Chapter V: Field application of organic and inorganic fertilizers

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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 of manure with air 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 sulfate, 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 sulfate. 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.

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). Note that these are

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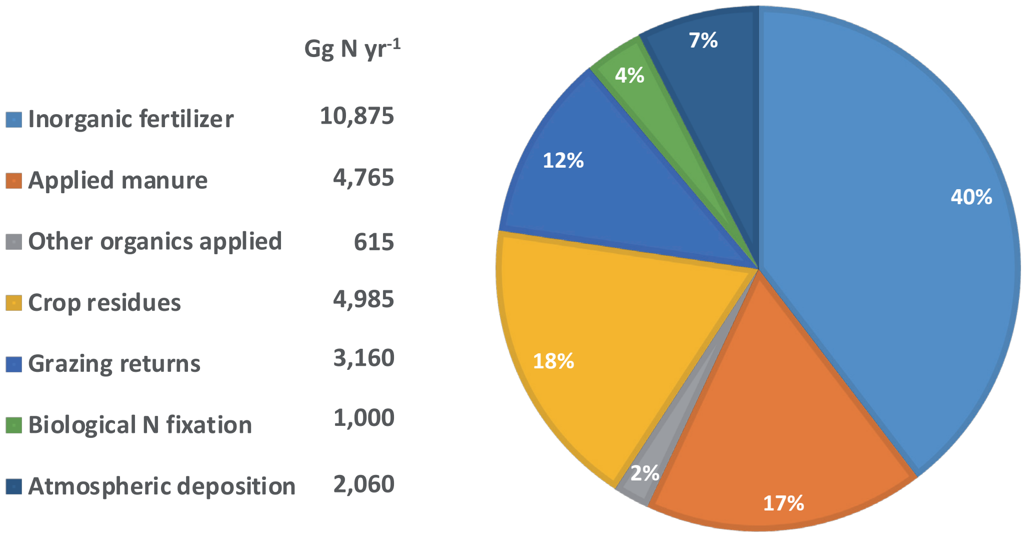
[23] Directive (EU) 2016/2284 of the European Parliament and of the Council of 14 December 2016 on the reduction of national emissions of certain atmospheric pollutants, amending Directive 2003/35/EC and repealing Directive 2001/81/EC, *Official Journal of the European Union*, L 344 (2016), pp. 1–31.

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: https://unfccc.int/process/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories/submissions-of-annual-greenhouse-gas-inventories-for-2017/submissions-of-annual-ghg-inventories-2016), 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.

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 appendix I of this document.

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 sulfate, 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.

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.

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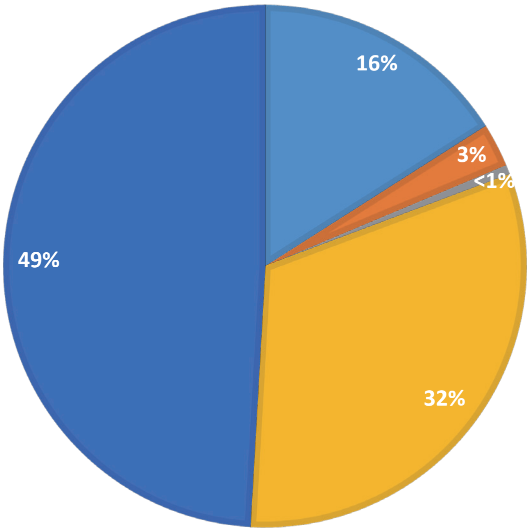
[24] See www.ifastat.org/databases/plant-nutrition.

[25] See http://epp.eurostat.ec.europa.eu/newxtweb.

[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

	Gg N yr^{-1}
🟦 **NH3 emission**	**2,075**
🟧 **N2O emission**	**350**
⬛ **NOx emission**	**75**
🟨 **N2 emission**	**4,100**
🟦 **Leaching and runoff**	**6,365**
Total	**12,965**



Source: Values are derived from the 2016 GHG inventory submission to UNFCCC by the European Union (see: https://unfccc.int/process/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories/submissions-of-annual-greenhouse-gas-inventories-for-2017/submissions-of-annual-ghg-inventories-2016), 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. 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) 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 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).

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[27] See footnote 2.

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 chapter III, figure III.1). Therefore, it is important that application rates be adjusted accordingly.

296. Following the description of each measure below, a table (see tables V.1–V.20) 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.

1. Measures applicable to both inorganic and organic fertilizers, including manures, urine and other organic materials

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[28] See chapter I, paras. 16–20, for a description of the UNECE categories and system for representing the magnitude of effect.

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.

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 the 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.

Image 15: Precision fertiliser application (supporting Field Measure 2). In advanced systems, individual sections across the boom width can be turned off (**B**), so that combination with a global-positioning system (GPS) during the spreading operation can be used to avoid overlap or to calibrate dose according to requirements based on leaf-colour sensing (photographs: © Rothamsted Research).

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 of manure 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 sulfate 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.

