffer strips and riparian zones along N sensitive watercourses. Woodlands and unfertilized agricultural land are land-uses with capacity to absorb and recycle (utilize) N inputs from atmospheric N deposition (for example, Dragosits and others, 2006; cf. chapter VI). Border areas and transition zones also offer habitat for biodiversity in an agricultural landscape for vulnerable organisms such as pollinators. 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) can 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). However, woodland soils receiving high N deposition over the long-term may transform from a sink to a source of Nr pollution; for example, emitting NO_x (Luo and others, 2012; Medinets and others, 2019). This also holds true for buffer strips and riparian zones along water courses; the capacity to utilize or store reactive N and/or to transform reactive N into N_2 may change over time (chapter VI).

Principle 12: In order to minimize pollution associated with N losses, all factors that define, limit and reduce crop growth need to be addressed simultaneously, and in balance, to optimize crop yield and N use efficiency.

123. Crop yield, N uptake and N use efficiency depend on:

(a) Yield-defining factors (crop type and variety, climate);

(b) Yield- limiting factors (availability of all 14 essential nutrient elements and water, and soil quality); and

(c) Yield-reducing factors (competition by weeds, incidence of pest and diseases, occurrence of highly soluble salt and/or toxic compounds in soil, and air pollution (for example, ozone) (van Ittersum and Rabbinge, 1997).

124. According to the Law of the Optimum, the yield-enhancing effect of nitrogen is largest when all yield-defining factors are at optimal levels, and yield-limiting and -reducing factors are nullified (De Wit, 1992). This will thus have an impact on N losses to the environment. Hence, optimizing yield and N use efficiency and reducing N losses in crop production requires an integrated approach:

(a) Selecting high-yielding crop varieties, adapted to the local climatic and environmental conditions;

(b) Preparing seedbeds according to crop seed type prior to seeding/planting and providing adequate levels of all essential nutrient elements and water; and

(c) Ensuring proper weed control, pest and disease management and pollution control.

125. As a result of the complex factors involved, yield optimization remains challenging. For example, the important beneficial and negative effects of crop sequences are not fully understood. There are emerging issues of pesticide resistance, invasive species, climate change, etc.

Principle 13: In order to minimize pollution associated with N losses, all factors that define, limit or reduce animal growth have to be addressed simultaneously and in balance to optimize animal production and N use efficiency, which can also decrease N excretion per unit of animal produce.

126. Animal production and N retention in animal products also depend on:

(a) Yield-defining factors (animal species and breed, climate)

(b) Production-limiting factors (feed quality, availability of all 22 essential nutrient elements and water); and

(c) Production-reducing factors (diseases, fertility, toxicity, air pollution, for example, ammonia, H2S, ozone).

127. According to the Law of the Optimum, optimizing animal production and N use efficiency in animal production and decreasing N losses requires an integrated approach:

(a) Selecting animal species and breeds adapted to the local climatic and environmental conditions;

(b) Ensuring availability of high-quality feed and water, good feeding management and herd management; and

(c) Ensuring proper disease, health, fertility and pollution control, including animal welfare aspects (McDonald and others, 2010; Suttle, 2010).

128. Optimization must take into account the reproductive phase, including the number of lactations, conception rates, birth weight, etc. This principle and the previous one hold true equally well for mixed crop and animal production systems.

Principle 14: Slowing down hydrolysis of urea and uric acid containing resources helps to reduce NH_3 emissions.

129. Hydrolysis of these resources produces NH_3 in solution and increases 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. This principle underlies several measures in manure and fertilizer management. For example, immediate separation of urine from faeces can reduce NH_3 emissions because urine contains most urea, while faeces are rich in the enzyme urease that breaks down urea to release CO_2 and NH_3. The same principle underlies the benefit of keeping poultry litter dry to avoid breakdown of uric acid, which similarly releases NH_3. “Urease inhibitors” are substances added to urea fertilizer to reduce NH_3 and other N losses. By reducing the effectiveness of the urease enzyme, these products slow down urea hydrolysis (Bitmann and others, 2014).

Principle 15: Reducing the exposure of ammonium-rich resources to the air is fundamental to reducing NH3 emissions.

130. Hence, reducing the surface area and covering ammonium-rich resources reduces NH_3 emissions. Lowering the pH (to ≤6.5) of ammonium-rich resources also lowers NH_3 emissions. Lowering the temperature of ammonium-rich resources and the wind speed above the surface also reduces NH_3 emissions. All these emission-abatement techniques must be applied with consideration to a whole manure management chain approach, to minimize the loss at later stages of any N retained during the first part of the management chain (Bittman and others, 2014).

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.

131. Because of its positive charge, NH_4^+ can be held in soil (depending on the cation exchange capacity of the soil). This means that NH_4^+ is less mobile and less vulnerable to losses via leaching and nitrification-denitrification processes than NO_3^-, the other dominant N form in soil utilized by crops. Therefore, promoting conditions that slow down the biological oxidation of NH_4^+ to NO_3^- may contribute to a reduction of N losses and to increasing N use efficiency. Synthetic nitrification inhibitors and biological nitrification inhibitors exuded by plant roots and leaves slow down nitrification and help conserve N in the system and thereby may increase N use efficiency. However, the possible (long-term) side effects on soil health (including the soil microbial community) of such strategies have to be considered (Medinets, and others, 2015; Lam and others, 2017; Coskun and others, 2017; Norton and Ouyang, 2019).

Principle 17: Some measures aimed at reducing N_2O emissions may also reduce losses of N_2, since both are related to denitrification processes.

132. Conversely, measures aimed at minimizing denitrification to N_2 may also reduce N_2O emissions. Nitrogen losses from agriculture via the greenhouse gas N_2O represent a relatively small loss, but N_2O is a potent greenhouse gas and contributes to the depletion of stratospheric ozone (UNEP, 2013). The associated N_2 loss via nitrification-denitrification represents a much larger loss of N resources, although N_2 losses do not have a direct negative effect on the environment. Hence, measures aimed at jointly reducing N_2O and N_2 losses from nitrification-denitrification processes may contribute to saving N resources within the system 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.

133. This requires consideration of system-wide changes in human diets, livestock diets, management of fertilizer and biological and recycled nitrogen resources. 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 ambitious reduction targets for climate and stratospheric ozone (Oenema and others, 2013; UNEP, 2013; Cayuela and others, 2017; Thompson and others, 2019). At the same time, a focus on improving full system efficiency provides a positive approach that highlights the economic, environment and health co-benefits.

Principle 19: Strategies aimed at jointly decreasing N, P and other nutrient losses from agriculture are expected to offer added abatement/mitigation benefits compared with single nutrient emission-abatement strategies, because of the coupling between nutrient cycles.

134. For example, interactions between N and P affect the efficiencies of N and P use in crop and animal production, as well as their impacts on the eutrophication of surface waters. A suboptimal availability of P limits the uptake and utilization of N and P in crop and animal production and may limit eutrophication effects of N in surface waters. Conversely, a suboptimal availability of N limits the uptake and utilization of P in crop and animal production and may limit the eutrophication effects of P in surface waters (Conley and others, 2009). However, overoptimal availability of N and P decreases both N and P use efficiencies, greatly increases the risk of both N and P losses, and exaggerates their eutrophication effects in surface waters. Furthermore, total losses of both N and P have already been estimated to exceed "planetary boundaries", which indicates that both N and P losses have to decrease greatly (Steffen and others, 2015; Springmann and others, 2018). While these points illustrate scientific reasons for linked management of nutrient cycles (Sutton and others, 2013), there are also social and political barriers that must be addressed, related to the development of multisector narratives (air, water, climate, etc.) and sector sensitivities concerning mobilization of change. In this way, 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 in semi-arid and arid conditions.

135. Interactions between N and water affect the N and water use efficiencies in crop production, as well as affecting all N loss pathways (Quemada and Gabriel, 2016). A suboptimal availability of water limits the uptake and utilization of N in crop production, and can reduce N leaching and denitrification losses, according to soil characteristics; it may lead to accumulation of nitrate-N in soil. In addition, rainfall and sprinkler irrigation may reduce N losses via NH_3 volatilization from urea fertilizers and animal manures applied to land (Sanz-Cobena and others, 2011). Conversely, a suboptimal availability of N limits water use efficiency in crop production. The joint coupling of N and water management also underlies the safe storage of solid manures to avoid run-off and leaching. However, an overoptimal availability of N and water decreases both N and water use efficiencies, and greatly increases the risk of N losses via leaching, erosion and denitrification. Application of targeted amounts of water and N through drip irrigation (fertigation) in semi-arid regions has the potential to greatly increase N and water use efficiencies simultaneously, and to minimize N losses. Furthermore, crop yields at the global scale are mostly limited by the availability of both water and N (Mueller and others, 2012). 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, and where food production has to increase to meet the demands of the growing human population (Godfray and others, 2010). Irrigation must be used judiciously to conserve water and to avoid soil salinization, especially on fine textured soils.

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 C and soil quality over time and the impacts of soil C sequestration strategies.

136. The carbon-to-nitrogen ratio in organic matter in soil ranges roughly from 10 to 15 (exceeding 30 in organic soils). This rather narrow range has a number of implications. First, C sequestration in soil aimed at reducing carbon dioxide (CO_2) emissions to the atmosphere and improving soil quality is associated with N sequestration in soil. If this results in a lower C:N ratio and hence a higher turnover of N in the soil, there is a risk that this could increase losses of N (including direct and indirect N_2O emissions), especially when there is little crop uptake. Second, storing organic C in soil means that the organic C first has to be produced. While this might be achieved by increasing crop production, there is a risk that the management required to increase the input of C to the soil (i.e. crop residues) might result in a reduction in N use efficiency. For example, achieving the objectives of the "4 per 1,000" initiative[13] may lead to a storage of N in soil nearly equivalent to the current annual global N fertilizer use (Van Groenigen and others, 2017). The possible interactions between C and N in soil and the effects of soil quality and N use efficiency must therefore be taken into account in integrated N management strategies (Cassman, 1999). In addition, protection of soil organic matter against degradation by, for example, excessive tillage (N mining) and erosion must have high priority to be able to sustain agricultural productivity, especially in regions with low N input; for example, Africa and Eastern Europe (Boincean and Dent, 2019).

Principle 22: Strategies aimed at reducing NH_3 emissions from animal manures through low-protein animal feeding need to consider the possible impacts of diet manipulations on enteric methane (CH_4) emissions from ruminants.

137. Protein-rich diets are conducive to a relatively high N excretion, and the resulting manures have a high potential for NH_3 volatilization losses. Conversely, low-protein diets are conducive to a relatively low N excretion, and the resulting manures have a low potential for NH_3 volatilization losses. However, some low-protein diets may have relatively high-fibre content, which is conducive to enteric CH_4 production in ruminants (Dalgaard and others, 2015). Methane is a potent greenhouse gas and ruminants are one of the main sources of CH_4 emissions to the atmosphere in the world. Evidently, the aim is to find the optimal protein and fibre levels in the diet of ruminants, to minimize both NH_3 and CH_4 emissions

[13] See www.4p1000.org.

(Bittman and others, 2014; Hristov and others, 2019; Van Gastelen and others, 2019). For ruminants especially, it is important to balance protein degradability (and possibly tannins) with energy level and availability such as high sugar concentrations, which may also improve palatability and intake. High sugar content may improve the ensiling process thus reducing losses by spoilage.

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.

138. The effectiveness and costs must be examined as much as possible under practical farm conditions and taking particular account of farm size and basic environmental limitations. Management practices need to be tested on-farm and good practices need to be shared among the farming community. Socioeconomic factors, such as the educational and age structure of the farming population, availability of skilled labour and good advice and access to finance, are important. Cost-effectiveness analysis should take into consideration the 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 effectiveness of emission-abatement/mitigation measures will have to be assessed at this level.

139. Interactions between different measures and interactions between N losses and greenhouse gas (GHG) emissions can be assessed well at the whole-farming system level, including consideration of the wider landscape, regional and transboundary interactions.

E. Tools to support integrated nitrogen management

140. The toolbox for developing integrated approaches to N management contains tools that are uniformly applicable, as well as more specific tools suitable for just one dimension of integration. Important common tools are:

(a) Systems analysis;

(b N input-output budgeting;

(c) Integrated assessment modelling and cost-benefit analyses;

(d Food-chain management;

(e) Stakeholder dialogue and communication; and

(f) So called Best Management Practices (BMPs).

141. These tools for integrated nitrogen management approaches in general are briefly discussed below. Specific measures are discussed in chapters IV–VI:

(a) **Systems analysis** represents the starting point for developing integrated approaches, as it provides information that is needed for all dimensions of integration. Systems analysis allows for the identification and quantification of components, processes, flows, actors, interactions and interlinkages within and between systems. It provides a practical tool for discussing integrated approaches to N management. In essence, system analysis encompasses the view that changes in one component will promote changes in all the components of the systems. These types of tools are especially useful at the science-policy-practice interface.

(b) **Nitrogen budgets** allow the comparison of nitrogen inputs and outputs of systems (for example, a farm, a catchment, a country) and of the compartments of these systems. Nitrogen budgets are an indispensable tool as they integrate over N sources and N species for well-defined areas and/or components (Zhang and others, 2020). They allow calculation of the “nitrogen balance”, which is the difference between total inputs and total outputs. The nitrogen balance reflects the amount of N stored or removed from the system plus the N losses from the system to the wider environment. Input-output balances are robust and easy-to-understand management tools for farmers (Jarvis and others, 2011) and policymakers. They are useful in that they help set priorities in optimizing inputs and in reducing unintended losses, also providing the basis for monitoring system efficiency or surpluses likely to be wasted. Nitrogen budgets are flexible tools, but require protocols (such as appropriate default values for N concentrations for various materials) for recording N inputs and N outputs in a uniform manner, so as to allow fair comparisons between farms and across sectors, and to avoid bias (Leip and others, 2011; UNECE, 2013).

(c) **Integrated assessment modelling** allows relationships between emissions, emissions-abatement, environmental impacts and benefits of effects mitigation to be simulated, including consideration of cost-benefit relationships and target setting. Integrated assessment modelling may also analyse the possible effects of responses by society (actors) through scenario analysis. The DPSIR framework can be used as a starting point for conceptually analysing cause-effect relationships; it relates Driving forces of environmental change (for example, population growth, economic growth, technology development), to Pressures on the environment (for example, N_r emissions), to State of the environment (for example, N concentrations in air and waters, and N deposition on natural habitats), to Impacts (for example, human health, biodiversity, economic growth, eutrophication, ecosystems services) to the Responses of society (for example, policy measures, changes in behaviour; EEA, 1995). Examples of integrated assessments include reviews of the Gothenburg Protocol by the Task Force on Integrated Assessment Modelling (TFIAM/CIAM, 2007). Cost benefit analysis (CBA) goes a step further by expressing costs and benefits of policy measures in monetary terms (Hanley and Barbier 2009; OECD, 2018). Strategic environmental assessment (SEA) has also been suggested as a useful tool. SEA is a systematic decision-support process, aiming to ensure that environmental aspects are considered effectively in policy planning and programme making (Fischer, 2007; Ahmed and Sánchez-Triana, 2008). The UNECE Protocol on Strategic Environmental Assessment to the Convention on Environmental Impact Assessment in a Transboundary Context sets legally binding requirements.

(d) **Food-chain assessment and management** relates to the planning and management of activities and information between actors in the whole food production – consumption chain, including suppliers, processing industries, retail, waste-recycling companies and citizens. In essence, food-chain management integrates the supply and demand of information and activities within and across all actors in the whole chain (Erisman and others, 2018). Specific issues relate to:

(i) How to ensure that consumers have access to and are aware of nutritious food, and have information about sustainable food choices;

(ii) How consumers' demands can be met by the producers, in terms of, for example, quality, production methods and N footprint;

(iii) How the costs of emission-abatement measures implemented by producers are remunerated across the actors of the food chain; and

(iv) How food waste and losses can be minimized and how all wastes in the food chain can be recycled back to crop land. This type of chain management is still poorly developed, apart from in specific sectors and food-processing chains.

(e) **Stakeholder dialogue and communication** are indispensable for exchanging actors' views on N management issues. Stakeholder dialogue is the interaction between different stakeholders to address specific problems related to competing interests and competing views on how N and other resources should be used and managed. Communication is both the transferral of information and the means of raising awareness among and explaining the meaning, purpose, targets and actions of integrated approaches to N management to all the actors concerned. Clear communication is important, as there is often ambiguity in the use of the terms "integrated" and "management" and insufficient clarity about the objectives and required actions. Communication (and training) can help make the key concepts transparent and thereby facilitate adoption of targets and implementation of agreed measures in practice.

(f) **Best management practices and abatement/mitigation measures**. The concept of best management practices (BMPs) includes best available techniques (BATs) and best system practices (BSPs). In the case of nitrogen, they encompass a set of activities and techniques based on the above-mentioned principles for integrated sustainable nitrogen management. A possible definition of BMPs could be management practices that have been shown to yield on average the best performances in practice. This means that, when agreeing on and assigning BMPs, those involved must first agree on the relevant performance criteria and their weighting. As a consequence, there are many views of BMPs, as they depend on:

(i) The objectives (for example, reducing N losses, achieving high yield and making sure that the most appropriate N use efficiency and/or water use efficiency values are applied, farm-scale cost-benefit, societal cost-benefit);

(ii) The farm type (for example, arable farm, vegetable farm, mixed farm, livestock farm);

(iii) The socioeconomic conditions (for example, access to markets, knowledge and technology); and

(iv) The environmental conditions (for example, climate, soil, hydrology).

142. Given this complexity and recognizing differences of opinion as to what approach or level-of-ambition constitutes “best”, options in chapters IV–VI are simply referred to as “measures”. The measures are actions focused on abatement of emissions or mitigation of adverse effects, or both.

F. Conclusions and recommendations

143. The following conclusions can be drawn regarding the principles of integrated sustainable nitrogen management:

(a) The purpose of integrated sustainable nitrogen management in agriculture is to minimize nitrogen losses to the environment and to protect human health, ecosystems and climate, while ensuring adequate levels of crop and animal production and N use efficiency through balanced fertilization and circular economy principles. The negative effects of N losses on human health, ecosystem services, biodiversity, water and climate need to be fully addressed;

(b) It is important to have an understanding of the drivers of the leaky N cycle and N transformation processes. This underpins understanding of how intensification and regional specialization of agriculture systems affect N cycling. Such understanding is a prerequisite for developing effective N policies for protecting air, soil and water in order to preserve human health, climate and biodiversity;

(c) The Law of the Optimum, the “hole-in-the-pipe” model (see figure III.1 above) and appreciation of the interactions between nitrogen and other elements are key reasons for focusing on integrated N management;

(d) An integrated and sustainable N management approach, based on a series of key points regarding N cycling and management, is the foundation for efficient N abatement/mitigation policies and sustainable agricultural practices that help stimulate an emerging nitrogen circular economy;

(e) Integrated approaches to sustainable nitrogen management make use of five possible dimensions of integration (chapter III, section 1). These dimensions can be combined;

(f) Integrated and sustainable N management makes use of the five following tools, which can be combined: systems analysis; nitrogen budgets; integrated assessment; stakeholder dialogue and communication; and best management practices;

(g) Measures considered as “best management practices” for abating emissions and mitigating impacts are based on the above-mentioned principles, dimensions and tools.

Measures are often site- and region-specific and so represent a menu of options from which coherent packages of actions can be constructed.

144. The following recommendations can be made concerning the principles of integrated sustainable nitrogen management:

(a) Measures for integrated sustainable nitrogen management should be based on the dimensions, principles and tools outlined in the present chapter;

(b) Integrated sustainable nitrogen management is needed to help achieve multiple Sustainable Development Goals, including those related to human health, food, water, climate and biodiversity;

(c) Though farmers are the main N managers on the ground, and also bear many of the costs and reap some of the benefits of N emission-abatement measures, all societal actors in the food production-consumption chain, including policymakers and citizens, should take responsibility for achieving integrated sustainable nitrogen management, with fair remuneration for nitrogen managers.

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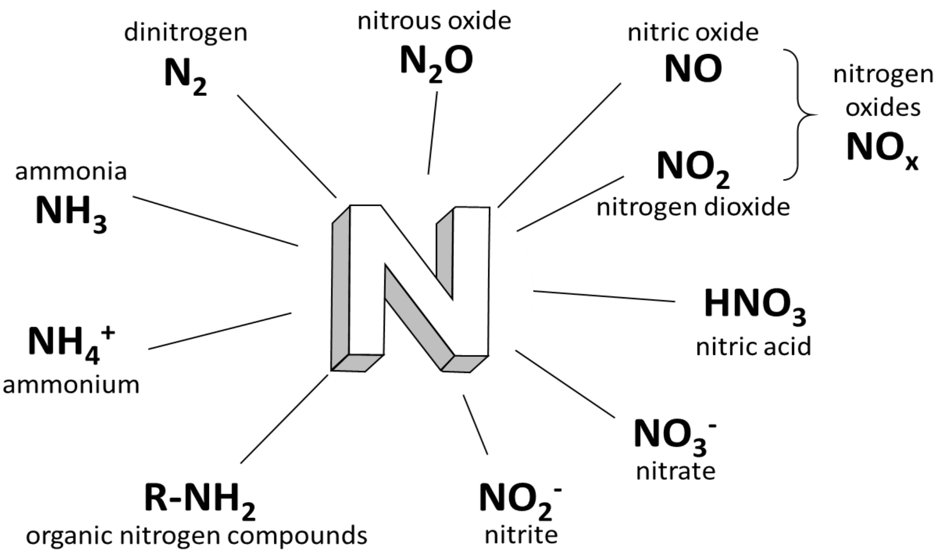
IV. Housed livestock, manure storage and manure processing

A. Introduction and background

145. Nitrogen (N) can take various forms (see figure IV.1 below), including atmospheric di-nitrogen (N_2) and a wide range of reactive nitrogen (N_r) compounds, including all forms of nitrogen that are biologically, photochemically and radiatively active. Compounds of nitrogen that are reactive include ammonia (NH_3) and ammonium (NH_4^+), nitrous oxide (N_2O), nitrogen oxides (NO_x),[14] nitrite (NO_2^-), nitrate (NO_3^-), nitric acid (HNO_3) and a wide range of organic nitrogen compounds ($R\text{-}NH_2$). Reactive forms of nitrogen are capable of cascading through the environment and causing an impact through smog, acid rain, biodiversity loss, etc.,[15] as well as affecting climate (Butterbach-Bahl and others, 2011b). The design of abatement/mitigation measures requires a sound knowledge of the processes that influence formation and emission of all N_r compounds and N_2 into the environment, where nitrogen is lost to a wide range of atmospheric and aquatic pathways.

Figure IV.1:
Major forms of nitrogen occurring in the environment



Source: The figure was created for the current document.
Note: The sum of all forms except N_2 is often termed as fixed or reactive nitrogen (N_r).

Ammonia

146. The principles of ammonia formation and the influencing factors are well known. Degradation of N containing organic substance results in ammonium formation. There is an equilibrium between ammonium and ammonia. The degree to which ammonia forms the ammonium ion depends on the pH of the solution. If the pH is low, the equilibrium shifts to the right: more ammonia molecules are converted into ammonium ions. If the pH is high, the equilibrium shifts to the left: the hydroxide ion abstracts a proton from the ammonium ion, generating ammonia. See the following equation:

$H_2O + NH_3 \rightleftharpoons OH- + NH_4+$

147. Ammonia emissions are governed by the difference between solution and atmosphere NH_3 partial pressure. High NH_3 concentrations in the solution and low NH_3 concentrations in the surrounding atmosphere increase NH_3 emissions. According to Henry's Law, ammonia

[14] See footnote 2.
[15] See www.n-print.org/node/5.

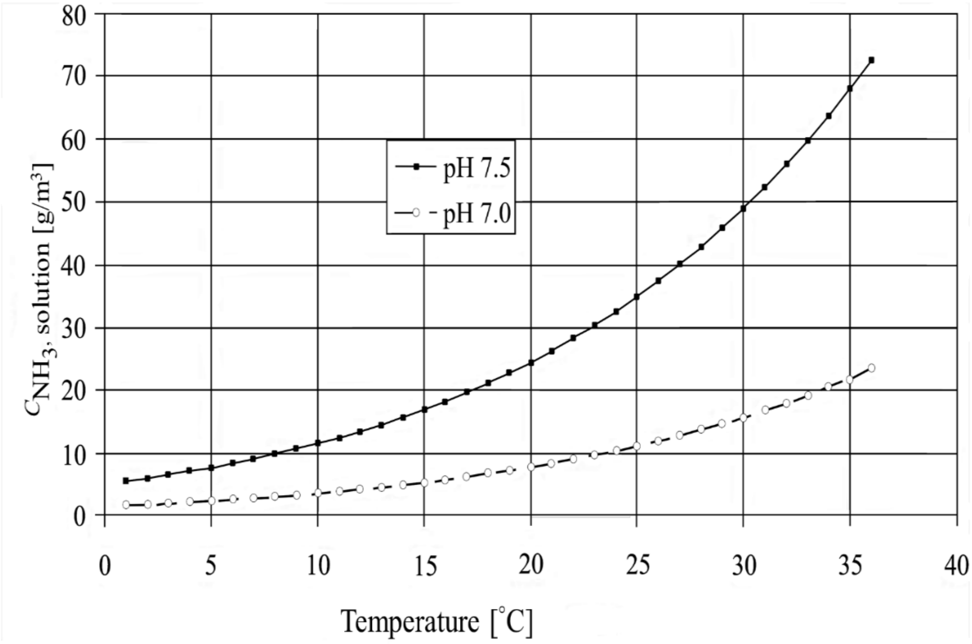
emissions are also temperature dependent, with rising temperatures increasing emissions (see figure IV.2 below). Denmead and others (1982) give the following equation:

NH_3(solution) = (NH_3(solution) + NH_4^+ (solution))/(1 + 100.09018+(2729.92/T)- pH)

where

NH_3(solution)	= NH_3 concentration in the solution
NH_3(solution) + NH_4^+ (solution)	= The sum NH_3 and NH_4^+ in the solution
T	= Temperature in the solution [K]
pH	= pH value in the solution

Figure IV.2:
NH_3 concentration in the solution as a function of temperature for pH 7.0 and pH 7.5 given a constant value of NH_4^+ in solution



Source: After Denmead and others (1982).

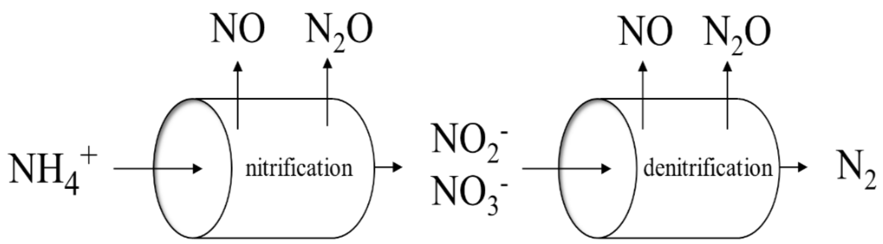
148. Ammonia emissions associated with animal housing, manure storage and processing result from the degradation of urea by the ubiquitous enzyme urease, which results in NH_4^+ formation. Urea is mainly excreted in the urine and, once it is hydrolysed, it is much more prone to ammonia losses than organic nitrogen excreted in faeces. In the case of poultry, nitrogen is excreted largely in the form of uric acid, which hydrolyses like urea to produce ammonia. Where it is possible to dry excreta (for example, in poultry litter), strategies may focus on reducing the hydrolysis rate of uric acid and urea. Once ammoniacal nitrogen (the sum of NH_3 + NH_4^+) is formed, strategies in animal housing and manure management focus on avoiding its volatilization to the atmosphere; for example, by reducing access to air, by reducing pH, or by keeping the manure surface cool (cf. figure IV.2 above).

Nitrous oxide and dinitrogen

149. The gases N_2O, NO_x and N_2 are formed during both the nitrification and the denitrification processes in the environment. The "leakage" model developed by Firestone and Davidson (1989) shows N_2O, and NO_x losses as leakage flows during nitrification and denitrification (figure IV.3).

Figure IV.3:

Leaky Pipe model for N_2O and NO_x losses during nitrification and denitrification



Source: After Firestone and Davidson (1989).

150. Nitrification oxidizes ammonium via nitrite to nitrate. This process is strictly aerobic. Autotrophic nitrifying bacteria belong to the widespread group of Nitrosomonas, Nitrospira and Nitrobacter, which are capable of growing on carbon dioxide (CO_2), oxygen (O_2) and NH_4^+. Availability of NH_4^+ is mostly the limiting factor, as CO_2 and O_2 are available in abundance. Low pH, lack of phosphorus (P) and temperatures below 5°C or above 40°C lead to a reduction in nitrification activities. A water content of around 60 per cent of the soil's water holding capacity is optimal for the nitrification process.

151. At low pH values, nitrification is carried out by bacteria and fungi. In contrast to the autotrophic nitrifiers, they need carbon sources for their growth. Their turnover rate is much lower compared to the autotrophic nitrifiers, but a substantial total turnover can still be achieved as a wider range of species have the ability for heterotrophic nitrification. N_2O production during nitrification is around 1 per cent, NO_x production ranges between 1 and 4 per cent of N inputs (Butterbach-Bahl and others, 2011a).

152. Denitrification reduces nitrate (NO_3–) to nitrite (NO_2-), NO_x, N_2O or N_2 when oxygen availability is low. NO_3–, NO_x and N_2O all serve as alternative electron acceptors when O_2 is lacking, and hence denitrification occurs only under strictly anaerobic conditions. Molecular N_2 is the ultimate product of the denitrification reaction chain and is the only biological process that can turn reactive nitrogen into non-reactive molecular N_2. Denitrifying bacteria are heterotrophic and facultative anaerobic. This means that they use O_2 as an electron acceptor and switch to alternative electron acceptors (NO_3–, NO_x and N_2O) when oxygen availability is low. Denitrifying bacteria are widespread and show a high biodiversity.

153. Controlling factors for denitrification have been extensively investigated, mainly under laboratory conditions. Complex interactions exist between the various influencing factors, which make an actual prediction of N_2O emissions in time and space difficult under practical conditions.

154. Denitrification is mainly governed by oxygen availability. Denitrification starts when the O_2 concentration decreases to below 5 per cent (for example, Hutchinson and Davidson, 1993). This may be the case in poorly aerated soils (for example, high water content, in excess of 80 per cent water-filled pore space), but also in soils where a high biological turnover consumes the oxygen faster than the supply. Easily degradable carbon (C) sources and high nitrate concentrations also enhance the denitrification rate, while low temperature and low pH limit denitrification activity.

155. The relationship between N_2 and N_2O formation is mainly governed by the relationship between electron acceptor and reducing agent, and by the O_2 concentration in the substrate. N_2 is only formed under strictly anaerobic conditions and a wide C:NO_3– ratio. High nitrate concentrations increase the rate of N_2O production. These differences have effects in practice concerning N losses from housed livestock and manure storage, according to the extent of oxygen and carbon availability in different systems.

Nitrate and other nitrogen leaching and run-off

156. Diffuse pollution of groundwater and surface waters with N (and phosphorus) is a problem in many regions of the world, especially in areas with high livestock production. Animal manures contain substantial quantities of organic matter, N and P that, if managed inappropriately, may be lost from animal housing, manure storage or after field application.

157. Nitrogen and organic matter losses to aquatic systems mainly occur by leaching through the soil profile and through surface run-off when the infiltration capacity of the soil is exceeded. Point-source emissions can also be acutely damaging to local environments, for example, in the case of slurry store leakages. In surface waters, the losses cause problems with eutrophication and algal bloom, and in areas that rely on the use of groundwater, high nitrate concentrations can be a problem for the potable water quality. For drinking water, the European Union limit has been set at a nitrate (NO_3-) concentration of 50 mg l−1 (see European Union Drinking Water Directive).[16] Once leached to surface waters, this N may also become a source of emissions of nitrous oxide, which is a potent greenhouse gas. In addition, significant loss of N resources is also an economic cost for the farmer, and N fertilizer production uses substantial amounts of fossil energy, causing global warming and other environmental emissions. Appropriate management and use of manures is therefore essential for minimizing nutrient leaching and the environmental impact of agriculture.

Consideration of nitrogen flows

158. Measures to reduce nitrogen losses from livestock feeding, housing and manure processing need to be seen in relation to other measures described in this guidance document. “Manure management is a continuum from generation by livestock to storage and treatment and finally to land spreading” (Chadwick and others, 2011). This means that there is the potential for nitrogen, carbon and phosphorus losses at each stage of this continuum. A “mass flow” approach has been used by Webb and Misselbrook (2004) to estimate NH_3 emissions from the manure management continuum. This approach allows effects of measures to reduce emissions and conserve manure N at one state to be considered as the manure passes to the next stage in the continuum. Similarly, other gaseous N losses, including N_2O, NO_x and N_2, may be assessed using a mass flow approach in a manner similar to that of Dämmgen and Hutchings (2008). The importance of such a whole system approach is that effects of abatement methods at one stage are considered in downstream stages (Sommer and others, 2009; 2013), including losses of nitrogen to water through leaching and run-off.

B. Approach used to describe abatement measures

159. The following sections present the main management practices and abatement/mitigation measures that will influence N utilization and losses from housed livestock, manure storage, manure treatment and manure processing. Some measures will mitigate all forms of N loss, whereas others may mitigate a specific N loss pathway with either little impact or a negative impact on other N loss pathways. Enhanced abatement may be possible through the combined implementation of certain packages of measures.

160. Following the description of each measure, a table (see tables IV.1–IV.23 and IV.25–IV.40 below) summarizes for each form of N loss the UNECE category for effectiveness/practicality of implementation (using the approach of ECE/EB.AIR/120; Bittman and others, 2014),[17] and the magnitude of effect of each measure. Expert judgements are provided for NH_3 volatilization, losses as N_2O, NO_x and N_2, run-off and leaching losses as NO_3^-, as well as overall total N losses.

161. Where a measure is considered to result in an increase in losses of a specific nitrogen form, it is, by definition, also assigned to category 3 for that nitrogen form. The magnitude of effect can be considered as an indication of “effectiveness” of the measure, as distinct from

[16] Council Directive 98/83/EC of 3 November 1998 on the quality of water intended for human consumption, *Official Journal of the European Communities*, L 330 (1998), pp. 32–58.

[17] See chapter I, para. 16, of the present document for a description of the UNECE categories and system for representing the magnitude of effect.

the extent to which the measure is "applicable" in different contexts. Where clarification is necessary, magnitude of effect of a measure is described in comparison to a specified reference system. For example, in the case of livestock housing, this includes *ad libitum* feeding, as well as storage of slurry without cover and without an impermeable base. In some parts of the UNECE region, use of certain reference systems may be prohibited, for example, because of the associated pollution levels

C Livestock feeding

162. The crude protein content and composition of the animal diet is the main driver of urine excretion. Excess crude protein (CP) that is not needed by the animal is excreted and can easily be lost in the manure management chain. Adaptation of crude protein in the diet to the needs of the animal is therefore the first and most efficient measure to mitigate nitrogen emissions. This measure reduces the loss of all N forms (see figure II.1 above) because it reduces the amount of excreted nitrogen. As there is much natural variation in nitrogen use efficiency (NUE) between individual animals, targeted breeding for better NUE can also be an option.

163. Reduction of CP in animal feed is one of the most cost-effective ways of reducing N emissions throughout the entire manure management chain. For each per cent (absolute value) decrease in protein content of animal feed, NH_3 emissions from animal housing, manure storage and the application of animal manure to land are decreased by 5–15 per cent, depending also on the pH of the urine and dung. Low-protein animal feeding also decreases N_2O emissions and increases the efficiency of N use in animal production. Potential trade-offs with CH_4 emissions from enteric fermentation are not yet fully researched and need to be assessed. However, efficient N use is crucial for environmentally friendly milk production. Moreover, there are no animal health or animal welfare implications as long as the requirements for all amino acids are met.

164. Low-protein animal feeding is most applicable to housed animals. It is less applicable for grassland-based systems with grazing animals because grass is eaten by the animals at an early physiological growth stage and thus is typically high in degradable protein. It should be noted that grassland with leguminous species (for example, clover, lucerne) also has a relatively high protein content, and so may be associated with excess dietary N for livestock. Strategies to lower the protein content in herbage include: balanced N fertilization; grazing/harvesting the grassland at a later physiological growth stage, etc.; and alteration of the ration of grassland-based systems, such as use of supplementary feeding with low-protein feeds.

1. Dairy and beef cattle

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

165. Lowering crude protein (CP) of ruminant diets is an effective strategy for decreasing NH_3 and overall N loss. The following guidelines hold:

(a) The average CP content of diets for dairy cattle should not exceed 15–16 per cent in the dry matter (DM) (Broderick, 2003; Swensson, 2003). For beef cattle older than six months this could be further reduced to 12 per cent;

(b) Phase feeding can be applied in such a way that the CP content of dairy diets is gradually decreased from 16 per cent of DM just before parturition and in early lactation to below 14 per cent in late lactation and the main part of the dry period;

(c) Phase feeding can also be applied in beef cattle in such a way that the CP content of the diets is gradually decreased from 16 to 12 per cent over time. More information and associated costs can be found in the TFRN costs assessment (Chapter 3.4 "Low nitrogen feeding strategies in dairy cattle" in Reis and others, 2015.

