Innovative and cost-effective technologies to reduce N losses to water from agriculture in the EU: a catalogue of farm level strategies

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# Table of Contents

Introduction ........................................................................................................................................ 5

How to use the catalogue .................................................................................................................. 6

Strategies to reduce N losses to water from agriculture ................................................................. 8

1. Manure storage and handling solutions ..................................................................................... 8

1.1 Enhance manure storage capacity ............................................................................................ 9

1.2 Stabilization of available N in slurry (composting, bedding livestock on high C materials) .................................................................................................................................. 11

1.3 Site solid manure heaps away from watercourses and field drains ...................................... 13

1.4 Cover solid manure storage and livestock loafing areas ....................................................... 14

1.5 Store solid manure on a concrete pad with a runoff collection system ................................ 16

1.6 Separate solid and liquid fractions of manures ...................................................................... 17

1.7 Anaerobic digestion of slurry .................................................................................................. 19

2. Livestock management ............................................................................................................... 21

2.1 Decrease number of young cattle and reduce cattle turnover rate on dairy farms ................ 22

2.2 Reduce dietary N ..................................................................................................................... 23

2.3 Phase feeding .......................................................................................................................... 24

2.4 Balance dietary nitrogen and carbohydrates to optimize rumen function ............................ 25

3. Pasture management for reduced N losses ................................................................................ 27

3.1 Reduce damage to soil structure by foot traffic (poaching) .................................................. 28

3.2 Livestock exclusion from surface waters ............................................................................... 30

3.3 Increase the clover content in pastures ................................................................................... 31

3.4 Reduce time on pasture .......................................................................................................... 33

3.5 Reseed older, permanent swards ............................................................................................. 35

3.6 Reduce stocking densities ....................................................................................................... 36

3.7 Application of nitrification inhibitors to pastures ................................................................. 37
4. Balanced N application rates ........................................................................................................38

4.1 Determine optimum fertilizer rates using decision support tools and accounting for all sources of available N ........................................................................................................39

4.2 Use in season estimates of crop N status to determine N application rates ..............41

5. BMP for manure use on land ...........................................................................................................43

5.1 Do not apply manure to high-risk areas ....................................................................................44

5.2 Apply manure to land when conditions are optimum.................................................................45

5.3 Accurately estimate manure N release over the growing season............................................47

5.4 Regular maintenance and calibration of manure application equipment to ensure even and accurate application........................................................................................................48

5.5 Test manure for available N content before use.........................................................................49

6. Strategies for irrigated land ................................................................................................................51

6.1 Adjust the quantity of water applied to match crop needs .......................................................52

6.2 Fertigation....................................................................................................................................56

6.3 Install more water use efficient irrigation systems ....................................................................58

7. Efficient N cycling at the field level ...............................................................................................60

7.1 Split fertilizer / manure applications .........................................................................................61

7.2 Cultivate land for crop establishment in spring rather than autumn ...................................62

7.3 Use a catch crop............................................................................................................................63

7.4 Incorporation of high C:N ratio residues to promote immobilization of mineral N.............65

7.5 Include N fixing green manures in the rotation as an alternative to manufactured N fertilizers ........................................................................................................................................67

7.6 Use slow- or controlled-release fertilizers ..............................................................................69

7.7 Rotate N efficient and N inefficient crops ................................................................................71

8. Runoff, drainage and wastewater management ..........................................................................72

8.1 Yardworks for clean and dirty water separation .....................................................................73
8.2 Sedimentation ponds for treatment of surface runoff from fields ...................... 75
8.3 Artificial wetlands for dirty water treatment ......................................................... 77
8.4 Riparian buffer strips ............................................................................................... 79
Introduction

This catalogue is an output from the European Union FP7 Project – N-TOOLBOX (Toolbox of cost-effective strategies for on-farm reductions in N losses to water). The project was developed out of the recognition that while numerous previous EU and national level research projects have identified strategies to reduce N losses to water from agriculture, uptake of many of these strategies has been limited and variable. This project aims to compile and organize effective strategies in an easily accessible format, so that farmers and agricultural advisors can easily select the subset of strategies that is most suited to their particular situation.

It has never been the goal of the N-TOOLBOX project to “re-invent the wheel”. There have been numerous national level and European scale projects that have tackled the challenge of identifying on-farm strategies to reduce pollution from agriculture. This document draws on many of these projects. A full review of EU and national projects that were considered when compiling this catalogue is available as WP 1 Deliverable 1.1 Report on findings from EU and national (UK, Denmark, Spain, The Netherlands) projects relating to nitrate contamination of groundwater and surface water from agricultural systems, and is available on the N-TOOLBOX website (www.ntoolbox.eu). We would like to specifically recognize the valuable information included in the UK’s Department of the Environment, Food and Rural Affairs (Defra) project: An Inventory of Methods to Control Diffuse Water Pollution from Agriculture (DWPA)\(^1\), hereafter referred to as the Defra User Manual. This project followed on from another seminal Defra project: Cost curve of nitrate mitigation options\(^2\). The ongoing work of the Network on Recycling of Agricultural, Municipal and Industrial Residues in Agriculture (www.ramiran.net) has also been a valuable resource.

The scientific background information on many of mitigation measures in this catalogue is summarized in WP 1 Deliverable 1.2 Report on literature findings related to the effectiveness of techniques to reduce N losses to water from agricultural systems, and useful data on the economics of implementing these measures in irrigated systems is included in WP 1 Additional Deliverable Economic Analysis of Farm Management Strategies to Reduce Nitrate Losses, both of which are also available on the N-TOOLBOX website.

There is no magic bullet that will solve the problem of N losses to water from agriculture. Overall reductions in total imports of N to farms (particularly as livestock feed or purchased fertilizer) will be essential if N surpluses on farms, and resultant losses of N by leaching, are to be reduced. Many of the strategies included in this catalogue will result in reductions of N imports to farms. In reality a network of partial solutions is required, that when applied together, can significantly reduce these losses. In many cases adoption of these strategies

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\(^2\) Defra project NT2511. 2004.
will also address other farm management goals, including reducing P and sediment losses to water and reducing greenhouse gas emissions from agriculture.

### How to use the catalogue

Strategies within this catalogue have been organized into 8 categories. The catalogue is designed to be used in conjunction with the N-TOOLBOX Decision Tree. By following the arrows and answering the questions, an appropriate subset of strategies can be identified for a specific situation. Within a category the strategies have been ranked, using the following criteria:

- **Win-win strategies**: These are strategies which are known to reduce N losses to water at minimal cost to the farmer, and also are expected to result in an improved net margin for the farmer.
- **Low-cost strategies**: These are strategies that will reduce N losses to water and have a small cost, so they may reduce net margins slightly.
- **High-cost strategies**: These are strategies that will reduce N losses to water and will require some investment by the farmer, so they will reduce net margins. These options are not likely to be adopted unless there is some compensation available to the farmer.
Figure 1. N-TOOLBOX decision tree for identification of sub-sets of N loss reducing strategies for specific production systems
Strategies to reduce N losses to water from agriculture

1. Manure storage and handling solutions

Animal manures can be a valuable resource, representing a source of major and minor plant nutrients, as well as organic matter. But they can also become a pollution hazard if not managed well. Storing manure where runoff can contaminate surface and groundwater, and poor spreading practices (including timing and placement of manure), can result in major water pollution problems. Manure storage and handling solutions including improved storage conditions and a variety of manure treatment options, can greatly reduce the risk of pollution from animal manures. In general, the strategies in this category require a degree of capital investment by the farmer. The net benefit of the strategy will depend on how well the farmer is already using the manure on the farm. Farms where manure is already highly valued may not gain much further economic benefit; while, farms where manure is not valued may benefit economically by uptake of these strategies along with good nutrient management planning (see 4. Balanced N application rates). Listed below in order of efficacy and cost-effectiveness, are the top manure storage and handling solutions we recommend for livestock producers.

