Field application of organic and inorganic fertilizers and manure

Draft section for a Guidance Document

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Field application of organic and inorganic fertilizers

1. Introduction and background

Nitrogen (N) is the nutrient recovered in largest quantities from soil by agricultural crops, and the availability of N to crops has a major impact on yields. 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, focus has largely been on controlling individual N loss pathways – e.g. nitrate leaching (Nitrates Directive), ammonia (Gothenburg Protocol, National Emissions Ceilings Directive and Habitats Directive) and nitrous oxide (Kyoto protocol) and guidance given accordingly (e.g. TFRN Options for Ammonia Mitigation Guidance document). It is critical in trying to develop a more joined-up approach to N guidance to have a good understanding of how management practices and targeted mitigation measures might impact on the whole N cycle and not just one specific pathway. This chapter discusses integrated approaches to reducing N losses to air and water from N inputs to agricultural land, highlighting the major inputs, loss pathways and prioritising recommendations for mitigation for policy makers and practitioners.

1.1. Nitrogen inputs to agricultural land

Nitrogen is applied directly to agricultural land as a crop nutrient in the form of manufactured inorganic fertilizers, as livestock manure or as other organic amendments deriving from waste or by-products (e.g. sewage sludge, digestate from anaerobic digestion, composts). For managed livestock manures, an integrated approach should account for improved practices during the storage and/or processing of manures (Chapter 2) potentially resulting in more and/or higher availability of N at land application. Grazed land will receive N in a less managed form through usually 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 are discussed at the landscape scale in Chapter 4. Together, these direct and indirect inputs are estimated to total approximately 27 million tonnes of N per year for the EU28 (Fig. 1), although these are not all new N inputs to land; 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 potentially damaging impacts on the environment and climate. The existing EU legal framework limits N inputs to agricultural land in regions specifically covered by the Nitrates Directive and guidance on practices for reducing the impact of agricultural practices on N and P leaching to water are given (see listed under Section 6 below).
Figure 1. Estimate of N inputs to agricultural soils for EU28 (Gg N yr$^{-1}$) for 2014. Values derived from the 2016 GHG inventory submission to UNFCCC by the European Union (http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/9492.php) with the exception of biological N fixation and atmospheric deposition, which were derived from Leip et al. (2011a) for the year 2002. Note that inputs from crop residues, grazing returns and, to some extent managed animal manure, represent recycling of N within the agricultural system.

Manufactured mineral fertilizers represent the largest category of N inputs to agricultural land in the European Union (Fig. 1). Use of fertilizer N commonly doubles crop yields and fertilizer N is therefore vital to the profitability of crop production in all regions of the EU, and N fertilizers are used by almost all farms other than those committed to ‘organic’ production. There are a number of different formulations and blends of N-containing 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 H$^+$ ions into the soil. These two forms of N will 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$\text{_2}O$, NO and N$\text{_2}$) and leaching. Urea hydrolyses after application 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. Straight N fertilizer products include ammonium nitrate (AN), calcium ammonium nitrate (CAN), urea and urea ammonium nitrate (UAN, a liquid formulation). Anhydrous ammonia is a liquid (gas under pressure) fertilizer that requires special equipment and safety measures, and suitable soil conditions for injection-application. Combinations with other nutrients include ammonium sulphate, diammonium phosphate and potassium nitrate. Ammonium nitrate and CAN represent the major fertilizer forms used in Europe, with urea (either as urea or UAN)
accounting for approximately 20% of total fertilizer N use in Europe (IFA statistics), but this may be increasing in some countries which is a potential concern for emissions.

The major livestock types for which managed manure is applied to land are cattle (dairy and beef), pigs and poultry. Nitrogen will be present 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 storage systems and any subsequent processing prior to land application. For cattle and pigs, manure type can be categorized as either slurry, consisting of mixed urine, faeces and water with relatively little bedding material and with a dry matter content typically in the range 1-10%, or as farm yard manure (FYM) consisting of urine and faeces mixed with large amounts of bedding material (typically straw) having higher dry matter content (>15%). Slurries will typically contain 40-80% of the N in the ammonium form with the remainder as organic N and very little as nitrate. Farm yard manure typically contains a much lower proportion of the N in the ammonium form and may contain a small fraction in the nitrate form. Pig manure will typically have a higher total N and available (inorganic) N content than cattle manure but this depends on water content. For poultry, manure can generally be categorized as litter, deriving from systems where excreta are mixed with bedding (e.g. broiler and turkey houses) or as manure where excreta are collected, generally air-dried, without bedding material (e.g. laying hens). Both have relatively high dry matter contents (>30%) and higher total N contents than cattle or pig manures. Between 30-50% of the total N may be in an inorganic form as uric acid or ammonium. Manures will also vary regarding the content of other nutrients and application rates of all manures may be limited by the concentration of phosphorus (P) rather than N because of their high P:N ratios. The mineralization, availability and utilization of manure N is strongly influenced by the C:N ratio.