166. In general, increasing the energy/protein ratio in the diet by using "older" grass (higher sward surface height) or swathed forage cereal and/or supplementing grass by high energy feeds (for example, maize silage) is a well-proven strategy for reducing levels of crude

protein. However, for grassland-based ruminant production systems, the feasibility of these strategies may be limited, as older grass may reduce feeding quality, especially when conditions for growing high-energy feeds are poor (for example, warm climates), and therefore such feeds have to be purchased. Hence, full use of the grass production would no longer be guaranteed. In the absence of other measures, such a strategy may also risk increasing methane emissions.

167. In many parts of the world, cattle production is grassland-based or partly grassland-based. In such systems, protein-rich grass and grass products form a significant proportion of the diet, and the target values for CP may be difficult to achieve, given the high CP content of grass from managed grasslands. The CP content of fresh grass in the grazing stage (2,000–2,500 kg DM/ha) is often in the range of 18–20 per cent (or even higher, especially when legumes are present), whereas the CP content of grass silage is often between 16 and 18 per cent and the CP content of hay is between 12 and 15 per cent (for example, Whitehead, 2000). In contrast, the CP content of maize silage is only in the range of 7–8 per cent. Hence, grass-based diets often contain a surplus of protein and the magnitude of the resulting high N excretion strongly depends on the proportions of grass, grass silage and hay in the ration and the protein content of these feeds. The protein surplus and the resulting N excretion and N losses will be highest for grass-only summer rations (or grass-legume rations) with grazing of young, intensively fertilized grass or grass-legume mixtures.

168. Urine excreted by grazing animals typically infiltrates into the soil. This means that NH_3 emissions per animal are reduced by extending the periods during which animal graze compared with the time spent with animals housed, where the excreta is collected, stored and applied to land. It should be noted that grazing of animals may increase other forms of N emissions (for example, nitrate-N leaching and N_2O emissions). However, given the clear and well-quantified effect on NH_3 emissions, increasing the period that animals are grazing all day can be considered as a strategy to reduce emissions (see chapter III, Field Measure 18).

Table IV.1
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Dietary Measure 1

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

[a] The measure would be expected to reduce NO_x 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 N_r and N_2 losses.

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

169. Overall, increasing the productivity of dairy cattle in terms of milk or meat can decrease emissions per unit of animal production. Optimized productivity will also result in a reduction of enteric methane emissions. However, optimum productivity levels vary according to breed and region and must also take into consideration the fact that ruminants can only cope with a certain amount of concentrates and require sufficient roughage in their diet to stay healthy.

Table IV.2
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Dietary Measure 2

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

[a] The measure would be expected to reduce NO_x 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 N_r and N_2 losses.

Dietary Measure 3: Increase longevity (dairy cattle)

170. Productivity can be increased though increasing milk production per year and through increasing the amount of milk production cycles per animal. Optimized diet and housing conditions enable a higher longevity of dairy cattle. Improving the longevity of dairy cattle also decreases the number of young cattle necessary for replacement. Reducing endemic disease and genetic gain through targeted breeding can also offer value.

Table IV.3
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Dietary Measure 3

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

[a] The measure would be expected to reduce NO_x 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 N_r and N_2 losses.

2. Pigs

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

171. Feeding measures in pig production include: phase feeding; formulating diets based on digestible/available nutrients; and using low-protein amino acid-supplemented diets and feed additives/supplements. Further techniques are currently being investigated (for example, different feeds for males (boars and castrated males) and females) and might also be available in the future.

172. The crude protein (CP) content of pig ration can be reduced if the amino acid supply is optimized through the addition of synthetic amino acids (for example, lysine, methionine, threonine, tryptophan, typically limiting amino acids, which are too low in normal grain rations) or special feed components, using the best available information on “ideal protein” combined with dietary supplementation. Lassaletta and others (2019) performed a global analysis for pig systems that included the simulation of changes in CP. More information and associated costs can be found in the TFRN Costs Assessment (Chapter 3.2 “Low nitrogen feeding strategies in pigs”, in Reis and others, 2015).

173. A CP reduction of 2–3 per cent in the feed can be achieved, depending on the pig production category and the current starting point (Canh and others, 1998). It has been shown that a decrease of 1 per cent CP in the diet of finishing pigs results in a 10 per cent lower total ammoniacal nitrogen (TAN) content of the pig slurry and 10 per cent lower NH_3 emissions (Canh and others, 1998). The inclusion of processed household and industry residues or wastes in the feed rations with a controlled energy/protein ratio is a complementary measure

that reduces dependence on imported feedstuff. This measure also represents a reduction of upstream N_r emissions associated with feed production and downstream emissions associated with waste management (Lassaletta and others, 2019; zu Ermgassen and others, 2016).

Table IV.4
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Dietary Measure 4

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

[a] The measure would be expected to reduce NO_x 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 N_r and N_2 losses.

3. Poultry

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

174. 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. A CP reduction of 1–2 per cent may be achieved depending on the species and the current starting point but is already a well-proven measure for growers and finishers. Further applied nutrition research is currently being carried out in European Union member States and North America and this may support further possible reductions in the future.

Table IV.5
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Dietary Measure 5

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

[a] The measure would be expected to reduce NO_x 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 N_r and N_2 losses.

D. Livestock housing

1. Cattle housing

175. When using measures to abate emissions from livestock houses of all types of animals, it is important to minimize loss of the conserved N during downstream handling of the manure, in storage and in spreading to maximize the benefit from the cost of abatement.

176. Housing systems for cattle vary across the UNECE region. While loose housing is most common, dairy cattle are still bred in tied stalls in some countries. In loose housing systems, all or part of the excreta is collected in the form of slurry. In systems where solid manure is produced (such as straw-based systems), it may be removed from the house daily or it may remain there for up to the whole season, such as in deep litter stables. The most commonly researched system is the "cubicle house" for dairy cows, where substantial NH_3 emissions arise from fouled slatted and/or solid floors and from manure in pits and channels beneath the slats/floor. There has been much less research to measure NO_x, N_2O and N_2

emissions from cattle housing, so recommendations in some cases have to be based on general principles and are therefore subject to larger uncertainty than for NH_3 emissions from such systems.

177. Housed cattle systems are generally set on stone or concrete bases, so direct nitrate leaching is not expected, unless there are cracked bases associated with poor maintenance. Run-off of N_r compounds from cattle housing systems may occur if ponded excreta is not correctly drained into storage tanks (for example, associated with flooding events).

178. While ”hard standings” (typically concrete areas adjacent to dairies) provide a significant source of ammonia emissions outside of animal houses, in some parts of the UNECE region, cattle are kept in confined areas outside (for example, feed lots), where N_r leaching, run-off and gaseous N losses may be substantial.

179. Animal welfare considerations tend to lead to an increase of soiled walking area per animal, increased ventilation and an overall increase in emissions. Changes in building design to comply with new animal welfare regulations in some countries (for example, changing from tied stall to cubicle housing) will therefore increase NH_3 emissions unless abatement measures are introduced at the same time to combat this increase.

180. Solid versus slurry manure systems: straw-based systems producing solid manure for cattle are unlikely to emit less NH_3 in the animal houses than slurry-based systems. Furthermore, N_2O, NO_x and N_2 losses due to (de)nitrification tend to be larger in litter-based systems than slurry-based systems.

181. While straw-based solid manure can emit less NH_3 than slurry after surface spreading on fields (see, for example, Powell and others, 2008), slurry provides a greater opportunity for reduced emissions application methods.

182. Abatement options for cattle housing can be grouped into the following types:

(a) Floor-based systems and related management techniques (including scrapers and cleaning robots);

(b) Litter-based systems (use of alternative organic material);

(c) Slurry management techniques at pit level;

(d) Indoor climate control techniques;

(e) End-of-pipe techniques (hybrid ventilation + air cleaning techniques) and GHGs abatement/mitigation techniques.

183. Several pathways can be identified to further optimize existing and develop new abatement techniques. In this respect, emission reduction techniques at animal housing level should aim to affect one or more of the following important key factors and/or driving forces of the nitrogen emission process:

(a) Draining capacity of the floor for direct transportation of urine to the manure storage;

(b) Residence time of open urine/manure sources;

(c) Emitting surface area of open urine/manure sources;

(d) Urease activity in urine puddles;

(e) Temperature and urine/manure pH (see Housing Measures 6 and 8, respectively);

(f) Indoor air temperature;

(g) Air velocities at emitting surfaces (urine puddles and manure surface in the pit);

(h) Air exchange between pit headspace and indoor air;

(i) Exhaust of indoor air.

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

184. A physical segregation (for example, keeping separately) of faeces, which contain urease, and urine in the housing system reduces hydrolysis of urea, resulting in reduced emissions from both housing and manure spreading (Burton, 2007; Fangueiro and others, 2008a, 2008b; Møller and others, 2007). Both acidification and alkalization of the in-house segregated urine reliably inhibits urea hydrolysis. The duration of the inactivation period can be adjusted by the dosage of acid or alkali addition (VDLUFA 2019).

185. Verification of any NH_3 emission reductions from using solid-manure versus slurry-based systems and from solid-liquid separation should consider all the stages of emission (housing, storage and land application). Additional advantages of solid-liquid separation can also be expected during land-application, where urine (containing most of the available ammoniacal N) infiltrates more easily due to its lower dry-matter content than slurry, reducing NH_3 emissions. Although solid manure does not infiltrate, it mainly consists of organic N forms, which are much less liable to NH_3 emissions. Less is known about the consequences of solid-liquid separation on the emissions of N_2O, NO_x, N_2 and nitrate leaching, although substantial adverse effects are not expected.

Table IV.6
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Housing Measure 1

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

[a] Immediate segregation of urine and faeces will reduce NH_3 emissions substantially, in the same way as increased grazing period (category 1). However, subsequent separation of previously mixed slurry is considered less effective (category 2) (cf. Bittman and others, 2014, para. 159).

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

186. The "grooved floor" system for dairy and beef cattle housing, employing "toothed" scrapers running over a grooved floor, is a reliable technique to abate NH_3 emissions. Grooves should be equipped with perforations to allow drainage of urine. This results in a cleaner, low-emission floor surface with good traction for cattle to prevent slipping. Ammonia emission reduction ranges from 25 to 46 per cent relative to the reference system (Smits, 1998; Swierstra and others, 2001). In the absence of measurement data, it is expected that use of the grooved floor system would have little impact on other N_r and N_2 losses since it is mainly directed to reducing immediate exposure to air of ammonium rich excreta.

Table IV.7
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Housing Measure 2

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

[a] Although this measure does not directly reduce other N_r 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 N_r and N_2 losses.

Housing Measure 3: Regular cleaning of floors in cattle houses

187. Thorough cleaning of walking areas in dairy cattle houses by mechanical scrapers or robots has the potential to substantially reduce NH_3 emissions. The automatic cleaning should

be performed at regular intervals (for example, on an hourly basis) to achieve the full benefits of the measure.

Table IV.8
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Housing Measure 3

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

Housing Measure 4: Frequent slurry removal (cattle)

188. Regular removal of liquid manure from under the slats in the house to an outside store can substantially reduce NH_3 emissions by reducing the emitting surface and the slurry storage temperature. A reduced storage temperature will also result in a reduction of methane emissions.

Table IV.9
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Housing Measure 4

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

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

189. Bedding material in animal housing can affect NH_3, N_2O, NO_x and N_2 emissions. The physical characteristics (urine absorbance capacity, bulk density) of bedding materials are of more importance than their chemical characteristics (pH, cation exchange capacity, carbon to nitrogen ratio) in determining NH_3 emissions from dairy barn floors (Misselbrook and Powell, 2005; Powell and others, 2008; Gilhespy and others, 2009). However, further assessment is needed on the effect of bedding on emissions for specific systems while taking into account the whole manure management path. The approach can have a positive interaction with animal welfare measures.

Table IV.10
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Housing Measure 5

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

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

190. In houses with traditional slats (either non-sloping, 1 per cent sloping, or grooved), optimal barn climatization with roof insulation and/or automatically controlled natural ventilation can achieve a moderate emission reduction (20 per cent) of NH_3 due to the decreased temperature (especially in summer) and reduced air velocities (Bram and others, 1997a, b; Smits, 1998; Monteny, 2000). To the extent that such systems cool stored manure, emissions of methane will also be reduced.

Table IV.11
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Housing Measure 6

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE category [a]	1	⅔	⅔	⅔	⅔	1
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: Use of acid air-scrubbers (cattle)

191. Chemical or acid air-scrubbers are effective in decreasing NH_3 emissions from force-ventilated pig housing. However, they cannot yet be generally implemented in cattle housing because these are mostly naturally ventilated across the ECE region. Also, there are few data on scrubbers for cattle (Ellen and others, 2008). In any situations where cattle are housed with forced ventilation, this measure can be considered as category 1. Recent developments consider combining targeted ventilation of naturally ventilated barns with air-scrubbers. More research and development are needed here.

Table IV.12
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Housing Measure 7

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE category	1-2	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 N_r and N_2 losses, where recovered N_r contributes to replace inorganic fertilizer inputs from newly fixed N, it can contribute to increased system efficiency and circularity, reducing wider N_r and N_2 losses.

192. Different improved floor types based on slats or solid, profiled concrete elements have been tested. These designs combine emission reduction from the floor (increased run-off of urine) and from the pit (reduction of air exchange by rubber flaps in the floor slots). The emission-abatement efficiency depends on the specific technical characteristics of the system.

193. Decreasing the amount of animal excrement in animal housing systems through increased grazing is an effective measure to decrease NH_3 emissions, as discussed further in chapter IV. Total annual emissions (including housing, storage and spreading) from dairy systems may decrease by up to 50 per cent with nearly all-day grazing, as compared with animals that are fully confined. While increased grazing is a reliable NH_3 emission reduction measure for dairy cows, the amount of emission reduction depends on the daily grazing time and the cleanliness of the house and holding area. In some cases, grazing may also contribute to increased run-off and leaching of NO_3– and other N_r compounds, as well as N_2O and NO_x emissions. Grazing can also be associated with increased pathogen mobilization.

2. Pig housing

194. Designs to reduce NH_3 emissions from pig housing systems have been described in detail in the IPPC document on Best Available Techniques (BATs) (Santonja and others 2017). These apply the following main elements:

(a) Reducing manure surfaces such as soiled floors using channels for slurry holding surfaces and sloped walls. Partly slatted floors (~50 per cent area) generally emit less

NH_3, particularly if the slats are metal- or plastic-coated rather than concrete, allowing the manure to fall rapidly and completely into the pit below. Emissions from the non-slatted areas are reduced by inclined, smooth surfaces, by locating the feeding and watering facilities to minimize fouling of these areas, and by good climate control in the building;

(b) Removing the slurry from the pit frequently to an external slurry store with vacuum or gravity removal systems or by flushing systems at least twice a week;

(c) Additional treatment, such as liquid/solid separation; provided that the storage of the separated fractions maintains low emissions;

(d) Circulating groundwater or other cooling agents in floating heat exchangers or walls of slurry pits to cool the surface of the manure in the underfloor pit to at least below12°C. Constraints include costs and need to locate a source of groundwater away from the source of drinking water;

(e) Changing the chemical/physical properties of the manure, such as decreasing pH;

(f) Using surfaces that are smooth and easy to clean (see above);

(g) Treatment of exhaust air by acid scrubbers or biotrickling filters;

(h) Lowering the indoor temperature and ventilation rate, taking into account animal welfare and production considerations;

(i) Reducing airflow over the manure surface.

195. For a given floor slat width, manure drains from concrete slats less efficiently than from steel- and plastic-covered slats and this is associated with greater emissions of NH_3. Note that steel slats are not allowed in some countries for animal welfare reasons. Cross-media effects have been taken into account in defining BATs for the various housing designs. For example, frequent flushing of slurry (normally once in the morning and once in the evening) causes nuisance odour events. Flushing slurry also consumes energy unless manually operated passive systems are used.

196. Use of straw litter in pig housing is expected to increase due to concern for the welfare of the pigs. In conjunction with (automatically controlled) naturally ventilated housing systems, straw allows the animals to self-regulate their temperature with less ventilation and heating, reducing energy consumption. In systems with litter, the pen is sometimes divided into solid areas with litter and slatted dunging areas. However, pigs do not always use these areas in the desired way, using the littered area to dung and the slatted area to cool off in warm weather. Generally, pens should be designed to accommodate desired excreting behaviour of pigs to minimize fouling of solid floors. However, this is more difficult in regions with a warm climate. Note that integrated evaluation of straw use should consider:

(a) The added cost of the straw and mucking out the pens;

(b) The possible increased emissions from storage and application of manure with straw; and

(c) The benefit of adding organic matter from straw to the soil.

197. The reference system, used commonly in Europe, is a fully slatted floor with a deep manure pit underneath and mechanical ventilation; emission ranges from 2.4 to 3.2 kg NH_3 per finisher pig place per year. Since growers/finishers are always housed in a group, most systems used for group housing of sows are applicable to growers. Emissions from different abatement/mitigation approaches are compared with this reference system in terms of the emission reduction amount (Bittman and others, 2014). Most data available are on NH_3, with little data concerning effects on N_2O, NO_x, N_2 and nitrate leaching. The underlying principles for these losses are largely similar to those for cattle housing systems, recognizing the different housing needs of pigs and the particular characteristics of pig excreta.

Housing Measure 8: Slurry acidification (pig and cattle housing)

198. Reductions in NH_3 emissions can be achieved by acidifying slurry to shift the chemical balance from molecular NH_3 to ionic NH_4^+. The manure (especially the liquid

fraction) is collected into a tank with acidified liquid (usually using sulphuric acid, but organic acids can be used as well, though at higher cost) maintaining a pH of less than 6 (Bittman and others, 2014; Fangueiro and others, 2015). In pig housing systems, emission reductions of 60 per cent or more have been observed (Kai and others, 2008). The measure is not anticipated to affect other N_r or N_2 losses. Acidification of slurry is anticipated to be effective for both cattle and pig slurry, though measurements have so far concentrated on investigating pig slurry. One study (Petersen and others, 2012) showed that acidification of cattle slurry to pH 5.5 reduced the NH_3 emissions by more than 90 per cent and at the same time reduced emissions of the greenhouse gas (GHG) CH_4 by 67 to 87 per cent. As nitrification and denitrification are reduced, the method can also be expected to reduce emissions of NO_x, N_2O and N_2. Attention should be given to monitoring soil pH and metal content if acidified slurry is to be used in agriculture. In-house acidification will reduce NH_3 emissions throughout the manure management chain. Furthermore, slurry acidified with sulphuric acid is not suitable as the sole feedstock for biogas production (but can be used as a smaller proportion).

Table IV.13

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Housing Measure 8

Nitrogen form	NH_3	N_2O	NO_x	NO_3^-	N_2	*Overall N Loss*
UNECE category	1	2	2	3 [a]	2	1 [a]
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 N_r and N_2 losses.

Housing Measure 9: Reduce emitting surface (pigs)

199. Ammonia emissions can be reduced by 25 per cent by decreasing the surface area of the emitting floor through frequent and complete vacuum-assisted drainage of slurry from the floor of the pit. Where this is possible, this technique has no cost. Partly slatted floors covering 50 per cent of floor area generally emit 15–20 per cent less NH_3, particularly if the slats are metal or plastic-coated which is less sticky for manure than concrete. Decreasing the risk of emissions from the solid part of the floor can be achieved by:

(a) Using an inclined (or convex), smoothly finished surface;

(b) Appropriate siting of the feeding and watering facilities to minimize fouling of the solid areas; and

(c) Good climate control (Aarnink and others, 1996; Guigand and Courboulay, 2007; Ye and others, 2008a, 2008b).

200. Further reduction of the emitting area can be achieved by making both the partly slatted area and the pit underneath smaller. With the smaller slatted area, the risk of greater fouling of the solid area can be mitigated by installing a small second slatted area with a water canal underneath at the other side of the pen where the pigs tend to eat and drink. The canal is filled with about 2 cm of water to dilute any manure that might eventually drop into it. This slatted area will have low emissions because any manure dropped here will be diluted. This combined manure-canal and water-canal system can reduce NH_3 emissions by 40–50 per cent, depending on the size of the water canal. This approach is not expected to have a significant effect on emissions of N_2 or other N_r compounds.

201. Reducing the emitting surface area by having one or two slanted pit walls, in combination with partly slatted floors and frequent manure removal, can reduce emissions by up to 65 per cent. Reducing the emitting surface area with shallow V-shaped gutters (maximum 60 cm wide, 20 cm deep) can reduce emission in pig houses by 40 to 65 per cent, depending on the pig category and the presence of partly slatted floors. The gutters should be

flushed twice a day with the liquid (thin) fraction of the slurry rather than water; flushing with water dilutes the manure and increases the cost of transporting and applying it in the field.

Table IV.14
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Housing Measure 9

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

[a] Although this measure does not directly reduce other N_r 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 N_r and N_2 losses.

Housing Measure 10: Regular cleaning of floors (pigs)

202. Cleaning of floors in pig houses by mechanical scrapers or robots has the potential to substantially reduce NH_3 emissions. The automatic cleaning should be performed at regular intervals to achieve the full benefits of the measure (Amon and others, 2007). It is worth mentioning that, in warm countries (for example, Mediterranean region), for sanitary reasons, floor cleaning is done more frequently with consequences for the slurry composition, which may reach up to 98 per cent water.

Table IV.15
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Housing Measure 10

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

Housing Measure 11: Frequent slurry removal (pigs)

203. Regular removal of slurry from under the slats in the house to an outside store can substantially reduce NH_3 emissions by reducing the emitting surface and the slurry storage temperature. A reduced storage temperature will also result in a reduction of methane (Amon and others, 2007).

Table IV.16
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Housing Measure 11

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

Housing Measure 12: Increase bedding material (pigs with solid manure)

204. Bedding material in animal housing can affect NH_3, N_2O, NO_x and N_2 emissions. The physical characteristics (urine absorbance capacity, bulk density) of bedding materials are of more importance than their chemical characteristics (pH, cation exchange capacity, carbon to nitrogen ratio) in determining NH_3 emissions from dairy barn floors (Misselbrook and Powell, 2005; Powell and others, 2008; Gilhespy and others, 2009). However, further assessment is needed on the effect of bedding on emissions for specific systems while taking

into account the whole manure management path. The approach can have a positive interaction with animal welfare measures. However, approaches benefiting animal welfare can also be operated as slurry-based systems, with only little straw supply.

Table IV.17
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Housing Measure 12

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

Housing Measure 13: Barn climatization to reduce indoor temperature and air flow (pigs)

205. Surface cooling of manure with fans using a closed heat exchange system is a technique with a reduction efficiency of 45–75 per cent depending on animal category and surface of cooling fins. This technique is most economical if the collected heat can be exchanged to warm other facilities such as weaner houses (Huynh and others, 2004). In slurry systems this technique can often be retrofitted into existing buildings. However, this system is not applicable when straw bedding is used or when the feed contains a lot of roughage. This is because a layer of floating residue may develop on top of the slurry.

Table IV.18
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Housing Measure 13

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE category [a]	1	⅔	⅔	⅔	⅔	1
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 14: Use of acid air-scrubbers (pigs)

206. Treatment of exhaust air by acid scrubbers (mainly using sulphuric acid) or biotrickling filters has proven to be practical and effective for large-scale operations in Denmark, France, Germany and the Netherlands (for example, see Melse and Ogink, 2005; Guingand, 2009). This is most economical when installed in new houses, because retrofitting in existing housing requires costly modification of ventilation systems. Acid scrubbers have demonstrated NH_3 removal efficiencies of more than 90 per cent, depending on their pH-set values. Scrubbers and biotrickling filters also reduce odour and PM by 75 per cent and 70 per cent, respectively (Guingand, 2009). Further information is needed on the suitability of these systems in Southern and Central Europe. Operational costs of both acid scrubbers and trickling filters are especially dependent on the extra energy use for water recirculation and to overcome increased back pressure on the fans. Optimization methods are available to minimize costs (Melse and others, 2012) and costs will be lower for large operations. The approach may also contribute to reducing N_2O and NO_x emissions, but more research is needed here.

Table IV.19

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Housing Measure 14

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE category	1	2	2	3 [a]	3 [a]	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 N_r contributes to replace inorganic fertilizer inputs from newly fixed N, it can contribute to increased system efficiency and circularity, reducing wider N_r and N_2 losses.

Housing Measure 15: Use of biological air-scrubbers (pigs)

207. Biological air-scrubbers operate with bacteria that remove ammonia and odours from the exhaust air. Ammonia captured in biological air-scrubbers typically undergoes nitrification and denitrification associated with increased emissions of N_2O, NO_x and N_2. Recovery of the collected N_r in bioscrubbers may help offset this increase by reducing the need for fresh N fixation and production of chemical fertilizers.

Table IV.20

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Housing Measure 15

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

[a] Ammonia captured in biological air-scrubbers typically undergoes nitrification and denitrification associated with increased emissions of N_2O, NO_x and N_2. Recovery of the collected N_r in bioscrubbers may help offset this increase by reducing the need for fresh N fixation and production of chemical fertilizers.

3. Poultry housing

208. Designs to reduce NH_3 emissions from poultry housing systems have been described in detail in the document on BAT under the European Union Industrial Emissions Directive[18] (Santonja and others, 2017), and apply the following principles:

(a) Reducing the open surface area of emitting manure;

(b) Removing the manure frequently from the poultry house to an external slurry store (for example, with belt removal systems);

(c) Quickly drying the manure to reduce hydrolysis of uric acid to ammonia;

(d) Using smooth, easy-to-clean surfaces;

(e) Treatment of exhaust air by acid scrubbers or biotrickling filters (for example, biological air-scrubbers);

(f) Lowering the indoor temperature and ventilation as animal welfare and/or production allow, reducing microbial processes that mobilize N_r losses.

209. Many of the measures listed for cattle and pigs are also applicable to poultry systems, especially Housing Measures 2 and 9 (Reduce emitting surface), 6 and 13 (Barn climatization to reduce indoor temperature and air flow) and 7 and 14 (acid air-scrubbers). This section

[18] Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control), *Official Journal of the European Union*, L 334 (2010), pp. 17–119

therefore focuses on additional considerations for poultry housing. Further information can be found in the IPPC Best Available Techniques Reference document (Santonja and others, 2017) and the UNECE Ammonia Guidance Document (Bittman and others, 2014).

210. Where poultry houses are disconnected from the ground (for example, concrete base), emission-reduction measures for NH_3 are not directly expected to affect nitrate and other N_r leaching and run-off. For smaller farms, which are not required to comply with national legislation (for example, BAT) for layers, and for free-range poultry, pathways to the soil can also be anticipated. In such cases, NH_3 emission reduction including rapid drying and dry storage of poultry litter may also have benefits to reduce N_r leaching. In addition, expert observations have shown that downward-pointing air exhausts onto porous ground surfaces surrounding poultry houses can lead to localized increases of N_r leaching and run-off into groundwaters. Reduction of NH_3 emissions (and N_r -containing dusts) can therefore also contribute to reducing such hot spots of N_r leaching and run-off.

4. Laying hens

211. A wide range of regulations and minimum standards for protecting laying hens exist across the UNECE region. For example, in the European Union, regulations apply under Council Directive 1999/74/EC[19]. Under the Directive, the use of conventional cage systems has been prohibited since 2012. Instead, only enriched cages (also called "furniture cages"), or non-cage systems, such as litter (or deep litter) housing systems or aviary systems, are allowed.

Housing Measure 16: Rapid drying of poultry litter

212. Ammonia emissions from battery deep-pit or channel systems can be lowered by reducing the moisture content of the manure by ventilating the manure pit. The collection of manure on belts and the subsequent removal of manure to covered storage outside the building can also reduce NH_3 emissions, particularly if the manure has been dried on the belts through forced ventilation. The manure should be dried to 60–70 per cent DM to minimize the subsequent formation of NH_3. Manure collected from the belts into intensively ventilated drying tunnels, inside or outside the building, can reach 60–80 per cent DM content in less than 48 hours, but in this case exposure to air is increased, risking an increase in NH_3 emissions. Weekly removal from the manure belts to covered storages reduces emissions by 50 per cent compared with bi-weekly removal. In general, emissions from laying hen houses with manure belts will depend on:

(a) The length of time that the manure is present on the belts;

(b) The drying systems;

(c) The poultry breed;

(d) The ventilation rate at the belt (low rate = high emissions); and

(e) The feed composition.

213. Aviary systems with manure belts for frequent collection and removal of manure to closed storages reduce emission by more than 70 per cent compared with the deep litter housing system. While the primary drying poultry litter has been on reducing NH3 emissions, keeping excreted N in the form of uric acid can also be expected to reduce N_2O, NO_x and N_2, since this will also reduce nitrification and denitrification. Dried poultry litter will therefore have a higher fertilizer value for farmers, which should be compensated by using reduced doses during land application (see chapter V), as compared with decomposed poultry litter.

[19] Council Directive 1999/74/EC of 19 July 1999 laying down minimum standards for the protection of laying hens, *Official Journal of the European Communities*, L 203 (1999), pp. 53–57.

Table IV.21

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Housing Measure 16

Nitrogen form	NH_3	N_2O	NO_x	NO_3^-	N_2	*Overall N Loss*
UNECE category	1	2 [a]	2 [a]	3 [a]	2 [a]	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 N_r and N_2 losses, and reducing the need for fresh N_r production.

Housing Measure 17: Use of acid air-scrubbers (poultry)

214. Treatment of exhaust air by acid scrubbers has been successfully employed in several countries (Melse and Ogink, 2005; Ritz and others, 2006; Patterson and Adrizal, 2005; Melse and others, 2012). In Germany, Hahne and others (2016) counted 179 installed air-scrubbers in poultry installations and 1,012 scrubbers installed in pig houses. The main difference between pig systems and poultry houses is that the latter (especially with dried litter) typically emit a much larger amount of dust. Acid scrubbers remove 70–90 per cent of NH_3, and also remove fine dust and odour. To deal with the high dust loads, multistage air-scrubbers with pre-filtering of coarse particles have been developed (Ogink and others, 2007; Melse and others, 2008). Yet some experts consider this technique as only category 2 because of the dust loading issue.

Table IV.22

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Housing Measure 17

Nitrogen form	NH_3	N_2O	NO_x	NO_3^-	N_2	*Overall N Loss*
UNECE category	1	2	2	3 [a]	3 [a]	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 N_r contributes to replace inorganic fertilizer inputs from newly fixed N, it can contribute to increased system efficiency and circularity, reducing wider N_r and N_2 losses.

Housing Measure 18: Use of biological air-scrubbers (poultry)

215. Treatment of exhaust air by use of biotrickling filters (biological air-scrubbers) has been successfully employed in several countries (Melse and Ogink, 2005; Ritz and others, 2006; Patterson and Adrizal, 2005; Melse, Hofschreuder and Ogink, 2012). Biological scrubbers have been found to reduce NH_3 emissions by 70 per cent of NH_3, also removing fine dust and odour. To deal with the high dust loads, multistage air-scrubbers with pre-filtering of coarse particles have been developed (Ogink and Bosma, 2007; Melse, Ogink and Bosma, 2008). Yet some experts consider this technique as only category 2 because of the dust loading issue and possible trade-offs with increases of other N_r losses. .

Table IV.23
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Housing Measure 18

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

[a] Ammonia captured in biological air-scrubbers typically undergoes nitrification and denitrification, which is expected to increase emissions of N_2O, NO_x and N_2. Recovery of the collected N_r in bioscrubbers may help offset this increase by reducing the need for fresh N fixation and production of chemical fertilizers.

5. Broilers

216. To minimize NH_3 emission in broiler housing, it is important to keep the litter dry. Litter moisture and emissions are influenced by:

(a) Drinking-water design and function (leakage and spills);

(b) Animal weight and density, and duration of the growing period;

(c) Ventilation rate, use of in-house air purification and ambient weather;

(d) Use of floor insulation;

(e) Type and amount of litter;

(f) Feed.

217. Reducing spillage of water from the drinking system: A simple way to reduce spillage of water from the drinking system is by using “nipple drinkers” instead of “bell drinkers”. This approach should be integrated into wider systems designed to keep poultry litter dry, as described under Housing Measure 16 (Rapid drying of poultry litter).

218. Air scrubber technology to remove NH_3 from ventilation air is highly effective, but not currently widely implemented because of high installation and running costs. Packed-bed filters and acid scrubbers currently available in the Netherlands and Germany remove 70–90 per cent of NH_3 from exhaust air. Comprehensive measuring of air-scrubbers is done by the German Agricultural Association (DLG, 2020), based on a scientific standard testing frame. As with such systems for laying poultry, questions about long-term reliability due to high dust loads need to be further clarified. Various multi-pollutant scrubbers have been developed to also remove odour and PM (PM10 and PM2.5) from the exhaust air (Zhao and others, 2011; Ritz and others, 2006; Patterson and Adrizal, 2005). Implementation of both acid air-scrubbers (Housing Measure 17) and biological air-scrubbers (Housing Measure 18) for broiler housing is largely similar to that for laying hens.

E. Manure storage, treatment and processing

1. Principles of manure storage, treatment and processing

219. For livestock agriculture to become sustainable, an optimal and efficient use of manure nutrients and organic matter is essential. However, manure nitrogen may be easily lost via gaseous emissions (NH_3, N_2O, NO_x, N_2) and leaching of nitrate (NO_3–) and other N_r compounds. Besides nitrogen losses, animal and manure emissions of methane (CH_4) to the atmosphere must be reduced as far as possible, to limit climate change impacts. Nitrate leaching and pollution of watercourses with N, P and organic compounds are possible if manures are not stored with impermeable barriers to prevent leakages of slurry or leachate from solid manures.

220. Significant N losses may occur during storage of either urine, faeces, or mixtures (slurries and farmyard manures/deep litters), and simple treatment (for example, solid-liquid

separation) or more advanced processing (for example, anaerobic digestion, ultrafiltration) may enable more appropriate manure management with lower N losses.

221. The treatment of manures typically involves a one-step operation to improve the properties of the manure. Expected effects include: the improvement of the fluid properties (by adding water or by separating solids); the stabilization of volatile nutrients (by acidification); and a reduction in odour nuisance (for example, aeration). Single-stage treatment of manures is typically applied on farms in the proximity of livestock buildings. The mass and ingredients of manures are not, or are only slightly, changed by treatment systems.

222. The processing of manures generally describes more complex and multi-step processes, which are used specifically to produce new products; for example, higher nutrient content, lower water content, free of undesirable odours and hygienically safe. In most cases, manure processing is used to produce marketable products that can be used as fertilizers and soil conditioners, as well as secondary raw materials (for example, fibres). Manure processing technologies may either be located on farms or operated as central/decentral plants.

223. Manure treatment and processing always come at a cost, both in economic, energy and environmental terms, so the simplest option fulfilling the goal(s) should always be the priority option:

(a) Direct land application;

(b) Simple treatment;

(c) Advanced processing (with (a) first, according to local limitations, including those related to pollution).

224. Simple treatment and advanced processing are most relevant when conditions (for example, high regional livestock density, large manure N surplus relative to local crop demand) favour overall environmental benefits from treatment or processing. Such systems should be designed with awareness of the need to avoid pollution swapping (for example, reducing ammonia loss, but increasing nitrate leaching somewhere else and vice versa).

225. Animal slurry composition is typically not ideal with regard to low emission handling and crop fertilizing properties. In particular, the high dry matter and carbon content pose several problems during slurry storage, application and crop utilization (see table IV.24 below). This points to the opportunity for increased development of systems to collect and store urine and dung separately (Housing Measure 1), or to apply manure treatment by solid-liquid separation.

226. High slurry dry matter tends to result in crust formation on the slurry surface and/or in sedimentation on the bottom of the slurry tank. In order to achieve an even distribution of nutrients in the slurry, slurry must be mixed/homogenized prior to application. Homogenization of slurry with high dry matter content is energy consuming and increases NH_3 emissions, as a larger volume of the slurry comes into close contact with the atmosphere.

227. Slurry contains considerable amounts of easily degradable carbon that serves as substrate for microbes. During slurry storage, a continuous degradation of organic matter can be observed. Degradation intensity is strongly dependent on the slurry dry matter content. Amon and others (1995) investigated changes in slurry composition over a 200-day storage period for stored cattle, beef and pig slurry. Degradation of organic matter was found to be significantly greater with higher slurry dry matter content. Such slurry degradation will include mineralization to form of ammonium (NH_4^+) from organic matter. This points to an opportunity for increasing the immediate fertilizer value of the slurry, provided that storage is covered, thereby avoiding NH_3 emissions and benefiting from increased slurry NH_4^+ content.

228. As conditions in slurry are anaerobic, degradation of organic matter is always dominated by anaerobic pathways. This means that both CH_4 and CO_2 are formed as end products of the degradation process. It is thus to be assumed that high dry matter slurry bears a greater risk for CH_4 emissions, contributing significantly to climate change. This also points

to the opportunity for CH_4 and CO_2 recovery; for example, linked to anaerobic digestion for production of biogas (cf. Manure Measure 8).