Dairy cows on deep straw bedding at Newcastle University’s Nafferton farm; Image: Nafferton Ecological Farming Group
1.1 Enhance manure storage capacity

The strategy

Require that all farmers with livestock in indoor housing at some point during the year have the capacity to store manure for a length of time that not only corresponds to the restricted periods for manure spreading on land, but ideally exceeds this length of time.

How it works

Many farmers currently have limited capacity to store livestock manure and generally spread their manure as soon as the prohibited period has passed. This means that manure is often not spread at the optimum time for nutrient uptake i.e. soils are often still partially frozen and crop growth is slow or non-existent.

Having the capacity to store manure for longer periods allows farmers greater flexibility to time the application of manure to coincide with periods when crop uptake can be maximized. For example, they can wait until immediately before crop planting to spread the manure, or even wait until the crop is actively growing, to sidedress or topdress with manure. This should improve the efficiency of N use from manures and reduce the risk of losses, not only from leaching, but also from denitrification or volatilization.

It is not always necessary to meet this objective by enlarging existing manure storage capacities. Improvements to water management in the farm yard including diverting wash water to a separate dirty water tank and separating “clean” runoff water (i.e. rainwater from roofs) from dirty runoff water can significantly reduce the size of the slurry tank required to meet storage period criteria.

Simulations using the PLANET Nutrient Management software, developed by ADAS UK and the Scottish Agricultural College, demonstrated that for a typical dairy farm in the Eden Valley of northwest England (with approximately 250 grazing livestock units), the required slurry tank size of 3500 m$^3$ could be reduced to 2000 m$^3$ by installing a separate dirty water tank (400 m$^3$ in size).

Regions and systems of applicability

This approach is applicable across a broad range of regions and systems of livestock production.

Cost

Initial capital costs will be high for this approach, however, ongoing running costs should be minimal. For example, a tank to provide sufficient storage for a dairy farm milking about 180 cattle in northwestern England, would require an initial capital outlay of £60,000 (for a 3500 m$^3$) tank. However, the size of tank required can be significantly reduced (to 2000 m$^3$) if dirty water is diverted to a dirty water storage tank. Additional yardworks to further
separate clean water from dirty water, can further reduce the need for constructed water storage facilities on the farm (see 8.4 Yardworks for clean and dirty water separation).

**Effectiveness**

This is an indirect way of reducing N losses to water from manure. The Manure Nitrogen Evaluation Routine software package (MANNER, ADAS 2000) estimates that a surface application of dairy slurry at a rate of $10 \text{ m}^3/\text{ha}$ on a sandy soil on 1 January provides a total of 30 kg N/ha of which 5 kg/ha is lost due to volatilization and a further 9 kg/ha is lost due to leaching. Postponing this application to 15 March reduces the leaching losses to 0 kg/ha and provides an estimated 11 kg N/ha to the crop.

**Other considerations**

To reduce loss of N by volatilization, the storage of manure and slurry should be covered either by a roof or a layer of straw. Incorporation of manure, e.g. by deep injection for slurry, can completely eliminate the risk of volatilization in the field; however, during the period of excess winter drainage, injection can increase the risk of leaching.
1.2 Stabilization of available N in slurry (composting, bedding livestock on high C materials)

The strategy

Any system of manure handling that converts readily available N to more stable organic N can reduce the risk of N leaching after application. Potential systems include: composting and bedding livestock on high C materials such as straw.

How it works

Composting of solid manure involves storage of the manure in a windrow (see below) with frequent turning to stimulate the activity of microorganisms within the pile. These microorganisms convert readily available forms of N in the manure into more stable organic forms of N. Further benefits include a reduction in the mass of the solid manure, which means lower costs for spreading in the field.

![Image: Nafferton Ecological Farming Group, 2008. Note that the pile is covered to reduce water infiltration and leaching of nutrients from the manure.](image)

Using high C:N ratio materials as livestock bedding (e.g. straw or shavings) also reduces the availability of the inorganic N in manure by: a) providing a negatively charged surface which can bind ammonium ions and prevent them from volatilizing, and b) promoting biological activity within the manure pack in the barn, which is similar to the composting process described above. This solid manure can then be used for further composting before application in the field.

Regions and systems of applicability

Composting and use of high C:N ratio materials for bedding is applicable across a range of operations, however, the uptake of these strategies will be constrained by the availability of straw or shavings (or other high C materials) to use as bedding and/or to mix with manure prior to composting.
Cost

Composting of manure can incur extra costs for the farmer. These costs include:

1. Costs of high C:N material for bedding the animals or mixing with manure when it comes out of the barn. Currently (autumn 2011) straw is expensive to purchase (£55/tonne for wheat straw and £80/tonne for barley straw, in the UK). It can be estimated that for good composting to occur, about 100 tonnes (bales) of straw would be required for every tonne of fresh slurry.
2. Energy costs from turning the compost. It has been estimated that about 0.5 L of diesel fuel are burned every time a tonne of compost is turned.

Effectiveness

Stabilization of inorganic N in manure by composting or mixing with high C:N ratio materials is an indirect approach to reducing the risk of N losses to water. It will only reduce N losses to water if the available N in the compost or manure is accounted for in fertilizer calculations. Over time the organic N content of the soil will increase if composted manure is used. Therefore future fertilizer recommendations will need to take account of the release of available N from organic pools in the soil, to reduce the risk of N losses from excess soil N mineralization.
**1.3 Site solid manure heaps away from watercourses and field drains**

**The strategy**

Manure heaps that are stored outside should be situated where they pose no pollution risk to watercourses and field drains. This may be controlled by regulation e.g. in the UK heaps should be at least 10 m from watercourses or field drains, while in other jurisdictions location may be left to the farmer’s discretion.

**How it works**

Flow of effluent from the manure heaps down through the soil can transport N to field drains. Similarly, effluent from the heap can run over the surface into a watercourse. The risk of N losses in these ways can be reduced if the manure heap is sited away from field drains and watercourses. If the heap is situated on soil, the soil structure in the area immediately surrounding the heap may be damaged by farm machinery when loading and unloading manure. As this will increase the risk of run-off, this will be an additional reason to apply this method.

**Regions and systems of applicability**

This strategy applies mainly to soils that have a heavy texture, since these soils have the potential for runoff and/or movement of nitrates to drains through preferential flow. This method is simple to adopt, applicable across a broad range of regions and to all livestock systems in which solid manure is produced.

**Cost**

This strategy should not entail any costs.

**Effectiveness**

This method is not as effective as strategy 1.5 Store solid manure on a concrete pad with a runoff collection system and will provide little additional benefit if the above-mentioned strategy has already been properly implemented.

This method will not be highly effective in reducing N leaching loss. It is estimated that the reduction in N leaching is 0-1 kg N ha\(^{-1}\) year\(^{-1}\) on a clay loam soil in the fields concerned.

**Other considerations**

On farms in which most fields have a system of closely-spaced drains, it will be challenging to find suitable sites for manure heaps. This method will also reduce the risk of NH\(_4\)-N loss.
1.4 Cover solid manure storage and livestock loafing areas

The strategy

The strategy is to provide a roof to cover solid manure storage areas and areas where livestock gather and where manure accumulates.