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. 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 dependant on soil and environmental factors, whereas N in urine is predominantly in an inorganic form and immediately susceptible to losses via ammonia volatilization, leaching and denitrification (Selbie et al., 2015).

A range of other N-containing organic amendments are applied to agricultural land and 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, and the processing of such organic amendments (e.g. anaerobic digestion) may increase the plant availability of N. These materials may be liquids (e.g. digestates) or solids (e.g. composts), deriving from human wastes, food processing, green wastes, etc., and for the purposes of this background document they will be 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 is likely to be small compared to manure and fertiliser inputs. There may also be barriers to farmer acceptance of some materials because
of concerns regarding contaminants such as trace metals, pathogens, antibiotics and hormones and perhaps nano-particles. Processing these products for reuse is expensive.

1.2. Nitrogen losses from land

![Figure 2. Estimates of N losses from agricultural soils in EU28 (Gg N yr\(^{-1}\)) for the year 2014. Values derived from the 2016 GHG inventory submission to UNFCCC by the European Union (http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/9492.php) with the exception of NO\(_x\) and N\(_2\) emissions which were estimated as a ratio of reported N\(_2\)O emission based on values given by Leip et al. (2011a).](image)

Estimates of N losses from agricultural soils for the EU28 are given in Figure 2. These loss estimates are subject to large uncertainties but imply that 50% or greater of N inputs to agricultural soils in the EU28 (including atmospheric deposition) are subsequently lost to the environment through gaseous emissions, leaching and runoff. Of this, almost half is via leaching and run-off and another third as dinitrogen 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).

Emissions of ammonia, nitrous oxide and particularly NO\(_x\) account for smaller proportions of the total N loss from agricultural soils, but for nitrous oxide and ammonia, agricultural soils represent one of the most significant emission sources and therefore a key target area for interventions to meet national and international emission reduction targets.

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, including density of livestock, soils and climate, as well as socioeconomics and governance systems that regulate N inputs at the farm scale (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 runoff will have a local, catchment and potentially regional effect on water quality depending on flow pathway and N transformation and reduction processes along this pathway. For these reactive N species therefore, a good understanding of source-receptor matrices is required including appropriate spatial and temporal distributions. In contrast, nitrous oxide has a global, rather than local impact as a greenhouse gas. Nitric oxide is an environmental pollutant involved in photochemical reactions in the troposphere and is the main precursor of ground-level ozone in rural areas. For these gases an understanding of the spatial and temporal influences on their emissions is useful, but such influences on dispersion has little relevance for impacts and therefore need not be considered.

2. Guiding principles

Nitrogen is applied to agricultural land to increase crop yield (and quality). Most of the applied N that is captured by the crop will not be subject to losses directly 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 uptake efficiency (N recovered in crop as a proportion of N applied), allowing a reduction in applied N while maintaining crop yield and quality at acceptable social and economic levels. This is captured in the ‘4 Rs’ approach, promoted by the International Fertilizer Association and is the underlying concept of precision fertilizer and manure application: i.e. applying N in the appropriate form, at the most effective time, at the most economical and sustainable rate, and using precision placement near plant roots.

- 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
- Time – the applied N should become readily available at the time that the crop requires it with least risk to the environment
- Rate – the amount of N applied should closely match the amount that will be required by the crop
- Place – the N should be easily accessible by crop roots, without damaging them, soon after application

For managed livestock manures, this should also take into account any improved practices during storage and/or processing that will have reduced N losses at those stages (Chapter 3) and may have transformed N to more available forms. Appropriate adjustment of application rate according to theoretical or measured changes in the material being applied should therefore be made.