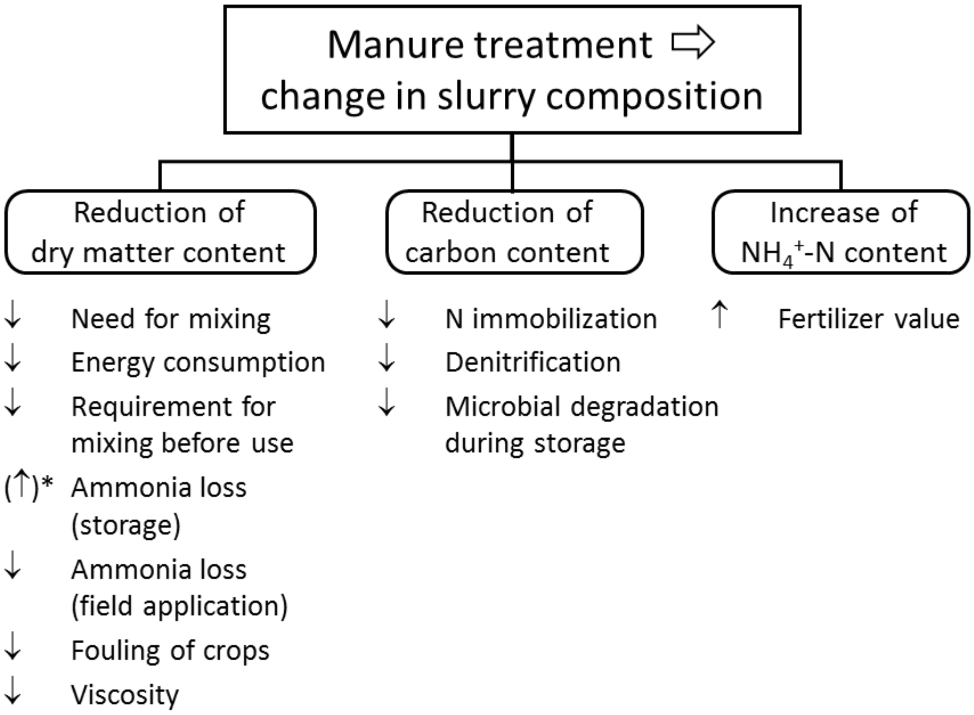
229. Environmentally friendly slurry application in the field requires that the slurry be more evenly applied near or below the soil surface. It is much more complicated to fulfil this requirement when the slurry has a higher dry matter content, causing a higher viscosity and less easy flow through band-spreading hoses. Following application of slurry, NH_3 emissions can be substantial and are found to increase with an increase in slurry dry matter content, due to slower soil infiltration (Sommer and others, 2013; Bitmann and others 2014). This emphasizes the importance of maintaining low dry matter contents of slurries. By reducing NH_3 and other nitrogen losses, available N resources on farms are increased, decreasing the need for additional N to be bought as manufactured inorganic fertilizer.

Table IV.24
Problems and benefits resulting from slurry high dry matter and carbon content and low nutrient content

	Problems
Storage	Natural crust formation and sedimentation of solids, giving heterogenous concentration of nutrients
	High energy consumption per unit of nutrient for pumping and mixing
	Potentially higher emissions of NH_3, N_2O, N_2, CH_4, and odour
Field application	High potential risk of NH_3 losses due to slow infiltration
	Major technical effort required (at high economic cost) for even and low emission application
	Suffering of crop plants due to scorching by broadcasted slurry
Crop utilization	Less effective crop uptake of slurry N than from mineral fertilizer
	Increased temporary N immobilization in the soil, increasing risk of lower crop N effect
	Higher risk of denitrification and subsequent N_2O and N_2 emissions
	Crop N effect less predictable/more variable than from mineral fertilizer
	Benefits
Storage	Natural crust formation may serve as a natural barrier, inhibiting NH_3 transport to the atmosphere; furthermore, the crust may have significant capacity for CH_4 oxidation, due to its partial aerobic conditions and high microbial activity
Field/soil	High dry matter and carbon content contribute to maintenance of soil organic matter content and biologically active soil

230. The N availability to plants is difficult to calculate with high dry matter slurry, because a high dry matter content drives increased microbial immobilization right after application. The narrower the C/N-ratio, and the higher the NH_4-N content, the more slurry N is potentially available to plants, whereas with a wide C/N-ratio, part of the slurry N is immobilized in the soil N pool and becomes available only at a later stage, which is often unpredictable or even too late, causing increased risk of nitrate leaching. In addition, an increase in slurry dry matter and subsequent soil N content has the potential to increase rates of nitrification and denitrification, increasing subsequent N_2O, NO_x and N_2 losses (for example, Dosch 1996). It may thus be beneficial to reduce slurry dry matter and carbon content at an early stage of manure management. This leads to several manure treatment options, which can be evaluated in relation to the requirements listed in figure IV.4 below.

Figure IV.4
Effect of changes in slurry composition achieved by manure treatment



Source: The figure was created for the current document.
Note: Arrows indicate decrease (↓) or increase (↑) in the listed property. *If depending on natural crusting of manure to reduce emissions rather than other types of cover.

231. In line with the objectives of the European Union Circular Economy Action Plan,[20] there is an opportunity to encourage the use of recycled nutrients that can replace nutrients otherwise obtained from primary raw materials. The main challenge is to use recycled nutrient resources with an environmental performance that is equal to, or better than, that of the primary nutrient resources they replace. Efforts are ongoing across the European Union to develop manure processing technologies that allow manure to be turned into a safe and agronomically valuable resource that can be used more widely.[21]

232. Techniques for simple manure treatment can be classified as physical, chemical or biological (see figure IV.5 below, Bernal and others, 2015). Furthermore, a number of different options/technologies are available for further and more advanced processing of raw or treated manures for recovering and upgrading nutrients and organic matter from different manure types (see figure IV.6 below). For slurries or other liquid manures, such as digestate from anaerobic digestion of manure and other biowaste, all treatment steps start with mechanical separation into:

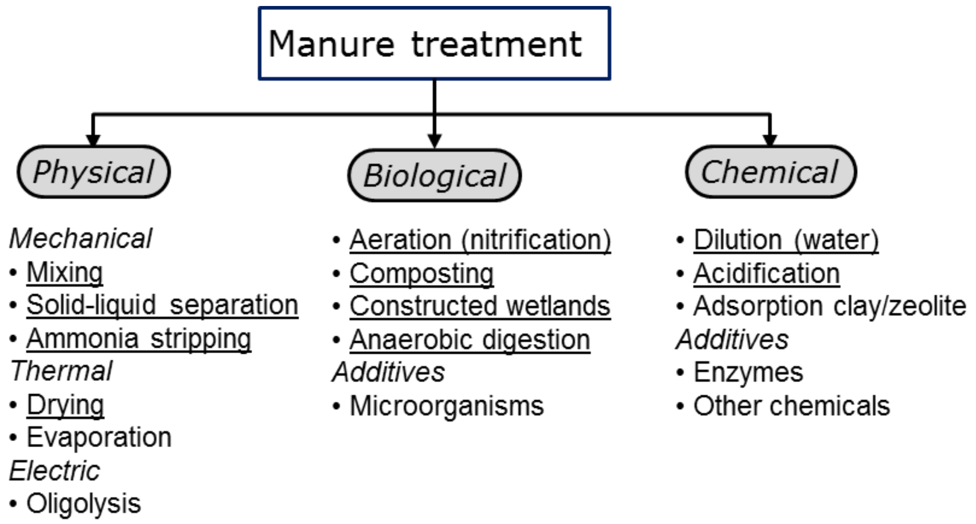
(a) A solid fraction that is relatively rich in organic N and P; and

(b) A liquid fraction, with low P, but relatively high mineral N and K contents.

233. Different simple techniques can be combined with each other. This allows a wide variety of by-products to be combined, resulting in highly variable distribution of organic nitrogen, ammoniacal nitrogen, phosphorus, carbon and other nutrients, which must be taken into account when managing the different fractions.

[20] See https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52015DC0614.
[21] See https://ec.europa.eu/jrc/en/research-topic/waste-and-recycling.

Figure IV.5
Options for simple manure treatment



Source: The figure was created for the current document.

Note: Underlined options are commonly applied in some regions in full scale on commercial farms (mainly pig farms); other options are applied either rarely or only in experimental/pilot scale – these are not dealt with further here, pending the availability of proof-of-concept and documentation.

234. There may be additional possible treatments of the liquid phase. In order to save water without increasing the amount of nitrogen supplied to the soil, and to favour the circular economy of water, it is common to carry out successive treatments of the liquid phase, so that the resulting product can be used in fertigation. For example, in the south of Spain, wetlands are being constructed to allow the reuse of water for irrigation in areas of scarce availability. In addition to nitrogen, many other characteristics have an influence on the decision to choose a procedure, such as: the contribution of organic matter; the formation of methane and other greenhouse gases; the presence of other nutrients; type of agricultural systems; salinity; weather; and, importantly in the countries of Southern Europe, the water footprint.

235. Each of these processing pathways and resulting products (see figure IV.6 below) has certain advantages and disadvantages, and the net environmental benefits/impacts and economic costs/profits differ greatly. A number of factors must be considered when prioritizing the processing options (Jensen, 2013):

(a) The primary aim should be nutrient recycling, mainly N and P; N is consumed in the largest quantities, is expensive and has impacts on energy consumption and greenhouse gas (GHG) emissions, while P is a scarce and non-renewable resource, with the highest price;

(b) Splitting N and P into different fractions is generally beneficial, as this enables more flexible and balanced fertilization in accordance with the needs of many crops;

(c) The technology or combination of technologies applied should preferably also produce energy or consume relatively little energy, so net energy production should be taken into account for both environmental and economic reasons;

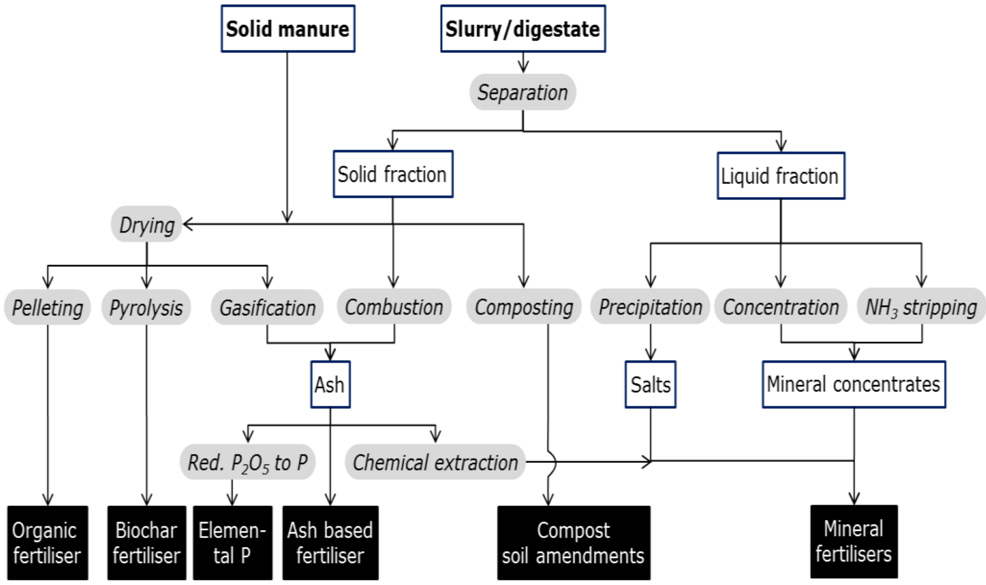
(d) Local solutions should be preferred, avoiding overly high transport cost and impacts; regional or more central solutions are therefore only justified if the economy of scale via higher efficiency outweighs the negative impacts of transporting the manure to a common facility;

(e) The quality of end-products and by-products is assessed differently depending on the user's perspective. For instance, a manure combustion ash, where the majority of the N has been lost, will not be appreciated by an organic farmer, while a compost is highly appreciated for its soil-ameliorating effect and slow release of N, even if some N is lost in the process;

(f) Biochars and compost may be valued highly by orchard and vineyard producers for their effects on soil-water holding capacity and nutrient retention, whereas conventional crop production farmers may value mineral concentrates and salts more highly. Production of recovered, biobased fertilizer products should not be supply driven (trying to solve a waste problem), but rather demand driven (biobased fertilizers that the farmers want).

Figure IV.6

Options for combining simple treatment with more advanced processing of manures to recover and upgrade nutrient and energy



Source: Modified from Jensen (2013).

Note: The options displayed result in widely different biobased fertilizers. Only a few are currently applied in full commercial scale; other are still at the experimental/pilot stage (and are therefore not dealt with further here).

2. Abatement measures for manure storage, treatment and processing

Manure storage

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

236. A wide range of options are available for covered manure storage using solid covers, 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 ammonia emission if well operated (Principle 14). Further details of such systems are provided by Bittman and others (2014). Less focus has been given to ensuring that solid manure (for example, farmyard manure and poultry manure) is covered; for example, through use of plastic sheeting. The reference system is taken as uncovered storage, including a permeable surface, which explains the benefit of using an impermeable base to reduce nitrate leaching (cf. Manure Measure 5).

Table IV.25

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Manure Measure 1

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

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

237. Where slurries have a high dry matter content, these may form a natural crust during storage, which is associated with substantially reduced ammonia emission (Bittman and others, 2014). There is broad agreement that crusting has an impact on gas release in many ways:

(a) Enhanced resistance to mass transfer (Olesen and Sommer, 1993);

(b) Oxidation of NH_3 (Nielsen and others, 2010) and CH_4 (Petersen and others, 2005); and

(c) Formation of N_2O related to nitrification and denitrification occurring in liquid–air interfaces near air-filled pores present in crusts (Petersen and Miller, 2006).

238. Ammonia and CH4 may be consumed due to microbial activity in the crust, leading to an emission reduction (Petersen and Ambus, 2006; Nielsen and others, 2010), while N_2O production may be enhanced (van der Zaag and others, 2009). A comprehensive assessment of the current knowledge on the effect of natural crusts can be found in Kupper and others (2020). The reference system is taken as uncovered storage, including a permeable surface, which explains the benefit of using an impermeable base to reduce nitrate leaching (cf. Manure Measure 5).

Table IV.26

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Manure Measure 2

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

Manure Measure 3: Covered storage of solid manure (dispersed coverings)

239. Ammonia emissions can be significantly reduced when covering solid organic fertilizers with dispersed coverings such as peat, clay, zeolite and phosphogypsum. The basis of the approach is to prevent contact of NH_3-emitting surfaces with the air, especially when covering them with ammonium-absorbing substances (Principle 15). Lukin and others (2014) found that total NH_3 emissions from poultry manure amounted to 5.9 per cent when it was covered with peat, 4.7 per cent when it was covered with loam, 1.3 per cent when it was covered with zeolites, and 16.9 per cent when it was covered with phosphogypsum. These values are relative to NH_3 emissions in the reference system with no covering. Use of these simple materials to cover piles of organic fertilizers thereby substantially reduces NH_3 emissions into the atmosphere (Lukin and others, 2014). Protocols are needed to specify minimum thickness of each type of covering material. Further testing is needed to assess the effect on N_2O, NO and N_2 emissions. Unless an impermeable base is used, the approach risks significant nitrate leaching. A combination of Manure Measures 3 and 5 can reduce both N_r emissions to air and leaching losses to water.

Table IV.27
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Manure Measure 3

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

Manure Measure 4: Storage of solid manure under dry conditions

240. Simply storing manure in a dry place, out of the rain, can also reduce nitrogen emissions from a range of Nr compounds and N_2. This is even more important for dried poultry litter, where keeping manure dry and out of the rain helps to avoid hydrolysis of uric acid to form ammonia. However, poultry litter is hydroscopic and will emit some ammonia when in humid atmospheres, even when kept free of rain (for example, Elliot and Collins, 1982). Keeping solid manure dry during storage minimizes mineralization and denitrification, which can give rise to N_2O, NO_x and N_2 emissions, as well as reducing nitrate and other Nr leaching. The reference system is taken as uncovered storage, including a permeable surface, which explains the benefit of storing under dry conditions to reduce nitrate leaching (cf. Manure Measure 5).

Table IV.28
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Manure Measure 4

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

[a] Simple storage under dry conditions is most effective for dry poultry litter to avoid hydrolysis of uric acid and associated microbial processes.

Manure Measure 5: Storage of solid manure on a solid concrete base with walls

241. Investments in this approach have been motivated out of the need to reduce nitrate leaching and other N_r leaching by avoiding run-off and infiltration into the soil. The approach has the benefit of being low-cost, but risks substantial NH_3 emissions, while also being ineffective at avoiding nitrification and denitrification, which contribute to N_2O, NO_x and N_2 emissions. The reference system is taken as uncovered storage, including a permeable surface, which explains the benefit of using an impermeable base to reduce nitrate leaching. Storage of solid manure on concrete areas is considered good agricultural practice for nitrate pollution but makes no contribution to reducing NH_3 emissions

Table IV.29
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Manure Measure 5

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

[a] The approach can be considered as preferable to open field storage of solid manure but risks substantial emissions of other N_r forms and N_2.

Simple Manure Treatment Measures

Manure Measure 6: Slurry mixing (during storage)

242. Slurry mixing in the storage is one of the most commonly applied manure treatment technologies. Slurry is thereby homogenized, typically shortly prior to field application, in order to achieve a more homogenous distribution of nutrients across the field(s) to which the volume of the slurry storage is applied. Apart from this, mixing does not offer any additional benefits compared to untreated slurry. Neither dry matter nor carbon content are reduced, and the C/N-ratio is not altered. No significant changes in N_2O or CH_4 emissions are expected, but NH_3 may tend to increase, depending on the extent and timing of mixing (mixing will tend to increase pH by promoting CO_2 loss from slurry), so mixing should only be done shortly before field application.

Table IV.30
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Manure Measure 6

Nitrogen form	NH_3	N_2O	NO_x	NO_3^-	N_2	*Overall N Loss*
UNECE category	3	3	3	3	3	3
Magnitude of effect	~/ (↑)	~	~	~	~	~

Manure Measure 7: Adsorption of slurry ammonium

243. Slurry additives can act on a chemical, physical or biological basis. Clay/zeolite mineral additives have been shown to adsorb NH_4-N and can thus potentially reduce NH_3 losses. However, this can only be achieved effectively with high amounts of additives; for example, it has been shown that 25 kg of Zeolite per m^3 slurry are needed to adsorb 55 per cent of NH_4-N (Kocatürk and others, 2017, 2019). On most commercial farms, it is neither logistically possible nor economically profitable to add such high amounts of slurry additives. Addition of biochar may also reduce NH_3 emissions from stored manure

Table IV.31
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Manure Measure 7

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

[a] The effect of ammonium adsorbing additives for stored slurry on losses of N_2O, NO_x, NO_3^- and N_2 remains uncertain.

Manure Measure 8: Slurry acidification (manure storage)

244. An obvious way to minimize ammonia emissions from stored slurry is to decrease pH by adding strong acids or other acidifying substances. This can also be done in the animal house (Housing Measure 8). Care must be taken to ensure that a low pH is maintained to get the full benefit of this measure. Slurry with a sufficiently reduced pH will also emit less methane. This solution has been used commercially since 2010 in countries such as Denmark (by 2018, around 15–20 per cent of all slurry applied in Denmark was acidified; Birkmose, personal communication), and its high efficiency for minimizing NH_3 emissions has been documented in many studies (see review by Fangueiro and others, 2015), with emission reductions by >80 per cent possible. It is most typical to acidify slurry using sulphuric acid (cheapest industrial acid; also, the sulfate added serves as a relevant plant nutrient source), although use of other acids is also possible. Acidification also reduces methane formation very effectively, by up to 67–87 per cent (Petersen and others, 2012). Reduced nitrification and denitrification decrease the potential for N_2O and N_2 emissions, though further studies

are required to demonstrate efficiency for this. In one novel variant of this method, electricity is used to produce a plasma that oxidizes N_2 to NO and thence to nitrogen dioxide (NO_2), which converts in slurry to produce nitric acid (HNO_3). In this way, slurry acidification is achieved while augmenting the nutrient value of the manure (Graves and others, 2019). More research is needed to assess this option fully.

245. Costs for in-house acidification systems can be higher than acidification during field application (Manure Measure 9), but are counteracted by additional benefits including: improved in-house air quality benefiting animal and staff, which may influence productivity; retention of more slurry N throughout the manure management chain; and associated savings in fertilizer costs.

Table IV.32

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Manure Measure 8

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE category	1	2	2	3 [a]	2	1 [a]
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 N_r and N_2 losses.

Manure Measure 9: Slurry aeration

246. Slurry aeration introduces oxygen into the slurry rapidly in order to allow aerobic microbes to develop. Oxidation of organic matter to CO_2 and H_2O increases, and thus CH_4-production and emission is reduced. Odorous compounds are degraded. Slurry dry matter content decreases. Thus, less mixing is needed and technical properties of slurry are often improved. However, successful aeration requires 200 m-3 oxygen per ton of slurry (Burton 1998).

247. Slurry aeration increases NH_3 emissions and in energy consumption. The potential for NO_x emissions is also expected to increase, as increased oxygen availability promotes nitrification, while subsequently higher levels of nitrate availability may increase other oxidized Nr losses and denitrification. Only a few studies have quantified the extent of these increases (Amon and others, 2006) and more research is necessary to allow a complete evaluation. In the present context, an increase in denitrification to form N2 is considered a waste of available Nr resources.

Table IV.33

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Manure Measure 9

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE category	3	3	3	3	3	3
Magnitude of effect	↑↑	↑↑	↑?	?	?	↑↑

Manure Measure 10: Mechanical solid-liquid separation of slurry fractions

248. During slurry separation, solids and liquids are mechanically separated from each other. This results in two fractions: a liquid slurry fraction, with relatively low dry matter content compared with the slurry; and a solid fraction that can be stored in heaps. Energy consumption for slurry separation is relatively low but depends on the technology used for separation. Dry matter content in the liquid fraction is reduced by 40–45 per cent, and vice versa for the solid. Carbon content in the liquid is typically reduced by 45–50 per cent, with

the C/N-ratio of the liquid decreasing from about 10:1 to about 5:1 (Amon 1995; Sommer and others, 2013). As carbon is removed from the slurry, microbial degradation of organic matter during slurry storage is reduced. However, the opposite may be the case for the solid fraction, depending on storage conditions.

249. The removal of solids reduces crust formation and sedimentation of the liquid fraction in comparison with raw slurry. Thus, less intensive mixing is necessary to homogenize the slurry prior to application. Conversely, the potential for ammonia losses is increased if slurry is stored without a cover. Therefore, other emission-reduction measures during storage of the liquid fraction need to be applied (Manure Measures 1, 2 or 8). Efforts for low-emission application techniques are also reduced as separated slurry has a lower viscosity and flows more easily through band-spreading hoses (Owusu-Twuma and others, 2017). Slurries with very low dry matter content can be spread with simple nozzle-beam-dischargers that can be operated on slopes >10 per cent, which is not possible with other band-spreading techniques. Furthermore, separated slurry liquid fraction has a low viscosity and infiltrates rapidly into the soil. Thus, plants get less dirty, and ammonia emissions after liquid fraction spreading are typically reduced. A substantial reduction of ammonia emissions by slurry separation is therefore possible for the liquid phase, especially following land application (for example, Amon and others, 2006).

250. The liquid fraction of separated slurry has a narrow C/N-ratio, which reduces the potential for both microbial N immobilization in the soil and N_2O emissions. Crop N availability of the liquid fraction is therefore more predictable and can be better calculated in order to match nutrient requirements of crops to actual fertilization. Dosch (1996) investigated fertilization with untreated and separated slurries and found significantly higher denitrification rates with untreated slurry. Separated slurry liquid fraction on the other hand resulted in significantly higher crop yield. However, the solid fraction needs to be handled with care during storage to avoid elevated ammonia emissions. Furthermore, the solid fraction may become a source of methane emissions, if not properly treated. Alternatively, if the solid fraction is used as feedstock for biogas production, this methane potential may be recovered and utilized as renewable energy source. After application, the solid fraction serves mainly as soil improvement and slow-release N fertilizer.

251. Slurry separation fulfils most requirements of appropriate manure treatment. Costs could be further reduced if the technology were more widespread and more separators were on the market and available to farmers. As the fertilizer value of the liquid fraction from separated slurry is improved, mineral N fertilizer input can be reduced. The slurry liquid fraction can be applied at the soil surface in a growing crop with very simple low-cost slurry band spreaders (for example, trailing hose, see chapter V) with a high uptake efficiency and fertilizer replacement value. The main caveat to the method is the difficulty of appropriate storage, handling and utilization of the solid fraction; this needs to be low emission (for example, Field Measure 11), in order not to compromise benefits of the liquid fraction. An alternative is to use the solid fraction as a feedstock in nutrient anaerobic digestion (Manure Measure 11) with nutrient recovery.

Table IV.34

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Manure Measure 10

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

[a] Although this measure is not known to reduce NO_x 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 N_r and N_2 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 11: Anaerobic Digestion

252. Anaerobic digestion of animal manures is mainly implemented at present for bioenergy production reasons. Improvement of manure quality is therefore typically considered to be a "by-product" of anaerobic digestion. However, when combined with nutrient recovery methods (see figure IV.6 above; for example, Nutrient Recovery Measures 3–5), nutrient management can be considered as fully integrated as a key goal in implementation of anaerobic digestion. The value of products from anaerobic digestion (biogas produced, available nutrients) can help provide an extra income to farmers, enabling them to make investments (for example, for adequate manure storage and application technology).

253. Biogas production from animal manures through anaerobic digestion aims at maximizing the biomethane yield. Where no biogas recovery system is available, unintended anaerobic degradation of organic substances into methane during manure storage should be limited as far as possible, to prevent emission to the atmosphere of this strong GHG. This also maximizes the resource availability for subsequent biogas production when facilities are available. Anaerobic digestion can include heating of the manure to promote digestion, leading to increased methane production, which may be used in a variety of systems (for example, in combined heat and power production). Anaerobic digestion not only reduces methane emissions from subsequent storage of the manure digestate, but the energy produced typically substitutes consumption of use of fossil energy. Both effects reduce anthropogenic greenhouse gas emissions.

254. Anaerobic digestion reduces manure carbon and dry matter content by about 50 per cent (Amon and Boxberger 2000). Ammonium content and pH in digested slurry are higher than in untreated slurry. Thus, the potential for NH_3 emissions during subsequent slurry storage is increased. Digested slurry therefore has to be stored in covered slurry stores. These should be connected to the gas-bearing system of the biogas plant, because methane is still formed after the main digestion phase has taken place in the heated digester.

Due to the reduced dry matter content, biogas slurry can infiltrate more rapidly into the soil, which tends to reduce ammonia emissions after slurry application. However, the increased NH_4^+ content and pH give rise to higher potential for ammonia loss, especially after surface application. It is therefore strongly recommended to apply biogas slurry with low-emission techniques near or below the soil surface (for example, band application or injection, chapter V).

255. It should be noted that the process of anaerobic digestion itself does not reduce NH_3 emission, but rather provides the opportunity to reduce NH_3 emission by virtue of the requirement for a closed system. Similarly, anaerobic digestion produces a digestate with high TAN content and low dry matter content, which is more easily manageable to increase

crop nitrogen use efficiency than slurry or solid manure with a high carbon content. These points mean that, while anaerobic digestion increases the opportunity to reduce NH_3 emissions, achieving this will depend on the deployment of an appropriate package of measures. The combined implementation of anaerobic digestion (reducing dry matter content, increased NH_4^+ and pH), covered storage prior to use, and low-emission application to land (for example, trailing hose, injection) therefore considerably reduces NH_3 emissions. In addition, N immobilization and N_2O losses are likely to be smaller than from untreated slurry, due to the removal of easily degradable organic substances during the anaerobic digestion process. Energy consumption for pumping and mixing is considerably reduced due to the reduced dry matter content. When combined with appropriate methods for low-emission land-spreading of the digestate, anaerobic digestion therefore has multiple benefits. In addition, it provides the opportunity for further processing for more advanced forms of nutrient recovery, including nutrient precipitation, concentration and ammonia stripping (see figure IV.6 above; Nutrient Recovery Measures 3–5).

Table IV.35

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Manure Measure 11

Nitrogen form	NH_3	N_2O	NO_x	NO_3^-	N_2	*Overall N Loss*
UNECE category	1 [a]	2 [a]	3	1 [a]	2 [a]	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 NO_x 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 N_r losses. The requirement for an impermeable base implies less nitrate leaching than storage/treatment of manure on a permeable surface.

Manure Measure 12: Manure Composting

256. Composting of manure is done in order to create a stable and odourless biobased fertilizer product, with lower moisture content, while containing most of the initial nutrients, free of pathogens and seeds (Jensen, 2013). Composting significantly reduces mass (as a result of water evaporation and volatile solids decomposition to release CO_2) and hence transport costs. However, it is difficult to avoid some loss of manure N in the form of NH_3 and the process also emits greenhouse gases, with potential for increased N_2O and CH_4 emissions, in addition to NO_x and N_2 (Chowdhury and others, 2014). The N fertilizer value of composts is often significantly lower than the N-rich manure components it is made from, which is largely a result of associated NH_3 and N_2 emissions (Jensen, 2013). Composting on porous soil surfaces may also be associated with significant leachate, including NH_4^+, NO_3^- and other N_r compounds. Composting is typically a low-cost technology but implies space requirements and energy consumption. Overall, it is not therefore usually recommended to mitigate nitrogen losses but may be preferred on other criteria (for example, volume and weight reduction, compost product stability, reduced odour, improved marketability and soil amelioration).

Table IV.36

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Manure Measure 12

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE category	3	3	3	3 (2)	3	2
Magnitude of effect	↑	~/↑	↑	↑(↓ [a])	↑	~.[b]

[a] If conducted on an impervious surface with recovery of composting leachate.

[b] A more favourable overall assessment for N_r may be achieved for "closed vessel composting" combined with acid scrubbing of exhaust air (cf. see Nutrient Recovery Measures), which may be used in certain contexts to manage biohazards, though significantly increasing implementation costs.

257. In addition to these simple manure treatment options, constructed wetlands have also been used to treat liquid manure (see Landscape Measure 5).

Advanced Manure Processing and Nutrient Recovery

Nutrient Recovery Measure 1: Drying and pelletizing of manure solids

258. Drying and pelletizing of solid manures, slurry or digestate solids can be done to create a more stable and odourless biobased fertilizer product. Drying is energy intensive and thereby relatively expensive, unless excess energy (for example, from the combined heat and power plant engine on a biogas plant) is freely or cheaply available. Increased ammonia loss is inevitable in the process, unless exhaust filtering or scrubbing and recovery is applied, or the solids are acidified prior to drying. Drying is usually combined with a pelletizing process to facilitate handling. The pelleted material can be marketed as an organic matter and P-rich soil amendment; if acidified prior to drying, the resulting product may also be rich in plant-available N (Pantelopoulos and others, 2017).

Table IV.37

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Nutrient Recovery Measure 1

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE category	3 (1 [a])	3	3	3	3	2
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

259. 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, at present, the method leads to an almost complete loss of the manure N, which is converted into gaseous N_2, NO_x and NH_3. Available advanced technologies (for example, selective non-catalytic reduction, focus on denitrifying these N_r gases to N_2. Until systems are implemented to minimize N_2 formation and recover the N_r gases, this measure cannot be considered appropriate for abating overall N loss.

260. At the same time, the approach produces ash or biochar residuals. These ashes contain the non-volatile nutrients, concentrated relative to the solids. They can be used as an ash-based, P- and K-rich soil amendment or biobased fertilizer. The availability of the remaining nutrients in the ash is generally much lower than for the raw manure, whereas for biochar it is in between ash and raw manure. Organic compounds in the biochar that are produced are very recalcitrant to biological decay and have a very large specific surface area, being

potentially charged. This means that such biochar may be used for soil amendment, ameliorating soil pH and organic matter positively.

Table IV.38

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Nutrient Recovery Measure 2

Nitrogen form	NH_3	N_2O	NO_x	NO_3^-	N_2	*Overall N Loss*
UNECE category	3 (2 [a])	3	3	3	3	3 (2 [a])
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 NO_x and NH_3 emissions. However, current methods still increase N_2 emission, so that the N_r 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 N_r gases (Sutton and others, 2013).

Nutrient Recovery Measure 3: Precipitation of nitrogen salts

261. Struvite ($MgNH_4PO_4 \cdot 6H_2O$) can be precipitated from liquid manures, provided that the appropriate conditions are present (pH ∼9, a molar ratio 1:1:1 of Mg2+ : NH_4^+ : PO_{43}–, conducive physical settling conditions). As such, the precipitation of struvite is a method for removal and recovery of both N and P from liquid manures. The method has been developed for wastewater treatment, where P removal can easily reach more than 70 per cent and it is commercially available for sewage treatment plants, although not yet widely applied. For manures, the struvite technique is particularly relevant for anaerobically digested slurries and the liquid fraction from digestate separation; hence, it has been the subject of massive research in the past decade and quite high removal efficiencies have been achieved (56–93 per cent; see further review in Jensen, 2013). However, it only works for the N already present as NH_4^+ and further development is needed for appropriate application to liquid manures and digestates. So far, only a few commercial-scale plants are in operation worldwide. The main advantage of struvite is its high concentration and similarity in physical-chemical properties to conventional mineral N fertilizer.

Table IV.39

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Nutrient Recovery Measure 3

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

[a] The table refers to precipitation of struvite only. As the approach recaptures N_r 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 N_r and N_2 losses, by mobilizing recovery and reuse of available N_r resources.

Nutrient Recovery Measure 4: Concentration of nitrogen salts and solutions

262. Mineral concentrates are highly nutrient-rich solutions that may be obtained via ultrafiltration, evaporation or reverse osmosis of the liquid fraction from separation of slurry or digestate. These mineral concentrates (the retentate) may be directly applied to agricultural land, while the by-product water, which is low in nutrients (the permeate), may be directly discharged to surface waters or the sewage system. The greatest wealth of experience with these technologies in Europe can be found in the livestock regions of the Netherlands and Belgium, where a number of centralized and large-scale manure processing plants utilize a range of technologies in combination (for example, anaerobic digestion, solid-liquid

separation, ultrafiltration/reverse osmosis/solids drying). Provided that the losses can be kept to a minimum, the mineral fertilizer replacement value of the mineral concentrates can be relatively high, as they resemble commercial liquid fertilizers, with nearly all the nutrients in a mineral, plant-available form. However, to avoid gaseous NH_3 losses, this may require prior acidification or injection of the concentrate into the soil (Jensen, 2013). At present, such approaches have significant energy requirements, so the challenge for the future must include improving energy efficiency, with lower energy requirements per kg of recovered nitrogen and other nutrients. As these technologies are still under investigation, the UNECE categories are currently uncertain (for example, category 3, pending further assessment).

Nutrient Recovery Measure 5: Ammonia stripping

263. Air stripping of NH_3 is a process whereby the liquid fraction after manure separation is brought into contact with air, upon which NH_3 evaporates and is carried away by the gas. Instead of ambient air, "'steam stripping" can be used whereby steam replaces air as the ammonia carrier. Since evaporation occurs from the liquid surface, it is advantageous to ensure that the liquid has a large surface area. This can be achieved in a stripping column with structured packing, where it spreads over the packing material in a thin film and therefore has a considerably larger surface. The mass transport also increases with the concentration of NH_3 (aq) in the liquid phase; hence, if pH and/or temperature is increased, an increasing part of total ammoniacal nitrogen is in NH_3 (aq) form and the mass transport of NH_3 increases (Sommer and others, 2013). Altogether, this makes the technology relatively energy demanding and costly, although cheap/free surplus energy from, for example, a biogas- combined heat and power plant may reduce energy costs. Alternatively, using selectively permeable membrane contact systems at lower temperatures may offer a cheaper solution, if membrane fouling can be avoided.

264. Ammonia released from an NH_3 stripping column or from a manure drying facility can be collected using wet scrubbing with an acid solution, typically sulphuric acid, to make ammonium sulphate (which is most common). Application of the approach using nitric acid to make ammonium nitrate has also been reported. Both compounds can serve as raw materials for mineral fertilizers, and thus provide the opportunity for circular economy development as part of the fertilizer industry's commitment to including recovered and recycled N_r. In general, this is a well-known, and generally effective technology. The main barriers are: the relatively low N concentrations achievable in the scrubber-liquid (and thus high logistic costs); and the quality requirements for introduction of the scrubber-liquid into the raw materials market for the fertilizer industry.

Table IV.40
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Nutrient Recovery Measure 5

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

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

F. Best practices and priority measures

265. Best practices and priorities for the selection of abatement/mitigation measures must be based on the following criteria:

(a) Ease with which approaches can be implemented;

(b) Effectiveness;

(c) Impact on environmental emissions;

(d) Secondary effects;

(e) Controllability; and

(f) Cost efficiency.

266. Based on these criteria, we suggest the priority measures listed below.

Livestock feeding

267. The following priorities through livestock feeding help to reduce nitrogen losses:

(a) Avoid N surplus from the very beginning of the manure management continuum;

(b) Adjust animal diet to animal performance (in line with existing guidance in the UNECE Ammonia Framework Code, Bittman and others, 2014);

(c) Adapt animal diet to shift N excretion from urine to faecal excreta;

(d) Dairy cattle:

(i) Reduction of crude protein content in the diet;

(ii) Adapt diet and dairy production system to site-specific conditions;

(iii) Increase milk yield with moderate level of concentrates;

(iv) Increase production cycles per cow.

(e) Pigs:

(i) Reduction of crude protein content in the diet;

(ii) Multiphase feeding;

(iii) More use of food wastes (including from processing and retail) as a way to reduce upstream and downstream emissions.

Livestock housing

268. The following priorities help to reduce nitrogen losses from livestock housing:

(a) Reduction of indoor temperature;

(b) Reduction of emitting surfaces, reduction of soiled areas;

(c) Reduction of air flow over soiled surfaces;

(d) Use of additives (for example, acidification);

(e) Frequent removal of slurry to an outside store;

(f) In the longer term: smart barns with optimized ventilation (open housing) or ventilation air scrubbing (closed housing), immediate segregation of urine and faeces components, in-house acidification of slurry (pigs and cattle).