How it works

Covering solid manure storage areas will reduce runoff, thereby reducing the volume of dirty water that must be collected and stored before application to the land. It will also improve the quality of the manure since valuable nutrients, especially potassium, will be conserved within the solid manure.

Regions and systems of applicability

This is applicable across the EU, but is particularly important in areas with high levels of rainfall.

Cost

The strategy requires a high level of investment. Incentives are available in some areas; for example, in the UK farmers in Catchment Sensitive Farming priority areas can receive £42/m² for providing roofing for manure storage and livestock gathering areas. They can also receive a range of subsidies for covering slurry storage facilities.

Effectiveness

The strategy has both direct and indirect impacts on water quality. It will directly reduce the volume of dirty water running off manure storage areas. This water should be collected and stored until a suitable time for spreading on the land. The reduction in volume will reduce pressure on the storage facilities and reduce the likelihood that the farmer has to spread the water when crops are not actively growing. Indirectly, there will be benefits to the quality of the manure i.e. it is likely to have a higher nutrient value. This may reduce the need for fertilizer purchase on the farm and increase the overall efficiency of N use on the farm. This should have an indirect effect on the risk of nitrate leaching from the farm.
Other considerations

The England Catchment Sensitive Farming Grant Scheme also provides grants for covering above-ground slurry stores; however, benefits from this would be limited. Based on estimates using the Organic Manures Inventory and Storage module of PLANET (ADAS UK) covering a 36 m$^2$ slurry store would reduce the volume of liquid collected in the store on an annual basis by just 32 m$^3$. Other strategies listed in this catalogue may prove more cost effective for improving slurry storage capacity (see 1.6 Separate solid and liquid fractions of manures and 8.1 Yardworks for clean and dirty water separation).

Further reductions in N losses from solid manure can be made by covering the manure pile itself with an impermeable plastic cover. This can significantly reduce losses of C and N from the pile. Covering the manure heaps blocks air circulation, inhibits OM degradation, and lowers internal heat production as well as the pH, which ultimately reduces the NH$_3$ emission. Further, the formation of nitrate/nitrite is prevented through anaerobic conditions and thus also the possibility of denitrification losses.
1.5 Store solid manure on a concrete pad with a runoff collection system

The strategy

Manure heaps that are stored outside, should be situated on an impermeable concrete pad with a collection system for effluent that drains from the heap (preferably to a dirty water store, rather than to the slurry store). The dirty water should be spread on land at times when the risk of N leaching is low.

How it works

Liquid from the manure heap will seep into the soil and/or flow over the surface if the heap is stored directly on soil. Rainfall will increase the flows coming from the heap. By using a concrete pad with a runoff collection system, the transport of NO$_3^-$ in runoff and via infiltration through the soil is prevented. Runoff accumulated by the collection system can be used as a nutrient source on crops (taking into consideration wastewater N content and timing for optimum N use by the crop). In addition, the concrete pad reduces the area of soil compaction that is caused by farm machinery during loading and unloading of manure.

Regions and systems of applicability

This approach is applicable across a broad range of regions. Applicable to all livestock systems in which solid manure is produced. This method is simple to adopt.

Cost

Costs for this method will vary from one country to the next. The table below indicates estimated costs reported in the Defra project ES0203 User Manual (2007).

Table 1. Estimated costs for construction of concrete manure storage pads in the UK

<table>
<thead>
<tr>
<th>Costs for farm system</th>
<th>Arable</th>
<th>Dairy</th>
<th>Beef</th>
<th>Broilers</th>
<th>Pigs (indoor)</th>
<th>Pigs (outdoor)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital cost/farm</td>
<td>9,800</td>
<td>n/a</td>
<td>6,860</td>
<td>7,830</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Annual cost £/ha</td>
<td>3.10</td>
<td>n/a</td>
<td>6.45</td>
<td>1.65</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Annual cost £/farm</td>
<td>920</td>
<td>n/a</td>
<td>645</td>
<td>720</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Effectiveness

This method will not be highly effective in reducing N leaching loss. It is estimated that the reduction in N leaching is 0-1 kg N ha$^{-1}$ year$^{-1}$ on the fields concerned.

Other considerations

This method will also reduce the risk of NH$_4$-N loss.
1.6 Separate solid and liquid fractions of manures

The strategy

Liquid and solid components of manures are physically separated to produce different fractions with different properties, which can then be handled, stored and used separately. The solid (or thick fraction) contains mainly organic nitrogen (N) and phosphorus (P) and the liquid (or thin) fraction contains mainly ammonium N (NH₄-N; 85-95% of the total N) and potassium (K).

How it works

By producing two fractions of manure (liquid and solid) each component can be used in a targeted way, e.g. the solid component can potentially be used as a soil improver, organic fertilizer or as a component of a compost-based plant-growth medium, potentially replacing peat-based products. The liquid fraction contains low concentrations of nutrients in a readily-available form and can be used in a similar way to mineral fertilizer, or in fertigation systems.

Mechanism of action

Separation of the liquid and solid components of manures can aid in reducing N losses to water from agricultural systems by facilitating more targeted distribution of the nutrients. Nutrient rich fractions can be applied to rapidly growing crops with high N demands, while fractions that are lower in nutrients can be used as soil conditioners. This will allow for improved efficiency of manure nutrients within the farm enterprise.

Simulations using the PLANET Nutrient Management software, developed by ADAS UK and the Scottish Agricultural College, demonstrated that for a typical dairy farm in the Eden Valley of northwest England (with approximately 250 grazing livestock units), introducing slurry separation (as well as yardworks to divert clean water from storage tanks) could reduce the volume of slurry produced annually from 2,507 m³ to 1,980 m³ and would also reduce the quantity of readily available N on the farm from 4,050 kg N yr⁻¹ to 2,570 kg N yr⁻¹. This effect is due to the increased volume of solid manure stored on the farm, in which readily available N would be converted to organic forms of N, which are more stable and less susceptible to losses by leaching or volatilization immediately after field application.

Regions and systems of applicability

This approach is applicable across a broad range of regions. Applicable to all livestock systems in which liquid manure is produced.

Cost

A screwpress for separation of solid and liquid manure fractions costs about £10,000 in the UK with an expected lifespan of 10 years.
Separation of manures may have an economic benefit through reduced costs for handling and transport of the manure, since its weight and volume are reduced by the process.

**Effectiveness**

This is another indirect method of reducing N losses to water from agriculture. It should be considered as part of a holistic approach to dealing with the problem of excess manure, in conjunction with proper use of manure on cropland, balanced N applications and efficient N cycling at the field level.

*Mobile slurry separator at Scottish Agricultural College; Image courtesy Kate Gascoyne*

**Other considerations**

The decreased weight and volume of the products allows for easier handling and a reduction in the quantity of raw manure that needs to be transported over long distances. When using this technique, account should be taken that storage conditions can affect the rate of greenhouse gas emissions from the separated solid fraction. Higher N₂O losses have been observed in the solid and liquid fractions compared with the whole slurry after application to land but this difference has been relatively small.
1.7 Anaerobic digestion of slurry

The strategy

Slurry (liquid manure with 0-10% solids) is digested on-farm in a biogas digester, producing energy (methane gas which can be converted to heat or electricity) and anaerobically digested slurry (digestate). Anaerobic digestion of liquid manures produces a renewable energy stream on the farm, while also reducing the volume of manure for spreading (because of losses of carbon and water during the digestion process). The digestate has a higher N concentration than the original material, with a higher proportion of ammonium-N, and can be used for targeted application to growing crops. It is therefore an indirect strategy to reduce N losses to water from agriculture, through the reduction in manure volume, and the creation of a more concentrated nutrient source that is easier to manage in an environmentally friendly way.