It should also be noted that N uptake efficiency will be influenced by other factors affecting crop performance, including the availability of other essential nutrients, water, soil physical
conditions and impacts of any pests and diseases. Even if there is good N management, a lack of attention to any of these other factors may compromise N uptake efficiency, resulting in potentially greater losses of N to the wider environment.

3. Mitigation measures

This section presents briefly the main management practices and mitigation measures that will influence N utilization and losses from N applications to land. A summary of the impacts on the different N losses is given in Table 1.

3.1. Measures for mineral nitrogen fertilizers

3.1.1. Apply at the appropriate rate

Under-application of N fertilizer will result in reduced crop yields, soil carbo and profit and will lead to N mining of the soil. Over-application can also result in reduced crop yields (e.g. due to lodging, fertilizer imbalances, poor harvest index) and profits, and in surplus available soil N increasing the risk of losses to air and water. Applying at a rate to match crop requirement at an economic and sustainable level is therefore desirable. This requires a knowledge of the specific crop requirement in a given environment and of the amount being applied.

Knowledge of crop requirement can generally be gained from regionally-specific fertilizer recommendation systems, using N response curves which account for crop type and typical yield, soil, climatic and previous cropping history. The farmer needs to adjust these rates according to yield potential (affected by soil, crop history and variety and anticipated weather). The application rate is also sensitive to crop and fertilizer prices but must also consider dangers of losses to vulnerable surface and ground water. Targeting optimum economic rates gives more consistent results than optimum yield because the N response curves are flatter. 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 (e.g. Adapt-N for corn in north-eastern USA).

Defining an appropriate application rate requires knowledge of the N content of the fertilizer product, which is generally well known, 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 are used and that these are regularly calibrated (recommended annually) both for total application rate and for evenness of spread. Spreading systems incorporating GPS improve uniformity by avoiding over- or underlapping of spread widths. Systems including GPS and systems based on real-time sensing or previous maps of soil nutrient supply can vary fertilizer rates according to variation in predicted requirement across the field. 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 fertilizer application enables better decisions but also limits application windows, which could be a problem. In-crop testing is not compatible with slow and controlled release fertilizer products since these are applied at or before seeding.

Costs associated with this measure can be minimal (annual calibration of a fertilizer spreader), or modest if investing in GPS or variable rate application systems but will typically justified by increased crop yield and/or quality, or cost-savings associated with lower fertilizer use.

### 3.1.2. Apply at the appropriate time

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 Europe. In most European countries, though, the application timing is regulated by the nitrate vulnerable zones actions plans (Nitrate Directive). Application timing should therefore be matched to crop requirement, which will be influenced by crop type and physiological stage, soil and climatic factors. Good fertilizer recommendations will 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. However, under drought conditions, delayed or split applications may reduce yield, especially for fast growing crops like oilseed rape.

Within the correct 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 application can result in high losses via runoff 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. If irrigation is available, applying a small amount (e.g. 10 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 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 much worse if the urea is applied in bands on the surface of the soil because of the increase in pH.

Specific costs associated with such measures are relatively small and there may actually be cost savings.

### 3.1.3. Replace urea with another fertilizer type
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. 20%, IFA 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 greatly increases pH around the urea fertiliser granules, especially if the urea is concentrated in bands on the soil surface (surface banding) and leads to an enhanced potential for ammonia emissions (typically accounting for 10 – 20% of the applied nitrogen). This is in contrast to fertiliser 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% of the applied N).

There is a risk of increased losses through denitrification and/or leaching and runoff because of the additional available N being retained in the soil through the use of an alternative 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 will not be realized.

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.

### 3.1.4. Urease inhibitors

This measure primarily targets ammonia emissions. Urease inhibitors, such as N-(n-butyl)-thiophosphoric triamide (nBTPT) 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 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 of 70% have been reported through the use of inhibitors. 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.

In some studies, urease inhibitors have also decreased nitrous oxide and nitric oxide emissions, 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 runoff 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 any delays in the availability of N to plant roots is minimal. There is the possibility that urea, unlike ammonium, can be leached under high rain conditions.

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 below)

There are no known environmental implications to the use of urease inhibitors.

Costs associated with this measure are the additional product cost for a urea fertilizer product with urease inhibitor incorporated. Market prices vary, but the additional cost is generally offset (or even exceeded) by the cost-saving through being able to use lower application rates.