Manure storage, treatment and processing

269. The following priorities help to reduce nitrogen loses and to mobilize nitrogen recovery and reuse from manure storage, treatment and processing:

(a) Store solid manures outside the barn on a solid concrete base in a dry/covered location;

(b) Ensure tight slurry stores, and cover either by a solid cover, or by ensuring sufficient natural crust formation;

(c) Use manure treatment where relevant to:

(i) Homogenize nutrient content for more even field spreading to ensure that all available nutrient resources are used effectively for crop growth;

(ii) Reduce slurry dry matter content, for example, by solid-liquid separation, to enhance soil infiltration and limit NH_3 loss;

(iii) Increase slurry NH_4^+ content to maximize crop N availability;

(iv) Lower pH by acidification to reduce NH_3 volatilization and enhance fertilizer value;

(v) Apply manure treatment methods to enable combined energy and nutrient recovery, for example, anaerobic digestion, where relevant.

270. The use of manure advanced processing for N recapture and production of value-added nutrient products from recycled manure N resources should be focused on situations where other effective options are not available, for example, high-tech separation by filtration, reverse osmosis and NH_3 scrubbing, drying of manure and digestate solids for organic fertilizer production. Ideally, production of recovered, biobased fertilizer products should not be supply driven (trying to solve a waste problem), but rather demand driven (biobased fertilizers that farmers want). However, this implies the need to also address regional manure surpluses that can result from large-scale livestock feeding operations.

G. Conclusions and research questions

271. It is clear that manure management has an impact on quantities of N_r emissions (NH_3, direct and indirect N_2O emissions, NO_x 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 N_r, 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 livestock 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.

272. 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 Union Nitrates Directive,[22] 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 (chapter III, principle 6) 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.

273. 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).

[22] Council Directive of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources, *Official Journal of the European Communities*, L 375 (1991), pp. 1–8.

Addressing environmental needs

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

(a) Relationship between nitrogen and greenhouse gas emissions;

(b) Influence of climate change on nitrogen emissions;

(c) Interaction between abatement/mitigation and adaptation measures;

(d) Interaction between nitrogen emissions and animal welfare;

(e) Integrated assessment of the whole manure management continuum;

(f) Integrated assessment considering the three pillars of sustainability: economy; environment; society;

(g) Interaction between consumer demand and nitrogen emissions;

(h) Development of region-specific concepts for sustainable intensification;

(i) Modelling of livestock production at the regional, national and global scales;

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

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

(a) Assessment of emissions from naturally ventilated barns;

(b Assessment of emissions from new, animal-friendly housing systems;

(c) Development of abatement/mitigation measures, especially for naturally ventilated dairy barns (for example, targeted ventilation and air-scrubbers, manure acidification);

(d) Interaction between climate change and heat stress/animal behaviour/emissions;

(e) Interaction between low-protein diets and N and greenhouse gas emissions;

(f) Interactions between N and greenhouse gas emissions during housing, storage and application to field;

(g) Life-cycle assessment: for example, grass-based dairy feeding versus low-protein dairy feeding;

(h) Feed and manure additives for improved N use efficiency;

(i) 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.

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

(a) Climate and site-specific conditions vary across the UNECE region and globally;

(b) All three columns of sustainability must be considered: economic, environmental and social sustainability;

(c) Conflicts of interest must be addressed;

d) Targeting approaches according to the needs of different regions.

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

(a) Establishing networks to exchange manure management information, connect people, and forge partnerships;

(b) Launching an online knowledge hub on best practices for livestock housing and manure management;

(c) 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 resources from partners;

(d) 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.

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V. Field application of organic and inorganic fertilizers

A. Introduction and background

278. Nitrogen (N) is the nutrient recovered in largest quantities from soil by agricultural crops, and the availability of N to crops has a dominant impact on crop yields and nutritional quality, and hence the ability of farms to produce food for humanity. Management of the different N inputs to agricultural soils will influence the subsequent N cycling, N utilization by crops and losses of N in different forms to the environment. Until now, the focus has largely been on controlling individual N loss pathways, for example, nitrate leaching (European Union Nitrates Directive), ammonia (Gothenburg Protocol, European Union National Emissions Ceilings Directive[23] and Habitats Directive) and nitrous oxide (Kyoto Protocol to the United Nations Framework Convention on Climate Change), with guidance given accordingly (for example, UNECE Ammonia Guidance Document, Bittman and others, 2014). It is critical when trying to develop a more joined-up approach to N guidance to have a good understanding of how management practices and targeted abatement/mitigation measures have an impact on the whole N cycle rather than just on specific pathways. This requires an understanding of how human activity, including farming, is able to affect all nutrient cycles, and especially N, which is highly dependent on microbiological activities and hence particularly sensitive to soil carbon, moisture and temperature. This chapter discusses integrated approaches to reducing N losses to air and water from N inputs to agricultural land, highlighting the major inputs and loss pathways, while describing the most important measures and prioritizing recommendations for abatement/mitigation for policymakers and practitioners.

279. This chapter should be read in conjunction with chapter IV regarding the management of livestock manures. An integrated approach to reducing N losses throughout the entire manure management chain needs to be taken to ensure that the benefit (for example, reduced losses) of measures taken during the livestock housing and manure storage stages is maintained during the field application stage. The aim is to ensure that nitrogen savings made in previous stages are not subsequently lost through poor management associated with field application of manures. This connection is very important for NH_3, where it is necessary to minimize contact with air of manure throughout the manure management chain (principle 15).

280. The term “inorganic fertilizers” is used throughout this chapter to refer to manufactured inorganic and organo-mineral fertilizers, often referred to as “synthetic” fertilizers. This includes all mineral N fertilizer types such as ammonium nitrate and ammonium sulphate, and also urea (and urea-based fertilizers). Although urea is chemically an organic molecule, it is typically categorized as an “inorganic” fertilizer because it is usually manufactured from inorganic materials (NH_3 and CO_2) and grouped with other inorganic fertilizers, such as ammonium nitrate, phosphate and sulphate. With the development of circular economy recapture of N from organic sources for production of inorganic fertilizers (for example, Nutrient Recovery Measures 3–5), such distinctions are becoming increasingly flexible.

B. Nitrogen inputs to agricultural land

281. Nitrogen is applied directly to agricultural land as a crop nutrient in the form of manufactured inorganic fertilizers, as organic fertilizers such as livestock manure (including urine), or as other organic amendments deriving from waste or by-products (for example, sewage sludge, household and food wastes, food-processing residue, animal rendering, digestate from anaerobic digestion, composts). For the purposes of this chapter, all these sources are considered as organic or inorganic fertilizers.

[23] Directive (EU) 2016/2284 of the European Parliament and of the Council of 14 December 2016 on the reduction of national emissions of certain atmospheric pollutants, amending Directive 2003/35/EC and repealing Directive 2001/81/EC, *Official Journal of the European Union*, L 344 (2016), pp. 1–31.

282. For managed livestock manures, an integrated approach should account for improved practices during the storage, handling and/or processing of manures (chapter IV), potentially resulting in more and/or higher availability of N at land application. Grazed land will receive N in a less managed form, usually through uneven dung and urine deposition by grazing livestock. Managed land will also receive N inputs from biological fixation by legumes and non-symbiotic microbes, from wet and dry atmospheric deposition of N species and, more indirectly, from the recycling of crop residues; these inputs are discussed at the landscape scale in chapter VI.

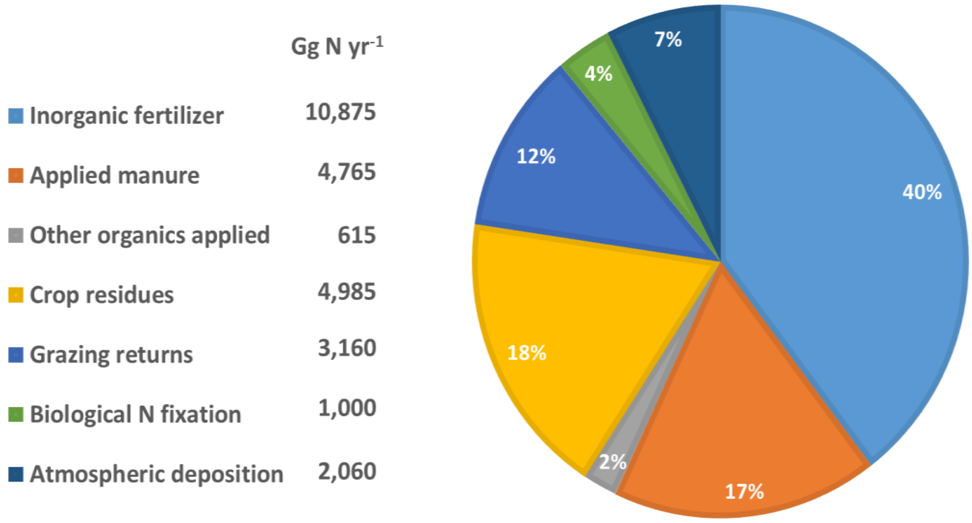
283. Together, these direct and indirect inputs are estimated to total approximately 27 million tons of N per year for the European Union (see figure V.1 below). Note that these are not all new N inputs to land; for example, grazing returns, crop residues and some of the applied manure represent a recycling of N previously removed from the soil as forage or feed for animals and subsequently returned in a different, and often more reactive, form. The characteristics of these different sources of N and their management are important in determining and improving the agronomic value to crop and forage production and reducing potentially damaging impacts on the environment and climate. Across the UNECE region, existing legal frameworks limit N inputs to agricultural land in certain vulnerable regions (such as those covered by the Nitrates Directive within the European Union). Further sources of guidance on practices for reducing the impact of agricultural practices on N and P leaching to water are listed in section 4.1 of this chapter.

284. Inorganic fertilizers represent the largest category of N inputs to agricultural land across much of the UNECE region, as illustrated for the European Union in figure V.1. In the absence of other N inputs, fertilizer N commonly doubles crop yields and fertilizer N is therefore vital to the profitability and productivity of crops in all parts of the UNECE region. Inorganic N fertilizers are used by almost all farms in the UNECE region, other than those committed to “organic” production (although even these can use some forms of inorganic fertilizer, including rock phosphate). There are a number of different formulations and blends of N-containing manufactured fertilizers used in Europe, but these can be broadly considered to deliver N in the chemical form of ammonium, nitrate or urea. Ammonium and nitrate are directly available for plant uptake (with different plant preferences and tolerances), although ammonium will also convert to nitrate in the soil through the microbial oxidative process of nitrification, which releases acidifying H+ ions into the soil solution. Ammonium and nitrate behave differently in the soil, with ammonium more susceptible to losses via ammonia volatilization, while nitrate is more susceptible to losses via denitrification (as gases N_2O, NO_x and N_2) and leaching (NO_3^-). Urea hydrolyses after contact with moist soils in the presence of the ubiquitous urease enzyme to form ammonium (and subsequently nitrate); the hydrolysis process is associated with an increase in pH near the granules, which greatly increases the susceptibility to losses via ammonia volatilization.

285. Inorganic fertilizers containing only nitrogen (referred to as “straight nitrogen products”) include granular ammonium nitrate (AN), calcium ammonium nitrate (CAN), urea and liquid urea ammonium nitrate (UAN). Anhydrous ammonia is a liquid (gas under pressure) fertilizer that requires special equipment and safety measures, and suitable soil conditions for injection-application (for example, trafficable soils that are not too hard or stony for the penetration of injector tines). Nitrogen combinations with other nutrients include ammonium sulphate, diammonium phosphate and potassium nitrate. Ammonium nitrate and CAN represent the major fertilizer forms used in Europe, while urea use predominates in the wider UNECE region, including in North America and Central Asia. In Europe, urea (either as straight urea or UAN) accounts for only approximately 25 per cent of total fertilizer N use (based on statistics from the International Fertilizer Association[24]), but this may be increasing in some European countries, which poses a risk of increasing ammonia emissions. Fertilizers Europe and Eurostat[25]estimate that urea imports to the European Union roughly doubled from ~2.4 million tons in 2000/2001 to 4.8–5.3 million tons in 2015–2017.

[24] See www.ifastat.org/databases/plant-nutrition.
[25] See http://epp.eurostat.ec.europa.eu/newxtweb/.

Figure V.1
Estimate of N inputs to agricultural soils for European Union 28 (Gg N per year) for 2014



Source: Values derived from the 2016 greenhouse gas (GHG) inventory submission to the United Nations Framework Convention on Climate Change (UNFCCC) by the European Union (see: http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories _submissions/items/9492.php), with the exception of biological N fixation and atmospheric deposition, which were derived from Leip and others, (2011) for the year 2002.

Note: Inputs from crop residues, grazing returns and, to some extent, managed animal manure, represent recycling of N within the agricultural system.

286. The major livestock types for which managed manure is applied to land are cattle (dairy and beef), pigs and poultry. Cattle and pigs excrete N as urea and complex organic compounds, but the urea quickly dissociates to ammonia during livestock housing and manure storage, so manure applied to soils contains N in organic and inorganic forms (ammonium and nitrate and, for poultry, uric acid and urea). Manure characteristics depend on livestock diet and performance, housing (including bedding use) and manure storage systems and any subsequent processing prior to land application (as described in chapter IV). See below for further information on manure characteristics:

(a) For cattle and pigs, manure type can be categorized as either slurry, consisting of mixed urine, faeces and water with relatively little bedding material (straw or wood shavings) and with a dry matter content typically in the range 1–10 per cent, or as a more solid farmyard manure (FYM) consisting of urine and faeces mixed with large amounts of bedding material (typically straw) having a higher dry matter content (>15 per cent);

(b) Slurries will typically contain 40–80 per cent of the N in the ammonium form, with the remainder as organic N and very little as nitrate, due to anaerobic conditions;

(c) Farmyard manure typically contains a much lower proportion of the N in the ammonium form, due to volatilization and nitrification of ammonia, and may contain a small fraction in the nitrate form. The organic N in FYM will mineralize to ammonium over time, becoming available for crop uptake, but is also susceptible to the N loss pathways to water and air;

(d) Pig manure will typically have a higher total N and available (inorganic) N content than cattle manure, depending on feeding and management practices;

(e) For poultry, manure can generally be categorized as litter, deriving from systems where excreta are mixed with bedding (for example, broiler and turkey houses) or as manure where excreta are collected, generally air-dried, without bedding material (for example, laying hens). Both have relatively high dry matter contents (>30 per cent) and higher total N contents than cattle or pig manures. Between 30–50 per cent of poultry manure N may be labile as uric acid or ammonium;

(f) Livestock manures also vary regarding the content of other essential and non-essential nutrients, and application rates may be limited by the concentration of phosphorus (P) rather than N because of their relatively high P:N ratios compared to crop uptake;

(g) The mineralization/immobilization, availability and utilization of manure N is strongly influenced by the C:N ratio of manure and soil, soil pH, soil moisture and temperature, as well as spreading techniques such as subsurface placement.

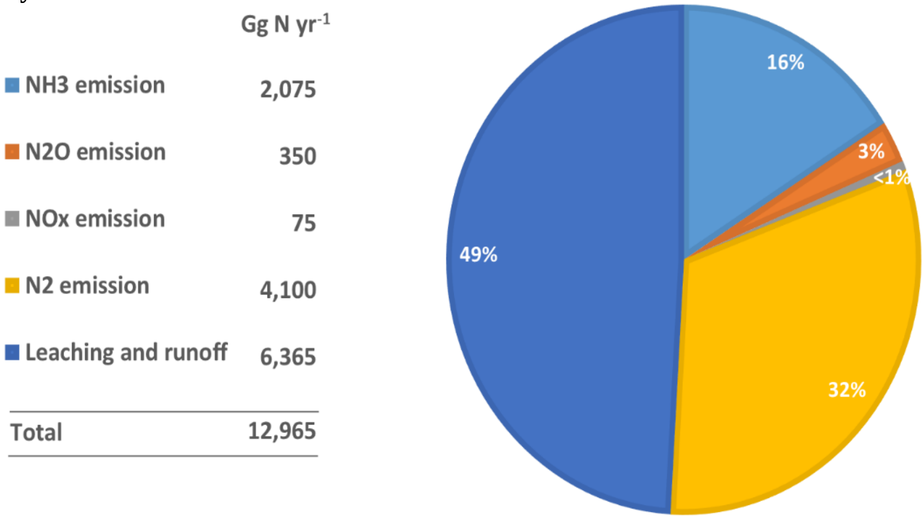
287. Cattle and sheep can spend a substantial proportion of the year at pasture grazing, depending on regional soil and climate characteristics and management systems, and some pigs and poultry will also spend time outdoors under certain production systems (for example, “free-range”). Pigs have behavioural traits that result in specific areas being designated for dunging/urinating, whereas cattle and sheep will excrete more randomly across the grazed area, with higher loadings in camping areas (where animals prefer to sit) or high traffic areas. During grazing, dietary N not retained by the animal is deposited directly back to the pasture in highly concentrated patches as dung and urine. Dung contains mostly organic N forms, which will subsequently mineralize at a rate dependent on soil and environmental factors, whereas N in urine is effectively in an inorganic form[26] and immediately susceptible to losses via ammonia volatilization, leaching and denitrification (Selbie and others, 2015). Under dry conditions, both urine and faeces patches may create small dead areas of grass, reducing N uptake, or may increase grass growth. In addition, the grass in dung patches may be avoided for a time by cattle, a behaviour which may be associated with avoiding intestinal worms. Intensively managed grazing will generally favour more uniform deposition of manure and urine and more even grass production and consumption (as well as larger N losses).

288. A range of other N-containing organic amendments are applied to agricultural land. While the total amount applied is currently small, this is likely to increase (and be encouraged) as the concept of the circular economy becomes more prevalent. The processing of such organic amendments may increase (for example, anaerobic digestion) or decrease (for example, composting) the plant availability of N. These materials may be liquids (for example, digestates) or solids (for example, composts), deriving from human wastes, food processing, green wastes, etc., and, for the purposes of this chapter on inorganic and organic fertilizers, they are implicitly included in discussions regarding management of livestock manures. Even though this recycling is important for the overall sustainability of society, the additional N added to agricultural systems from other organic amendments is likely to be smaller than manure and fertilizer inputs due to the magnitude of available mass flows and distances to crop production. There may also be barriers to farmer and consumer acceptance of some materials (including livestock manures) because of concerns regarding contaminants such as trace metals, microplastics, pathogens, antibiotics and hormones and possibly nanoparticles. Processing these products for easier transport and reuse can add significant additional costs.

[26] Most nitrogen in urine is in the form of urea. Although this is a small organic compound, for example, $(NH_2)_2CO$, it rapidly hydrolyses to release ammoniacal nitrogen (NH_3 and NH_4^+) plus carbon dioxide (CO_2).

Figure V.2

Estimate of N losses from agricultural soils in European Union 28 (Gg N per year) for the year 2014



Source: Values are derived from the 2016 GHG inventory submission to UNFCCC by the European Union:(see http://unfccc.int/national_reports/annex_i_ghg _inventories /national_ inventories_submissions/items/9492.php), with the exception of NO_x and N_2 emissions, which were estimated as a ratio of reported N_2O emission based on Leip and others, (2011).

C. Nitrogen losses from land

289. Estimates of N losses from agricultural soils across the European Union 28 region are given in figure V.2 above. These loss estimates are subject to large uncertainties, but imply that 50 per cent or more of N inputs to agricultural soils in this region (including atmospheric deposition) are subsequently lost to the environment through gaseous emissions, leaching and run-off, with the remaining 50 per cent being recovered by crops (field losses associated with imported crops are not considered). Of the field losses, almost half are via leaching and run-off and another third as dinitrogen (N_2) via denitrification. Dinitrogen is environmentally benign, but this represents a large loss of agronomically useful N, so mitigating its loss enables agricultural N inputs to be reduced, with subsequent savings in other parts of the system (including manufacture of fertilizer N). Since N losses in the field are subject to the elements, more extreme and unpredictable weather events as a result of climate change increase the challenges of land management to minimize N losses, particularly to water. In expanding clays prone to cracking, especially on untilled soils, drought promotes soil cracking, which may contribute to bypass flow of water (irrigation or rain) and N.

290. Emissions of nitrous oxide (N_2O) and NO_x[27] are estimated by Leip and others, 2011 (see figure V.2 above) to account for smaller proportions of the total N loss from agricultural soils compared with dinitrogen and ammonia emissions and nitrogen leaching/run-off. However, agricultural soils are among the most significant emission sources for these gases and therefore represent a key target area for interventions to meet national and international emission reduction targets.

291. The impacts of N losses from agricultural soils on the environment will vary spatially, according to the variation in the underlying driving factors influencing losses (for example, de Vries and Schulte-Uebbing, 2019). Such factors include density of livestock, intensity of cropping, soils and climate, as well as socioeconomics and governance systems that regulate N inputs at the farm and regional scales (including spatial distribution of farms). A large proportion of ammonia emissions from N applied to agricultural soils may be redeposited locally, with potential impacts through eutrophication and acidification, but a proportion will also be subject to longer-range transport and processes associated with aerosol and particulate

[27] See footnote 2.

formation, with subsequent human health and biodiversity implications. Similarly, N losses through leaching and run-off will have local, catchment and, potentially, regional effects on water quality, depending on the flow pathway and the N transformation and reduction processes along this pathway (Billen and others, 2013). Nitric oxide (NO) and nitrogen dioxide (NO_2) (together NO_x) are environmental pollutants involved in photochemical reactions in the troposphere and are the main precursors of ground-level ozone in rural areas. For these reactive N species therefore, a good understanding of source-receptor relationships is required, including appropriate spatial and temporal distributions. In contrast, nitrous oxide (N_2O) has a global, rather than local, impact as a greenhouse gas and stratospheric ozone depleting substance (Bouwman and others, 2013).

D. Guiding principles

292. Nitrogen, in the form of organic and inorganic fertilizers, is applied to agricultural land to increase crop yield and quality. Most of the applied N captured by the crop will not be subject to direct losses to the environment. The exceptions are nutrients released from plants in freeze-thaw cycles, during senescence and losses of crop residues by water and wind. The overriding principle for an integrated approach to mitigating losses from the field application of N is therefore to improve the N use efficiency (for example, fraction of N recovered in the harvested crop yield) and N uptake efficiency (for example, fraction of N recovered in crop) as proportions of the N applied. Greater N efficiencies allow a reduction in applied N while maintaining crop yield and quality at acceptable social and economic levels, which is beneficial for farmers and society (recognizing that intensification of production usually reduces N efficiency). This is the underlying concept of precision application of chemical fertilizers and manures, for example, applying N at the most economical and sustainable rate, at the most effective time, in the appropriate form, and using precision placement near plant roots. These concepts are summarized in the "4R Nutrient Stewardship" approach (Bruulsema, 2018) promoted by the International Fertilizer Association, and are also applicable to the use of organic fertilizers, such as urine, manures and other organic amendments. Farmers avoiding inorganic fertilizers may also consider the relevance of these principles to nitrogen resources produced by increasing biological N fixation (for example, though effective tillage, cover crops and crop rotation practices). The "4R Nutrient Stewardship" approach incorporates:

(a) Rate – the amount of N applied should closely match the amount that will be required and taken up by the crop, while taking account of that also supplied by previous applications or mineralization of crop residues;

(b) Time – the applied N should be readily available at the time that the crop requires it with least risk to the environment;

(c) Form – the applied N should match (or quickly be transformed to) the form in which the crop can readily take it up in its growing period while minimizing risk of losses to water and air;

(d) Place – the N should be easily accessible by crop roots, without damaging them, soon after application.

293. For managed livestock manures, it is important that storage and processing practices aim to minimize losses (especially to the atmosphere, chapter IV), so that as much as possible of the N resource is available for application to crops. Application rates should be adjusted according to estimated or measured N concentrations of manures after storage, including adjustments to take account of N savings from abatement measures.

294. Nitrogen use and uptake efficiencies will also be influenced by other factors affecting crop performance, including cropping practices, the availability of other essential nutrients, weather, water, soil physical conditions, soil pH (which can be amended through liming) and impacts of any pests or diseases. A lack of attention to any of these factors may compromise N uptake efficiency, yields and N use efficiency, which may result in greater losses of N to the environment.

E. Abatement measures

295. This section presents the main management practices and abatement/mitigation measures that will influence N utilization and losses from N applications to land. Some measures will mitigate all forms of N loss, whereas others may mitigate a specific N loss pathway (for example, ammonia volatilization) with either little impact or a negative impact on other N loss pathways (for example, denitrification, leaching/run-off), but may still be beneficial in terms of reducing overall N losses. The effectiveness of some measures may be context-and region-specific, being influenced by factors such as soil and climate. Abatement may be enhanced by combining implementation of certain measures. However, reduction of one loss pathway without addressing N surplus will inevitably lead to losses via other pathways (see figure III.1 above). Therefore, it is important that application rates be adjusted accordingly.

296. Following the description of each measure below, a table (see tables V1–V.20 below) summarizes, for each form of N loss, the UNECE category for effectiveness/practicality of implementation (following the approach of ECE/EB.AIR/120, Bittman and others, 2014), and the magnitude of effect of each measure.[28] Expert judgements are provided for ammonia volatilization, denitrification losses as nitrous oxide, NO_x and dinitrogen, run-off and leaching losses as nitrate, and overall total N losses. Where a measure is considered to result in an increase in losses of a specific nitrogen form, it is, by definition, assigned to category 3 for that nitrogen form. The magnitude of effect can be considered as an indication of "effectiveness" of the measure as distinct from the extent to which the measure is "applicable" in different contexts. Where clarification is necessary, magnitude of effect of a measure is described in comparison to a specified reference system. For example, in the case of slurry application to land, the reference system is surface application without any specific restriction or additive. In some parts of the UNECE region, use of certain reference systems may be prohibited, for example, because of the associated pollution levels.

Measures applicable to both inorganic and organic fertilizers, including manures, urine and other organic materials

Field Measure 1: Integrated nutrient management plan

297. This approach focuses on integrating recognition of all the nutrient requirements of arable and forage crops on the farm, through the use of all available organic and inorganic nutrient sources. Integrated nutrient management plans work to optimize nutrient use efficiency through a range of measures, including through attention to N application rate, timing, form and application method (as discussed previously), and through appropriate agronomic practices including: crop rotations; cover crops; tillage practices; manure history; and soil, water and other nutrient management. 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 consistent with Field Measure 3.

298. Recommendation systems should be used to provide robust estimates of the amounts of N (and other nutrients) supplied by organic manure applications. Ideally, these will incorporate chemical analyses of the materials applied (representatively sampled and sent to appropriate laboratories, or through the use of on-farm "rapid meters") and be informed by local soil testing of current nutrient availability. If direct analyses are unavailable then default "book" values may need to be assumed (for example, UK RB209 https://ahdb.org.uk/knowledge-library/rb209-section-2-organic-materials). A proportion of the N in organic amendments (differing according to amendment type) will be in an organic form, rather than readily plant-available mineral form. As such, some of the applied N will become available some time after application, including in subsequent cropping seasons (Yan and others, 2020). Therefore, consideration of N requirements over the whole crop rotation should be included.

[28] See chapter I, paras. 16(a)–(c), for a description of the UNECE categories and system for representing the magnitude of effect.

299. Nutrient availability is affected by crop rotations, as relatively large amounts of N are released after cultivation of a grass sward, even when there is little historical applied N. A knowledge of the P content is also important, as this may limit overall application rates of manure in some cases. The manure nutrient information is needed to determine the amount and timing of additional inorganic fertilizers needed by the crop. Fertilizer statistics suggest that proper consideration for the value of N in organic amendments may result in a reduction in fertilizer inputs and a concomitant reduction in nutrient pollution (for example, Dalgaard and others, 2014). Fertilizer inputs may be further reduced as a result of the net benefits of using emission reduction measures.

300. When developing farm nutrient management plans, consideration should be given to the availability, the nutrient and carbon (C) content, and the carbon to nitrogen ratio of organic residues available within reasonable transport distance.

301. Costs associated with the transport (<10 km) and spreading of organic amendments may be offset by savings in inorganic fertilizer and improved crop growth due to inputs of carbon and other nutrients (for example, S, K, Zn etc.) and improving soil pH. However, soils with a history of manure applications may not benefit from these nutrients.

Table V.1
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Field Measure 1

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE category	1 [a]	1 [a]	1 [a]	1 [a]	1 [a]	1 [a]
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

302. Underapplication of N may reduce crop yield and protein, soil organic matter (because of the close coupling of soil N and C cycles) and profit and can result in N mining of the soil. Overapplication of N can also result in reduced crop yields (for example, due to crop lodging, fertilizer imbalances, poor harvest index) and profits, and surplus available soil N, increasing the risk of losses to air and water. Applying N at an environmentally and economically sustainable rate is therefore important. This requires a knowledge of both crop requirement in a given field and of the amount of N being applied. Application rates must also be within legislative limits where these exist.

303. Knowledge of crop requirement can generally be gained from regionally specific fertilizer recommendation systems (for example, UK RB209 https://ahdb.org.uk/nutrient-management-guide-rb209), using N response curves, which account for crop type and management, and typical yield, soil, climate and previous cropping history. The farmer needs to adjust these rates according to the anticipated yield, which is not known in advance (affected by soil, crop variety and management history; for example, seeding date and anticipated weather). The application rate is also sensitive to crop and fertilizer prices but must also consider dangers of losses to the environment. It is important to note that targeting optimum economic rates gives more consistent results than targeting optimum yield because the economic N curve is always flatter than the crop growth curves, which means farmers should experiment with reduced application rates using test strips and, where possible, yield monitors. More advanced decision-support systems that are available for major crops in some regions can account for site- and season-specific conditions and adjust predicted yield and N requirement accordingly (for example, Adapt-N for corn in the north-east of the United States of America). Planned application rate can be at the overall field level or, if sufficient data are available, at field level. In-crop testing using visual indicators or soil tests can improve accuracy of nutrient application rates, but these systems are still in development.

304. Defining an appropriate application rate requires knowledge of the N content of the organic manure or fertilizer product, which is generally well known for inorganic fertilizers, and of the quantity of product being applied. Inaccurate spreading can result in parts of a field receiving too little and other parts too much N, so it is important that only precise fertilizer spreaders be used and that these be regularly calibrated (recommended annually), both for total application rate and for evenness of spread. They should also be adjusted according to the spreader manual, depending on the speed, rate and type of fertilizer (granulometry, hardness, sphericity and density). Spreading systems with Global Positioning System (GPS) guidance improve spreading uniformity. GPS systems combined with real-time sensing or previous yield maps can adjust fertilizer rates according to in-field variability. In-crop testing of soil or crop is most suitable for relatively long season crops like maize but use of starter fertilizer, which is generally a good practice, delays the applicability of crop-based testing. Delayed N application enables better decision-making but also limits application windows, which could be a problem, for example, during drought. In-crop testing helps with split or delayed applications but is not compatible with slow- or controlled-release fertilizer products, since these are applied at or before seeding.

305. Costs associated with this measure can be minimal (annual calibration of a fertilizer and/or manure spreader), or modest if investing in GPS or variable rate application systems, but will typically be justified by increased crop yield and/or quality, or cost-savings associated with lower fertilizer use. In future, real-time artificial intelligence simulation modelling, combined with multisensors, and improved forecasting of weather and crop commodity pricing, will guide fertilizer application rates more precisely.

Table V.2
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Field Measure 2

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE category	1 [a]	1 [a]	1 [a]	1 [a]	1 [a]	1 [a]
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 N_r 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

306. Applying readily available mineral N to the soil at times when it is not required by an actively growing crop risks the loss of a substantial proportion of the applied N to water or air. Seasonally, this generally means avoiding applications during the autumn/winter period, when losses by leaching are greatest across most of the UNECE region. For parts of the UNECE within the European Union, this is regulated by National Action Programmes under the European Union Nitrates Directive. Other national legislation across the UNECE region will often include the definition of closed periods when applications to land are not allowed (either at whole country level or within defined regions). Such approaches help avoid the worst-case scenarios, but do not guarantee best agricultural practice. Application timing should therefore be matched to crop requirement, which will be influenced by crop type and physiological stage, soil and climatic factors. Fertilizer recommendations provide advice on quantities and timing of N application, which typically may be split across several application timings over the growing season to maximize crop uptake efficiency and yield response and minimize losses to air and water. Multiple applications reduce the risk of large leaching events and enable delaying some of the application decision, enabling adjustment if yield expectations should change. However, under drought conditions, delayed or split applications may reduce yield, especially for fast-growing crops like oilseed rape. Appropriate timing may differ markedly according to climatic regions across the UNECE region.

307. Within a given season, losses will be influenced by the specific weather conditions at the time of application. Hot, dry conditions are conducive to poor N use, as crop uptake is limited and losses via ammonia volatilization may be exacerbated. Similarly, heavy rainfall immediately after nutrient application can result in high losses via run-off and leaching. Timing applications to coincide with ideal growing conditions (warm, moist soils), with some light rainfall to aid movement of applied N into the soil and crop root zone, is therefore ideal, and access to reliable weather forecasting (and decision-support tools based on this) can help greatly. However, manure applied to warm soils will have higher nitrous oxide and ammonia emissions than when applied to cool soils, as illustrated by the Application Timing Management system in the UNECE Ammonia Guidance document (Bittman and others, 2014). Similarly, ammonia volatilization from urea fertilizer is lower under cool conditions (Ni and others, 2014). If irrigation is available, applying a small amount (for example, 5 mm) after application of fertilizer N facilitates its diffusion within the soil, and mitigates ammonia volatilization. For urea fertilizer, >5 mm of rain after application (or irrigation, for example, Sanz-Cobena and others, 2011; Viero and others, 2015) will reduce the risk of ammonia loss, but if applying urea to wet soils, or if the fertilizer is subject to light rains, extensive N losses can occur. This is particularly important for surface-banded urea because of the high risk of ammonia volatilization losses associated with the higher increase in pH under banding on moist soils.

308. It may not be appropriate to apply organic amendments and mineral fertilizers simultaneously. For example, combined application of cattle slurry and N fertilizer has been shown to increase N_2O emissions through denitrification, because of the enhanced available carbon and soil moisture compared with slurry and fertilizer applied at separate timings (for example, Stevens and Laughlin, 2002). Simultaneous addition of lime and urea fertilizer should also be avoided, which may risk increasing NH_3 emissions by raising pH on soil and plant surfaces. It has been reported that liming may reduce N_2O emissions (Hénault and others, 2019), though further assessment is needed of the potential and limitations in the context of integrated nitrogen management.

309. Specific costs associated with such measures are relatively small and there may actually be cost savings.

Table V.3
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Field Measure 3

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE category	1 [a]	1 [a]	1 [a]	1 [a]	1 [a]	1 [a]
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 ofmanure to agricultural land in winter due to insufficient manure storage capacity.

Field Measure 4: Apply nutrients in the appropriate form

310. This measure primarily targets ammonia emissions. Urea is the most commonly used fertilizer type globally because of availability and price and, while used proportionately less in Europe, it still represents a significant volume of total fertilizer N use (c. 25 per cent, International Fertilizer Association statistics). Urea ammonium nitrate, usually a liquid fertilizer, is also used and has properties intermediate between urea and ammonium nitrate. Following land application, urea will undergo hydrolysis to form ammonium carbonate (the rate depends on temperature, moisture and presence of the urease enzyme). This process increases pH around the urea fertilizer granules and leads to an enhanced potential for ammonia emissions (typically accounting for 10–20 per cent of the applied nitrogen for the reference system of surface spreading with prilled urea, depending on soil temperature and moisture). This is in contrast to fertilizer forms such as ammonium nitrate, where ammonium

will be in equilibrium at a much lower pH, greatly reducing the potential for ammonia volatilization (typically less than 5 per cent of the applied N).

311. The placement of urea in bands on the soil surface may increase emissions (by concentrating the location of urea hydrolysis, locally increasing pH), while incorporation of urea within the soil (for example, 5 cm depth) will greatly reduce emissions by avoiding direct contacts with the air (Principle 15). By slowing urea hydrolysis, one of the ways that urease inhibitors (Field Measure 13) work to reduce NH_3 emissions is by reducing the extent to which pH increases occur in the immediate vicinity of the fertilizer. Ammonium sulphate is associated with high ammonia emissions when applied to calcareous soils, where replacement with ammonium nitrate will result in lower losses (Bittman and others, 2014). Ammonium bicarbonate is a cheap inorganic fertilizer that has been used widely globally but is associated with a very high ammonia emission potential, unless it is immediately incorporated into soil. The use of ammonium bicarbonate is currently prohibited under annex IX to the Gothenburg Protocol.

312. There is a risk of increased losses through denitrification and/or leaching and run-off because of the additional available N being retained in the soil through the use of an alternative low-emission fertilizer type. However, if the N application rate is reduced to account for the lower ammonia volatilization losses and greater response consistency, then these risks can be avoided (Sanz-Cobena and others, 2014). This reflects the overall principle that methods to mitigate N losses should be accompanied by reduced N inputs (or increased crop uptake and harvest outputs) in order to achieve the full benefit of the abatement/mitigation measure (Principle 6, chapter III).

313. Costs associated with this measure depend on the relative prices of different fertilizer types; any consequent change in fertilizer rates should also be taken into account when considering the merits of different fertilizer forms (for example, less fertilizer would be needed where N emissions and leaching are smaller).

314. For manure, the form (liquid or solid; cattle, pig or poultry manure) cannot usually be chosen because it depends on the type of manure produced on the farm or in the surrounding area. However, if there is a choice, it is advisable to use solid manure only on tillage and at times when it can be incorporated into the soil immediately after application. Field Measures 8 and 9 focus on specific actions to modify the form of organic manure to reduce N losses.