How it works

This strategy turns the manure “problem” on farm, into a resource which can be used for energy generation. It also concentrates the nutrients in the original material making it less energy intensive to move and spread the digestate. This is therefore an ideal approach for indirectly addressing the problem of N losses to water from livestock operations, particularly ILOs.

Regions and systems of applicability

Anaerobic digestion of slurry is appropriate across all regions within Europe, and is mainly constrained by the size of the livestock enterprise where it is appropriate.

Cost

Costs of installation and running for an anaerobic digester will vary depending on the region. As an example, Encraft in the UK (www.encraft.co.uk) provide these estimates: “For an on farm digester with an annual capacity of around 3,000 tonnes per year the capital cost will be between £100,000 – £200,000 with annual running costs of around £2,000. Larger systems with a capacity to handle 10,000 tonnes per year will cost £500,000 to install.”

In Denmark, systems have been set up that operate on a cooperative basis, with several farms bearing the investment costs and operational costs, while also benefiting from the revenue generated through energy sales.

Effectiveness

Anaerobic digestion of slurry to produce methane and digestate, is an indirect method of reducing N losses to water from agriculture. As such, it is not possible to quantify the effects of this method on nitrate leaching or losses to water.
Other considerations

This method has the potential to provide an economic benefit to the farmer through either reducing the need to purchase energy from off the farm, or through generating revenue when electricity produced on farm is sold to the “grid”. This method can also satisfy other environmental objectives including reducing ammonia emissions from manure and offsetting GHG emissions from energy produced by fossil fuels. For these reasons, the promotion of anaerobic digestion as a strategy to manage manure is attractive.

However, it is rare that an anaerobic digester operates with manure as the sole feedstock. For most efficient operation it is usually necessary to mix slurry with plant material (waste vegetable matter, crop residues, or crops grown as feedstock). For this reason, a careful assessment of feedstocks available on farm and in the area is recommended before installation of an anaerobic digestion system on farm.

Anaerobic digester at Cockle Park Farm, Newcastle University; Image courtesy Paul Bilsborrow
2. Livestock management

Livestock farmers face unique challenges when managing nitrogen, since it can arrive on the farm in several forms (feed, fertilizer, imported animals, imported manure, N fixation) and can also leave by many pathways (exported products, losses to the atmosphere, losses to water from manure in the barn or in the fields). In many cases nitrate pollution problems arise when inputs greatly exceed outputs, e.g. on livestock farms where feeds are mainly imported and there is a small land base for manure disposal. As well as managing manures wisely, livestock farmers can reduce the risk of losses of N to water by reducing the inputs of N to the farm, and by improving the efficiency of N flow within the farm system. The strategies listed for this category are knowledge-intensive, rather than capital intensive. This means that they should be relatively inexpensive to implement, and that annual costs should steadily decline as the on-farm management expertise grows. Listed below in order of efficacy and cost-effectiveness, are the top livestock management solutions we recommend to reduce N surpluses on farms.

*Replacement dairy heifers at Newcastle University’s Nafferton Farm; image Nafferton Ecological Farming Group, 2011.*
2.1 Decrease number of young cattle and reduce cattle turnover rate on dairy farms

The strategy

In general, farms with a lower stocking rate will have a lower N surplus; however, the challenge is to lower stocking rates without reducing productivity. This can be achieved if the herd replacement rate is reduced, and cattle stay on the farm longer.

How it works

Younger cattle use nutrients less efficiently. By reducing the turnover rate, the proportion of older cows staying on the farm will be increased, thereby increasing the efficiency of nutrient use. In older cows, a higher proportion of the dietary protein is used for milk protein and less is used for maintenance. For this reason, the N excretion per kg milk is lower in older cows.

Regions and systems of applicability

This approach is applicable across a broad range of regions.

Cost

Increasing the longevity of dairy cows is a management target that makes good economic sense. However, currently the most economic model of dairy production, results in a high turnover of cattle. Therefore there may be an economic trade-off between improved nutrient use efficiency in the cattle, and economic returns.

Effectiveness

As this is an indirect method of reducing N losses to water, it is difficult to estimate effects on N leaching. However, farmgate N balances are an index of the risk of N losses to water.

Other considerations

Currently older cows tend to be culled due to fertility and health problems, and these problems would need to be addressed before this strategy could be implemented.
2.2 Reduce dietary N

The strategy

Supply feed that contains less N (e.g. by reducing the crude protein content of the feed).

How it works

By avoiding excess N in feed as much as possible, the amount of N unused by the animal will be reduced and so also the amount of N excreted. In agriculture, animals are often fed diets with higher than recommended contents of N to avoid a loss in production arising from nutrient deficiency. Surplus N is not utilised by the animal and is excreted in the urine. By feeding the animals with the recommended levels of N, the amounts of N excretion can be reduced without adverse effects on animal performance.

Regions and systems of applicability

This approach is applicable across a broad range of regions and systems of livestock production except those primarily based on extensive grazing.

Cost

The primary cost associated with this strategy will be the knowledge acquisition cost - most likely a fee for diet formulation advice. However, if the advice comes from a feed company, the advice may still be free of charge. Since the diet selected may be lower in protein, this may result in a reduction in feed costs for the farmer.

Effectiveness

Diet modification by formulating diets closer to requirements has been shown to reduce N excretion by 10-15% in chickens and pigs. A reduction of ca. 22% in total N excreted occurred when beef cattle were fed a constant diet of 11.5% instead of 13% crude protein without adverse effects on animal performance.

Other considerations

A lowered crude protein content in feed will not only decrease the amount of N excretion in dairy cattle, it will, in addition, reduce the short-term N availability of manure (as dietary change has more effect on urinary than faecal N excretion), making it less susceptible to leaching and volatilization.

This strategy will reduce the N surplus on the farm; thereby reducing the overall risk of N losses to water. However, good manure management practices as outlined in Section 1. Manure storage and handling solutions, will still need to be in place if this strategy is to prove effective for reducing N losses to water from agriculture.
2.3 Phase feeding

The strategy

Provide diets that are nutritionally optimized for a specific growth or reproductive stage or, in the case of dairy cattle, lactation cycle.

How it works

In phase feeding nutrient levels in the animal’s feed are matched with its nutritional requirements at a given stage of growth or production. This allows for more complete use of the nutrients in the feed for animal production, and less excretion of excess nutrients in the manure. Phase feeding therefore ensures that N and P contents of manures are as low as possible for a given production system, thereby reducing the problem of excess nutrient supply from livestock operations, especially intensive livestock operations (ILOs).

Regions and systems of applicability

This approach is applicable across a broad range of regions and systems of livestock production except those primarily based on extensive grazing.

Cost

The primary cost associated with this strategy will be the knowledge acquisition cost - most likely a fee for diet formulation advice. However, if the advice comes from a feed company, the advice may still be free of charge. In some cases there may be an adverse effect on animal performance which could be reflected in lower revenues to the farm.

Effectiveness

Reductions of N excretion in pigs and chickens of 10% have been reported, without losses in production.

Dietary supplements using synthetic amino acids have been shown to reduce N excretion by 10-27% in broiler chickens, 18-35% in laying hens and 19-62% in pigs

Other considerations

This strategy will reduce the N surplus on the farm; thereby reducing the overall risk of N losses to water. However, good manure management practices as outlined in Section 1. Manure storage and handling solutions will still need to be in place if this strategy is to prove effective for reducing N losses to water from agriculture.
2.4 Balance dietary nitrogen and carbohydrates to optimize rumen function

The strategy

Excess nitrogen, especially in the form of rumen degradable protein and non-protein nitrogen, can increase ammonia levels in the rumen and lead to excessive levels of N excretion in urine. Supplying balanced amounts and types of protein and carbohydrates, can minimize rumen ammonia levels and optimize rumen function.