3.1.5. Nitrification inhibitors

Nitrification inhibitors (such as DCD, DMPP) are chemicals (benign anti-microbials) that can be incorporated into ammonia- or urea-based fertilizer products which slow the rate of conversion of ammonium to nitrate, so that nitrate becomes available at a rate that is theoretically in better synchrony with crop demand and 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 runoff. Reductions in nitrous oxide emissions of 35-70% are typical, with the efficacy being dependant 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 nitric oxide and dinitrogen may be expected as they arise from the same process pathways, but there are limited data. There have been cases where DCD applied to pastures grazed by dairy cows has been found in the milk, so great caution should be exercised in these situations.

There is some evidence that the use of nitrification inhibitors may increase ammonia emissions, as N is retained in the ammonium form for longer. The use of urea fertilizer products containing double inhibitors to reduce both ammonia and nitrous oxide emissions may be effective, but further studies are required to understand the factors influencing the efficacy of such products to be able to provide recommendations. While some small positive impacts on crop yield have been reported, 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. It may be appropriate therefore 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. Split applications enable use of in-crop N testing for N requirements (precision agriculture) but delay effect products must be applied early so are less compatible with in-crop testing. 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. However, policy tools may be used
to encourage their use where they can target environmental risks such as nitrate leaching and nitrous oxide emissions.

3.1.6. Slow release fertilizers

Sulphur and polymer coated fertilizer products, many of which are urea-based, rely on the gradual breakdown of the polymer coating to release the plant nutrients into the soil over a prolonged period (e.g. 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. The breakdown in the coating may rely on temperature, soil moisture or microbial action, depending on product specification. These products also provide logistical advantages, as fewer fertilizer applications are needed and seedlings show a greater tolerance of fertilizer placement (See section 3.1.8), particularly under reduced tillage.

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 release 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).

The enhancement in N use efficiency is particularly dependent on the release of the fertilizer N in plant-available form in synchrony with the N requirement of the plant. This can be difficult to achieve, depending on which are 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 like maize 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.

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.

3.1.7. Drip fertigation

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, minimising 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 holes to allow the solution to drip out at consistent rates close to each plant. 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 (e.g. pivot, ranger), in which the whole soil profile is wetted, the nutrient solution is just delivered to where plant roots are growing. Water delivery is at a much lower rate (e.g. 2-20 litres per hour per emitter), but at a higher frequency (e.g. every 2-3 days), than other irrigation systems. As with any irrigation system, the concentration of N in the water, which can be high, needs to be considered in establishing the appropriate application rates.

With an adequate water management using this irrigation system, avoiding drainage, nitrate leaching is mitigated. Nitrous oxide is generally also mitigated due to the lower soil moisture content compared with other surface irrigated systems. With subsurface drip fertigation the upper part of the soil is maintained dry. This could enhance nitric oxide emissions through nitrification if using ammonium or urea-based fertigation solutions, but ammonia volatilization is reduced because of the rapid contact of ammonium with the soil colloids.

Drip fertigation is most suited to high-value perennial row crops or to high production annual crops such as maize, because of the relatively high costs involved in set-up and operation. 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.

3.1.8. Precision placement of fertilizers

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’. Placement within the soil reduces direct exposure to the air and the risk of losses by ammonia volatilization. It also enhances the ability of plants to better compete with the soil microbial community for the applied N fertiliser by having better temporal and spatial access to the mineral N. However, under high soil moisture contents, concentrated ‘pockets’ of placed fertilizer nitrogen may increase losses via denitrification. Specialist machines as well as new fertilizer materials (granular, urea supergranules or briquettes, liquids) have been introduced to improve the performance of this approach.

Specialist application equipment is required for the precision placement of fertilizers, which is often done with the planter using an additional injection tools and fertilizer hoppers, with associated capital and running costs but saves on application time since it is done in the seeding operation. These can be offset to some extent by savings in fertilizer use and/or through the use of specialist contractors.

3.1.9. Avoid high risk areas
Certain areas on the farm (or within the landscape – see Chapter 4) can be classified as higher risk in terms of N losses to water, by direct runoff or leaching, or to air through denitrification. This measure is particularly relevant to the application of livestock manures and other organic amendments (Section 3.2). Farm-specific risk maps could be developed, highlighting key areas in which to limit or avoid applications of fertilizers and/or organic amendments.