315. With organic materials, such as livestock manure, inorganic forms of N (ammonium and nitrate), which are present in greater quantities in slurries compared with farmyard manure, are more immediately available for plant uptake and therefore have greater inorganic fertilizer N replacement value, but also greater potential for environmental losses if not applied according to suitable rates, timing and method. There are also greater opportunities to reduce losses and ensure higher nitrogen use efficiency with manures that have a higher fraction of urea (pig) or uric acid (poultry) compared with manures with typically a higher fraction of slowly decomposable organic compounds (for example, extensively managed cattle). This is because it is harder to control the timing of nitrogen released through mineralization of slowly decomposable organic matter. There are opportunities to improve handling of all manure types to reduce N losses.

Table V.4
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Field Measure 4

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

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

316. The following unabated references for "nitrogen form" may be defined for comparison with possible improvements:

(a) The unabated reference for a manufactured inorganic fertilizer is field application of prilled urea (surface applied);

(b) The unabated reference for manure is manure without any chemical modification (for example, without additions to alter pH, water content, enzyme activity, etc.) either fresh manure; or following 3 months' uncovered outdoor storage for:

(i) Liquid mixture of faeces and urine or of poultry excreta (for example, "slurry");

(ii) Solid mixture of faeces and urine, including bedding ("farmyard manure");

(iii) Solid mixture of poultry manure, including bedding ("poultry litter").

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

317. Certain areas on the farm (or within the landscape – see chapter VI) can be classified as higher risk in terms of N losses to water, by direct run-off or leaching, or to air through denitrification. Farm-specific risk maps could be developed, highlighting key areas in which to limit or avoid applications of fertilizers and/or organic amendments. This may include areas with high rates of historical manure applications near housing, which may show up as P hot spots.

318. Risks of direct transfers to vulnerable water bodies include: from field areas directly bordering surface waters, such as ditches, streams, rivers, lakes and ponds, or close to boreholes supplying drinking water; free-draining soils above aquifers; and steeply sloping areas leading to water bodies. Expanding clay soils are especially prone to leaching via macropores. Risks of transfer may be reduced by imposing zones in which fertilizers and manures should not be applied, or in which application rates and timings are strictly regulated (for example, Nitrate Vulnerable Zones within the European Union).

319. Field areas that generally remain wetter, such as those associated with depressions or compacted areas with fine-textured soils, are likely to have much higher rates of denitrification and hence higher losses of N as N_2O, NO_x and N_2. Minimizing N application rates to such areas will mitigate such losses. However, managed wetlands are often used to encourage denitrification to minimize damage from excess N. Constructed "bioreactors" can be used to denitrify N from water collected from field drains (see Landscape Measure 5); the collected water may be stored as a potential source of irrigation. While such practices can reduce nitrate run-off, increased emissions of dinitrogen reduce landscape level N use efficiency, risking increasing losses of other N forms. Overall avoidance of N inputs in high-risk areas will help minimize these trade-offs. As discussed further on in chapter VI, buffer strips in addition to tree belts can help protect riparian areas.

Table V.5
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Field Measure 5

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE category	3 [a]	1 [a]	1 [a]	1 [a]	1 [a]	1 [a]
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 are described in chapter VI.

Measures specific to the application of manures and other organic materials

320. This section focuses primarily on measures for the application of livestock manures to land. These measures can also be appropriate for the application of other organic residues – including digestate from anaerobic digestion, sewage sludge and compost with relevance and reduction efficiency – depending on the specific physical and chemical characteristics of the material. A review of the use of organic amendments within agriculture is given by Goss and others (2013).

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

321. This measure primarily addresses losses via ammonia volatilization (Bittman and others, 2014), which occurs from the surface of applied slurries. Reducing the overall surface area of slurry, by application in narrow bands, will lead to a reduction in ammonia emissions compared with surface broadcast application, particularly during the daytime, when conditions are generally more favourable for volatilization. The higher hydraulic loading of slurry within the bands may reduce the infiltration rate, meaning that emissions may occur for longer than from broadcast, but this extended emission period will generally be during the night-time, when conditions are less favourable for volatilization. In addition, if slurry is placed beneath the crop canopy or stubble, there will be less canopy contamination and the canopy will provide a physical barrier to airflow and insolation to further reduce the rate of ammonia loss.

322. Slurry can be placed in narrow bands via trailing hoses that hang down from a boom and run along or just above the soil surface (NB: some so-called “dribble bars” that release the slurry via hoses well above the soil surface will be less effective in reducing emissions, as the slurry bands will spread out; it is essential that the hoses release the slurry at, or just above, the soil surface). However, band spreading also increases the hydraulic loading rate per unit area, which can, on occasions (especially for high dry matter content slurries), impede infiltration into the soil. For taller crops, slurry will be delivered below the canopy, reducing air movement and temperatures at the emitting surface, thereby reducing ammonia emissions. Trailing hose application is particularly suited to spring application to arable crops (for example, winter wheat, oil seed rape), where wide boom widths enable application from existing tramlines. The window for trailing hose application is extended later into the spring, when crop height would normally exclude conventional surface slurry application (because of crop damage and contamination risks). Trailing hose typically reduces NH_3 emissions by 30–35 per cent (Bittman and others, 2014).

323. Trailing shoe application is more effective than trailing hose and is more suited to grassland. The grass canopy is parted by a “shoe”, following which slurry is placed in a narrow band directly on the soil surface. The grass canopy tends to close over the band, further protecting from ammonia volatilization. The technique is more effective in taller stubble (i.e. cutting height) or if some sward regrowth (for example, one week) is allowed following grazing or silage cutting. Trailing shoe reduces NH_3 emissions by 30–60 per cent, with the highest reductions for when application is made under a plant canopy (Bittman and others, 2014).

324. Band spreading can potentially increase N losses via denitrification because of the lower ammonia losses and more concentrated placement of slurry N, available carbon and moisture to the soil. However, the risk of a significant increase is low because the bands will dry before emissions will begin, especially if applications are made at agronomically sensible times (cool weather and avoiding excess soil moisture) and rates.

325. Note that a co-benefit is that the effective N:P ratio of the applied manure is improved by the reduction in N losses at each stage of manure handling. Subsequent mineral N fertilizer applications will also improve the N:P ratio, but the added N should be reduced according to the improved N availability in the applied slurry arising from the lower ammonia losses. Other important co-benefits are more precise and uniform applications and less drift.

326. Initial capital cost of the equipment is relatively high, with some operational costs, although costs will be offset over the lifetime of the machine through fertilizer savings. The distributor head of the equipment, which may be with or without a chopper, is the critical component because of its role in evenly dividing the flow and in causing or reducing blockages, especially for cattle manure. Local manufacturing of applicators may help reduce costs and support local enterprises. For many farms, it may be more practical and cost-effective to use contractors with specialist slurry-spreading equipment. Additional co-benefits are improved aesthetics, reduced odour and better community relations, in part because manure application is less visible.

Table V.6
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Field Measure 6

Nitrogen form	NH_3	N_2O	NO_x	NO_3^-	N_2	*Overall N Loss*
UNECE category	1[a]	3[a]	3[a]	3[a]	3[a]	1[a]
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 NO_x emissions resulting from atmospheric ammonia deposition to forest and other land are also reduced.

Field Measure 7: Slurry injection

327. This measure primarily addresses losses via ammonia volatilization. Placing slurry in narrow surface slots, via shallow injection (c. 5 cm depth) greatly reduces bandwidth and hence the exposed slurry surface area. Placing slurry deeper into the soil behind cultivation tines, as with closed slot (10–20 cm depth at 15–30 cm apart) or deep injection (c. 20–30 cm depth and at least 30 cm apart), or with spade-type tools, eliminates most of the exposed slurry surface area. Some of the ammonium N in the slurry placed in the soil may also be fixed onto clay particles, further reducing the potential for ammonia emission. Ammonia emission reductions are typically 70 per cent for shallow injection and >90 per cent for closed slot and deep injection compared with surface broadcast application (Bittman and others, 2014).

328. Nitrous oxide emissions (and by association, NO_x and N_2 emissions) may be increased with slurry injection through the creation in the soil of zones with high available N, degradable carbon and moisture, favouring denitrification. However, the risk of significant increase is reduced if applications are made at agronomically sensible times (cool soils) and rates and when the soil is not excessively wet (Sanz-Cobena and others, 2019) and can be mitigated with a nitrification inhibitor. Subsequent mineral N fertilizer applications should account for the improved N availability in the applied slurry arising from the lower ammonia losses. Slurry injection will reduce crop contamination and odour emissions compared with

surface broadcast application. However, there is greater soil disturbance, energy consumption and possibly greater soil compaction due to heavy equipment.

329. Shallow injection is most suited to grassland, where field slopes and/or stoniness are not limiting, and on arable land prior to crop establishment. Shallow injection furrows cannot accommodate more than about 30 m3 of slurry per hectare. In contrast, deep injection is most suited to arable land prior to crop establishment; current deep injector designs are generally not suited to application in growing crops, where crop damage can be great, although some deep injection is practiced between corn rows on sandy soils. Work rates with all injectors are slower (particularly for deep injection), due to slower travel speed and narrower spreading widths, than with conventional surface broadcast application, but spreading speed is increased and compaction reduced with "umbilical hose" delivery systems. Under hot and dry conditions, injection can result in significant grassland sward damage due to root pruning. Shallow injection (particularly of dilute slurries) on sloping land can result in run-off along the injection slots. With deep injection, it is important to avoid slurry application directly into gravel backfill over field drains. The soil disturbance caused by deep injection may not be compatible with no-till systems. Precision planting maize within 10 cm of deep injection furrows may obviate the need for starter P fertilizer – a co-benefit (for example, Bittman and others, 2012).

330. The initial capital cost of the equipment is relatively high, with some ongoing operational costs, including more fuel and draught requirement, although this will be offset (potentially completely) over the lifetime of the machine through fertilizer savings. For many farms, it may be more cost-effective to use contractors with specialist slurry-spreading equipment.

Table V.7
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Field Measure 7

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE category	1[a]	3[a]	3[a]	3[a]	3[a]	1[a]
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 N_2O and NO_x emissions resulting from atmospheric ammonia deposition to forest and other land are also reduced.

Field Measure 8: Slurry dilution

331. This measure primarily addresses losses via ammonia volatilization. Ammonia losses following surface broadcast slurry application to land are known to be positively correlated with the slurry dry matter content and viscosity, with lower losses for lower dry matter slurries because of the more rapid infiltration into the soil (for example, Beudert and others, 1988; Sommer and Olesen, 1991; Misselbrook and others, 2005). 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, but a minimum of 1:1 dilution with water is needed to achieve 30 per cent reduction in emission (Bittman and others, 2014, para. 146).

332. This technique is particularly suited to systems where slurry (or digestate) can be applied using manure delivery to the field by umbilical hoses or pipes and irrigation/fertigation systems, as the water addition greatly increases the volume of slurry, and hence cost and potential soil compaction if being applied by tanker systems. The method is not suited to drip-fertigation systems because of issues with blockages, unless a microfiltration technique is used (see comments under Field Measure 16). The applicability of the measure is also linked to the availability of water for dilution. Water may also be added

coincidentally from washing dairy parlours and rainwater ingress to slurry stores, which is not the primary purpose but has the same effect. Applications should be at timings and rates according to crop requirements for water and nutrients. There is a risk of increased losses through denitrification because of additional wetting of the soil profile, but the risk of significant increase is low if applications are made at agronomically sensible times and rates. As with all measures, subsequent mineral N fertilizer applications should account for the improved N availability in the applied slurry arising from the lower ammonia losses.

333. Costs for application systems relying on tractor and tanker transport of the slurry would be very high, depending on transport distances and tank capacity. Adaptation/installation of irrigation systems would incur moderate costs, which would be offset to some extent by savings from not having to spread slurry by tanker and partially through savings in fertilizer costs. Underground piping is used to deliver rain-diluted manure to fields on some large dairy farms in the United States of America.

Table V.8

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Field Measure 8

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

334. This measure primarily addresses losses via ammonia volatilization. As with in-house or in-store slurry acidification (Housing Measure 8 and Manure Measure 8, respectively), a lower pH favours the ammoniacal N in solution to be in the ammonium rather than ammonia form, and thus less susceptible to volatilization, and reducing slurry pH to values of 6 or less can give substantial emission reductions. Sulphuric acid is commonly used to lower the pH because it is more readily available and cheaper than other acids. The volume of acid required will depend on the existing slurry pH (typically in the range 7–8) and buffering capacity. Addition during slurry application, using specially designed tankers, tends to be less effective than prior acidification in-house or in-store (which may achieve >80 per cent reduction), with typical emission reduction of 40–50 per cent. Effects of slurry acidification on nitrous oxide emissions following slurry application have been less-well quantified, although there is some evidence of emission reductions. Potential impacts on soil health are also less well understood.

335. Costs associated with in-field acidification systems are generally low to moderate, particularly if making use of contractors. Such costs will be offset partially or entirely by savings in fertilizer use. There may be an increased requirement to add lime to fields receiving acidified slurries; where lime is readily available, costs are small but should be included in any assessments. Slurry application rates should also be adjusted for the greater N availability to avoid increased leaching. Care needs to be taken to avoid injury from the concentrated acids and from possible hydrogen sulphide gas release. Appropriate safety procedures for field transportation of strong acid are required.

Table V.9

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Field Measure 9

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

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

Field Measure 10: Nitrification inhibitors (addition to slurry)

336. While usually associated with inorganic fertilizers, nitrification inhibitors can be added to livestock slurries just prior to application to delay the conversion of the slurry ammonium to nitrate, which is more susceptible to losses through denitrification, run-off and leaching. Reducing soil peak nitrate concentrations and prolonging the conversion of ammonium to nitrate by increasing plant N uptake can thus reduce emissions of nitrous oxide and associated NO_x and dinitrogen while enhancing N uptake efficiency by the plant. The measure is most effective under conditions conducive to high denitrification losses (for example, semi-anaerobic soils with much available N and C for microbial activity), typically achieving 50 per cent reduction in nitrous oxide emissions, although it could be argued that slurry applications should be avoided under such conditions (Recio and others, 2018). In cases where weather conditions interfere with timely slurry application, addition of nitrification inhibitors may enhance N use efficiency. The efficacy of the inhibitors may be influenced by soil and climatic factors, being less effective at higher temperatures or when applied to more finely textured/higher organic matter soils. Nitrification inhibitors can help to greatly reduce N_2O emissions from deep-injected manure. They will also reduce N_2O and NO_x losses arising directly from the nitrification process (under aerobic conditions), which can form an important part of the total loss of these gases from soils in some regions.

337. While the use of nitrification inhibitors with livestock slurries may increase NH_3 emissions from slurry, in practice this is not considered a major concern because most NH_3 emission occurs within 24 hours of spreading. Few studies have shown significant crop-yield gains through the use of nitrification inhibitors with livestock slurries, but reductions (likely to be small) in fertilizer N application could be considered, depending on the estimated savings in N losses from the applied slurry.

338. There is a modest cost associated with the purchase of inhibitor products, which is unlikely to be wholly offset by any crop-yield gains or savings in fertilizer costs. These products can potentially be encouraged by policy tools.

339. There are a variety of inhibitor compounds and products that have been assessed for their effect on nitrification, but the few studies to date indicate no harmful side effects on soil health (for example, O'Callaghan and others, 2010).

Table V.10

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Field Measure 10

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

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

Field Measure 11: Rapid incorporation of manures into the soil

340. This measure primarily addresses losses via ammonia volatilization. The rapid soil incorporation of applied manure (within the first few hours after application) reduces the exposed surface area of manure and can therefore 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. Ammonia volatilization losses are greatest immediately after manure application, with up to 50 per cent of total loss occurring within the first few hours depending on conditions, so the effectiveness of this measure is dependent on minimizing the time for which the manure remains on the soil surface, and the degree of incorporation (which varies with method: plough inversion, disc or tine cultivation) and, to some extent, on the manure characteristics. Reductions in ammonia emission of 90 per cent may be achieved by ploughing immediately after application (Bittman and others, 2014), or <20 per cent by tine cultivation after 24 hours. Incorporation is one of the few techniques to reduce ammonia loss from solid (farmyard manure (FYM)) and poultry manure, although some solid manures may be low in ammonia, depending on type and handling. For solid manure, the need to reduce the risk of nutrient run-off favours the use of incorporation, since deep injection is not available.

341. There is potential for soil incorporation to increase N losses via denitrification because of the lower ammonia losses and subsequently higher available N content in the soil. However, the risk of significant increase is low if applications are made at agronomically sensible times and rates (for example, with less manure input per hectare to account for the nitrogen savings). Subsequent mineral N fertilizer applications can also be reduced according to the improved N availability in the soil. In this way, the measure can help improve nitrogen use efficiency, leading to an overall system-wide reduction in nitrogen losses.

342. Costs associated with this measure, assuming the field is to be cultivated, depend on the availability of staff and equipment needed to achieve a balance between complete and rapid incorporation required after manure application. Assessment of costs should include cost savings through any reduction in fertilizer use.

Table V.11
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Field Measure 11

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE category	1[a]	3[a]	3[a]	3[a]	3[a]	1[a]
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 NO_x emissions resulting from atmospheric ammonia deposition to forest and other land are also reduced.

Measures specific to the application of inorganic fertilizers

Field Measure 12: Replace urea with an alternative N fertilizer

343. This measure primarily targets NH_3 emissions. As discussed regarding Field Measure 4, urea and urea-based fertilizers can be subject to large N losses via NH_3 volatilization. Under high-loss conditions (warm or hot conditions with moderate water availability, when losses can be >20–30 per cent of the N applied), substitution of urea with another N fertilizer type, such as (calcium) ammonium nitrate, can greatly reduce ammonia emissions (Bittman and others, 2014). However, if urea is applied in spring, when conditions are predictably cool and moist, the risk of ammonia loss is greatly diminished (with <10 per cent loss of the nitrogen applied). However, even under cool conditions, NH_3 losses from surface-applied urea tend to be much larger than for ammonium nitrate (which are also smaller under these

conditions). In calcareous and semi-arid soils, the replacement of urea by (calcium) ammonium nitrate usually also leads to the abatement of N_2O and NO.

344. There is a risk of increased losses through denitrification and/or leaching because of the additional available N being retained in the soil through the use of an alternative fertilizer type with smaller NH_3 emissions. However, if the N application rate is reduced to account for the lower NH^3 volatilization losses and greater response consistency, then these risks will not be realized (Principle 6). From a system-wide perspective, the need to use less fertilizer indicates higher nitrogen use efficiency, with overall less N losses per unit of food produce.

345. Costs associated with this measure depend on the relative prices of urea and other N fertilizer types; any consequent change in fertilizer rates should also be taken into account.

Table V.12
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Field Measure 12

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE category	1 [a]	3 [a]	3 [a]	3 [a]	3 [a]	1 [a]
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 13: Urease inhibitors

346. This measure primarily targets ammonia emissions from urea-based fertilizers. Urease inhibitors, such as N-(n-butyl)-thiophosphoric triamide (NBPT) or other similar products, slow the hydrolysis of urea by inhibiting the urease enzyme in the soil. Slowing urea hydrolysis allows more time for urea to be “washed” into the soil, which protects released ammonia and, by spreading out the time for hydrolysis, moderates the increase in soil pH close to the urea granules and, thereby, the potential for ammonia emissions. Average reductions in ammonia emission from granular urea fertilizer of 70 per cent have been reported through the use of inhibitors (Bittman and others, 2014). The efficacy may be influenced by soil and climatic factors (although this is not yet well understood) but is likely to be greatest under conditions most conducive to high ammonia volatilization.

347. In some studies, urease inhibitors have also decreased N_2O and NO_x emissions (Sanz Cobena and others, 2016), most likely because of the slower conversion of urea to ammonium, hence lower peak ammonium concentration, which is the substrate for nitrification/denitrification processes that cause these emissions. There is also evidence that addition of NBPT significantly reduces the population of ammonia oxidizers under some field conditions, probably because NBPT has the capacity to inhibit urease within the cells of ammonia oxidizers and thereby limits the availability of ammonia for the intracellular nitrification. There is, however, a potential risk of increased losses through denitrification and/or leaching and run-off because of the additional available N being retained in the soil through lower ammonia volatilization losses. However, if the N application rate is reduced to account for the lower ammonia volatilization losses, then these risks will not be realized. The inhibitory effect is relatively short-lived following application to the soil (days), so delay in the availability of N to plant roots is minimal. There is the possibility that inhibited urea, unlike ammonium, can be leached under high rain conditions. Urease inhibitors may be used in combination with nitrification inhibitors (see Field Measure 14).

348. Another use of urease inhibitors is to allow higher rates of N placement near the seed (in furrow, side-banding with the planter or side-dressing after emergence; see fertilizer placement, Field Measure 17) which may improve efficacy and reduce costs.

349. While there is a lack of comprehensive assessment of potential impacts of urease inhibitors on soil health, studies to date indicate no negative effects (for example Ruzek and others, 2014).

Table V.13

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Field Measure 13

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE category	1[a]	2[a]	2[a]	3[a]	2[a]	1[a]
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 14: Nitrification inhibitors (with inorganic fertilizers)

350. Nitrification inhibitors (such as DCD, DMPP) are chemicals (environmentally and pharmaceutically benign antimicrobials) that can be incorporated into ammonia- or urea-based fertilizer products, which slow the rate of conversion (oxidation) of ammonium to nitrate. The concept is that nitrate becomes available to crops in better synchrony with crop demand, thus leading to higher yields, but this is contingent on environmental factors such as adequate soil moisture during the growing season. Importantly, there is a lower soil peak nitrate concentration, which will be associated with lower N losses to air through denitrification, and a lower risk of nitrate leaching or run-off. Reductions in nitrous oxide emissions of 35–70 per cent are typical (for example, Akiyama and others, 2010), with the efficacy being dependent to some extent on soil and climatic factors (less effective at higher temperatures and when applied to more finely textured/higher organic matter soils). Similar reductions in emissions of NO_x and N_2 may be expected as they arise from the same process pathways, but there are limited data. Great caution should be exercised in using nitrification inhibitors in dairy pastures to ensure that none is transferred to the milk (because there is no withdrawal time). Potential concerns have been expressed about wider adverse effects on non-target terrestrial and aquatic organisms, however such effects remain to be demonstrated.

351. There is some evidence that the use of nitrification inhibitors may increase NH_3 emissions (Kim and others, 2012), as N is retained in the ammonium form for longer, although this is not consistently reported (for example, Ni and others, 2014). While some small positive impacts on crop yield have been reported (Abalos and others, 2014), there is also evidence that crop N uptake can, in some cases, be compromised through the delayed availability of soil nitrate, negatively influencing yield and N content, so fertilizer application must be timed carefully. For example, it may be appropriate to apply fertilizer products containing nitrification inhibitors slightly earlier than conventional fertilizers to allow for this delay in N availability to the crop, or to blend treated and untreated fertilizer, which also reduces cost. Note that splitting fertilizer applications has a similar effect to using these inhibitors but entails additional labour and may be forestalled by poor field conditions. Split applications enable use of in-crop N testing for N requirements (precision agriculture) but fertilizer products designed to have a delayed effect must be applied early, so are less compatible with in-crop testing.

352. Higher costs are associated with fertilizer products with nitrification inhibitors and these are unlikely to be completely offset through any savings in higher yields or lower fertilizer use, hence farmers will be less inclined to use these products (unless prices are reduced). However, policy tools may be used to encourage their use where they can target environmental risks such as nitrate leaching and nitrous oxide emissions.

353. There are a variety of inhibitor compounds and products that have been assessed for their effect on nitrification, but a comprehensive assessment of the impacts of inhibitors or their residues on soil functioning and on animal and human health is lacking. However, the limited studies to date indicate no negative impacts (for example, O'Callaghan and others, 2010).

354. The use of urea fertilizer products containing double inhibitors (urease and nitrification – combining Field Measures 13 and 14) to reduce NH_3, N_2O and NO_x emissions simultaneously is complementary and may be effective, but further studies are required to

understand the factors influencing the efficacy of such products to be able to justify the added cost and provide recommendations.

Table V.14

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Field Measure 14

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

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

Field Measure 15: Controlled release fertilizers

355. Sulphur- and polymer-coated fertilizer products, many of which are urea-based, rely on the gradual breakdown of the coating or temperature-mediated diffusion to release the plant nutrients into the soil over a prolonged period (for example, several months), depending on the thickness and composition of the coating. This gradual release of nutrients is associated with lower leaching and gaseous N losses, particularly for urea where the gradual release is associated with a much smaller pH increase and therefore less ammonia volatilization losses (Bittman and others, 2014). These products also provide logistical advantages, as fewer fertilizer applications are needed and seedlings show a greater tolerance of fertilizer placement (See Field Measure 17), particularly under reduced tillage. The breakdown of the coating may rely on temperature, soil moisture or microbial action, depending on product specification; residual polymer (or microplastics) in the soil has been tested to allow registration (for example, Canada), but this are not fully acceptable in all countries and the potential effects from the degradation of polymer coatings to form microplastics remain to be demonstrated.

356. Organic N products with low water solubility, such as isobutylidene diurea (IBDU), crotonylidene diurea (CDU) and methylene-urea polymers, are also considered as slow-release fertilizers. In this case, N is released slowly due to chemical or microbial degradation. The release period (typically c. 4 months) is very dependent on moisture conditions and the characteristics of the polymers (urea-form).

357. The enhancement in N use efficiency is particularly dependent on the release of the fertilizer N in plant-available forms and in synchrony with the N requirement of the plant. This can be difficult to achieve, depending on the influencing factors affecting the rate of fertilizer release and the extent to which these may vary across seasons and years. The products have greater potential for longer-season crops under good season-long moisture, such as with irrigation. Summer drought can produce a negative effect. However, polymer-coated products might in future enable autumn application of urea to grass to hasten spring growth, especially for early grazing.

358. Costs of these fertilizer products are higher than for conventional fertilizers but may be offset to some extent by labour saving in reducing the number of application timings and by any reduction in application rate through improved N use efficiency.

Table V.15

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Field Measure 15

Nitrogen form	NH_3	N_2O	NO_x	NO_3^-	N_2	*Overall N Loss*
UNECE category	1	2	2	2	2	1
Magnitude of effect	~↓	~↓	~↓	~↓	~↓	~↓

Note: The reference method for this measure is the surface application of a nitrogen-containing fertilizer without additional controlled release functionality (for example, prilled urea or ammonium nitrate, etc.).

Field Measure 16: Fertigation

359. In areas subject to drought or limited soil water availability for all or part of the crop-growing season, the efficiency of water and N use should be managed in tandem. Drip irrigation combined with split application of fertilizer N dissolved in the irrigation water (i.e. drip fertigation) is considered an efficient technique for control of water and nutrients during crop production. This irrigation system provides precision application (in space and time) of both water and nutrients to the growing plants, minimizing evaporative losses of water and losses of N to air and water, thereby greatly enhancing the N use efficiency. Water containing plant nutrients at predetermined concentrations is pumped through an extensive pipe network with specialized emitters to allow the solution to drip out at consistent rates close to each plant largely independent of distance from source. This pipe network can be installed on the surface (non-permanent) or subsurface (permanent, normally 20–40 cm depth). Unlike sprinkler or other surface irrigation or fertigation systems (for example, pivot, ranger), in which the whole soil profile is wetted, the nutrient solution is delivered just to where plant roots are growing. Water delivery is at a much lower rate (for example, 2–20 litres per hour per emitter), but at a higher frequency (for example, every 2–3 days), than other irrigation systems. As with any irrigation system, the concentration of N in the irrigation water, which can be high, needs to be considered in establishing the appropriate N application rates.

360. With adequate water management using this irrigation system, by avoiding drainage, nitrate leaching is mitigated. Nitrous oxide is generally also mitigated due to the improved gradient in soil moisture and mineral N concentration. With subsurface drip fertigation, the upper part of the soil is maintained dry. This could enhance NO_x emissions through nitrification if using ammonium or urea-based fertigation solutions, but NH_3 volatilization is reduced because of the rapid contact of ammonium with the soil colloids, unless the water is dripped onto mulch.

361. Drip fertigation is most suited to high-value perennial row crops or to high-production annual crops such as maize, cotton, vegetables, etc., because of the relatively high costs involved in set-up and operation (Sanz-Cobena and others, 2017). New below-ground fertigation pipes allow for use on annual crops, greatly extending their potential use. Fertigation is well-established in horticultural production, including in greenhouse systems. These systems are expected to become more common with adaptation to climate change. Drip fertigation can also be applied to clarified and microfiltered digestate (Mantovi and others, 2020).

Table V.16

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Field Measure 16

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

[a] The reference method for this measure is the surface application of a solid nitrogen containing fertilizer (for example, prilled urea or ammonium nitrate, etc.). The UNECE categories for N_2O, NO_x and N_2 indicate the need for further performance assessment.

[b] While there is some risk of increased nitrification/denitrification losses associated with fertigation, precision placement and reduction in overall amount of N input will generally result in an overall decrease in emissions.

Field Measure 17: Precision placement of fertilizers, including deep placement

362. 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 on the seedbed or subsequent “top dressing”. The approach includes fertilizer injection methods, but may also be achieved by immediate incorporation of fertilizer into the soil. Placement within the soil reduces direct exposure to the air and the risk of losses by ammonia volatilization (Bittman and others, 2014). It also enhances the ability of plants to better compete with the soil microbial community for the applied N fertilizer by having better temporal and spatial access to the mineral N. However, under high soil moisture contents, concentrated “pockets” of placed fertilizer N may risk increased losses via denitrification (data are needed to demonstrate that this concern is significant). It may also inhibit deeper root development, reducing the ability of the plants to cope with drought periods if irrigation is not provided. Specialist machines, as well as new fertilizer materials (granular, urea supergranules or briquettes for “urea deep placement”, liquids), have been introduced to improve the performance of this approach.

363. In the UNECE region, where labour costs of manual deep placement of fertilizers are generally prohibitive, specialist application equipment is required for the precision placement of fertilizers. Application is often done using a seed planter fitted with additional injection tools and fertilizer hoppers. These come with associated capital and running costs, but save on application time, since fertilizer placement is done as part of the seeding operation. This may also expedite crop establishment, improving timing. Additional costs may be offset by savings in fertilizer use and/or through the use of specialist contractors.

Table V.17

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Field Measure 17

Nitrogen form	NH_3	N_2O	NO_x	NO_3^-	N_2	*Overall N Loss*
UNECE category	1.[a]	3.[a]	3.[a]	1.[a]	3.[a]	1.[a]
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 NO_x emissions resulting from atmospheric ammonia deposition to forest and other land are also reduced..

Measures for grazing livestock

364. The most efficient way to reduce N losses from grazing systems is through good grass management, which includes optimizing the grazing livestock density (required animal intake) with the grass availability (and rotation of animals around paddocks, as appropriate), sward composition and structure, and appropriate provision of nitrogen and other nutrient inputs.

Field Measure 18: Extend the grazing season

365. Managed manure is associated with ammonia volatilization losses, which are generally significantly greater than the ammonia emissions arising from dung and urine excreted to pasture by grazing livestock. This is primarily because of the rapid infiltration of urine into the soil that occurs during grazing. Where climate and soil conditions allow, extending the grazing season will result in less accumulation of manure to be managed and a higher proportion of excreta being returned via dung and urine during grazing. The result is that extending the grazing season and shortening the period during which animals are confined will reduce ammonia emissions.

366. Contrary to the reduction in ammonia emissions, this measure may increase the risk of leaching and denitrification losses, particularly from urine patches deposited in late summer/autumn. Such increases can be mitigated if effective N uptake by the grass sward can be achieved over high rainfall autumn/winter periods. If annual crops are grazed, spring tillage will help disperse the hot spots associated with urine and dung excretion. Note that hot spots are especially concentrated where cows gather, such as laneways, water troughs, salt licks and shady areas. The occurrence of such hot spots (and associated nitrogen losses), can be mitigated and N dispersion can be improved by restricting animal movement into small grazing blocks provided with drinking water, and with frequent movement between blocks (intensive grazing management). Extending the grazing season into the spring and autumn months, and even winter, may be associated with less intensive practices, including lower density of livestock, appropriate to grass availability, and lower input/output systems. It is thought that winter grazing may increase risks of N_2O and N_2 emissions and of NO_3– leaching (for example, where urine patches create local N surplus with limited plant uptake outside of the growing season), although further evidence is needed to demonstrate this and to demonstrate how to minimize the possible trade-offs.

367. This measure will generally be economically beneficial, as there will be less manure management costs. It has been suggested that there may be an increased requirement for nitrogen fertilizer (compared with a well-managed system of manure collection with low-emission housing, storage and manure spreading) because the nutrients excreted directly to pasture by the grazing animals may not be used as effectively; however, this still needs to be demonstrated.

368. This measure is mainly applicable to cattle (sheep are generally housed for very limited periods, if at all) and to extensive production systems. The measure is more efficient with indigenous breeds matched to local conditions. It is not generally suitable for pig production except for agrosilvo pastoral systems; for example, the indigenous black pig breed in traditional Mediterranean farming during the late fattening phase, as occurs in Spain and Portugal (Rodríguez-Estévez and others, 2009). Extension of grazing season should also be considered in relation to wider dietary considerations (chapter IV, Dietary Measure 1).

Table V.18
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Field Measure 18

Nitrogen form	NH_3	N_2O	NO_x	NO_3^-	N_2	*Overall N Loss*
UNECE category	1.[a]	3.[a]	3.[a]	3.[a]	3.[a]	2.[a]
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 19: Avoid grazing high-risk areas

369. High-risk areas with respect to nitrogen losses from grazing animals include areas with high connectivity to vulnerable surface waters and/or groundwaters, with the risk of direct transfer of excretal nitrogen by run-off or leaching. High-risk areas are also subject to waterlogging, poaching and compaction, with 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.

370. Proximity of grazing animals to aquifers contributes to water quality degradation, with N and other elements, and biological contamination. Safety distances must be observed to mitigate these risks. Water from compromised aquifers may threaten safety of irrigated crops, especially horticultural crops such as salad greens.

Table V.19
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Field Measure 19

Nitrogen form	NH_3	N_2O	NO_x	NO_3^-	N_2	*Overall N Loss*
UNECE category	3.[a]	1.[a]	1.[a]	1.[a]	1.[a]	1.[a]
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.

Field Measure 20: Nitrification inhibitors: addition to urine patches

371. Nitrification inhibitors, more commonly associated with mineral fertilizers, may also have an application in reducing leaching and denitrification from urine patches in grazed pastures, with evidence of about 50 per cent reduction in losses. The risk of increased ammonia emissions from urine patches associated with any delays in nitrification is likely to be minimal because of the rapid infiltration of urine into the soil.

372. There are still challenges in developing cost-effective delivery mechanisms for nitrification inhibitors to grazed pastures, hence this is included as a UNECE category 2 measure. Repeated surface application with inhibitor solutions, following grazing events, is costly and time consuming. Robotic systems or drones for automated identification and targeted application of inhibitors directly to urine patches are under development. Delivery of inhibitors through the grazing animal requires assurances that there are no residual effects on milk (for example, Welten and others, 2016) or meat products or impacts on animal health and welfare.

Table V.20
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Field Measure 20

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

[a] The reference for this method is grazing without the use of nitrification inhibitors.

Cropping measures

373. Cropping measures can be used to improve N use efficiency and reduce losses at the field and farm scale, as they impact on the use of inorganic fertilizer and organic manures on agricultural land. Relevant measures include the use of cover cropping and the use of legumes in crop rotations (Landscape Measures 2 and 3, chapter VI).

F. Priorities for policymakers

374. For policymakers, the main goal of implementing abatement/mitigation measures is to reduce and prevent pollution from different forms of reactive N in the most cost-effective way at a local, regional and/or national scale. From the perspective of organic and inorganic fertilizers, the top five considerations for policymakers regarding integrated sustainable nitrogen management to minimize pollution are:

(a) Integrated N planning at the field, farm, sectoral and regional level (including addressing the trend towards concentration of intensive livestock and crop farms, often near cities), fostering improved nitrogen use efficiency, reduced wastage of N_r resources and a cleaner environment with less N pollution;

(b) Minimizing nutrient applications to high-risk zones (water and N deposition sensitive habitats, high-risk drainage basins), being aware of region-specific requirements, vulnerabilities and conditions;

(c) Integrating nutrients from recycling of organic residues to agriculture (this may require regional planning and adequate quality control of materials to be applied);

(d) Identifying (or enabling) cost-effective abatement/mitigation measures for farmer implementation, especially in the light of better understanding of the socioeconomic barriers to implementation;

(e) Providing technical advice, guidance and incentives, as appropriate, to farmers relative to N use and management.

G. Priorities for practitioners

375. For farmers, the main goal of implementing abatement/mitigation measures is to increase the efficiency of use of applied N as fertilizer or manure to their crops on their farm. As such, the top five measures for farmers to improve nitrogen use efficiency from organic and inorganic fertilizers 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 and placement of N, according to local conditions;

(c) Use of the appropriate nitrogen source (including fertilizers with inhibitors and controlled-release fertilizers; legumes and other means of biological nitrogen fixation) in the appropriate context;

(d) Use of low-emission slurry-spreading technologies (taking into account the saved N in nutrient plans);

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

H. Conclusions and research questions

376. The most important measure to minimize N pollution from applications of inorganic N fertilizers and organic manures to agricultural land is to have an integrated N management plan at the farm-scale that ensures a balanced fertilization to meet crop requirements (see Principle 7, chapter III). Nutrient inputs should prioritize the use of organic manures and other recoverable nutrient resources when this is technically and environmentally feasible, with any remaining requirement met by bought-in inorganic fertilizers.

377. Measures are identified and described that can minimize different forms of N losses from fertilizers and manures applied to land and these should be implemented as appropriate, according to local and regional priorities and cost-effectiveness, including consideration of the environmental costs.