How it works

Balancing and synchronizing the carbohydrate and protein supply to the rumen will allow maximum conversion of N in the diet into animal protein, and minimize the amount of N excreted. Initially, levels of ammonia in the rumen should be monitored by measuring levels of milk urea nitrogen (MUN), which increases as rumen ammonia increases. High MUN levels suggest excess ruminal ammonia, perhaps due to overfeeding degradable protein and/or not enough fermentable carbohydrate, while low MUN levels indicate low ruminal ammonia levels or insufficient dietary protein. Once the problem has been identified, diets can be modified to improve the balance and supply of protein and carbohydrates to the rumen. For example, access to fresh pasture, which is high in protein and low in non-degradable carbohydrates, can be restricted, and animals fed a low digestibility supplementary feed to reduce levels of rumen ammonia.

Tools

Milk urea nitrogen testing can be done along with standard milk quality testing and is a useful way of monitoring the balance between proteins and carbohydrates in the rumen.

Regions and systems of applicability

This approach is applicable particularly to dairy systems where diets are relatively closely managed and collection of milk for MUN testing is feasible.

Cost

There will be an increase in management input due to the monitoring of rumen function (e.g. through milk testing, or observation of animal behaviour, or analysis of manure quality). The involvement of a nutritional advisor may also result in a cost being incurred. If feeding strategies need to change, costs may be incurred due to acquisition of alternative feeds, or feeding infrastructure (e.g. if animals must be housed for longer periods due to excessively lush pastures).

Effectiveness

Work on commercial dairy farms has shown that manipulation of dietary crude protein levels to better match requirements of cattle is possible and taken together with other
management strategies to increase herd productivity, could reduce herd N excretion by 11% on a per hectare basis.

**Other considerations**

Optimizing rumen function for N use can lead to increases in methane emissions i.e. increasing carbon inputs to the rumen to balance N may lead to increased activity of methanogens in the rumen.

*Organic dairy cattle eating silage at Newcastle University’s Nafferton Farm; image Nafferton Ecological Farming Group.*
3. Pasture management for reduced N losses

Pastures are a “hot-spot” for N leaching on farms with grazing animals. This is largely because animals on pastures tend to congregate in certain areas (e.g. around feeders and water troughs) damaging soil structure and depositing manure which is then susceptible to runoff and leaching. Urine patches in pastures are also a source of leachable N because of the high concentrations of N in these areas. Pasture management strategies focus on eliminating these high risk areas and facilitating more even movement of animals around the pasture and more even distribution of urine and faeces at the same time. Most of the strategies within this category are knowledge-intensive or require a relatively small investment. Listed below in order of efficacy and cost-effectiveness, are the top pasture management strategies we recommend to reduce N losses from these areas of the farm.

Strip grazing cattle at Newcastle University’s Nafferton farm, UK; Image Nafferton Ecological Farming Group
3.1 Reduce damage to soil structure by foot traffic (poaching)

The strategy

Manage livestock to reduce the damage caused by excessive foot traffic in certain areas of the field

How it works

Soil structural damage by foot traffic (poaching) occurs when livestock congregate in certain areas of the pasture, especially when the soil is wet. This can result in soil compaction, reduced water infiltration, and increased runoff. Discouragement of livestock congregation in certain areas of the field can therefore lower this risk. There are a number of methods (tools) to achieve this goal.

Tools

- Move feed and water troughs at regular intervals
- Place livestock drinkers and feeders on hard bases (e.g. option CSF007 in the UK’s Capital Grants Scheme in Catchment Sensitive Farming areas)
- Re-site gateways away from high risk areas
- Reduce stocking densities when soils are wet

Regions and systems of applicability

This strategy is applicable in all regions, but is particularly appropriate in northern regions of Europe where prolonged periods of wet weather can lead to saturated conditions in pastures (especially during the winter).

Poaching of wet land by livestock in the UK; Image: Natural England CSF Capital Grant Scheme Farmer Handbook

Cost

In most cases this strategy will require improved management input from the farmer, but minimal expense. There may be some labour costs associated with the movement of feeders around the field. If gateways are re-sited, this could result in a one-off cost. In many cases subsidies for re-siting gateways may be available (see Section 3.2 Livestock exclusion from surface waters).
Effectiveness

As described in Section 3.2 Livestock exclusion from surface waters, this strategy is primarily aimed at reducing total suspended solids and phosphorus loads in surface water. Nitrate concentrations are only indirectly affected through reductions in total N and ammonium loss. This method will be more effective on more intensively stocked farms.
3.2 Livestock exclusion from surface waters

The strategy
Restrict livestock to access surface waters

How it works
Livestock add N directly into the water when defecating and urinating in it. By restricting their access to watercourses, this can be prevented. In addition, severe damage can be done to stream and river banks when livestock attempt to gain access to the water by poaching and destroying the vegetative cover. This will lead to bank erosion.

Tools
Fence waterways; Provide alternative drinking systems for livestock that rely on surface water; for example, pasture nose pumps which use the cattle’s own energy to pump water (see picture below); Construct bridges for livestock crossing streams

![Cattle nose pump](Image: Natural England CSF Capital Grant Scheme Farmer Handbook)

Regions and systems of applicability
This approach is applicable across a broad range of regions and production systems where grazing takes place. It may be less feasible in areas where extensive grazing occurs.

Cost
Capital costs will be fairly high depending on the size of the area requiring fencing, ongoing running costs will be minimal. Currently environmental stewardship programmes in the UK provide some subsidy for this activity (see Error! Reference source not found.).

Effectiveness
This strategy is primarily aimed at reducing total suspended solids and phosphorus loads in surface water. Nitrate concentrations are only indirectly affected through reductions in total N and ammonium loss. This method will be more effective on more intensively stocked farms.

Other considerations
Alternative sources of drinking water must be provided if livestock use the surface water to drink from.
3.3 Increase the clover content in pastures

The strategy

Incorporate clover into the sward and reduce or eliminate the use of N fertilizer in this area.

How it works

By including clover in a sward and reducing N fertilizer inputs, the protein content of the feed can be maintained. Nitrate leaching is lower from unfertilized grass-clover swards than from mineral-N fertilized swards grazed by either sheep or cattle. Since the N acquisition mechanism in legumes is built into the plant (i.e. in the nodules) there is no need for high levels of inorganic N in the soil, in order for the plant to take up N. This reduces the risk of N leaching from pools of inorganic N.

Regions and systems of applicability

This approach is applicable across a broad range of regions and production systems where grazing on intensively managed grassland takes place.

Cost

This strategy will result in a reduction in N fertilizer costs for the farmer. Typically, in the UK a dairy farmer may apply up to 350 kg N ha\(^{-1}\) yr\(^{-1}\) to a high yielding grass sward, which equates to a cost of £350 ha\(^{-1}\) per year. Switching to a grass/clover mixture will eliminate this cost; however, total dry matter yields will also be reduced. Results of a Newcastle
University long-term trial showed that plots seeded to grass/clover yielded on average 17.9 t dry matter ha\(^{-1}\) (for three cuts) when fertilized with conventional rates of mineral N fertilizer, compared with 13.1 t dry matter ha\(^{-1}\) when unfertilized (i.e. when N supply was only from clover N fixation). Studies in Devon, UK showed that average annual liveweight gain was 19% lower for beef cattle steers grazing an unfertilized grass/clover pasture compared to those grazing pasture fertilized with 200 kg N ha\(^{-1}\). In contrast, a dairy farm survey conducted by Newcastle University indicated no difference in milk yields between dairy cattle grazing non-fertilized grass/clover swards and cattle on mineral fertilized swards.