Risks of direct transfers to vulnerable water bodies includes from field areas directly bordering surface waters including 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. 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.

Field areas that generally remain wetter, such as those associated with depressions or compacted areas are likely to be subject to much higher rates of denitrification, and hence higher losses of N as nitrous oxide, nitric oxide and dinitrogen. 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 by tillage drains; the collected water may be stored as a potential source of irrigation. As discussed further in Chapter 4, filter strips in addition to setbacks and tree-belts can help protect riparian areas, especially those that are used by fish. Runoff of ammonium is highly toxic to fish and P is the primary cause of eutrophication.

3.2. Measures for application of manures and other organic materials

3.2.1. Integrated nutrient management plan (balanced fertilization)

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’), but if direct analyses are unavailable then default ‘book’ values can be assumed. 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. 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 can then be used to determine the amount and timing of additional manufactured fertilizers needed by the crop. Fertilizer use statistics suggest that, in many cases, proper consideration for the value of N in organic amendments will result in a reduction in fertilizer inputs (particularly on arable crops, including maize) compared with current practice and a concomitant reduction in diffuse nutrient pollution. When developing the farm nutrient management plan, consideration should be given to the availability and nutrient content of different organic residues in the local area (within reasonable transport distance) including livestock manures, digestates, composts and other by-products. Availability is also determined
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.

It may not be appropriate to apply organic amendments and mineral fertilizers in direct combination. For example, combined application of cattle slurry and N fertilizer has been shown to increase nitrous oxide emissions through denitrification because of the enhanced available carbon and soil moisture compared with slurry and fertilizer applied at separate timings.

Costs associated with the spreading (and transport up to e.g. 10 km) of the organic amendments will be more than offset by savings in fertilizer use and improved crop growth from inputs of carbon and other nutrients (e.g. S, K, Zn etc.) and in helping to maintain soil pH.

3.2.2. Band spreading and trailing shoe application of livestock slurry

This measure primarily addresses losses via ammonia volatilization, 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 (provided that slurry infiltration into the soil is not delayed by the increased hydraulic loading rate on the slurry bands compared with broadcast spreading, or by dry, hydrophobic soils). In addition, if slurry is placed beneath the crop canopy, the canopy will also provide a physical barrier to further reduce the rate of ammonia loss.

With trailing hose application, slurry is placed in narrow bands via trailing hoses which hang down from a boom and run along or just above the soil surface. However, band spreading also increases the hydraulic loading rate per unit area, which can on some occasions (usually 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 suited to arable crops (e.g. winter wheat, oil seed rape), where wide boom widths enable application from existing tramlines. The window for slurry application is extended later into the spring when crop height would normally exclude conventional surface broadcast slurry application (because of crop damage and contamination risks).

Trailing shoe application 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 closes over this (if the grass is sufficiently long), further protecting from ammonia volatilization. The technique is more effective if some sward regrowth (e.g. one week) is allowed following grazing or silage cutting.

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 if applications are made at agronomically sensible times (cool weather and avoiding excess soil moisture) and rates.
Subsequent mineral N fertilizer applications should be reduced according to the improved N availability in the applied slurry arising from the lower ammonia losses. The effective N:P ratio of the applied manure is improved by the reduction in N losses.

Initial capital cost of the equipment is relatively high, with some ongoing operational costs, although this will be offset (potentially completely) over the lifetime of the machine through fertilizer savings. Local manufacturing of applicators may help reduce costs and support local enterprises. For many farms it may be more cost-effective to use contractors with specialist slurry spreading equipment.

3.2.3. Slurry injection

This measure primarily addresses losses via ammonia volatilization. Placing slurry in narrow surface slots, via shallow injection (c. 5 cm depth) greatly reduces the exposed slurry surface area. Placing slurry deeper into the soil behind cultivation tines, as with deep injection (c. 20-30 cm depth and at least 30 cm apart), or with spade-type tools, eliminates the exposed slurry surface area. Some of the ammonium N in the slurry placed in the soil may also be fixed on to clay particles, further reducing the potential for ammonia emission. Ammonia emission reductions are typically 70% for shallow injection and >90% for deep injection compared with surface broadcast application.