378. It must be recognized that challenges persist in being able to provide dependable local context-specific N application recommendations based on more generic guidance. However, further development of bespoke decision-support tools that integrate different nutrients and nutrient sources for specific soil, cropping and climatic conditions, particularly if combined with improved weather forecasting, will continue to improve the precision of guidance that can be given to farmers and help abate nitrogen losses. Improved knowledge of crop-specific requirements, soil N mineralization and the ability to predict these from remote sensing will also contribute to advances in this area.

379. Uptake of measures is also a great challenge, with many economic and social barriers to uptake not always well understood. Accurate quantification of the costs and benefits (and factors influencing them) is required, together with an understanding of practicalities, synergies and trade-offs that may exist, to enable development of policies based on encouragement and trust, incentives and/or legislation as means of achieving uptake. Farmer involvement at all stages of technological development is critical for successful implementation plans.

380. Finally, while a number of UNECE category 1 measures are already available, there also exist several category 2 measures for which further research and assessment is required to provide a better understanding of constraints, trade-offs, barriers to use (or context-specific issues) so that they may be promoted to UNECE category 1. These advancements will provide a wider range of options for farmers and policymakers.

I. Guidance documentation

381. Sources of further guidance are provided at the end of chapter VII.

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VI. Land-use and landscape management

A. Introduction and background

382. The overarching assumption of this chapter is the challenge of mitigating the environmental impact of nitrogen (N) use while keeping its benefits for production of crops and livestock. This requires the implementation of measures at the landscape scale that facilitate removal of reactive N (N_r) from water and air, thereby preventing N cascading along hydrological and atmospheric pathways.

383. This chapter reviews a range of land-use and landscape management practices, and how they can contribute to a more sustainable use of N for agricultural production, while mitigating the negative effects of reactive N_r in the environment. Key elements are summarized to provide guidance on integrated sustainable nitrogen management, taking into account air, water and climate co-benefits.

384. This chapter integrates knowledge from the previous chapters of this guidance document, including livestock and arable production systems measures at the landscape scale. Measures include use of land adjacent to agricultural production areas, and thereby add the benefits of a whole-landscape approach to the principles of sustainable N management (chapter III).

B. Why consider land-use and landscape level management?

385. Adaptation of land-use and landscape level management practices are necessary to optimize use of N_r, whilst mitigating unwanted effects of N_r pollution on air, water or climate. Some of the advantages of landscape management and measures and territorial management are set out below:

(a) Landscape management enables N_r pollution problems to be addressed exactly where they appear, both in space and time, which helps to achieve the desired N mitigation effect;

(b) Landscape measures can be economically favourable compared to other types of measures (see chapters IV and V). They can also be placed outside agricultural areas, retaining agricultural production, while creating new nature and recreational resources in the form of hedgerows, forests, extensive buffer-zones around fields, streams, or wetlands;

(c) Territorial management could help to maximize circular economy by optimally distributing the available fertilizer resources, improving the application of circular economy principles, and integrating knowledge on local resources.

386. As summarized in box VI.1 and the section below, strategic land-use changes and landscape level management practices have benefits via a combination of environmental and economic effects, as a result of physical/chemical, biological and socioeconomic factors.

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Box VI.1

Definition of landscape and land-use management practices for nitrogen mitigation.

Landscape can be defined as a delineated geographical area integrating all types of land-use and management practices, which includes effects on the N cycle and related emissions.

The typical view of a landscape is of a composite of land-uses seen altogether, typically from a few to several tens of square kilometres. Landscape areas may be defined according to many criteria, such as a mix of land ownership and land-use, a watershed or a legally defined administrative area. The idea of such a landscape is illustrated by figure VI.1 below.

The main focus here is the N_r-related management of agricultural (including livestock facilities) and forest land in rural landscapes. Urban land-use and infrastructure are relevant for other landscapes but are not the focus of this chapter.

Landscape measures are sometimes employed in situations where applicable measures designed to reduce the input of N_r to the rural environment have already been implemented, and where socioeconomic factors argue for the retention of activities, which, however, are the source of N_r pollution, typically from agriculture. In terms of pollution, mitigation is here taken to mean "reducing the adverse effect" of any Nr compound such as the atmospheric pollutant ammonia (NH_3), the aquatic pollutant nitrate (NO_3–), or the greenhouse gas nitrous oxide (N_2O). The term "abatement" is here taken to mean "reducing the loss to the environment" of such Nr compounds and dinitrogen (N_2). In general, landscape measures are primarily mitigation, rather than abatement, strategies. This is to say that they provide an additional means to reduce specific adverse effects in the environment, which is typically larger than their effect on reducing overall losses to the environment.

C. Land-use and landscape management effects in practice

387. In this section, the active use of landscape management for N_r effects mitigation is illustrated using the following examples:

(a) Mitigation/abatement of NH_3 emission hot spots from livestock houses and slurry tanks by planting trees downwind of the source area, to adsorb NH_3 and disperse it vertically;

(b) Planting vegetation around protected nature areas or along streams, to intercept Nr (for example, in the form of airborne NH_3 or leaching of NO_3– to surface waters) before reaching the protected natural areas, which are often vulnerable to Nr pollution;

(c) Strategic establishment of wetlands to clean/treat water polluted with nitrates and dissolved organic N from field drains or dikes via denitrification and sedimentation before it reaches vulnerable surface waters;

(d) Spatio-temporal timing of grassland management and manure distribution to minimize N-losses in vulnerable areas or times of the year (for example, in dedicated groundwater protection areas);

(e) Adaption of N_r fertilization schemes (fertilizer types, nitrification and urease inhibitors, timing of fertilizer application) depending on the distribution of soil, subsoil and geology across a landscape;

(f) Reduction of N fertilization, and changes in management practice to reduce the nitrate losses to vulnerable surface waters and groundwater in geographically targeted areas with a low N retention potential of the subsurface.

388. One of the major challenges in the shift towards more geographically targeted, landscape level Nr measures is the knowledge and documentation of their effects. This conclusion was also reached in the European Union-funded integrated research project

NitroEurope,[29] where pilot research studies were carried out in six European case landscapes (for example, Dalgaard and others, 2012); as further described in the European Nitrogen Assessment (Cellier and others, 2011; Sutton and others, 2011), which included experiences from key national research projects in France, Denmark, the Netherlands, Scotland (United Kingdom of Great Britain and Northern Ireland) and other countries with different climatic conditions. Based on these studies, Cellier and others (2011) concluded that, at field or farm scales, processes of N transformation and transfer have been extensively studied and have provided a fair insight into the fate of N at restricted spatio-temporal scales, even though the majority of studies are from North-Western Europe.

389. Reactive nitrogen cannot be addressed as a single environmental pressure due to the cumulative effects of land-use and climate change processing of nitrogen. Leaching of N_r reflects non-linear interactions, so that it is threshold-dependent and interlinked with acute stressors. Treating these stressors in isolation, or in a simplified additive manner, may seriously underestimate future N-related risks, including eutrophication, acidification, greenhouse gas emissions and biodiversity change, as well as changes in the functioning of forest, natural land and water systems.

390. Reactive nitrogen cascades along hydrological and atmospheric pathways at a range of scales, from landscape to regional scales. N_r can be transferred by a variety of pathways in significant amounts from their sources to the recipient ecosystems (see figure VI.1 below). For example, gaseous NH_3 emitted from animal housing or a field can be redeposited to the foliage of nearby ecosystems in amounts that increase the closer the source is horizontally to the recipient ecosystem and vertically to the soil surface (Fowler and others, 1998; Loubet and others, 2006). Similarly, wetlands or crops/grasslands at the bottom of slopes can intercept NO_3^- in the groundwater that originates from N applied further up the slope, due to a lateral flow of water at landscape scales (Casal and others, 2019). In both cases, this can lead to large inputs of N_r to the receptor ecosystem that may have potential impacts on the ecosystem function (Pitcairn and others, 2003). This increases the risk of enhanced N_2O and NO_x emission (Beaujouan and others, 2001; Skiba and others, 2006; Pilegaard and others, 2006), pointing to the need for integrated N management and assessment beyond the field scale (Quemada and others, 2020). Without immobilization of N_r in biomass or its removal via denitrification, lateral losses of N_r continue along the N cascade (Galloway and others, 2003; Billen and others, 2013) (see figure VI.1 below).

391. These N_r emissions resulting from N_r transfer from source to receptor ecosystem are often termed “indirect emissions” and represent a significant fraction of total soil N_2O and NO_x emissions, although their magnitude is still debated (Mosier and others, 1998; Liu and Greaver, 2009, Tian and others, 2019). The inclusion of uncultivated or marginal areas that are outside or peripheral to the agricultural systems is important for understanding flows and budgets of energy and matter, including N, which emphasizes the need to adopt a landscape perspective.

392. Livestock are a major source of N_r pollution, specifically in regions with high livestock densities (Leip and others, 2015), but can provide services that are valued by society, such as habitat provisioning or being part of cultural and natural heritage (Dumont and others, 2017). Some countries that have intensive livestock production in close proximity to sensitive ecosystems have already imposed a range of measures to reduce N_r pollution (for example, the Netherlands, Denmark), but still have difficulty complying with requirements of European Union legislation such as the Water Framework Directive, the Habitats Directive and the National Emission Ceilings Directive. With the most cost-effective measures to reduce N_r losses at source already implemented, there has therefore been increased interest in measures at landscape level (Dalgaard and others, 2012, 2016; Jacobsen and Hansen, 2016).

[29] https://www.peer.eu/projects/peer-flagship-projects/nitroeurope/.

D. Main issues for the reduction of reactive nitrogen emissions via land-use and landscape management

Nitrogen flows in the rural landscape

393. Figure VI.1 provides an overview of N_r flows, sinks and sources in rural landscapes, and the cascade of reactions from N_r input in the form of fertilizers and feed, through the cropping and livestock system, and to the natural ecosystems, also put forward in the European Nitrogen Assessment by Sutton and others (2011). It is especially the N_r flows to and from the natural/semi-natural ecosystems, and from the farms and field to the aquatic ecosystems that are targeted by the landscape level measures exemplified above. These flows can be divided into those relating to: air pollution, including greenhouse gas (GHG) emissions (see figure VI.3 below); surface- and groundwater pollution (see figure VI.2 below); and sources and sinks of nitrogen (see figureVI.1 below). Each of these flows is described in the sections below.

Guiding principles

394. Rural environments have a range of stakeholders relevant to mitigation and abatement of N_r pollution using landscape measures (for example, farmers and other land managers, conservation agencies, regional government, other businesses, civil society organizations and citizens). Their involvement can help identify barriers to the effective implementation of measures, how these barriers can be avoided, and how to encourage the development of a consensus that lends the measures political and social legitimacy. According to Andersen and others (2019), guidance for land-use and landscape management to mitigate N pollution can be defined in two steps:

(a) **Step 1: Mapping of the present situation** (for example, current land-use, soil and geological properties, water flows) to understand the N cascade in the landscape, mapping of N management practices, as well as identifying relevant stakeholders and their targets for reduced N_r pollution. This can benefit from locally held workshops (involving farmers scientists, politicians, local stakeholders and other interest groups) to identify suitable approaches and measures for reducing landscape N loading. It is also important to collect relevant landscape-scale data, which can be relevant to publicly available policy targets for (reduced) impacts of N in the area. Each actor in the landscape can thereby gain an overview of the possibilities for action, both within the farming system and in the context of the whole landscape;

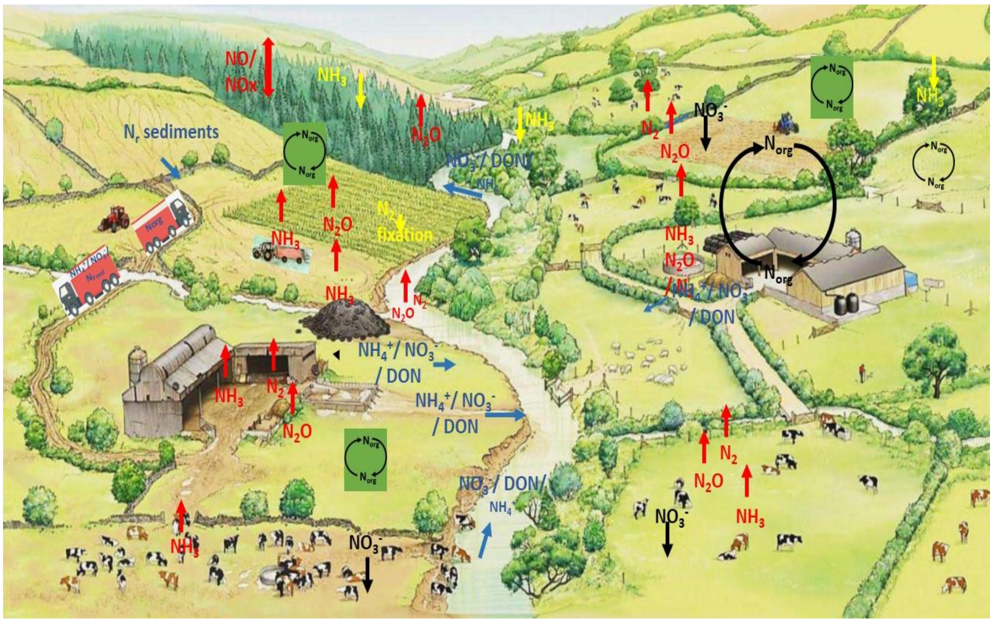
(b) **Step 2: Selection and prioritization of land-use and landscape management solutions to reach reduction targets.** These solutions are, in the first instance, influenced by geophysical constraints, which are rather difficult to overcome. However, other environmental and socio-economic goals of stakeholders/actors also need to be considered.

395. In this approach, each stakeholder/actor in the landscape may be provided with a list of measures as a basis for discussions and decisions, together with information on their potential environmental and economic effects at the farm and landscape scale. A hypothetical example could be a multi-actor discussion on the placement of a small wetland along a stream running through a farm. The wetland promotes the removal of N_r from upstream N_r sources via uptake into plant biomass and by denitrification to N_2, as far as possible avoiding N_2O emissions (Vymazal, 2017; Audet and others, 2020). Such upstream catchment management may cover both fields within an individual farm and the fields of other farms. Moreover, wetlands provide additional ecosystem services, for example, in the form of increased biodiversity, flood protection and scope for leisure activities such as fishing. Key risks in this example include the possibility of increased N_2O emission through denitrification and the loss of N_r resource from the farming system.

396. The integration of key stakeholders into both steps of the process is important to facilitate development towards the design of landscape measures, management and use, which minimizes N_r cascading and losses, while sustaining its landscape productivity. This process will normally require iterative repetitions of the above-mentioned two steps, to allow the consequences of different scenarios to be calculated. This also allows participants time for reflection and consultation with other members of their stakeholder groups.

Figure VI.1

Simplified overview of landscape N_r flows showing source and sink functions of landscape elements such as farm buildings, fields, forests, pasture etc. for various N_r forms



Source: This figure has been modified from http://www.westcountryrivers.co.uk/good-farm-bad-farm/ on basis of the Creative Common License https://creativecommons.org/licenses/by-nc-sa/4.0/.

Note: Major N_r sinks and sources are highlighted in the form of gaseous N_r flows (red for sources, yellow for sinks), N_r flows to and in surface waters (blue arrows, including sediment erosion and surface run-off), nitrate leaching to groundwater (black arrows) and changes in soil organic N pools (green squares with black arrows). The fixation of atmospheric N and the deposition of atmospheric ammonia (NH_3) is indicated (yellow arrow) together with the import and export in products to and from the landscape (trucks providing feed and fertilizer, and export of manures, crops, livestock and animal products). Major flows to air include NH_3, nitrogen oxides (NO_x),[30] nitrous oxide (N_2O) and dinitrogen (N_2); nitrates (NO_3^-), ammonium (NH_4^+) and dissolved organic nitrogen (DON) to waterbodies, and the organic nitrogen (N_{org}) balance in soils. Of most importance for air quality, ecosystems and health are emissions of NH_3 (mainly from livestock wastes and chemical fertilizers) and NO_x (which is emitted from agricultural soils and N-saturated forests mainly in the form of NO, reacting to form NO_2, in addition to NO_x from traffic sources).

397. The landscape illustrated includes the following major compartments:

(a) Farms; including livestock houses, manure and fodder storage, grazed grasslands, arable and grasslands fertilized with manure or mineral forms of N, permanent crops and rotations with and without tillage;

(b) Forests and other semi-natural systems in the form of hedgerows, small biotopes with woodlands, ponds etc., and more or less permanently set-aside agricultural land; and

(c) Aquatic ecosystems, such as ponds, lakes, streams and wetlands. These systems are fed by direct run-off, field-drains or groundwater. (The water system is illustrated in more detail in figure VI.2. below).

398. Depending on the characteristics of a given landscape, and the most urgent issues that require attention, a different priority order might be given to address N_r pollution of water, air, soil or climate impacts. For instance, in dry Mediterranean climates, like in Spain, impacts on air pollution may, for health reasons, be addressed first (for example, where respiratory diseases are frequent), whereas for a landscape situated in the wet coastal climate of Denmark, N_r impacts on water quality might be of highest priority (for example, where

30 See footnote 2.

legally binding limits for vulnerable estuaries and coastal water quality are exceeded, Dalgaard and others, 2014).

399. The effects of measures to reach one target (for example, for water) also often affect targets related to air, soil and climate. The same is the case for measures aimed at improving air and soil quality, which typically directly or indirectly also affect GHG emissions. This means that, in a situation where water is prioritized first, measures to reach the reduction targets set for the surface and groundwater would need to be defined first (primarily for nitrates, but possibly also for dissolved organic carbon). Subsequently, measures to reach air pollution reduction targets might follow (primarily for NH_3, and possibly also for NO_x). Finally, targets and measures might need to be identified and implemented for soil protection (and thereby rates for the build-up of soil N and organic carbon I stocks, or prevention of soil organic C and N mining), as well as reductions in net GHG emissions (here net balance of CO_2, N_2O and CH_4 fluxes in terms of CO_2 equivalents). Such an approach requires consideration of the GHG emissions from soils, as well as from other sources like manure storages, livestock and livestock houses, both in the form of nitrogen compounds (primarily N_2O) and carbon compounds related to the nitrogen cycle (primarily CO_2, but possibly also CH_4; Dalgaard and others, 2015).

E. Integrating aspects of water, soil, air and climate impacts

400. In accordance with figure VI.1 above, the two main categories of N_r pollution are via water (mainly NO_3– but also other N_r forms, including organic N compounds) or air (mainly NH_3, N_2O and NO_x and N_2). Although N_2 is not a pollutant, its loss is accompanied by reduced nitrogen use efficiency for crop production, thus requiring increased N_r inputs. Consequently, the emission of N_2 can be considered as representing an indirect form of nitrogen pollution. Understanding the different local conditions for these types of losses is important when prioritizing landscape mitigation measures following the above-mentioned guiding principles.

401. In the following two sections, the main pollutants are presented, showing how mitigation options for surface and groundwater pollution are linked to local soils, geology and geomorphology (first part), whereas mitigation options for GHG emissions are closely linked to air pollution (second part). When integrating the combined effects of N_r mitigation options for water, soil, air and climate impacts, it is important to assess all sources/sinks in the landscape together, as the potential mitigation options depend on landscape heterogeneity and the scale at which the mitigation options are carried out. This is discussed in a following third section.

1. Surface and groundwater pollution, soil and geology

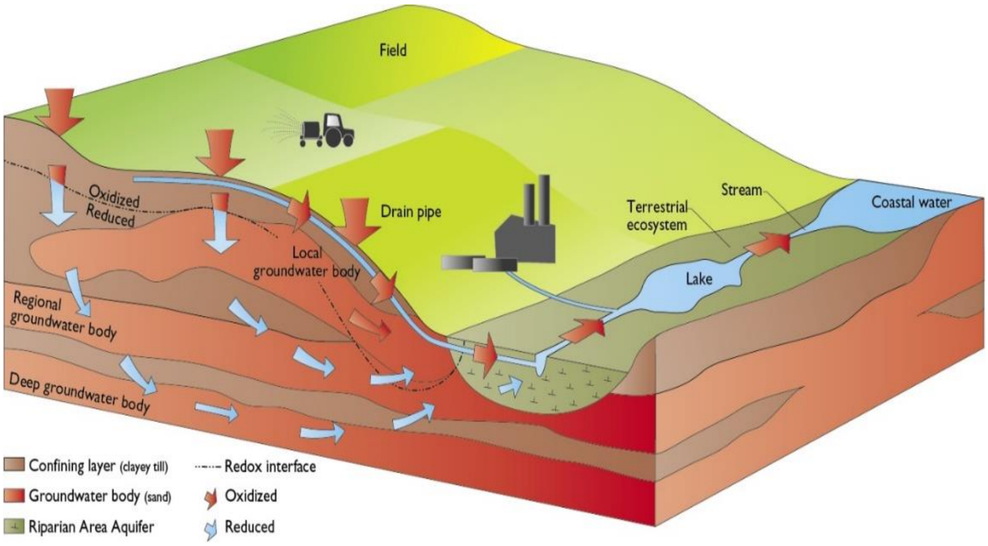
402. Nitrogen in water can be mapped in the form of concentrations of NO_3^-, NH_4^+ and DON in surface waters (streams, lakes and coastal waters) and in groundwater reservoirs, with concentrations being closely linked to N_r inputs, flows and removal in a given landscape (see figure VI.2). Based on this assessment, landscape-specific targets for ground- and surface-water quality can be set. Within the European Union, this must correspond to the related standards set from the objectives and targets of the Water Framework Directive, the Nitrates Directive and the Drinking Water Directive (good ecological and chemical status, reducing and preventing pollution of water by nitrates of agricultural origin). For example, the European Union Groundwater Directive[31] sets a groundwater quality standard of 50 mg of nitrate per litre, corresponding to the standard for the content of nitrate in drinking water according to the Drinking Water Directive. For other parts of the UNECE region, the World Health Organization (WHO) also applies a maximum of 50 mg of nitrates per litre for drinking water (see also the European Commission, 2019). From such information, and information on possible measures (see sections below), scenarios can be constructed that

[31] Directive 2006/118/EC of the European Parliament and of the Council of 12 December 2006 on the protection of groundwater against pollution and deterioration, *Official Journal of the European Union*, L 372 (2006), pp. 19–31.

include land-use and landscape management practices to meet these targets (Hashemi and others, 2018a, b).

Figure VI.2

Conceptual model of the interaction of shallow groundwater bodies with dependent aquatic ecosystems



Source: Based on Hinsby and others, 2008.

Note: The transport pathways to the aquatic ecosystems are indicated by arrows. The blue arrows symbolize reduced groundwater (below the redox zone) and the red arrows symbolize water flows in the upper oxidized zone.

2. Air pollution and related greenhouse gas emissions

403. On the basis of current agricultural practices, emissions of N_r to the air can be measured and/or estimated via modelling (as exemplified in figure VI.3), and compared to possible “critical loads” for atmospheric N_r deposition. Critical loads are deposition limits below which adverse effects are not known to occur according to present knowledge. The impact of agricultural developments on the exceedance of N_r critical loads for sensitive nature areas within or nearby the landscape should also be considered (Dragosits and others, 2006). From this, measures to reach reduction targets for, for example, NH_3 volatilization, can be defined. In addition, such an approach allows the identification of regional N_r pollution hot spots (see figure VI.3 below) and to estimate abatement/mitigation potential for emission of the greenhouse gas N_2O and other GHGs (see figure VI.3 below).

3. Sinks and source heterogeneity and scale issues

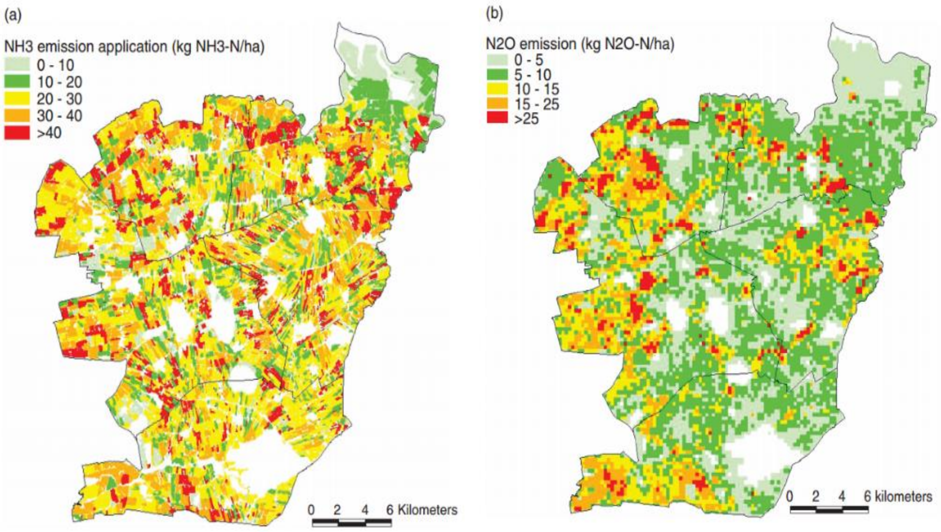
404. Water, air and greenhouse gas pollution within a landscape depend on both sinks and sources of nitrogen, and on the specific farm systems within the landscape, as agricultural systems are the dominating source for nitrogen pollution.

405. Figure VI.4 below provides an example of N_r sources and sinks in dependence of farm types. It illustrates that different types of production systems are associated with different types of environmental N_r losses, estimated by the www.Farm-N.dk model. For example, leaching of NO_3– is found to be the dominant form of N_r loss for cash crop farms in this context, and, to some degree also, for granivore production systems (for example, pig and poultry production farms). Conversely, in absolute values the leaching per hectare is higher for livestock as compared to cash crop farms in this context. Cattle (ruminant) production systems can have relatively low N_r leaching losses, depending on intensity and management practices, although such production systems show high NH_3 emissions, associated with animal housing, manure storage and spreading. In particular, intensive dairy production systems involve substantial N inputs with substantial NH_3 emissions. In cool oceanic climates, extensive grazing of beef cattle all year round can be associated with low NH_3

emissions (due to effective urine infiltration compared with livestock manures), though may still risk increased NO_3– leaching, N_2O, NO_x and N_2 emission.

Figure VI.3

Example of annual emissions of ammonia from manure application (a) and total nitrous oxide emissions from soils (b) in a rural landscape of the Netherlands



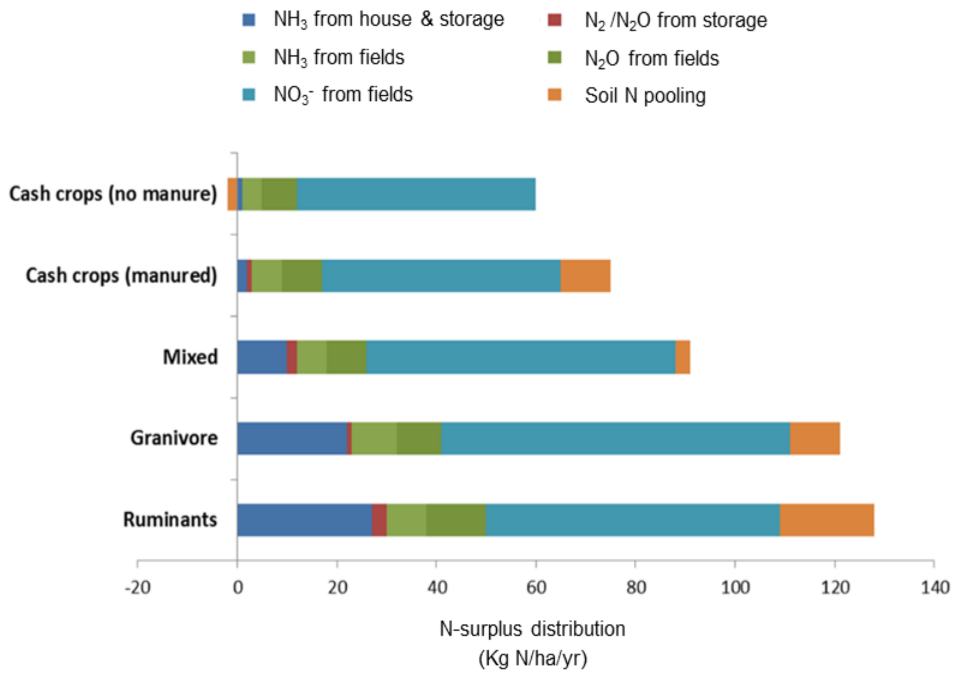
Source: Based on Cellier and others, 2011.

406. Other effects associated with manure management are changes in soil N stocks (and also soil C stocks) as a result of manures applied to pastures and cropland. In the study by Dalgaard and others (2011), the estimated increase in soil N stocks is highest for the ruminant systems (with relatively more grasslands and intensive use of manure, including straw in deep bedding etc., and manure applications to grass- and croplands). In contrast, cash crop systems, which do not receive manure applications, showed a net reduction in nitrogen (and carbon) stocks when manure addition was not included in this system.

407. The huge difference in environmental N_r loss pathways for different farming systems, and thereby in agricultural N_r sources and sinks within the landscape, means that the geographical position of a farm matters with regard to environmental N_r losses to sensitive water bodies or sensitive terrestrial nature areas. This source-sink relationship is also influenced by variations in geopedomorphological characteristics, which affect rates of leaching losses, surface Nr losses, lateral transport of N_r in soils and parent material (see figure VI.2 above). Consequently, appropriate planning of land-use, land management, placement of farms, etc., will have a significant effect on landscape N_r fluxes, offering an opportunity to reduce N_r loads at landscape scales.

Figure VI.4

Distribution of nitrogen surplus between types of N_r losses and pools, compared for five different agricultural systems within a Danish landscape



Source: Based on Dalgaard and others**,** 2011, estimated using the www.Farm-N.dk model.

Note: Losses of N_2, NO_x and organic N from soils were not estimated in this study. For cash-crop farms with no manure, a net N emission from soil N pools was estimated, while for the other farming system, a net build-up of soil N was estimated, thereby reducing the N_r emission for the year accounted.

408. Landscape measure might include: choosing a location for (new) livestock production facilities that is further away from sensitive ecosystems; incorporation of certain land-use types (for example, planting trees around livestock facilities, buffer zones around water bodies, and placement of N_r reducing wetlands, etc.); and cropping systems with different intensity (for example, grassland versus rotational land). Altering the rates of application and distribution of manure and manufactured inorganic fertilizers according to local sensitivity within the landscape (or even in and out of the landscape) provides another option that can help to reach N_r mitigation and abatement targets. Such targeted land-use and management practices can thereby be used as measures to help fulfil reduction targets for water-, air- and GHG-related Nr emissions.

409. It should be remembered that N_r at site or landscape scale is a valuable resource for crop, biomass and livestock production. Recycling of all N_r resources should therefore be prioritized. For example, biomass produced with the support of N_r recaptured in the landscape, such as paludal biomass in wetland areas or trees grown in the vicinity of livestock production, should be evaluated as bioenergy resources. This means that it is important not only to keep account of direct losses of N_r pollution, but also of the amount of N_r lost as N_2. This emphasizes the need to develop holistic assessments to quantify all N_r flows at landscape scales.

410. Flows and transformations of N_r within a landscape are determined by the topography and spatial variability of the biogeochemical and physical characteristics of the soil. These, together with climate and agricultural N management, determine soil microbial N cycling (with specific emphasis on nitrification and denitrification processes), plant-soil N interactions, and, thus, fluxes of NH_3, NO_x, N_2O, N_2 to the atmosphere and the leaching of dissolved organic N (Salazar and others, 2019) and NO_3– to the rivers and other aqueous bodies (see figures VI.1 and VI.2 above). In order to assess such N_r flows at landscape scale, it is important to gather information on field scale/farm scale “activities”, such as agronomic management, fertilizer type, N application rates, soil types and topography and emission-abatement and mitigation approaches. New technologies, for example, drones, satellites and

aircraft, are valuable tools to support relevant data collection (for example, soil moisture, topography, vegetation types). An example is the use of satellite vegetation maps to estimate landscape scale CH_4 fluxes (Dinsmore and others, 2017), which can inform the development of abatement strategies.

F. Priorities for policymakers

411. In general, recommendations for policymakers[32] follow the above-mentioned guidance principles, based on assessment of the present situation (Step 1: Mapping of the present situation) as a background for defining suitable land-use and landscape measures (Step 2: Selection and prioritization of land-use and landscape management solutions to reach reduction targets). This can provide a prioritized order of measures to fulfil targets set for (the reduction of) water, air, soil and climate impacts.

412. In line with the guidelines of the European Commission (2010), when designing policies for the implementation of such measures, it is recommended that, prior to implementing measures, their effects be assessed (ex ante assessment), and that the economic costs of measures be included and considered. Moreover, after a defined period of implementation, it is recommended that a corresponding assessment of their effectiveness in practice be carried out (ex post assessment). The second assessment might be used to revise policies, and to implement iteratively new additional measures on the basis of the above-outlined two-step approach. An example of such an iterative policy cycle is reported for the five subsequent national Danish Nitrogen Action Plans 1987–2015, which included both ex ante and ex post assessments of the costs of these action plans (Dalgaard and others, 2014).

413. Over the last five years, there has been increased emphasis on N_r measures, which contribute to a more circular bioeconomy, allowing the costs of measures to be offset by new revenue opportunities from recaptured N_r (for example, Dalgaard and others, 2014; Sutton and others, 2019). Relevant measures include those that help to use nitrogen more efficiently, such as the use of manures in biogas facilities, which, apart from making the N_r more readily available for plants, can also serve as distribution centres for a more optimal distribution of fertilizers recovered from organic materials (chapter IV) in a landscape or region. Other examples include:

(a) Use of N_r in locally grown protein from green biomass in biorefineries;

(b) Use of green manure in biogas plants, including N_r recovery;

(c) Use of crops for energy with N_r recovery;

(d) Use of mixed farming to increase overall landscape nitrogen use efficiency and N_r recovery (Wilkins and others, 2008);

(e) Agroforestry systems to maximize recovery of N_r already released to the landscape.

414. Such options may also lead to production systems that are more resilient to climate change and with more diverse services delivered, as well as having reduced N_r footprint. For example, woodlands in landscapes serve many functions, such as increasing landscape water retention to reduce flooding, provision of wildlife habitats and provision of shelter for livestock, where the potential to use them as N_r management tools is just one opportunity (for example, Sutton and others, 2004).

415. In this context, it is important to carry out both a N_r budget- and an economic/welfare impact assessment of the measures (for example, not only the environmental, but also the economic impacts for farming versus the wider socioeconomic impacts).

[32] Policymakers are considered in this section to include all kinds of representatives from central agencies (agricultural, environmental, finance, health, trade), leaders in food industry and agriculture, scientists, extension services and regions around the world (for example the UNECE regions, including North America, the Eastern Europe, the Caucasus and Central Asia region, the European Union, smaller administrative regions within countries, municipalities, watershed regions, etc.).

G. Land-use and landscape mitigation measures

416. The estimated effects of landscape measures as part of sustainable nitrogen management are summarized below according to five main categories .The landscape measures listed below provide options for consideration in steps 1 and 2 (for example, mapping of present situation, and selection of management solutions), which can then be selected and prioritized according to local context:

(a) Land-use measures for mitigation of N_r effects from crops and crop rotations;

(b) Landscape measures for mitigation of N_r effects from management of riparian areas and waters;

(c) Afforestation, set-aside and hedgerows as measures to mitigate N_r effects;

(d) Mitigating the cascade of N_r effects from livestock hot spots;

(e) Smart landscape farming in relation to mitigation of N_r effects.

417. Following the description of each measure below, a table (see tables VI.1–VI.16 below) summarizes the UNECE category for effectiveness/practicality of implementation (following the approach of ECE/EB.AIR/120, Bittman and others, 2014), and the magnitude of effect of each measure.[33] Expert judgement is used for ammonia volatilization, denitrification losses as N_2O, NO_x and N_2, run-off and leaching losses as $NO_3^–$, and overall total N losses.

418. In the present chapter on land-use and landscape scale measures, the primary focus is on mitigation of adverse impacts, though there can also be benefits for emissions abatement.

419. Where a measure is considered to result in an increase in losses of a specific nitrogen form, it is, by definition, also assigned to category 3 for that nitrogen form. The magnitude of effect can be considered as an indication of "effectiveness" of the measure as distinct from the extent to which the measure is "applicable" in different contexts. Where clarification is necessary, magnitude of effect of a measure is described in comparison to a specified reference system. For example, in the case of constructed wetlands, two reference systems are specified:

(a) Taking no action (with polluted water lost directly to streams and rivers); and

(b) Advanced processes focused on nutrient recovery.

420. In some parts of the UNECE region, use of certain reference systems may be prohibited, for example, because of the associated pollution levels. Table VI.17 below provides an overview of all the land-use and landscape management practices and the expected effects in relation to leaching/run-off (water pollution), NH_3 volatilization (air pollution) and other gaseous N emissions including N_2O emissions (climate impact), and the overall effect on N pollution.

Measures specific to placement of crops and crop rotations

421. The main effect of optimized selection of crops and sequences of crops (crop rotations) is to improve the uptake of nitrogen from the roots and thereby reduce the leaching of nitrate in a geographically targeted way, with minor direct effects on other N compounds. This can in general be achieved through the measures listed below:

Landscape Measure 1: Increasing land cover with perennial crops

422. Introducing perennial crops, such as grasslands, predominately grass or grass-clover mixtures, can reduce the risk of environmental N_r losses due to N_r immobilization in plant biomass and litter. It also increases soil N (and C) stocks, with higher soil organic carbon contents providing increased N_r retention capacities. This reduces the risk of N_r leaching, but could potentially increase the risk of higher soil N_2O emissions. However, in most studies,

[33] See chapter I, para. 16, for a description of the UNECE categories and system for representing the magnitude of effect.

increases in N_2O emissions were found to be insignificant (Li and others, 2005; Abdalla and others, 2019).