**Effectiveness**

Incorporating legumes in grasslands is a very effective strategy in reducing N leaching. As an indication, reductions of around 50 – 75% over a multiple-year period have been reported, although the use of clover as an alternative fertilizer was not the only cause of these reductions (other reasons being lower stocking rates and reseeding of grass-clover sward).
3.4 Reduce time on pasture

The strategy

Limit the amount of time that livestock (particularly cattle) are on the pasture, and supplement their feed with stored or fresh-cut forage in controlled housing situations.

How it works

Localized deposition of urine and dung on grazed pastures is a major source of NO$_3^-$ leaching; therefore, reducing the amount of time that animals are on pasture lowers this risk. Animal manure can be collected in the barn and managed to minimize losses of N during storage and handling and application in the field.

This strategy could be adopted to various degrees:

- Livestock could be permanently housed indoors and a zero grazing system adopted i.e. cutting forage mechanically and bringing it to the barn for feeding
- Daily time on pasture could be reduced by shortening the length of the grazing day and supplementing with stored feed
- Annual time on pasture could be reduced by shortening the length of the grazing season and supplementing with stored feed

Regions and systems of applicability

This system is applicable for intensively managed forage-based systems of production. It requires that the system includes: a) a barn or loafing area for housing the livestock when they are not on the pasture, and b) equipment for harvesting and feeding forage to the livestock. Therefore, it is not likely to be appropriate for extensive pasture-based systems of livestock production.
Cost

In all cases, reducing the amount of time that livestock are on pasture implies an increased cost for feeding in the barn. This increased cost will include:

- Labour inputs for feeding in the barn and for harvesting the forage that is fed in the barn
- Equipment costs if zero-grazing requires purchase of additional forage harvesting and feeding equipment
- Infrastructure costs i.e. larger facilities for storage of feed either as bales of hay or as silage

Effectiveness

In general, keeping livestock indoors allows the management of manure to be optimized for nutrient retention during storage and handling. It also allows for improved targeting of manure nutrient applications in the field. Therefore, this method should be highly effective.

Other considerations

Reducing the amount of time on pasture reduces the risk of nitrate leaching by lowering the frequency and intensity of manure (especially urine) deposition on pastures. The manure deposition is transferred to the barn or loafing area where the animals are housed when they are not on pasture. It is therefore essential that manure management in these areas is optimized by ideally bedding the animals on a high carbon material (straw, wood chips) that will trap the manure N and minimize NH$_3$ volatilization. If manure collection in the housing/loafing area is a slurry-based system, there is the risk that N losses by volatilization will be substituted for nitrate leaching losses in the field. This is known as “pollution swapping” and is not considered to be a desirable strategy for reducing N losses to water.

Zero grazing feeding system. Image courtesy of Jennifer Mackenzie for www.greenforage.co.uk
3.5 Reseed older, permanent swards

The strategy
Rejuvenation of permanent pastures through cultivation and re-seeding; there will be a short term increase in N losses immediately after cultivation, however in the long term, net losses of N should be lower in the newly re-seeded pasture. The short term losses of N can be reduced by a) ploughing in the late winter or spring, rather than the autumn, and b) adopting innovative approaches to pasture renovation including reduced tillage strategies for re-seeding.

How it works
There is evidence to indicate that older, permanent swards have higher rates of N losses due to leaching than more recently seeded swards. Although the short-term risk of N losses due to cultivation of an old sward and re-seeding can be high, in the long-term net losses of N by leaching could be lower. The reductions in N leaching in new swards are likely due to:

1. Deeper, more vigorous root growth and higher demand for N from above-ground plant parts in newly seeded swards
2. Lower rates of N mineralization from re-seeded swards due to less aerobic conditions in the top-soil and lower topsoil humus contents (especially if the soil has been deeply ploughed to mix the high OM surface layer with the lower OM subsurface)

Regions and systems of applicability
This approach is applicable in areas where the terrain is suitable for cultivation i.e. managed pastures rather than extensive, native stands of pasture.

Cost
This strategy will result in a periodic cost for equipment use, labour and time. Higher productivity from newly seeded pastures is to be expected which should compensate for this cost.

Effectiveness
A UK based study showed that average quantities of N leached from and old sward receiving 400 kg N/ha were 133.8 kg/ha per year compared with only 55.7 kg N/ha per year leached from a reseeded sward.

Other considerations
To reduce the risk of N leaching immediately after cultivation of the permanent sward, it is recommended to plough in late winter or early spring, rather than the autumn. This will allow the newly seeded sward to become established and begin to utilize soil mineral N as soon as possible.
3.6 Reduce stocking densities

The strategy

Reduce stocking densities on pastures to allow an overall reduction in the amounts of urine and faeces deposited on pasture land.

How it works

Most leaching risks from pastures occur from urine patches. This risk is increased as the density of cattle on the pasture increases. By reducing stocking densities, the volume of urine and faeces deposited on the land will decrease and the risk of leaching, particularly from urine patches will also decline. The objective of reduced stocking densities on pastures can be met by:

1. reduce overall stocking densities on the farm by lowering the number of animals on the enterprise
2. reduce stocking densities on specific areas of the farm when leaching risk is high e.g. on wet soils

Regions and systems of applicability

This strategy should be applicable in a wide range of regions.

Cost

A reduction in overall stocking densities on the farm will lead to a reduced economic return from the land. Controlled reductions in stocking densities for at-risk areas only, should not lead to a direct cost and could still significantly reduce the risk of leaching.

Effectiveness

There is a direct relationship between stocking rates and nitrate leaching from pastures; therefore this is likely to be an effective strategy. The N Cost Curve project (a UK Defra project) modeled the potential benefits of this method and predicted that a 20% reduction in livestock numbers on dairy farms would result in a reduction of 10-25 kg N ha\(^{-1}\) in nitrate leaching losses.

Other considerations

While lowering stocking densities on the whole farm will reduce the risk of N leaching from pastures, it will also reduce the economic return to the farmer from that piece of land. Generally, farmers stock at rates that they consider to be the economic optimum. Therefore, this is not likely to be a popular option unless there is some compensation provided to the farmer for uptake of the option.

Targeted reductions in stocking densities on areas of pasture that are at risk of leaching could be as effective as reducing the overall stocking rates on the farm.
### 3.7 Application of nitrification inhibitors to pastures

#### The strategy

A nitrification inhibitor is sprayed in the pasture at the beginning of the grazing season.

#### How it works

The inhibitor dicyandiamide (DCD) is applied to the pasture as a fine particle suspension at a rate of 10 kg DCD/ha and acts as a barrier between dung and urine deposited by grazing animals and the soil. The inhibitor prevents the conversion of ammonium-N in the cattle faeces and urine, into nitrate-N. This reduces the risk of nitrate losses from the pasture, especially from “urine hotspots”. The method has been shown to reduce nitrate leaching by up to 76% in pastures in New Zealand.

#### Regions and systems of applicability

This approach is applicable across a broad range of regions and production systems where grazing on intensively managed grassland takes place.