Nitrous oxide emissions (and by association, nitric oxide and dinitrogen emissions) may be increased with this application technique 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. 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 and possibly greater soil compaction due to heavy equipment.

Shallow injection is most suited to grassland, where field slopes and/or stoniness are not limiting, and on arable land prior to crop establishment. Deep injection is most suited to arable land prior to crop establishment; current deep injector designs are generally not suited to application to growing crops, where crop damage can be great although some deep injection is practiced between corn rows on sandy soils. Work rates are slower (particularly for deep injection), with narrower spreading widths, than for conventional surface broadcast application. Under hot and dry conditions injection can result in significant grassland sward damage. Shallow injection (particularly of dilute slurries) on sloping land can result in runoff 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.
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.

3.2.4. **Slurry dilution**

This measure primarily addresses losses via ammonia volatilization. Ammonia losses following surface broadcast slurry application to land are known to be influenced by the slurry dry matter content, with lower losses for lower dry matter slurries because of the more rapid infiltration into the soil. The reduction in ammonia emission will depend on the characteristics of the undiluted slurry and the soil and weather conditions at the time of application, but typically a 1:1 dilution with water will give a 30% reduction in emission.

This technique is particularly suited to systems where slurry can be applied using irrigation/fertigation systems (although not drip fertigation systems because of issues with blockages), as the water addition greatly increases the volume of slurry, and hence cost if being applied by tanker systems. 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. Subsequent mineral N fertilizer applications should account for the improved N availability in the applied slurry arising from the lower ammonia losses.

Costs for tanker spread systems would be prohibitive. 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 also partially through savings in fertilizer costs. Underground piping is used to deliver rain-diluted manure to fields on some large US dairy farms.

3.2.5. **Slurry acidification**

This measure primarily addresses losses via ammonia volatilization. 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. Typically, sulphuric acid is used to lower the pH and acid addition can be made at any of the livestock housing, slurry storage or slurry application stages. When added in the livestock house or prior to slurry storage, acidification has the additional advantage of reducing methane emissions from the stored slurry. The volume of acid required will depend on the existing slurry pH (typically in the range 7-8) and buffering capacity. Systems for slurry acidification in livestock housing can provide automated acid addition to slurry which is circulated through the under-slat storage channels. Emission reduction occurs throughout the livestock housing, slurry storage and application stages, with typically 60% reduction in
ammonia emissions at slurry spreading. Acid addition to storage is typically made just prior to slurry application, using controlled safe working systems, and typically achieves 85% emission reduction following application. Addition during slurry application, using specially designed tankers, tends to be less effective with typical emission reduction of 40-50%. Effects of slurry acidification on nitrous oxide emissions have been less well quantified, although there is some evidence of emission reductions.

Costs associated with the in-storage and 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. Costs for in-house acidification systems are higher but are counteracted by additional benefits including improved in-house air quality which may influence productivity, retention of more slurry N throughout the manure management chain and associated savings in fertilizer costs. There may be an increased requirement to add lime to fields receiving acidified slurries; costs are small but should be included in any assessments. Application rates should be adjusted for the greater N availability to avoid increased leaching. Also, care needs to be taken to avoid injury from the concentrated acids and from possible hydrogen sulphide gas release.

3.2.6. Nitrification inhibitors

While more usually associated with mineral fertilizers, nitrification inhibitors can be added to livestock slurries just prior to application to land with the aim of delaying the conversion of the slurry ammonium content to nitrate, which is more susceptible to losses through denitrification, runoff and leaching. Reducing soil peak nitrate concentrations and prolonging the conversion of ammonium to nitrate can reduce emissions of nitrous oxide and associated nitric oxide and dinitrogen and enhance N uptake efficiency by the plant. The measure is most effective under conditions conducive to high denitrification losses, typically achieving 50% reduction in nitrous oxide emissions, although it could be argued that slurry applications should be avoided under such conditions. However, in many cases the limited capacity for slurry application in association with weather conditions means that slurry cannot always be applied at the optimal time, and in such cases 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 heavily textured/higher organic matter soils. Nitrification inhibitors can help to greatly reduce nitrous oxide emissions from deep-injected manure.

The use of nitrification inhibitors with livestock slurries may increase ammonia emissions, as the plant available N content of the slurry is retained in the ammonium form for longer and therefore subject to volatilization losses, particularly if surface applied. 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.
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.