Table VI.1
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Landscape Measure 1

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

[a] Insufficient data to estimate the effect, though responses may be similar to N_2O and N_2.

Landscape Measure 2: Introducing catch crops

423. Introducing catch crops (sometimes called “cover crops”) following the main crop will help to reduce nitrate leaching (Gabriel and others, 2012). Such crops can be placed strategically in a landscape at target locations to reduce nitrate run-off. Nitrate originating from post-harvest decomposition and mineralization is taken up by catch crops between the main cropping season. Catch crops also help reduce the risk of soil surface fluxes (erosion) and surface sediment and N_r transport to streams. At the start of the new growing season, catch crops are ploughed into the soil (for example, as “green manure”), and provide additional organic matter and nutrients to the subsequent crop, which can be especially beneficial in intensively cultivated Mediterranean conditions (Karyoti and others, 2018). Under continental Russian conditions, Lukin and others (2014) found that growing a crop of oil radish after solid manure or slurry application led to substantially reduced losses to groundwater of both ammonium and nitrate, as well as for phosphorus and potassium.

424. Winter catch crops are used in some circumstances to minimize soil mineral N concentrations over the high-risk period for nitrate leaching, but their success in increasing N use efficiency over the whole cropping cycle depends on effective management of the cover crop residue and appropriate amendment to the fertilization of the subsequent crop. Most importantly, the cover crops must be planted early so they are well-established before the high-risk period.

425. Incorporation of catch crops is beneficial for increasing soil C and N stocks, but bears the risk of increased soil NH_3, N_2O and NO_x emissions associated with mineralization following the incorporation of the catch crops into the soil (Sanz-Cobena and others, 2014; Xia and others, 2018; Abdalla and others, 2019). An integrated management of cover crops adapted to local conditions can maximize agroenvironmental benefits while reducing trade-offs (Tribuillois and others 2016, Quemada and others, 2020). In colder climates, freeze-thaw cycles over the winter period can cause significant nutrient release and N_2O emissions (Wagner-Riddle and others, 2017). In order to minimize N loss, it is necessary to time tillage operations in order to optimize synchrony between N release and uptake by the subsequent crop. Where there is an N surplus, cover crops will not mitigate losses unless they displace imported N (for example, reducing N inputs to compensate N savings; Principle 6).

Table VI.2
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Landscape Measure 2

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

[a] Denitrification losses are assigned to category 2 because these may be increased following the incorporation of the cover crop/residue. The timing of this operation will typically be in spring after the drainage season, so that there is no significant risk of increased leaching. It is expected that

leaching will be greatly decreased because any surplus N at the end of the previous season will have been taken up by the cover crop over the risk period

Landscape Measure 3: Including N_2-fixing crops in crop rotations

426. Including N_2 fixing crops like legumes (for example, beans, lentils, etc.) in crop rotations allows N fertilizer application rates to be reduced. Under this approach, N_2 is reduced to NH_3, which is then assimilated into organic nitrogen compounds by bacteria associated with root nodules of the legume. This organic N_r becomes available to following crops by incorporation of crop residues. Legumes stimulate increases in soil C and N and are expected to have an overall beneficial effect in reducing nitrate leaching in comparison with the use of chemical fertilizers (Voisin and others, 2014; Jensen and others, 2020). The anticipated mechanism is that biological nitrogen fixation acts as a "slow-release" form of N_r provision, which proceeds according to the needs of plants (cf. Drinkwater and others, 1998). It has been suggested that adverse stimulating effects on N_2O emissions are possible, but not likely (Abdalla and others, 2019). By contrast, as with Landscape Measure 3, incorporation of legumes into the soil leads to a pulse of mineralization. While this can help satisfy the N needs of the subsequent crop, this mineralization pulse also risks increased N_r losses as NO_3– and N_2, as well as N_2O and NO_x and NH_3. Further experimental data are required to quantify these trade-offs, including at multiseasonal and landscape scales.

427. Clover is an important constituent of many grasslands across Europe, but the quantity of N provided by pasture is highly uncertain. During the growing season, N fixed by legumes will be mostly utilized by the crop (legume or companion crop). However, when active growth slows or ceases, then fixed N may be released to the soil through mineralization, with potential N losses through leaching and denitrification, in particular if the grassland is ploughed or chemically killed (or both) as part of a rotation system. While inclusion of legumes lowers the requirement for applied N (as fertilizer or manure) and the N losses associated with such applications, leaching losses may be greater in fallow periods following legumes if cover crops (see chapter V) are not included in the rotation. Use of intercropping offers the opportunity to make available slow-release N resources from a legume to an intercropped non-leguminous crop, which may reduce N losses.

Table VI.3
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Landscape Measure 3

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

[a] The arrows distinguish a general expected reduction in nitrogen losses compared with use of mineral fertilizers, while acknowledging that post-harvest N losses associated with incorporation of a legume crop into the soil to increase soil C and N stocks can also increase N emissions and leaching losses (shown in brackets).

Landscape Measure 4: Introducing agroforestry and trees in the landscape

428. Agroforestry land-uses include the cultivation of crops and trees, with alternate rows of trees and annual crops, or block of trees in the landscape. This approach offers the opportunity for including unfertilized crops in the landscape, such as short-rotation coppices for bioenergy production. This can increase biodiversity, remove surplus N_r from neighbouring arable fields, minimize erosion, provide wind shelter and increase deposition of NH_3 as surface roughness is increased (Sutton and others, 2004; Lawson and others, 2020). All these effects mitigate N_r transport at spatial scales and N_r pollution of air and water (Pavlidis and Tsihrintzis, 2018). The approach may also be compared with Landscape Measures 10 and 12.

Table VI.4
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Landscape Measure 4

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

[a] The effects will depend on configuration in relation to N_r sources and sinks in a landscape. Agroforestry to increase N sinks between an agricultural area and a stream provide an effective means to mitigate NO_3^- losses. Conversely, recapture of N_r emitted as NH_3 from livestock farms by trees risks increasing soil losses of N_2, NO_x and NO_3^- unless use of fast-growing trees ensures all surplus N_r is taken up by the trees.

2. Measures specific to management of riparian areas and waters

429. The main effect of this measure is to reduce the nitrate concentration and adverse effects of N-polluted water that have been lost from agricultural systems, for example, via tile drainage systems, surface fluxes or lateral water fluxes. In-field measures to reduce losses at source are discussed in chapter V.

Landscape Measure 5: Constructed wetlands for stimulating N_r removal

430. Constructed wetlands receive increasing attention due to their wide applicability for removing nutrients from water bodies or for wastewater treatment under various climatic conditions, including from animal manures and wastewater sources (Poach and others, 2003; Muñoz and others, 2016; Caballero-Lajarín and others, 2015; Wu and others, 2016; Vymazal, 2017; De La Mora-Orozco and others, 2018; Luo and others, 2018; Terrero and others, 2020). The design of such constructed wetlands varies considerably, and rates of nutrient removal depend on the plant species used, water-retention times, temperature, type of wetland, etc. (Sutar and others, 2018). The principle of operation of constructed wetlands is to encourage anaerobic conditions that favour denitrification to N_2, while other nutrients accumulate. This means that use of constructed wetlands to remove Nr risks increasing N_2O as well as CH_4 emissions, although further data are needed to quantify the extent of the trade-offs under different management conditions (Garnier and others, 2014). Since the focus is on denitrification, this means that the approach reduces overall landscape-level nitrogen use efficiency, preventing recovery of Nr resources. The popularity of the option is associated with its relative cheapness as a means of managing surface water quality, in comparison with more complex technologies.

Table VI.5
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Landscape Measure 5

Nitrogen form	*NH_3*	*N_2O*	*NO_x*	*NO_3^-*	*N_2*	*Overall N Loss*
UNECE category	3 (3)	3 (3)	3 (3)	1	3 (3)	3 (3)
Magnitude of effect	~ ?	↑? (↑)	~ ?	↓↓ (~)	↑ (↑↑)	↑ (↑↑)

[a] The UNECE category and Magnitude of effect are here compared with taking no action – for example, polluted water lost directly to streams and rivers (for example, reference is no action). Values in brackets show consequences compared with a reference system of advanced processes focused on nutrient recovery (chapter IV) (Effects on groundwater are not specified here).

Landscape Measure 6: Planting of paludal cultures in riparian areas or constructed wetlands

431. "Paludal plants" are plants growing in marsh and wetland ecosystems. These plants often develop a significant biomass during the growing period, thereby removing N_r from the

water. The biomass can be harvested and used, for example, as a source of bioenergy (Ren and others, 2019). Typical paludal plants used in the context of N_r removal are Typha latifolia (cat tail), Arundo plinii (false reed), Arundo donax (perennial cane) or Phragmites australis (common reed).

432. Planting of paludal cultures in riparian areas has been shown to be effective in reducing NO_3– loading in streams, though the efficiency of NO_3– removal will depend on interactions between riparian hydrological flow paths, soil biogeochemical processes and plant N_r uptake (for example, Hill, 2019). If these wetlands are poorly managed, it is highly likely that the mitigation of NO_3– will lead to increased emissions of the GHGs N_2O, N_2, CO_2 and CH_4. Further quantitative data on the trade-offs associated with different forms of constructed wetland are needed. It must be recognized that a focus on denitrification in constructed wetlands increases N_2 losses, meaning that the N_r resource is lost, reducing landscape-level nitrogen use efficiency. The advantage of such constructed wetlands is that they are low-cost, while the risks are that the effects on other N_r emissions are generally not quantified. Ensuring effective and rapid growth of paludal cultures will help reduce N_r losses but may be limited in dormant periods (for example, winter season, dry summer season).

Table VI.6

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Landscape Measure 6

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

[a] UNECE category and Magnitude of effect are here compared with a constructed wetland that does not include managed growth of paludal cultures, for example, the reference system. Values in brackets show consequences, compared with a reference system of advanced processes focused on nutrient recovery (chapter IV).

Landscape Measure 7: Use of organic layers to promote nitrate removal

433. Denitrification can be promoted, with the objective of reducing nitrates in water, by increasing the organic carbon content in soils, sediments, etc. On a practical level, this is done by introducing so-called denitrification barriers into the landscape (Bednarek and others, 2014). The term may appear confusing, but it is widely used to describe physical barriers that promote denitrification. According to Bednarek and others (2014), denitrification barriers can be classified as:

(a) Denitrification walls – constructed from carbon-rich materials, arranged vertically in shallow groundwater, perpendicular to the flow of these waters;

(b) Denitrification beds – containers filled with a material rich in carbon; or as

(c) Denitrification layers – horizontal layers of material rich in carbon.

434. Denitrification is the process by which NO_3– is converted to N_2. It is a heterotrophic microbial process that uses nitrate as an alternative electron acceptor instead of oxygen in oxygen-limited conditions to oxidize organic matter. In many environmental situations, the rate-limiting step for denitrification is the availability of organic matter. Therefore, the introduction of a carbon-rich layer can be used to promote denitrification.

435. Use of organic layers to promote denitrification can be used for both vertical and lateral water flows. Field and laboratory studies indicate that woodchip bioreactors can achieve nitrate removal efficiencies in a range of 80–100 per cent, with removal efficiencies depending on type and size of the wood chips, hydraulic loading rate, and recovery period between water applications, which affects the hydrolysis rate of the lignocellulose substrate becoming available for denitrification (Lopez-Ponnada and others, 2017). However, such organic layers may also promote the production of N_2O by denitrification. As anaerobic conditions prevail, significant production of CH_4 may also result, which could create landscape hot spots of GHG emissions (Davis and others, 2019). As the method focuses on

promoting denitrification, it reduces landscape-level nitrogen use efficiency, reducing the potential for N_r recovery.

Table VI.7
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Landscape Measure 7

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

[a] The effects are compared with a reference where no technology is used and water moves directly to streams.

Landscape Measure 8: Drainage management

436. Drainage measures, such as insertion of tile drains (promoting run-off and avoiding waterlogging), and water table management, influence the oxygen status of soils (increasing oxygen availability), increasing lateral water transport and reducing residence times of nutrients. All these factors affect the efficiency of N_r removal; for example, via denitrification (see Landscape Measures 5–7). The net consequence is that increasing drainage (such as through the use of tile drains) is expected to help abate emissions of N_r compounds relating to denitrification (N_2O, N_2). In contrast, shorter residence times are likely to increase run-off of NO_3– into stream waters. This measure can therefore only be considered as suitable where N_2O and N_2 abatement is considered a higher priority than nitrate pollution.

Table VI.8
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Landscape Measure 8

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

[a] Reverse if drains are blocked!

Landscape Measure 9: Stimulating N_r removal in coastal waters

437. Streams and groundwater loaded with N_r might directly reach the sea, specifically in agricultural regions close to coasts. It has been proposed that eel grass, seaweed growing, oyster farming or shellfish aquaculture are suitable for removing excess nutrients from coastal waters (Clements and Comeau, 2019; Kellogg and others, 2014) because nitrogen contained in phytoplankton is incorporated into biomass that is finally harvested, for example, as oysters, mussels or shellfish. However, reports on effects on N_r removal have been found to vary by orders of magnitude across sites, seasons and growing conditions (Kellogg and others, 2014). While the principle of encouraging N_r recovery into useful products is sound, further evidence of the quantitative performance of this system is needed before increased confidence can be given to support its wider adoption to mitigate coastal water pollution.

Table VI.9
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Landscape Measure 9

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

3. Afforestation, set-aside and hedgerows as N_r mitigation measures

438. Taking some parts of agricultural land out of production is an effective way to reduce all forms of direct N pollution from agriculture. In this approach, farmland may be converted to other types of land-uses that immobilize N_r and hence reduce N_r cascading at landscape scales. This has large local effects, and can be used for landscape planning, but will also have adverse indirect effects on the agricultural production in the target region. To maintain production, this might require the relocation of intensive agriculture production to other regions or other efficiency improvement measures. This mitigation approach applies, in particular, to low-productivity land, where the opportunities for N_r and other landscape benefits easily outweigh the benefits of keeping the land in agricultural production.

Landscape Measure 10: Introducing trees for afforestation and hedgerows in the landscape

439. Afforestation and the planting of hedgerows or strips of trees around agricultural fields can reduce NO_3– leaching, and has very positive effects on biodiversity, for example, with regard to pollinators, or soil organic C stocks (Montoya and others, 2020; Thomas and Abbott, 2018; Holden and others, 2019; Ford and others, 2019). Preservation of existing woodland and hedgerow features will help avoid potential negative effects. However, the efficacy of hedgerows for N_r retention will depend on: the size and placement of the hedgerows; the amount of NO_3– in soil and groundwater; hydrological flow-paths and timing; and landscape biogeochemical conditions in top- and subsoils (Benhamou and others, 2013; Viaud and others, 2005). There is a risk that increased N_r retention might go along with increased soil emissions of N_2O, although the net GHG balance is expected generally to favour reduced net emissions due to the increase in soil C stocks and perennial plant biomass (cf. Butterbach-Bahl and others, 2011). Hedgerows and forest edges also act as biofilters for nearby sources of NH_3 emissions (Kovář and others, 1996. See also Landscape Measure 12).

Table VI.10
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Landscape Measure 10

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

[a] The effects will depend on configuration in relation to N_r sources and sinks in a landscape. Increasing N sinks between an agricultural area and a stream provides an effective means to mitigate NO_3^- losses. Substantial tree plantings are required to mitigate NH_3 emissions, unless close to point sources (Landscape Measure 12). Recapture of N_r emitted as NH_3 risks increasing soil losses of N_2, NO_x and NO_3^-, unless surplus N_r is used in plant growth.

Landscape measure 11: Set-aside and other unfertilized grassland

440. Unfertilized grasslands (for example, “set-aside” grassland), have the potential to remove NO_3– from lateral soil hydrological water flows and can be used as buffers to protect adjacent natural land or streams. The biomass could be harvested for fodder. Unfertilized grasslands also tend to have increased biodiversity compared to fertilized grasslands. If arable land is converted to non-fertilized grasslands, soil C stocks will increase. The measure is mainly targeted at reducing nitrate leaching when set-aside land is placed adjacent to watercourses. The effectiveness of the measure depends on whether overall N inputs are accordingly reduced in the landscape. With appropriate design, there is also potential to reduce denitrification emissions to N_2, but further assessment is needed to demonstrate this.

Table VI.11

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Landscape Measure 11

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

[a] The effectiveness of the measure is listed here on the assumption that adoption of set-aside implies a proportionate reduction of N inputs to the agricultural landscape. If N inputs are increased to maintain the same levels of agricultural production, then pollution trade-offs may occur (cf. Landscape Measure 10).

4. Mitigating N_r cascading from livestock hot spots

441. Livestock facilities, including housing, manure storage, or feeding and resting places of livestock kept outside are hot spots of environmental N_r pollution due to ammonia volatilization, N_2O emissions and NO_3– leaching. This pattern can be exploited to mitigate the often very high point source losses from livestock facilities. Approaches include: the use of shelterbelts around large point sources; and smart relocation of livestock facilities and outdoor animals in a landscape; for example, away from sensitive natural areas such as natural conservation areas, streams, etc.

Landscape Measure 12: Shelterbelts around large point sources

442. Shelterbelts, such as woodland strips or set-aside land, can help to mitigate landscape N_r dispersion from emission hot spots, such as manure storage areas or animal housing facilities. This relies on the function of trees and hedges as biofilters for NH_3, while also promoting dispersion, which reduces local concentrations (Theobald and others, 2001; Bealey and others, 2014). The approach also favours immobilization of N_r into plant biomass and soil organic N stocks (Valkama and others, 2019). Shelterbelts have been shown to significantly promote air NH_3 dispersion and recapture, while at the same time increasing soil C and N stocks, biodiversity etc. (Haddaway and others, 2018). Thus, shelterbelts can also reduce NO_3– leaching losses due to plant N_r uptake, and/or immobilization in soil organic N stocks. However, N_r immobilization of NH_3 and NO_3– may increase soil N_2O emissions, although, given the observed increases in soil organic C stocks, the net GHG balance is likely to remain positive. This measure differs from Landscape Measure 10 in its function and effect. The focus here is on actions adjacent to point sources, where biodiversity may be adversely affected due to recapture of high ambient levels of N_r, which must be considered as part of the costs of this measure.

443. In the case of ammonia mitigation using trees, studies have shown that the architecture, placement and area of trees is critical to the success of the measure (for example, Dragosits and others, 2006; Bealey and others, 2014). For example, a substantial body of trees is needed to allow significant recapture, as contrasted with simply an increase in dispersion. Studies have shown increased N2O and NOx emissions from woodland soils in the vicinity of high NH3 emissions from poultry farming, pointing to a trade-off (Skiba and others, 2006). Appropriate design of tree planting (for example, fast-growth species with high N uptake) may maximize the net benefits and minimize the trade-offs.

444. Given the trade-offs associated with use of shelterbelts and other woodlands as buffers to increase landscape resilience to the effects of nitrogen, it is important to recognize that the approach is not suitable in all contexts. For example:

(a) It is unlikely to be considered appropriate to use a woodland that is prioritized for nature conservation of oligotrophic plant species as a buffer for nitrogen pollution (for example, a site designated under the European Union Habitats Directive), since this would be expected to result in adverse effects on the protected habitat itself;

(b) It is more likely to be considered appropriate to plant a woodland on former agricultural land with the specific purpose of increasing buffering capacity and landscape resilience. Such a planted structure can be designed to help protect priority- designated natural habitats.

Table VI.12
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Landscape Measure 12

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

[a] The effects will depend on configuration in relation to N_r sources and sinks in a landscape. Recapture of N_r emitted as NH_3 from livestock farms by trees risks increasing soil losses of N_2, NO_x and NO_3^-, unless use of fast-growing trees ensures all surplus N_r is taken up by the trees.

Landscape Measure 13: Environmentally smart placement of livestock facilities and outdoor animals

445. Livestock facilities, feeding and resting places of outdoor animals can be important point sources of NH_3 and NO_3–. Thus, such facilities should, as far as possible, be placed far from sensitive terrestrial habitats or water bodies (Panagopoulos and others, 2013). This can significantly reduce local N_r problems, but might require the relocation or even the closure of existing facilities. The approach is most commonly used as part of planning procedures for new developments for proposals to expand existing farms. In particular, where legal requirements apply to protect natural areas (such as the Natura 2000 sites in the European Union), avoiding intensive farm developments in the near vicinity may be one of the smartest approaches to avoid adverse effects on priority habitats. Simple online tools, such as the Simple Calculation of Atmospheric Impact Limits model,[34] can be used to support local decision-making (Theobald and others, 2009).

Table VI.13
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Landscape Measure 13

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

5. Smart landscape farming

446. There is often a large potential to optimize the use of the natural resources at the landscape scale. This would deliver a better use efficiency of the nitrogen input (with a resulting general reduction in various types of losses), and a (geographically targeted) lower loss of N to the environment, especially where it has the highest vulnerability to particular types of N compounds.

Landscape Measure 14: Digital planning of land-use on basis of a suitability assessment

447. Land-use and farm planning based on digital 3D precision maps of soil N_r retention can help to optimize fertilizer use and reduce N leaching and other losses. For example, clay and carbon-rich soils have a higher N_r retention capacity than sandy and carbon-poor soils, which may be used to inform fertilizer application rates.

448. In the same way, digital 2D precision maps of subsurface N_r retention can also inform the optimization of fertilizer use, minimizing the impact on groundwater and/or surface

[34] See www.scail.ceh.ac.uk/.

waters (Højbjerg and others, 2015). In addition, the reduction of NH_3 emissions from field operations (for example, slurry spreading) can be spatially and temporally targeted, thus increasing N_r use efficiency through space and time. Optimization of land-use and land management (for example, placement of cropping areas and crop rotations in a landscape, introduction of shelterbelts or wetlands, etc.) can help to reduce N_r cascading. In this way, it helps to improve nutrient retention at landscape scale, improve water quality in surface and groundwaters and reduce gaseous N_r losses. However, land-use optimization does require an understanding of landscape fluxes. It typically needs to be supported through detailed modelling, which depends on a sound understanding of soils, groundwater and surface water flows, gaseous transfers through the soil/plant/atmosphere continuum, subsurface geological and geochemical characterization, and consideration of economic constraints (Nguyen and others, 2019; Todman and others, 2019).

Table VI.14
Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Landscape Measure 14

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

[a] Further evidence is needed to demonstrate performance.

Landscape Measure 15: Towards mixed farming

449. Mixed farming combines livestock and cropping at farm and landscape scales. It provides opportunities to connect nitrogen inputs and surpluses, with the aim of reducing overall levels of nitrogen pollution and of increasing landscape-scale nitrogen use efficiency. The opposite can be illustrated by the situation where arable farming areas export grain to livestock farming areas, leading to excess manure in the livestock areas that cannot be used locally. Combining cropping and livestock locally can therefore help reduce pollution (for example, Key Action 10 in Sutton and others, 2013; Wilkins and others, 2008).

450. Significant synergies can be expected if mixed farming opportunities are combined with landscape planning (Landscape Measure 14). The goal is to achieve an optimized distribution of manure and fodder import/production between fields and farms (Asai and others, 2018; Garrett and others, 2017). The planning and development of different types of farming will depend on special regional production opportunities or environmental targets for the local area. For example, crop production associated with high environmental N_r losses could be relocated and replaced by extensive low-input farming, if fields are close to nature protection zones. The reconnection of crop and livestock increases the overall landscape-level nitrogen use efficiency and has been demonstrated to reduce N surplus and water pollution (Garnier and others, 2016).

451. Mixed cropping-livestock systems also provide the opportunity to develop free-range livestock production in combination with crops that mitigate N_r losses (for example, trees, Landscape Measure 12). Conversely, there can also be a role for closed high-tech livestock housing systems, where input and outputs to the landscape compartments can be controlled. Since housed livestock systems are associated with much larger NH_3 emissions, the appropriate technical options to reduce emissions from housing, storage and manure utilization need to be incorporated, including consideration of options for N_r recovery (chapters IV and V).

Table VI.15

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Landscape Measure 15

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

[a] Further evidence is needed to demonstrate performance.

Landscape Measure 16: Landscape-level targeting of technical options to reduce N_r losses

452. In chapters IV and V of the present guidance document, a wide range of technical options have been outlined, including the use of slow-release fertilizers, urea or nitrification inhibitors, acidification of manure, and manure injection in soils. Such measures are also useful at landscape levels, where they are targeted to be used in specific sensitive areas. For instance, more ambitious requirements (for example, requirements for very low-emission animal housing, manure storage and spreading) might be set in the immediate vicinity of wildlife areas, such as local nature reserves or internationally designated sites under the Convention on Wetlands of International Importance especially as Waterfowl Habitat. Planning the use of technical measures within a landscape context requires an understanding of the different ecological priorities and their local, national and international legislative context. For example, in the European Union, a higher degree of legal protection is accorded to Special Areas of Conservation under the European Union Habitats Directive (requiring a precautionary approach), than may be required for a locally designated reserve (for example, where a balance of economic and environmental objectives may apply).

453. Analysis at the landscape scale can also allow for a more nuanced analysis of the potential trade-offs and synergies between emissions abatement and effects mitigation of different N compounds. For example, manure injection in soils or acidification of slurry can significantly reduce NH_3 volatilization, thus leaving more nitrogen in the soil, which can increase the risk of NO_3– leaching and N_2O, NO_x and N_2 emissions. Conversely, use of these measures may similarly increase plant nitrogen uptake efficiency, enabling a corresponding reduction of fresh N_r inputs from fertilizers and biological nitrogen fixation. In this way, nitrogen use efficiency may be increased and N_r losses decreased when considered at the level of the landscape as a whole. Landscape application of technical measures allows these interactions to be considered (Theobald and others, 2004); for example, reducing NH_3 emissions will lead to less N deposition to forest and other nature areas (Dragosits and others, 2006), which, in turn, can be expected to reduce indirect NO_x and N_2O emissions from these ecosystems (Cellier and others, 2011).

Table VI.16

Summary for each form of N loss of the UNECE category for effectiveness/practicality of implementation and magnitude of effect of Landscape Measure 16

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

[a] Less evidence is available for the benefits on NO_x and N_2, though corresponding effects to N_2O can be expected.

Table VI.17
Summary of land-use and landscape management measures and impacts on nitrogen losses

Practice	*Effect*						*Principle*
	NH_3	N_2O	NO_x	NO_3^-	N_2	Overall	
Measures specific to crops and crop rotations:							
Landscape Measure 1: Increasing land cover with perennial crops	3 ~	2 ↓↑	3 ?	1 ↓↓	3 ↓↑	1 ↓	Permanent vegetation cover, highly productive, rapid immobilization of applied N_r in soil organic matter and plant biomass.
Landscape Measure 2: Introducing catch crops	3 ~	2 ↓↑	2 ↓↑	1 ↓	3 ~?	1 ↓	Fertilizer and manure applications should be adjusted to account for the N retained. N_2O and NO_x emissions may increase if catch crop is incorporated into the soil.
Landscape Measure 3: Including N_2-fixing crops in crop rotations	2 ~↓	2 (3) ↓(↑)	3 (3) ↓(↑)?	2 (3) ↓(↑)	3 (3) ~?	2 (3) ↓(?)	Reduce mineral N_r use, organic N mineralization better in-line with plant N demand (Values in brackets reflect the effect of increasing soil N stocks).
Landscape Measure 4: Introducing agroforestry	1 ↓	3 ~↑	3 ~↑	1 ↓↑	3 ~3	1 ↓	Combination of annual and perennial crops, non-competitive exploration of rooting zone, increased N removal per area.
Measures specific to management of riparian areas and waters:							
Landscape Measure 5: Constructed wetlands for stimulating N_r removal	3 (3) ~?	3 (3) ↑?(↑)	3 (3) ~?	1 ↓↓(~)	3 (3) ↑(↑↑)	3 (3) ↑ (↑↑)	Stimulation of N_r removal via denitrification (Values in brackets compare with a reference system of advanced water processing with nutrient recovery).
Landscape Measure 6: Planting of paludal cultures in riparian areas or constructed wetlands	3 (3) ~ (~?)	1 (3) ↑	1 (3) ↓ (↑)	2 (3) ↓ (↑)	1 (3) ↓ (↑)	2 (3) ↓ (↑)	N_r-fixation in biomass, which can be harvested (Values in brackets compare with a reference system of advanced nutrient processing and recovery).
Landscape Measure 7: Use of organic layers to promote denitrification	3 ~	3 ↑	3 ↑	1 ↑↑	3 ↑↑	3 ↑	
Landscape Measure 8: Drainage management	3 ~	1 ↓*	3 ↓	3 ↑*	2 ↓	2 ~?	Aeration of soils, which hampers denitrification but facilitates N leaching (*Reverse if drains are blocked!).

Practice	*Effect*						*Principle*
	NH_3	N_2O	NO_x	NO_3^-	N_2	Overall	
Landscape Measure 9: Stimulating N_r removal in coastal water	3 ~	3 ~	3 ~	2 ↓	2 ↑	2 ↓?	Activities to recover N_r in harvests; for example, planting of eelgrass, growing of seaweed, cultivating and harvesting mussels.
Afforestation, set-aside and hedgerows as N_r mitigation measures:							
Landscape Measure 10: Introducing trees for afforestation and hedgerows in the landscape	1 ↓	3 ↓↑	3 ↓↑	1 ↓↓	3 ↑	1 ↓↓	Selected cutting, continuous forestry /tree management. Planting on steep slopes.
Landscape Measure 11: Set-aside and other unfertilized grasslands	3 ~	2 ~↓	2 ~↓	1 ↓↓	2-3 ↓	1 ↓↓	Taking land out of production, might include biomass harvesting.
Mitigating N_r cascading from livestock hot spots:							
Landscape Measure 12: Shelterbelts around large point sources	1 ↓	3 ↑	3 ↑	2 ↓↑	3 ~?	2 ↓↑?	Captures ammonia. Disperses the remainder upwards (useful if an N sensitive ecosystem is nearby). Immobilizes N_r in plant biomass.
Landscape Measure 13: Environmental smart placement of livestock facilities and outdoor animals	1 ↓	3 ~	3 ~	1 ↓	3 ~	1 ↓	Locating livestock facilities away from N_r sensitive ecosystems reduces impact.
Smart landscape farming:							
Landscape Measure 14: Digital planning of land-use on basis of a suitability assessment	2 ↓	2 ↓	2 ↓	2 ↓↓	2-3 ↓	2 ↓↓	Fertilization loads depend on soil properties, parent material, crops, etc.; Placement of crops depends on landscape properties.
Landscape Measure 15: Towards mixed farming	2 ↓↓	2 ↓↓	2-3 ↓↓?	2 ↓↓	2-3 ↓↓?	2 ↓↓	Helps move to circular agronomy. Improved distribution of manures and fodder production.
Landscape Measure 16: Landscape-level targeting of technical options to reduce N_r losses	2 ↓↓	2 ↓	3 ↓?	2 ↓↓	3 ↓?	2 ↓	Uses highly effective but high-cost techniques close to sensitive ecosystems.

Note: The summary contained in the table above includes the assessed magnitude of effect for the specific submeasures listed: up ↑ down ↓ or little/no effect indicated by ~, and with double arrows for the largest effects. UNECE categories 1, 2, 3 are estimated. Unless specified, the reference is represented by “no action”.

454. In summary, the reviewed land-use and landscape management measures are effective in reducing the overall N_r pollution, and can help increase the effects of the measures reviewed in chapters IV and V, by targeting these measures in space and/or time. Landscape measures can be very effective in mitigating local effects of NO_3– and NH_3. However, other types of N_r losses and N_r pollution outside of the landscape, must be closely evaluated when implementing end-of-pipe solutions to reach local reduction targets.

H. Priorities for farmers and other practitioners

455. The top land-use and landscape management measures to be implemented in practice can be divided into two groups: those related to a geographically targeted land-use change; and those related to geographically adapted management practices.

456. Some of the top land-use change measures identified during the workshops organized by the European Commission Directorate-General for Environment and the Task Force on Reactive Nitrogen under the Convention on Long-range Transboundary Air Pollution in 2016 and 2019 included:

(a) Set-aside/grassland (with no addition of fertilizers);

(b) Establishment of riparian buffer strips, or biodiversity buffer strips around or within fields (the difference being the proximity to aquatic environment):

(i) Hedgerows and afforestation;

(ii) Changed crop rotation/perennial crops (for example, permanent grasslands);

(iii) Agroforestry;

(iv) Wetlands and watercourse restoration and/or constructed mini-wetlands.

457. In comparison, the suggested management options included geographically targeted implementation of measures such as:

(a) Soil tillage and conservation (for example, no tillage of organic soils);

(b) Drainage measures and controlled drainage;

(c) Grassland management;

(d) Placement of livestock production;

(e) Spatial (re)distribution of manure;

(f) Fertigation and installation of proper irrigation system for dry cultivated areas;

(g) Placement of biogas plants and biorefineries for biomass redistribution.

458. The increased number of farmers turning to practices commonly termed “regenerative agriculture” is recognized, with certain practices having the potential to reduce some N losses, including no-till, organic farming (avoiding manufactured inorganic fertilizers and focusing on biological nitrogen fixation) and activities designed to increase carbon sequestration, etc. Such methods require further assessment to quantify their performance for all forms of N loss.

459. National guidance may be available to consider the effects of such measures. In table VI.2, values from Eriksen and others (2014) are listed for some of the exemplified measures, including budget-economic versus welfare-economic costs (for example, the economic impacts for farming versus the wider economic impact for society). For farmers and other practitioners, the economic costs, and resulting possibilities for compensation for these costs, or payment for ecosystem services provided, will most often be the most important factor for the decision of whether or not to implement the proposed measures. This emphasises the importance of economic cost assessments such as those exemplified in table VI.18, both in relation to the production costs for farmers, and the wider welfare-economic costs relevant to policymakers. Further action is needed on how to monitor the success of measures at a landscape level.

Table VI.18

Examples on generalized effects in the form of reduction in N-leaching from the root zone and the related budget- and welfare-economic costs

Measure	*Comment*	*Annual N-effect (kg N/ha)*	*Budget-economic cost (EUR/kg N)*	*Welfare-economic cost (EUR/kg N)*
Set-aside	On rotational land	50	4–25	5–34
Riparian Buffer Strips	From rotation to permanent grass	37–74	6–12	8–16
Afforestation	On rotational land	50	7–20	9–27
Mini-wetlands	Surface run-off	5–20	3–23	4–31

Note: Examples on generalized effects in the form of reduction in N-leaching from the root zone and the related budget- and welfare-economic costs (for example, the economic impacts for farming versus the wider economic impact for society) according to Eriksen and others (2014). Other N effects in relation to nature and climate, and side effects from phosphorus, pesticides are also listed by these authors, but not shown here.

460. In accordance with the general guiding principles, a recommendation for the implementation of efficient land-use and landscape management practices amongst farmers and other practitioners involves the same steps as for the policymakers (see table VI.17). It is recommended that, in addition to assessing the economic costs, each farm should calculate the environmental benefits at farm or landscape level. Such “green accounts” should itemize estimated effects of the measures implemented and report key data about the measures implemented and their efficacy. These data could be collected in a central database, to provide impact assessments for whole landscapes, watersheds, etc., and their specific targets for N reductions.

461. For example, according to the regulations in some UNECE countries, specific N leaching reduction targets are set for each watershed, based on model results or real measurements. In one system, operating in Denmark, farmers within a watershed can voluntarily choose to take actions (for example, whether to plant catch crops), and get financial incentives to meet targets set for the whole watershed each specific year. The alternative is that the farmers will have an obligatory commitment to plant catch crops, until the overall target is met. A geographically targeted and more cost-efficient regulation is thereby implemented.

I. Summary of conclusions and recommendations

462. Overall recommendations are summarized in box VI.2 below. These recommendations are in line with earlier studies, such as the European Nitrogen Assessment chapter on N flows and fate in rural landscapes (Cellier and others, 2011), and include the following key points and needs for development of new approaches:

(a) The mitigation of N pollution at landscape scale requires consideration of interactions between natural and anthropogenic processes, including farm and other land management;

(b) The complex nature and spatial extent of rural landscapes means that experimental assessment of reactive N flows at this scale is difficult and often incomplete, but should include measurement of N flows in the different compartments of the environment, as well as comprehensive data sets on the environment (soils, hydrology, land-use, etc.) and on farm management.

Box VI.2.

Summarizing principles and recommendations for land-use and landscape management N mitigation based on multi-actor discussion.

Landscape scale N budgeting, which accounts for the main N_r flows, integrates all N_r sources and sinks over space and time, therefore providing the foundations to mobilize a more integrated N assessment to target appropriate measures.

A spatially targeted N budget approach is needed to better manage the N_r resource and operate within N_r limits for a defined area.

N_r budgeting is especially relevant in cases of stable conditions over time (for example, when farming systems are not under transition), and in relation to annual N accounts. In addition, shorter-term and longer-term assessments of N dynamics are important.

Landscape topography and soil properties are important factors controlling the fate of N_r at landscape scales, and the integration of 3D soil and geology maps is important in understanding N_r flows and mitigation options, in particular in relation to N leaching.

Landscape assessment includes evaluation of both sources and sinks, for example, both hot spots for emission and input/reception of N_r in the ecosystems, including effects in sensitive areas and water bodies and effects of atmospheric N_r pollution on terrestrial habitats.