#### Cost

The technology is not yet available in Europe. In New Zealand the current price is $NZ94.50 per hectare per application, with two applications required.\(^3\)

#### Effectiveness

Application of DCD to pastures has been shown to reduce nitrate leaching by 76% in New Zealand studies.

#### Other considerations

Nitrification inhibitors applied in a spray formulation for pastures are not yet available in Europe. Currently various research organizations are testing out this technology to see if this approach will result in (a) reductions in N losses from pastures, and (b) improved production from pastures. As yet, results have been mixed with considerable evidence for reductions in N leaching and nitrous oxide emissions but less consistent effects on pasture production. Therefore, if this technology becomes available in Europe it is likely that farmers will need an additional economic incentive (e.g. an environmental subsidy) if they are to take up this practice.

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\(^3\) Information courtesy of Richard Christie, General Manager Strategic Development, Ravensdown. [www.ravensdown.co.nz](http://www.ravensdown.co.nz)
4. Balanced N application rates

The balancing of manure and fertilizer N applications to meet crop needs is a knowledge-intensive approach that should ensure that only the N that is required for optimum crop growth will be applied. In this section we list just two general, knowledge-intensive strategies that should be adopted so that N applications can be adjusted to more closely meet crop needs.

*Testing leaf greenness for fertilizer optimization. Image: Nafferton Ecological Farming Group, 2010*
4.1 Determine optimum fertilizer rates using decision support tools and accounting for all sources of available N

The strategy

Ensure that the optimum amount of fertilizer or manure nitrogen is applied by using the best possible tool to estimate crop needs (basing requirements on a realistic crop yield) and accounting for the N that will be supplied by the soil as well as N in irrigation water where relevant.

How it works

The use of fertilizer (and manure) N in excess of crop requirements has been identified as one of the practices which results in considerable losses of N from agricultural systems. In most jurisdictions information on optimum amounts of fertilizer N required to produce a given yield of a crop is available. The first step towards applying a balanced amount of fertilizer or manure N and minimizing the risk of N losses from the field is to determine the optimum amount to apply. Accounting for supply of N from soil reserves needs to be included in this calculation. If optimum amounts of N are applied, most mineral N in the soil during the growing season will be used by the crop, minimizing the risk of N losses from the system.

In irrigated areas accounting for the N content of the irrigation water will ensure that crops are not over-fertilized. Information on the nitrate concentration of irrigation water can be obtained from a regional testing service or by using nitrate test strips or a handheld nitrate tester. Once water nitrate concentration is known, applications of N fertilizer can be reduced, assuming a value for irrigation system efficiency and crop N uptake efficiency.

Tools

There are a wide range of tools available to assist farmers to determine the optimum amount of N to apply to crops on their farms. These include:

- Local agriculture department fertilizer recommendation handbooks, e.g. RB209 in England and Wales
- Soil tests to determine mineral N status in the soil close to the time of fertilizer application
- Soil tests to determine the potentially mineralizable N during the upcoming growing season: usually an anaerobic incubation method for determining N mineralization potential
- Computer-based nutrient management software that take account of soil nitrogen supply by soil testing or historic field records (e.g. PLANET in the UK)
Regions and systems of applicability

Applicable in all regions where appropriate field testing has been done to determine optimum N fertilizer rates for typical crops.

Cost

In many cases fertilizer and manure recommendation services are available free of charge from government advisors or fertilizer salespeople. In other cases, farmers may be able to access this information themselves from resource material, or free nutrient management planning packages. Making the most of fertilizer recommendation services (i.e. applying the correct rate of fertilizer at the optimum time, keeping records that can be used to optimize recommendations) requires a high degree of management skill and some time input.

Ultimately, optimizing fertilizer use should result in the application of the most economical rates i.e. enough fertilizer N to achieve an economic crop yield, but not so much that yield gains are minimal relative to the added cost.

In irrigated areas, accounting for water nitrate contents can be especially profitable where irrigation water nitrate levels are high, and costs of irrigating are low. For example, in Spain where irrigation water can contain 51 mg/l of NO$_3^-$, accounting for this N could reduce fertilizer needs by 63 kg N/ha (assuming 660 mm irrigation water applied per annum).

Effectiveness

Balanced N applications have been identified as one of the key approaches to minimize N losses from agriculture to water. The Defra Cost curve of nitrate mitigation options project estimated that the use of a reliable recommendation system could result in average reductions of N fertilizer inputs of ~20 kg N/ha in fields with no history of manure application, and from 20 to 60 kg N/ha in crops where manure is used and had not been previously accounted for.

Soil sampling for mineral N testing before planting; Image: Nafferton Ecological Farming Group
4.2 *Use in season estimates of crop N status to determine N application rates*

**The strategy**

As well as determining the optimum N application rate before the growing season, application rates can be further optimized by adjusting later applications of N based on crop N status.

**How it works**

Splitting applications of N fertilizer to supply mineral N to the crop as close as possible to the time when the crop needs it, is a good strategy to improve crop N uptake and reduce losses from the field (see Section 7 *Split fertilizer/manure applications*). Adjustments to the amount of N supplied can be made at the time of the later applications, based on the crop’s N status. Crop N status can be determined directly by plant tissue testing, or indirectly by assessing leaf chlorophyll content, or by assessing crop canopy cover.

**Tools**

A number of tools are available to determine crop N status mid-season:

- **Hand held chlorophyll meters and tractor-mounted sensors** work by providing an indication of the N status of the crop immediately prior to N fertilizer application. Fertilizer rates are then adjusted accordingly. With the hand-held sensor, the farmer can take a representative measurement for the whole field and adjust average application rates for the whole field. The tractor-mounted sensor is linked to a variable-rate fertilizer spreader so that rates within a field can be varied.

- **Satellite imagery**, which allows variable rates of N to be applied based on satellite images of canopy cover

**Regions and systems of applicability**

These approaches are appropriate where there is the technical expertise available to advise farmers on interpretation of test results. In most cases this will require input from a paid advisor who markets the service. In other cases, a government advisor or employee of a farmer group or co-operative may be able to provide the advice.

**Cost**

A handheld N-tester along with the recommendation sheets (for winter barley and winter wheat only) retails for £1500 + VAT in the UK. Tractor-mounted N-sensors cost approximately £25,000 and require that the farmer owns a variable rate fertilizer spreader.

Satellite imagery systems require an annual payment to the service. As an example, a company offering this service in the UK in 2011 charged a maximum amount of £4,000 for up to 1,500 ha of crops.
Effectiveness

Research evidence suggests that the use of precision farming techniques such as those described above, can assist with determination of optimum fertilizer rates and improve the nitrogen use efficiency of the crop, thereby reducing the risk of nitrate leaching.

Other considerations

This is another indirect method of reducing N losses to water, based on the assumption that these methods will result in optimal fertilizer N use. It is not possible to find research studies that report a direct link between the use of in-season estimates of crop N status and N leaching. Anecdotal evidence from Denmark suggests that the methods have not yet shown a benefit in terms of reduced fertilizer use or improved yield; however, this does not mean that they have not reduced N losses to water.

The calibration or validation of these methods with the crop’s nitrogen nutrition status has not always been made and these methods show a strong dependence on cultivar and environment, that limits the relevance of such diagnostic tools in a large range of situations. Therefore it is important that these methods are calibrated to local conditions and cultivars, for them to be effective.
5. BMP for manure use on land

Improving manure storage and handling can reduce losses of N to water during this phase of the manure’s life cycle on the farm, but the greatest risk of losses of N to water arise during and after manure is applied in the field. Strategies to minimize these losses require that appropriate amounts of manure-N are applied, ideally to a growing crop that can take up the manure-N as it is released in an available form. Listed below in order of efficacy and cost-effectiveness, are the top best management practices (BMP) that we recommend to reduce N losses to water from manure use on land.