2. 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

Image 16: Comparison of slurry spreading with a traditional 'splash plate' spreader (**A**), maximizing ammonia emissions, (photograph: © Shabtai Bittman) with a trailing hose manure spreader (**B**, Field Measure 6) for reducing ammonia emissions, here deployed on-farm in a sensitive mountain landscape. For optimal performance, hose exits should be as low as possible within the canopy, though they may be raised when turning or transporting manure from the farm (photograph: © L`Albeitar, 2021).

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

Image 17: Trailing-hose band-spreader (**A**) (Field Measure 6). By setting the exit pipes immediately above the ground and by correct dosing, the result should achieve narrow bands of slurry on the surface (**B**), which reduce ammonia emissions while aiding infiltration (photographs: © ADAS).

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 for field application

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, chapter IV), 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

Image 18: Comparison of three types of low-emission spreader for liquid manure or 'slurry' (Field Measures 6 and 7). (**A**), 'trailing hose' exits just above the ground; (**B**), 'trailing show' deposits slurry on the soil surface, below the canopy; (**C**), 'injection system inserts manure into the soil through a slot cut by the preceding wheel (photograph: © ADAS).

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).

Image 19: In-field slurry acidification (Field Measure 9) lowers slurry pH to<6 reducing ammonia emissions. Sulphuric acid from the tank at the front of the tractor is added to the slurry at a controlled rate to achieve the desired pH during the spreading operation. North Jutland, 2013 (photograph: © BioCover).

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.

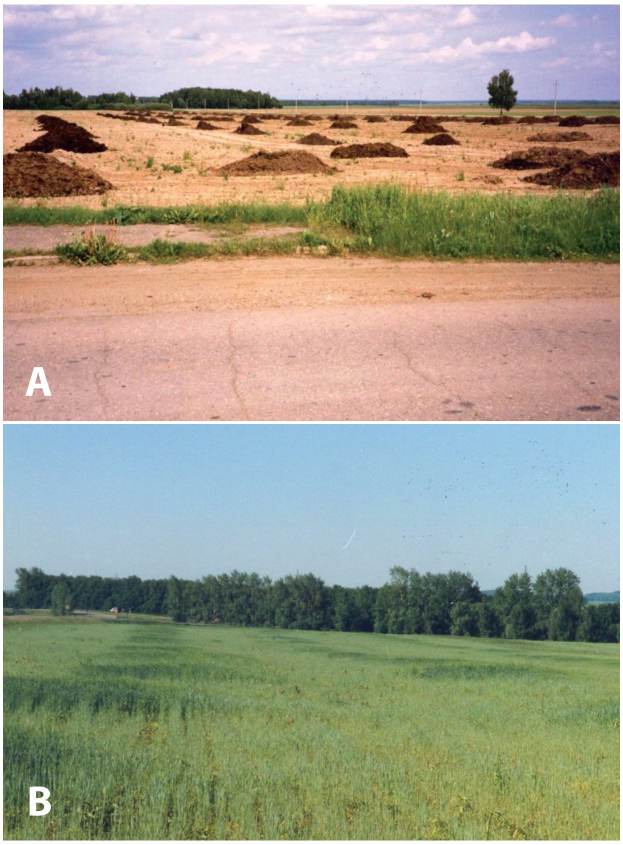

Image 20: Example of bad practice in applying solid manure (**A**), which has been left to stand before spreading and incorporation (Field Measure 11). In addition to ammonia emissions, this example shows the resulting effect on variable crop growth (**B**) (photographs: © Sergei Lukin).

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.

3. 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

Image 21: A spreading machine helps ensure uniform application of solid manure (**A**), resulting in more consistent crop growth. (**B**), Immediate incorporation of solid manure into the soil after spreading (Field Measure 11) minimizes ammonia emissions, while increasing the amount of nitrogen available to the crop (photograph **A**: © Petr Lukhverchik; photograph **B**: © Sergei Lukin).

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	2^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) 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	$1\text{-}2^a$
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.

4. 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

Image 22: Example of fertigation (Field Measure 16) here used for high-bush blueberries together with a sawdust mulch to reduce weeds. Such a slow-release integration of irrigation and nutrient supply can help reduce nitrogen losses (photograph: © Shabtai Bittman).

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.

Image 23: Extending grazing season can substantially reduce ammonia emissions (Field Measure 18). However, care is needed to avoid damaging the grass by over-grazing outside the growing season, which risks increasing N_2O, NO_x NO_3^- and N_2 losses (**A**, Cattle: photograph: © Rothamsted Research; **B**, Sheep: photograph: © António Marques dos Santos, 2019).

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.						

5. 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).

Image 24: An example of bad practice. Grazing of high risk areas should be avoided (Field Measure 19), such as nearby streams, which exacerbates aquatic nitrogen pollution and can increase emissions of N_2O, NO and N_2 (photograph: © Shutterstock, www.shutterstock.com, ID: 1756804670).

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 Nr 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 in Appendix I.

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