A certain amount of N_r release does not have the same effect at all places in the landscape. This means that landscape measures offer the opportunity to optimize the effects of landscape properties and heterogeneity in relation to N flows and impacts.

The processes for N loss consist of non-linear interactions, are threshold-dependent and are interlinked with acute stressors. Treating these stressors in isolation or in a simplified additive manner may cause pollution swapping and thereby underestimate future N-related risks, including eutrophication, acidification and changes in forests and other terrestrial ecosystems, as well as water systems functions and diversity.

A combination of several N_r mitigation measures is needed to reach multiple sustainable development objectives present in whole landscapes. These need to be ranked in order of importance, as the mitigation of some N flow pathways is more important than others, according to context.

Both the local and global effects of direct N emissions within the landscape, and indirect N emissions induced inside and outside of the landscape, should be included when assessing the impacts of the N mitigation measures.

Landscape-scale measures provide the opportunity for increased retention and sequestration of N in space and time, and thereby the opportunity for increased N harvest and nutrient recovery, optimizing manure redistribution and reducing impact on the aquatic environment, while promoting the bioeconomy.

The operational unit and the related economic benefits and/or trade-offs are important for the effective implementation of landscape scale measures, and vary from farm to farm and from the farm to the landscape scale and beyond (for example, watershed, local and regional scales). Legal frameworks may support optimal implementation.The application of new tools tailored to landscapes is needed to assist the implementation of landscape-scale measures. These can also support strengthening of cultural and natural infrastructures for a more sustainable nitrogen use.

463. Modelling is the preferred tool for investigating the complex relationships between anthropogenic and natural processes at landscape scale. Verification by measurements is also required, and simple measurements such as NO_3– concentrations in streams should be considered. It must be recognized that there is a significant time lag between implementation of a control measure and response in stream-water NO_3– concentrations. However, to date, only the NitroScape model – which was first developed for virtual landscapes (Duretz and others, 2011, under the NitroEurope integrated project) and only recently applied to real landscapes (for example, Franqueville and others, 2018, under the French Escapade project)

– has integrated all the components of landscape scale N flows: farm functioning; short-range atmospheric transfer; and hydrology and ecosystem modelling. Consequently, the further development and testing of such models is highly recommended, together with their integration into new landscape assessment and decision-support tools.

464. In conclusion, both from an environmental and a socioeconomic perspective, it is important to include landscape management and land-use measures in the mitigation of N pollution. The present chapter recommends a two-step guidance procedure for the implementation of N mitigation measures, and lists selected top measures relevant for policymakers, farmers and other practitioners.

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VII. Development of packages of measures for integrated sustainable nitrogen management

A. Introduction

465. The material presented in this guidance document provides the basis for improving understanding of the connections across the nitrogen (N) cycle, together with a menu of options. Reflection on the listed principles (chapter III) can inform national and regional approaches based on understanding the key issues. Together, the descriptions of measures for the different parts (chapters IV–VI) indicate the benefits and limitations of the actions.

466. While consideration of the overall nitrogen flow through the agrifood system is a key element of bringing these parts together, there is also a need to visualize these connections more fully. The present chapter therefore examines selected case studies to illustrate possible "packages of measures". These represent coherent groups of measures according to the locality, farming system and environmental context. The examples may be useful to Governments, agencies, businesses and community groups as they consider how to fit together the different measures and principles.

467. At the heart of the approach is consideration of the N flow in the context of the nitrogen cycle. Nitrogen inputs for fertilizer and feed are directly connected to N outputs in crops and livestock for food and wasteful losses to the environment. This means that decisions by all actors have an effect on system efficiency, amounts of N wasted and levels of pollution. Measures taken earlier in the nitrogen chain therefore need to be followed up by complementary measures later in the chain if the full benefit is to be achieved. For example, measures to reduce NH_3 emissions from animal housing should be matched with actions for manure storage and land application, if earlier savings are not to be lost.

468. Inspection of the different measures listed in chapters IV–VI quickly shows how they are complementary – addressing different parts of the system. This means that it is essential to consider "packages of measures" as part of integrated sustainable nitrogen management, both to realize synergies between measures and to minimize trade-offs.

469. The following examples illustrate how packages of measures are needed:

(a) Ammonia emissions tend to occur quickly (hours-days), so measures that minimize contact of ammonium-rich resources with air (Principle 15) are essential;

(b) Measures that reduce a large nitrogen loss (for example, $NO_3^–$, N_2 and NH_3) leave more N_r in the farming system. It is therefore essential to reduce additional N_r inputs (or increase outputs/storage) if the full benefits of the measures are to be realized in increasing nitrogen use efficiency (NUE) and reducing N losses (Principle 6);

(c) Emissions of N_2O, NO and N_2 to air and leaching of $NO_3^–$ and other N_r compounds to water tend to occur as a result of surplus ammonium and nitrate in soils, where these exceed plant needs. Therefore, reducing these emissions depends on knowing the amount and timing of plant N uptake (Principle 7) in order to avoid soil N surplus;

(d) The different processes controlling oxidized N_r losses (N_2O, NO, $NO_3^–$) versus NH_3 emissions mean that measures for the first group are not necessarily helpful for the second (and vice versa). Measures must therefore be considered together;

(e) According to mass balance, all measures that allow an appropriate reduction in total N_r inputs, while maintaining productivity, will increase system-wide NUE and lead to a reduction in all N_r losses (Principle 7);

(f) Wider land-use and landscape management strategies complement animal and crop abatement strategies by offering the opportunity to increase landscape resilience, mitigating environmental effects by managing temporal and spatial distribution (Principles 11 and 15). This means that land-use/landscape measures are especially relevant to reduced local adverse impacts (for example, effects on nature and water).

470. Further issues of this kind are detailed in chapter III. The case studies here show how this thinking may be applied to design coherent packages of measures. The focus here is on agricultural examples, although the philosophy is relevant for all source sectors.

B. Case studies

Case Study 1: Measures package for an intensively managed dairy farm

471. Intensive dairy production typically includes both housed animals and animals grazing for part of the year. This means that measures will need to consider both systems. In this case study, a broad approach is taken with the objective of the illustrative measures package being to:

(a) Reduce total N losses to maximize N_r retention in the farming system, and reduce denitrification losses to N_2, while offering financial benefit by reducing the need for bought-in manufactured fertilizers;

(b) Reduce, as a priority, NH_3 emissions, given close location to certain protected natural habitats;

(c) Follow good practice to minimize nitrate leaching and avoid N pollution of watercourses according to basic national guidelines;

(d) Reduce N_2O and NO_x emissions, so long as this is consistent with other measures.

472. The context of this case study is a rural country with low vehicular NO_x emissions, but with high tropospheric ozone concentrations, so any reductions in soil NO_x will be considered a significant benefit. The location has a mild climate, where it may be possible to increase the grazing season from that currently implemented. The soils are impermeable, with low risk of NO_3– leaching, but have high risk of surface run-off to vulnerable watercourses. The farm buildings have natural ventilation, with cattle on slatted floors over a slurry pit. There is no possibility of investment to alter significantly the housing design, though targeted modifications may be feasible. The farm is grass-based, with insignificant arable area. Manure is currently surface broadcast on grassland using a traditional vacuum spreader (splash plate).

473. The following issues are worth considering related to grassland N flows:

(a) With impacts of ammonia being relevant, an increase in the grazing season (Field Measure 18) provides an obvious opportunity to reduce NH_3 emissions. However, special measures would be needed to ensure that this does not exacerbate N lateral run-off to nearby watercourses. This could be managed by using landscape features such as wooded buffer zones (Landscape Measure 10);

(b) While the impermeable soil means that nitrate leaching to groundwater may not be a priority in the case study, this soil type is also vulnerable to increased denitrification, wasting N_r resources as N_2 and increasing N_2O emissions;

(c) If winter rainfall is high, poor drainage in the impermeable soils risks "poaching" of the grassland by cattle, where grass is destroyed by trampling and fields become muddy. Such poaching damage reduces plant nutrient uptake and can increase N_2O and N_2. This may be a key limiting factor for extending the grazing season in this case study.

474. With these considerations, a possible package of measures for emissions related to grazing animals in this case study could be:

(a) An increase in the time animals spend grazing (Field Measure 18), for example, by extending the grazing season by one to two weeks at each end, while recognizing the limits to maintain a healthy soil and sward and using appropriate grazing. This can contribute to reducing total NH_3 emissions from the farm;

(b) Ensuring healthy sward development and avoid "poaching" by active herd management through rotational grazing. This minimizes the risk of surplus N not being taken up by plants, helping to reduce N_2O and N_2 losses. It will also help to reduce any nitrate leaching to the extent that this occurs;

(c) Ensuring that there is appropriate fencing to restrict grazing within recommended distances of watercourses (Field Measure 19), and consider use of growing vegetation in buffer areas near streams (Landscape Measure 11). This can contribute to reducing run-off of N_r into streams;

(d) Working with a local research partner to test application of nitrification inhibitors to urine patches (Field Measure 20) (for example, by use of drones or as part of grazing rotation management).

475. The following issues are worth considering in relation to emissions from housing and manure management:

(a) The diet of each animal group during the winter housing period should be reviewed to see if there are opportunities for the total mixed ration to be optimized in relation to protein needs, as minimizing unnecessary excess may offer opportunities to reduce wasteful nitrogen excretion (Dietary Measure 1);

(b) The existing slatted floor system is not well suited to immediate segregation of urine and faeces (Housing Measure 1). With realistically available finance in this case study, substantial redesign of the building is not feasible;

(c) Add-on measures may be feasible if targeted funding can be obtained that does not require major rebuilding of the animal house;

(d) Liquid manure (slurry) is currently stored in an open tank, liable to significant NH_3 emissions.

476. With these considerations in mind, a possible package of measures to reduce N emissions from the animal housing and manure management could consist of:

(a) Targeting the protein content of the housed diet of the cattle to match requirement, for example, 15–16 per cent crude protein for dairy cows on average. Consider phase-feeding according to animal age if cows are block calved or kept in age groups to give even more precision, while ensuring that energy needs are also met. Start regular testing of the forage component of the diet (for example, stored farm silage) as it is used, to help achieve the target crude-protein intake (Dietary Measure 1);

(b) Exploring options for grants for low-emission housing, storage and manure spreading, especially given the priority that the farm is near a protected natural habitat sensitive to ammonia;

(c) Installing an automatic system for washing of animal house floors (on a twice-daily basis) (Housing Measure 3);

(d) Installing a system to acidify slurry in the slurry pit (Housing Measure 7). This system will reduce NH_3 emissions from the housing itself, as well as having further benefits to reduce emissions during manure storage and spreading;

(e) Upgrading the vacuum spreader to include a trailing hose or trailing shoe system (Field Measure 6). This will further reduce NH_3 emissions in addition to the benefit of slurry acidification and also ensure accurate spreading of manure to enabling consistent delivery (and fertilization benefits for crops), while minimizing the spreading of slurry near vulnerable habitats (Landscape Measure 16). Consultation with nature agencies and use of online models (for example, www.scail.ceh.ac.uk) may be needed to agree minimum distances between slurry spreading and sensitive nature areas).

477. The overall package of field and housing measures should be reviewed in relation to local goals for nitrogen saving, emission reduction of different N_r forms and ecosystem protection. Use of an integrated nutrient management plan (Field Measure 1) informed by soil nutrient testing, combined with the low-emission measures identified, will help to reduce bought-in fertilizer inputs to save money and realize the benefit of the emissions reductions (Principle 6). Monitoring of the farm-level N balance may prove a useful indicator to work out how fast to reduce purchased N inputs as part of improving farm level NUE and reducing

N surplus. Further measures may be included if higher ambition is needed (for example, covering of slurry store, installing solid surfaces for animal holding and traffic areas).

Case Study 2: Measures package for an organic dairy farm

478. It is relevant to consider how the preceding case study might be different if the context were an organic dairy farm at the same location. The following general considerations should be noted:

(a) It is assumed that the environmental objectives for sustainable nitrogen management are the same as in the previous case study. The major differences are that manufactured inorganic fertilizers will not be used, nor will strong acids be purchased to acidify slurry (for example, sulphuric acid);

(b) On this organic farm, nitrogen inputs are provided by using clover-rich swards, which generate a sufficiently protein-rich ration for winter feeding of cattle during the winter housing period. Preliminary estimates for this case study show that it is still relatively intensive, with high milk production, although N inputs are 30 per cent lower than in Case Study 1, with half the overall nitrogen surplus, but these estimates need to be checked;

(c) As a livestock farm, production of liquid manure (slurry), emissions of NH_3 from animal housing will still be significant, including from the open manure storage and surface broadcast application of slurry to surrounding grass fields. Ammonia emissions from this organic farm and from the field application still pose a significant risk to adjacent protected natural habitats;

(d) Although no inorganic fertilizers are used, the activities still contribute significantly to N_2O, NO and N_2 emissions, especially following field application of liquid manure. Nitrate and other N_r run-off are similarly a concern;

(e) As there are no bought-in N sources to the farm in this organic system, the farmer is strongly motivated to reduce N losses to maximize the benefit of the limited N resources that are available.

479. All of the measures described in Case Study 1 would be available except for the following:

(a) Acidification of slurry (Housing Measure 7);

(b) (Chemical) nitrification inhibitors during grazing (Field Measure 20).

475. To take account of the fact that some measures are not available in this organic context, the following package of measures may be considered:

(a) Extension of grazing season (Field Measure 18) – as per Case Study 1;

(b) Rotational grazing to avoid poaching – as per Case Study 1;

(c) Avoidance of grazing of sensitive areas near watercourses (Field Measure 19) and identify buffer areas (Landscape Measure 10) – as per Case Study 1;

(d) Working with local research partner to test application of a nitrification inhibitor to urine patches (Field Measure 20) – as per Case Study 1, but testing the use of an organic nitrification inhibitor, such as neem oil;

(e) Testing opportunities to fine-tune diet in relation to protein needs with a target crude protein content and consider the possibility of phase feeding (Dietary Measure 1) – as per Case Study 1;

(f) Exploring options for grants for low-emission housing, storage and manure spreading, given the priority that the farm is near a protected habitat sensitive to ammonia – as per Case Study 1, but opportunity for grants may be greater given the organic farm commitment of Case Study 2;

(g) Installing an automatic system for washing of animal house floors (Housing Measure 3) – as per Case Study 1;

(h) Undertaking work with a research partner to test a biotrickling system for capturing and recovering NH_3 from the slurry pit as an organic N resource (cf. Housing Measures 7 and 15), which reduces emissions from housing and manure storage;

(i) Investigating low-cost options for covering slurry stored outside the animal house. Consider whether natural crusting is feasible (Manure Measure 2) or whether it is possible to store manure with a solid cover (Manure Measure 1);

(j) Upgrading the vacuum spreader to include a trailing shoe system (Field Measure 6) – as per Case Study 1 – but with larger emission reductions than trailing hose and even better suited to grassland. This is especially important because no acidifying agent has been used in this organic farming case study;

(k) Minimizing the spreading of slurry near vulnerable habitats (Landscape Measure 16) – as per Case Study 1.

480. As with Case Study 1, the overall package should be reviewed in relation to local goals for nitrogen saving, emission reduction of different N_r forms and ecosystem protection. Use of an integrated nutrient management plan (Field Measure 1) informed by soil nutrient testing will be especially important to maximize efficient use of the limited available N resources, and to realize the benefit of savings through the emissions reductions (Principle 6). Additional measures may be included if higher ambition is sought (for example: Field Measure 7 – manure injection; Manure Measure 8 – local manure acidification and nitrogen enrichment augmented by wind/solar energy).

Case Study 3: Measures package for production of Mediterranean processing tomato

481. Production of the processing tomato (Lycopersicum esculentum L) is among the most important in the Mediterranean region (four Mediterranean countries are among the top 10 producers globally). It is a perennial crop, grown annually by transplanting seedlings at the beginning of spring and growing until the end of summer. This results in a superficial and widely spread root system that requires heavy irrigation and fertilization, especially with nitrogen. The measures package illustrated in this case study consists of a broad approach with the following objectives:

(a) Reduction of total N losses to maximize N_r retention in the cropping system, focusing in particular on the reduction of NO_3^- leaching losses, with soils located in vulnerable drainage basin areas;

(b) Reduction of N losses by surface run-off to vulnerable watercourses, given that irrigation is mostly done by drip systems on the soil surface;

(c) Reduction of soil N_2O and NO_x emissions, which are at risk of being substantial because of water availability and high temperatures. These nitrogen losses are also associated with the heavy tillage needed to prepare soil for tomato transplanting;

(d) Reduction and avoidance of possible increases in NH_3 emissions (if future markets increasingly favour urea-based fertilizer products);

(e) Reduction of the total amount and costs of bought-in fertilizer.

482. The context of tomato production in this case study is rural areas, where traffic is almost entirely restricted to agricultural vehicles. There are few NO_x emissions from traffic sources in the case study area. This means that reductions in soil NO_x will be considered a significant benefit for air quality. Manure is usually not currently used in this production system, which focuses on N and other nutrient inputs from manufactured inorganic fertilizers. Currently, the fertilizer formulations used in the case study are based on ammonium nitrate, augmented by other nutrients. Non-urea composite fertilizers are the most commonly used for basal dressing. This is followed by the application of diverse soluble compounds in fertigation, including urea solutions in the fertigation. The following issues should be considered in relation to N flows associated with production of processing tomato:

(a) The greatest risk of N loss relates to nitrate leaching to groundwater, due to the heavy irrigation demand for this crop in the Mediterranean climate. As irrigation is mostly done on the soil surface according to current practice, there is also potential for losses by run-off. An appropriate irrigation system and water management are necessary to ensure that irrigation does not exacerbate N leaching or surface run-off;

(b) The soil types are conducive to nitrate leaching to groundwater, with the farms of this case study located in vulnerable areas, which makes this loss a priority;

(c) Processing tomato is highly demanding for N fertilization, which results in farmers often applying more N fertilizer than is needed by the crop. Besides basal dressing with N and other nutrients, tomato fields are already "fertigated" (for example, fertilizer addition to irrigation water, Field Measure 16). The amounts of N added by fertigation are currently varied according to the crop-growth cycle, but lack of calibration according to the actual performance of crops increases the risk of N loss, with farmers typically using more N than is needed as part of their risk management (for example, in case of unfavourable weather or nitrogen losses);

(d) Soil preparation for tomato cropping before seedling transplantation is substantial and involves deep tillage and several machine transits. This increases N emission as N_2O and NO_x from soil, as well as fuel combustion from agricultural machinery. Increased mineralization of soil organic matter (SOM) from tillage increases NH_3 emissions in variable amounts, though the exact amounts lost are not well known. Significant losses of N through denitrification to N_2 are expected but are not currently well-quantified.

483. With these considerations, a possible package of measures for emissions related to production of processing tomato in the field could consist of:

(a) Installation of more accurate irrigation systems compatible with the crop management. These can contribute to reducing total N losses from the field, including leaching and surface run-off (Principle 16);

(b) Adoption of better-controlled systems for water management (Principle 20). This also maximizes tomato growth and production, increasing plant uptake of N, which then helps to reduce total N losses (especially N leaching);

(c) Recognizing the different watering needs of tomato plants over the growing cycle according to the actual conditions as they develop. This requires variable irrigation flow and N addition by fertigation to match crop needs, based on updatable calculation of crop needs. This can also lead to water savings, as well as savings in N and other nutrient inputs. This measure may be supported by computer estimates, updated in real time based on meteorological data and monitoring of crop-growth indicators;

(d) Ensuring that there is appropriate soil coverage with impervious sheeting to reduce evapotranspiration water losses. This can contribute to reducing the irrigation flow needed and thus losses of N_r into surface water and groundwater bodies. When using black sheeting, weed growth will be reduced to minimum, which will also help avoid pesticide use. Consideration should be given to plastic reuse and recycling;

(e) More carefully fine-tuning the amounts of N added during basal fertilization and fertigation, avoiding overapplication of nutrients (including N), as informed by soil nutrient testing and crop performance indicators (for example, leaf colour sensing). This can significantly reduce nitrate leaching and other N emissions depending on the extent of fertilizer overapplication in current practice (Principle 5; Field Measures 2, 3, 4 and 16). Use of electronic tools to calculate feasible cost-savings by fine-tuning N inputs to match requirements may help mobilize change;

(f) Reducing the intensity of soil tillage for tomato bedding preparation can also contribute to reducing N emissions derived both from fuel combustion and from soil itself. Alternative solutions include planting the seedlings in mulched non-tilled soil, to reduce weed growth, the use of sheeting and the need for tillage;

(g) Including an awareness campaign targeting farmers in the case study area to highlight the risks of unabated urea use for NH_3 emissions. This should raise awareness among farmers of the likely N losses by emission from urea-based fertilizers, the economic value of N losses and the environmental consequences. This awareness can then be used to mobilize adoption of additional measures (for example, inclusion of a urease inhibitor, Field Measure 13).

484. This list of field measures should be considered in relation to local conditions and local goals for nitrogen saving, emission reductions of different N_r forms, human health and ecosystem protection. Using a nutrient management plan supported by soil testing is beneficial to optimization of the use of fertilizers, saving of money and reduction of pollution (Field Measure 1). Further measures may be included if higher ambition is needed to meet agreed goals (for example, actions related to soil preparation prior to seedling transplanting).

C. Considerations for developing packages of measures

485. It is for users of this guidance to develop their own case studies, informed by the principles and measures presented herein. The following is a summary of key points to consider when developing packages of measures for integrated sustainable nitrogen management:

(a) **Consider which are the priority nitrogen threats** being managed in the area/country of concern (for example, air pollution, water pollution, climate change, biodiversity) and whether there are particular local risks (for example, designated sensitive nature areas or water bodies);

(b) **Consider whether there are other priority issues** that need to be considered at the same time concerning element flows (for example, carbon, phosphorus, sulphur) and other threats (for example, water scarcity);

(c) **Consider the level of ambition relevant for the situation**, for example, in relation to local or international commitments to reduce emissions and impacts;

(d) Consider which principles are most applicable for the situation (chapter III) according to the emission sources, local and regional context and priority nitrogen forms;

(e) **Identify relevant measures** needed to address the different nitrogen forms according to context and the relevant issues faced (drawing on chapters IV–VI).

486. Based on these actions, a draft package of measures may be proposed. This should be reviewed to consider what it might achieve for abatement of emissions to air and losses to water of different nitrogen forms. The following questions are relevant concerning each proposed package of measures:

(a) Does the package cover all important **nitrogen forms** according to agreed targets and priorities?;

(b) Are the measures in the package **complementary in achieving the overall goals,** for example, in relation to control of multiple nitrogen forms, and consistent with the principles of overall nitrogen flow?;

(c) What would the **overall outcome of the package** be, in terms of emissions reduction to air and losses to water, and is it sufficiently ambitious to meet agreed goals?;

(d) What would the **overall amount of nitrogen saved** from the measures package be that would otherwise have been wasted to air and water pollution and denitrification to N_2?;

(e) **By how much is wasted nitrogen to the environment reduced** compared with unabated practice? How does it compare with the Colombo Declaration ambition to “halve nitrogen waste” by 2030 (considering the sum of all loss pathways of N_r and N_2 emission)?;[35]

(f) What are the **initial implementation and running costs** of the package of measures, and what is the potential for reducing these costs?;

(g) What are the **initial and running benefits** of the package of measures, including monetary value of nitrogen saved in moving towards a circular economy for nitrogen?;

[35] See https://papersmart.unon.org/resolution/sustainable-nitrogen-management.

(h) What are the **wider societal benefits** of the package of measures, including valuation of the multiple benefits to environment, economy, health and well-being in the wider context of sustainability?;

(i) What is the **relationship to the Sustainable Development Goals**? How many of the Goals does the measures package help achieve and in what way?

487. As illustrated in chapter VI, multi-actor review of proposed packages of measures can serve to fine-tune the approach, building consensus on the way forward, including the need to highlight opportunities (for example, cost savings, environmental improvement, sustainability of resources) and discuss potential barriers (for example, implementation costs, need for harmonization, regulatory tools and opportunity for investment to catalyse action).

488. The above shortlist does not address all issues. Rather, it is intended to help support countries by illustrating how the different principles and measures described in this guidance document can be fitted together. The next step is for countries, regions and local communities to start considering their own packages of measures.

489. It is anticipated that feedback will be gathered through activities under the Air Convention and in partnership with other international processes, especially through the developing Inter-convention Nitrogen Coordination Mechanism (INCOM). This feedback will be essential as guidance is further developed for other United Nations regions within the context of the International Nitrogen Management System (INMS), as well as to evaluate progress in relation to achieving the Sustainable Development Goals.

D. Further guidance

The following sources of information can provide further guidance:

Ammonia: Options for Ammonia Abatement: Guidance from the UNECE Task Force on Reactive Nitrogen. Available at www.clrtap-tfrn.org/content/options-ammonia-abatement-guidance-unece-task-force-reactive-nitrogen.

Ammonia: United Nations Economic Commission for Europe Framework Code for Good Agricultural Practice for Reducing Ammonia Emissions. Available at www.unece.org/index.php?id=41358.

Nitrates and nutrient cycles: Recommendations for establishing Action Programmes under Directive (2012) 91/676/EEC concerning the protection of waters against pollution caused by nitrates from agricultural sources. Available at https://ec.europa.eu/environment/water/water-nitrates/studies.html.

Global overview of nutrient management: Our Nutrient World: The challenge to produce more food and energy with less pollution (see especially Chapter 6: Practical options to reduce adverse effects by improving nutrient use). Available at https://wedocs.unep.org/handle/20.500.11822/10747?show=full.

Region-specific leaflets on best practices: "Resource efficiency in Practice – Closing Mineral Cycles". Examples from: Brittany (France) [EN, FR], central Denmark [EN, DK], Lombardy (Italy) [EN, IT], Murcia (Spain) [EN, ES], North-Brabant (Netherlands) [EN, NL], southern and eastern Ireland [EN], Weser-Ems (Germany) [EN, DE], Wielkopolskie (Poland) [EN, PL]. Available at http://ec.europa.eu/environment/water/water-nitrates/index_ en.html including project report: https://ec.europa.eu/environment /water/water-nitrates/pdf/Closing_mineral_cycles_final%20report.pdf (see p. 87 onwards).

Baltic Sea Action Plan: Helsinki Commission for Baltic Marine Environment Protection, HELCOM, Available at http://helcom.fi/baltic-sea-action-plan. See pp. 86–96 for agricultural measures.

European Union River Basin Management Plans: including recommendations, Available at https://ec.europa.eu/environment/water/water-framework/impl_reports.htm.

Climate change: Mainstreaming climate change into rural development policy post 2013: Final report European Commission 2014. Available at http://ecologic.eu/sites/files/publication/2015/mainstreaming_climatechange_rdps_post2013_final.pdf) (see table 3 therein for list of measures).

Nitrogen use efficiency: European Union Nitrogen Expert Panel (2015). Nitrogen Use Efficiency (NUE) - an Indicator for the Utilization of Nitrogen in Agriculture and Food Systems. Wageningen University, Netherlands. Available at www.eunep.com/reports/.

Nitrogen use efficiency: European Union Nitrogen Expert Panel (2016). Nitrogen Use Efficiency (NUE) - Guidance Document for Assessing NUE at Farm Level. Available at www.eunep.com/reports/.

National fertilizer recommendations (for example, UK RB209, available at https://ahdb.org.uk/nutrient-management-guide-rb209.

National codes of good agricultural practice: including national ammonia codes of good agricultural practice, as required for signatories to the Gothenburg Protocol.

E. Glossary of key terms[36]

Abatement – strategies or methods to reduce nitrogen losses to the environment, and thereby reduce the direct and indirect effects.

Afforestation – establishment of a forest or stand of trees in an area where there was no previous tree cover.

Agroforestry – cultivation and use of trees and shrubs with crops and livestock in agricultural systems.

Ammonia stripping – physicochemical process used to remove ammonia from sewage, slurry, wastewaters, etc.

Anaerobic digestion – series of biological processes in which microorganisms break down biodegradable material in the absence of oxygen.

Anthropogenic processes – processes derived from human activities, as opposed to those occurring in natural environments without human influence.

Biobased fertilizer – naturally occurring substances rich in nutrients, such as manure, urine, bird guano, compost.

Biochar – charcoal-like by-product of the process of pyrolysis, or the anaerobic thermal decomposition of organic materials.

Biofilters – a filter bed in which exhaust air or liquid is subjected to the action of microorganisms that assist in its decomposition.

Biological nitrogen fixation – a process in which N_2 from the atmosphere is converted into NH_3 and other N_r forms mediated by specialist bacteria.

Biotrickling filters – a combination of a biofilter and a bioscrubber. They work in a similar manner to biofilters, except that an aqueous phase is trickled over an inert packing. The trickling solution contains essential inorganic nutrients that are usually recycled.

Carbon sequestration – the capture and removal of carbon dioxide from the atmosphere and its storage in an alternative carbon-related reservoir; for example, soil organic matter, charcoal, tree growth.

Catch crop – fast-growing crop that is grown between successive plantings of a main crop, and helps to reduce N losses during fallow.

Circular economy – an economic system aimed at reusing and recycling resources (hence “circularity”).

Co-benefit – a coincidental benefit that arises for a secondary issue as a result of addressing a primary issue (for example, employing a technique to mitigate pollution which is also more cost effective).

Companion crop – planting of different crops in proximity for a number of different reasons, including pest control.

Compost – material resulting from the process of composting, an aerobic method of decomposing organic solid wastes.

Constructed wetlands – treatment systems that use natural processes involving wetland vegetation, soils and their associated microbial communities to treat wastewater.

Crop rotations – the practice of growing different types of crops in the same area over several growing seasons.

Deep-injection – The application of liquid manure or digestate by placement in deep, vertical slots, typically about 150 mm deep, cut into the soil by specially designed tines.

[36] This glossary draws in part on the *RAMIRAN Glossary of terms on livestock and manure management.* Recycling Agricultural, Municipal and Industrial in Agriculture Network (eds. B. Pain and H. Menzi), 2011.

Deep-litter – an animal housing system, based on the repeated spreading of bedding material in indoor or outdoor contexts.

Denitrification – the reduction of nitrate (NO_3^-) to dinitrogen (N_2). Nitrous oxide (N_2O) may be produced as an intermediary, depending on conditions.

Dietary Measures – measures consisting of changes in the type, amount and quality of animal feed or human food.

Drainage management – practice that allows farmers to have more control over drainage, by using a water control structure drain to bring the drainage outlet to various depths.

Drip irrigation – a type of crop irrigation involving the controlled delivery of water directly to individual plants through a network of tubes or pipes.

Dung – animal faeces.

ECE – Economic Commission for Europe, one of the five regional commissions under the jurisdiction of the United Nations Economic and Social Council: includes Europe, Eastern Europe, the Caucasus, Central Asia and North America.

Ecosystem services – the benefits people obtain from ecosystems. These include: provisioning services, such as food and water; regulating services, such as flood and disease control; cultural services, such as spiritual, recreational and cultural benefits; and supporting services, such as nutrient cycling, that maintain the conditions for life on Earth.

Emissions abatement – technology applied, or measure taken, to reduce emissions and its impacts on the environment.

Enteric methane – methane that is produced in the first stomach (rumen) of ruminants. Ruminants are mammals that acquire nutrients from microbially mediated enteric fermentation of their food, such as cows and sheep.

Eutrophication – the enrichment of the nutrient load in ecosystems (terrestrial and aquatic), especially compounds of nitrogen and/or phosphorus.

***Ex ante* assessment** – evaluation of the potential success of an operation before it occurs.

***Ex post* assessment** – evaluation of an operation after it has occurred.

Exceedance – The amount of pollution above a “critical level” or “critical load”. It may be expressed in different ways, such as accumulated area of exceedance.

Faeces – dung, solid fraction of animal excreta.

Fertigation – addition of water-soluble products into irrigation systems, with the purpose of fertilizing.

Housed livestock – animal breeding systems involving animals being kept in different housing types.

Hydrolysis – chemical decomposition in which a compound is split into other compounds by reacting with water.

Immobilization – the conversion of nutrients in the soil into an inaccessible or immobile state. The opposite process is mineralization, in which decomposition releases nutrients, which are then accessible to plants.

Inorganic fertilizers – manufactured inorganic and organo-mineral fertilizers, often referred to as “synthetic” fertilizers. This includes all mineral N fertilizer types such as ammonium nitrate and ammonium sulphate, and also urea (and urea-based fertilizers).

Integrated – combining or coordinating separate elements to provide a harmonious, interrelated whole process.

Intercropping – farming method that involves planting or growing more than one crop at the same time and on the same piece of land.

Leaching – the washing out of soluble ions and compounds by water draining through soil.

Legumes – a group of plants, many of which are able to extract N_2 from the atmosphere using specialized “nodules” that contain symbiotic nitrogen-fixing bacteria.

Litter – excreta mixed with variable portions of bedding material. The term can also refer to decomposed fallen plant material (for example, leaf litter).

Manure – organic materials used as fertilizer in agriculture. Animal manure is composed of faeces and may contain bedding material and urine (when it may be referred to as “farmyard manure”). “Green manure” is a crop grown with the aim of being incorporated into the soil.

Manure management – collection, storage, treatment and utilization of animal manures in an environmentally sustainable manner.

Manure processing – processes to transform a variety of manure types and sources into value-added products. This includes forming them into pellets.

Manure treatment – a range of different processes that can be applied to manure and may add value. Examples include concentrating nutrients, odour reduction and volume reduction.

Mineralization – the decomposition of organic matter, releasing the nutrients in soluble inorganic forms that are then available to plants (the opposite of “”).

Mini-wetlands – constructed wetlands with biofilters used to reduce nitrogen and phosphorus emissions from field drains to aquatic environments.

Mitigation of nitrogen – reducing the adverse effect of any N_r compound, such as the atmospheric pollutants NH_3 and NO_x, the aquatic pollutant NO_3^-, or the greenhouse gas N_2O.

Mixed farming – type of farming that involves the growing of a variety of crops (for example, annual, multiannual and permanent crops) and livestock breeding.

Multi-actor – group of partners with complementary types of knowledge – scientific, practical and other. They join forces in project activities from beginning to end.

Natura 2000 – a network of core nature conservation sites across the European Union designated under the European Union Habitats Directive and the Birds Directive.

Nitrification – biological oxidation of ammonia to nitrite followed by the oxidation of the nitrite to nitrate.

Nitrification inhibitors – synthetic or natural chemicals used to slow the process of nitrification.

Nitrogen budget – calculation of inputs and outputs of nitrogen across the boundaries of a system defined in time and space.

Nitrogen cascade – sequential transfer of N_r through environmental systems. It results in multiple environmental changes as N_r moves through, or is stored within, each system.

Nitrogen-fixing crops – crops colonized by bacteria in the root system that are able to convert N_2 into a plant-available nitrogen (for example, legumes).

Nitrogen retention – difference between N inputs and N outputs. The term is typically applied to freshwater catchments but can be used in other contexts.

Nutrients – elements present in food and feed that are indispensable for life and health.

Paludal cultures – crops grown in a marshy habitat, predominantly in water-logged conditions.

Perennial crops – crop species that live longer than two years.

Permanent grassland – land used for growing, continuously, forage or fodder.

Pollution swapping – occurs when a mitigation measure introduced to reduce levels of one pollutant results in increased levels of another pollutant.

Ramsar sites – wetland sites designated to be of international importance under the Convention on Wetlands of International Importance especially as Waterfowl Habitat (Ramsar Convention).

Reactive nitrogen – Collectively, any chemical form of nitrogen other than dinitrogen (N_2).

Rhizobia – soil bacteria aiding in the nitrogen fixation in leguminous plants' root nodules.

Riparian buffer strip – a vegetated strip of land between agricultural land and a river or stream. It may be forested, created with the aim of reducing the impact of the adjacent land-use on the water quality of the stream.

Rotational land – agricultural practice of growing a series of different crops on the same land in successive seasons.

Run-off – portion of water on the soil surfaces that reaches the streams with suspended or dissolved material.

Set-aside – the policy of taking land out of production to reduce crop surpluses.

Shallow injection – the application of liquid manure by placement in shallow, vertical slots, typically about 50 mm deep, cut into the soil by a tine or disc.

Sprinkler irrigation – irrigation method to simulate natural rainfall.

Struvite – a compound consisting of magnesium ammonium phosphate. It can be precipitated from liquid slurry and wastewater, forming a solid fraction allowing the nutrients to be recovered.

Toothed scraper – tool with a variable number of teeth used to run over grooved floor of cattle houses, both to obtain a cleaner floor surface and to prevent slipping inside the house.

Trailing hose – a type of band spreader using an array of hoses to spread liquid manure close to the ground, thereby reducing ammonia emissions and odour.

Trailing shoe – a type of band spreader comprising an array of "shoe" units that follow the surface of the soil. The shoe-shaped units part the foliage and place liquid manure in bands on the soil surface, thereby reducing ammonia and odour emission.

Ultrafiltration – water-treatment process through membrane filtration.

Urease – enzyme that catalyses the hydrolysis of urea.

Urease inhibitor – compound used to slow down the hydrolysis rate of urea by reducing enzymatic activity.

Volatilization – transfer of a compound dissolved in water into the gaseous phase. Typically used to describe emission of ammonia into the air from substances containing ammonium.

Welfare-economic cost-benefit analysis – study of the impact on social welfare from the allocation of resources through a cost-benefit and social analysis.

Woodlands – habitat where trees are the dominant plant form.

Yield – amount of agricultural production harvested per unit of land area.

Zeolite – mineral from volcanogenic sedimentary rock having the ability for adsorption and ion exchange.+