3.2.7. Rapid soil incorporation

This measure primarily addresses losses via ammonia volatilization. The rapid soil incorporation of applied manure (within the first few hours after application) can reduce N and P losses in runoff and also reduce the exposed surface area of manure from which ammonia volatilization can occur. Ammonia volatilization losses are greatest immediately after manure application, with up to 50% 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. The measure is obviously only applicable to land that is being tilled and to which manure is being applied prior to crop establishment. Emission reductions depend on the time lapse between application and incorporation, 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% may be achieved by ploughing immediately after application, or <20% by tine cultivation after 24 hours. Incorporation is one of the few techniques to reduce ammonia loss from solid (FYM) manure, although this form of manure may be low in ammonia depending on type and handling. The need to reduce risk of P runoff favours the use of incorporation of solid manure where deep injection is not available.

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. Subsequent mineral N fertilizer applications can be reduced according to the improved N availability in the soil, providing that the crop being established following manure incorporation can effectively use that additional soil N.

Costs associated with this measure, assuming the field is to be cultivated, depend on the availability of staff and equipment needed to achieve the rapid incorporation required after manure application. If land cannot be cultivated, farmers may be compelled to carefully compost the their FYM so it can be transported to cultivated land such as potato cropping. Assessment of costs should include cost savings through any reduction in fertilizer use.

3.3. Measures for grazing livestock

3.3.1. Extend the grazing season for cattle

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, primarily because of the rapid infiltration of urine into the soil.
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. However, the risk of leaching and denitrification losses, particularly from urine patches deposited in late summer/autumn, will be increased, although the increase can be mitigated by effective N uptake by the sward over the autumn/winter period. If annual crops are grazed, spring tillage will help disperse the hotspots. Note that hotspots are concentrated where cows gather such as laneways, water troughs, salt licks and shady areas.

This measure may be associated more generally with less intensive practices, including lower density of livestock and lower input/output systems.

This measure will generally be economically beneficial, as there will be less manure management costs. However, there may be an increased requirement for fertilizer if the nutrients excreted directly to pasture by the grazing animals are not used as effectively as the managed manure.

3.3.2. Avoid grazing high risk areas

High risk areas with respect to nitrogen losses from grazing animals include areas with high connectivity to vulnerable surface and/or ground waters, with the risk of direct transfer of excretal nitrogen by runoff or leaching, and areas 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.

Proximity of grazing animals to aquifers contributes to water quality depletion not only with N but with other elements as well, and biological contamination/pollution. Safety distances must be observed.

3.3.3. Nitrification inhibitors

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 reduction in losses of the order of 50%. The risk of increased ammonia emissions from urine patches associated with any delays in nitrification are likely to be minimal because of the rapid infiltration of urine into the soil.

There are still current challenges in developing cost-effective delivery mechanisms for nitrification inhibitors to grazed pastures. 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, with intake through feed supplement or drinking water have also been assessed, but require assurances that there are no residual effects on milk or meat products or impacts on animal health and welfare.
4. Priorities for policy makers

To be discussed at the workshop, but likely to be associated with:

- Reducing and preventing pollution from nutrients; ensuring sustainable use of nutrients, how to achieve balanced fertilisation
- Minimising applications to high risk zones (water and nitrogen deposition sensitive habitats, high risk drainage basins); being aware of region specific requirements and conditions
- Encouragement of recycling of organic residues to agriculture – may include regional planning aspects and adequate quality control of materials to be applied
- Requirement for integrated nutrient planning at the farm, sectoral and regional level including trends to concentration of intensive livestock and crop farms, often near cities
- Costs per unit mitigation

5. Priorities for practitioners

To be discussed at the workshop, but likely to include:

- Farm-scale nutrient management planning
- Reducing and preventing pollution from nutrients; ensuring sustainable use of nutrients, how to achieve balanced fertilisation
- Measures to increase NUE
- Use of fertilizer products incorporating inhibitors
- Use of low emission slurry spreading technologies
- Rapid incorporation of ammonia-rich organic amendments
- Precision nutrient management – especially those allowing lower N application

6. Conclusions, final remarks and research questions

7. Existing guidance

• HELCOM Baltic Sea Action Plan (http://helcom.fi/baltic-sea-action-plan) See p86-96 for agricultural measures
• National fertilizer recommendations (e.g. UK RB209)
• National codes for good agricultural practice

8. References


Leip et al 2011 European Nitrogen Assessment

Table 1. Mitigation options for land application of mineral fertilizers and organic amendments

<table>
<thead>
<tr>
<th>Practice</th>
<th>Leaching/runoff</th>
<th>Ammonia volatilization</th>
<th>Nitrous oxide</th>
<th>Nitric oxide</th>
<th>Dinitrogen</th>
<th>Notes</th>
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</thead>
<tbody>
<tr>
<td><strong>Mineral fertilizers</strong></td>
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<td>Appropriate rate</td>
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<td>Match the application rate to the short to medium-term requirement of the crop; use fertilizer recommendation guidelines or decision support tools</td>
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<tr>
<td>Appropriate timing</td>
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<td>Apply when the crop is actively growing; ideally apply under cool, damp conditions to minimise ammonia volatilization and encourage dissolution/infiltration; avoid applying before heavy rainfall which increases risk of run-off</td>
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<td>Replace urea with AN</td>
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<td>Urea is subject to greater losses by ammonia volatilization than other fertilizer types; application rate should be reduced accordingly otherwise there is a risk of increasing losses via denitrification</td>
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<td>Use urease inhibitor</td>
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<td>~↓</td>
<td>~↓</td>
<td>Efficacy may be influenced by soil and climatic factors</td>
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<tr>
<td>Use nitrification inhibitor</td>
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<td>↓↓</td>
<td>↓↓</td>
<td>↓↓</td>
<td>Efficacy is influenced by soil and climatic factors; can reduce synchrony between crop demand and availability of N</td>
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<td>Use slow release fertilizers</td>
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<td>Efficacy is influenced by soil and climatic factors; can reduce synchrony between crop demand and availability of N</td>
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<td>Drip fertigation</td>
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<td>Combined water and nitrogen use efficiency by precise placement and rate</td>
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<td>Fertilizer placement</td>
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<td>Precision placement of fertilizer into the soil (depth and spacing) with respect to plant roots</td>
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<td>Avoid high risk areas</td>
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<td>Set buffer zone distances, exclusion periods and/or threshold application limits to limit N inputs to high risk areas</td>
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<td>Livestock manures</td>
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<td>Integrated N management plan</td>
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<td>Fully accounting for manure nutrients when calculating mineral fertilizer requirements; use recommendation guidelines and decision support tools</td>
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<td>Apply slurries by band spreading/trailing shoe</td>
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<td>~↑</td>
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<td>~↑</td>
<td>Trailing shoe is most suited to grassland and trailing hose band spreading to growing arable crops; fertilizer application rate should be adjusted appropriately to reduce the risk of increasing losses via denitrification or leaching/runoff</td>
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<td>Apply slurries by injection</td>
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<td>~↑</td>
<td>~↑</td>
<td>Not suited to stony soils or steep fields; beware of creating channels for runoff on sloping land</td>
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<tr>
<td>Slurry dilution for fertigation</td>
<td>~↑</td>
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<td>~↑</td>
<td>Increasing slurry infiltration rate into the soil, minimising ammonia losses</td>
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<td>Slurry acidification</td>
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<td>~↓</td>
<td>~↓</td>
<td>Slurry pH reduction to &lt;6</td>
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<td>Use nitrification inhibitors</td>
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<td>↓↓</td>
<td>Mix with slurry prior to/during application; efficacy is influenced by soil and climatic factors</td>
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<td>Rapid incorporation of manures after application</td>
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<td>Effectiveness depends on the delay in incorporation after application and the incorporation method</td>
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<td>Livestock grazing</td>
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<td>Shorter grazing season</td>
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<td>Removes grazing animals from land at times of greatest risk for soil damage and leaching/denitrification losses; increases the quantity of manure to be managed and associated ammonia emissions</td>
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<td>Activity</td>
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<tr>
<td>Extended grazing season</td>
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<td>Only suitable where soil conditions allow; reduces quantity of livestock manure to be managed</td>
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<td>Avoid grazing high risk areas</td>
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<tr>
<td>Avoiding direct contact between livestock excreta and waterways; minimizing poaching and compaction</td>
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<td>Use nitrification inhibitors</td>
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<td>Reduces leaching and denitrification losses associated with urine patches; delivery mechanism needs consideration</td>
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