Composted manure at Nafferton Farm. Image Nafferton Ecological Farming Group.
5.1 Do not apply manure to high-risk areas

The strategy

Avoid application of manure to areas of the land where there is a high risk of direct flow to watercourses. This includes: a) areas that are directly adjacent to a watercourse, borehole or road culvert, b) shallow soils over fissured rock or cracked soils over field drains, c) areas with a dense network of open (surface) drains, or d) wet depressions (flushes) draining to a nearby watercourse.

How it works

These areas are directly connected to groundwater or surface water therefore there is a high risk of N movement through or over the soil, into these water sources. Ideally, all of these areas should be considered buffer zones where no manure or fertilizer N is applied.

Tools

Good farm maps with a clear indication of restricted areas. Field markings would also be appropriate i.e. flags, to remind machinery operators about no-go areas for manure and fertilizer spreading.

Regions and systems of applicability

Applicable across the EU.

Cost

There will be a minimal increase in management costs to ensure that manure and fertilizer spreading is restricted in these areas. Crop productivity in these areas may be reduced due to the lower supply of N.

Effectiveness

Avoiding high risk areas should be highly effective and is a first line of defence against N losses to water.

Other considerations

Many farmers in the EU will be legally required to use this strategy if they are farming in a Nitrate Vulnerable Zone.
5.2 Apply manure to land when conditions are optimum

The strategy

Time manure applications to coincide with periods when there is a low risk of nutrient runoff or leaching.

How it works

There are recognized periods of time when conditions for application of manure to land are not optimal. Specifically, when ground is frozen it is not advisable to apply manure, since rainfall or snow melt on frozen ground can result in rapid movement of pollutants to surface water bodies. Even outside of prohibited periods, heavy rainfall can result in rapid surface runoff and a high risk of contamination of surface water. Ideally, manure should be applied to the land at a time when the growing crop can use its available nutrients; this implies application in the spring.

Most jurisdictions have now implemented prohibited periods for manure application which correspond to those times of year when weather causes soil conditions that are not suitable for manure application. Outside of these periods, farmers should still use their own judgment and not apply manure if exceptional weather conditions result in unsuitable conditions for application.

- use weather predictions and delay manure application when heavy rainfall will occur within the next 2-3 days or if ground will be frozen

Regions and systems of applicability

Throughout the EU

Cost

The flexibility to apply manure when timing is optimum increases as the on-farm manure storage capacity increases. Therefore, there may be an increase in cost for enlarged slurry tanks and manure storage areas. In addition, a higher degree of management, particularly relating to nutrient management planning, will be required to ensure optimum amounts and timing of manure application.

Effectiveness

Studies have demonstrated considerable reductions in N leaching to groundwater when manure applications are made in the spring, compared with late autumn applications. Defra’s Cost curve of nitrate mitigation options project estimated that switching manure spreading from autumn to spring, and restricting manure spreading to “safe” periods could reduce N losses by 34 kg N/ha on sandy soil compared autumn applications of manure.
Other considerations

Attention to weather predictions is important whenever manure is applied to land. Avoiding applications before a heavy rainfall is expected should reduce the risk of surface runoff or leaching.
5.3 Accurately estimate manure N release over the growing season

The strategy

Estimate the release of N from mineralization of recently applied manure

How it works

While manure testing gives an indication of the amount of readily-available N (ammonia-N) in the manure, the remainder of the N in the manure is in an organic form that is slowly released over the following growing seasons. Accounting for the supply of this slowly available N reduces the risk of over application of N to the crop and thereby reduces N leaching risk.

Tools

- Use manure N availability tables that provide an estimate of the percentage of total N in manure that is available to the next crop
- Use a software tool like MANNER-NPK to predict the fertilizer nitrogen value of field applied manures, taking into account the manure type, manure analysis data (total N, ammonium-N, nitrate-N and uric acid-N), soil type, application timing and technique, ammonia-N, nitrate-N and denitrification losses, and the mineralisation of organic-N
- Use a dynamic simulation model like NDICEA (www.ndicea.nl) that will include mineralization from recently added manure in its estimate of soil nitrogen supply

Regions and systems of applicability

Accurately estimating the N supply from manures is a strategy that is applicable across the EU.

Cost

The decision support tools (manuals and software tools) available for estimating N supply from manures are usually available free of charge or for a small fee. A relatively high degree of management expertise is required to use the information correctly.

Effectiveness

Estimating N supply from mineralization of manure-N will improve overall prediction of soil N supply in the season and reduce the risk of over application of N to the crop. Defra’s Cost curve of nitrate mitigation options project estimated that using a reliable recommendation system that accounted for the N supplied by manure could reduce N leaching on a sandy soil by 56 kg N/ha, when combined with optimum timing of manure application.
5.4 Regular maintenance and calibration of manure application equipment to ensure even and accurate application

The strategy

Ensure that manure spreaders are working correctly and be aware of how much manure is being spread (by accurate calibration of equipment)

How it works

If the nitrogen content of manure is to be accounted for in field nutrient management plans, then it is essential that manure spreading is even and accurate, and this requires that equipment is well maintained. It also requires that the user is aware of the rate of application when spreading a specific type of manure at a given speed. Good equipment maintenance and accurate calibration of equipment will ensure that the correct amounts of manure-N are applied and that there is no over application of manure.

Regions and systems of applicability

This is relevant across the European Union. It is particularly relevant for systems producing slurries that are high in available N, since over-application of these manures can dramatically increase the risk of N losses to water

Cost

There should be minimal cost to the farmer for this strategy. Some training in maintenance and calibration of spreading equipment may be required.

Effectiveness

It is very important that spreaders are accurately calibrated, and that farmers understand the importance of calibration. Studies have shown that farmers tend to underestimate application rates if they have not calibrated their equipment. This means that manure is frequently applied at higher than necessary rates, increasing the risk of surface runoff of excess manure and leaching of surplus N to the subsoil.
5.5 Test manure for available N content before use

The strategy

Determine the available N content of manure before its use in the field, either by sending samples for testing, or by using an on-farm testing method.

How it works

A key component of good nutrient management planning is a correct estimate of the N content of the manure being used. In particular, manures with high levels of available N (usually in the form of ammonia) can contribute to increased risk of nitrate leaching, since ammonia N is rapidly converted to nitrate after application to the soil. If the manure is tested, then application rates and timing can be optimized to ensure that: a) available N is applied to match crop needs, and b) fertilizer N application rates are adjusted to account for the N supplied by the added manure. The information is also valuable for accurate nutrient management planning in subsequent years.

Tools

- Manure testing services are available from commercial laboratories in most countries, and in government laboratories in a few countries.
- On-farm testing of manure is also possible using “do-it-yourself” kits that provide information on the ammonia-N content of slurry.

Sampling slurry just before spreading. Image: Cornell University; http://www.dairyn.cornell.edu/pages/20cropsoil/250credits/252manSample.shtml
Regions and systems of applicability

Testing is most useful in systems that are likely to produce manure high in available N (e.g. slurry). This would be relevant across the European Union.

Cost

Manure testing costs about £50 per sample in England. An on-farm ammonia meter retails for £230, therefore it would pay for itself relatively quickly.

Manure testing should result in an economic benefit since it will allow optimization of fertilizer N inputs, and may lead to a reduction in quantities of purchased fertilizer used on the farm.

Effectiveness

There is no doubt that accounting for the N content of manure in nutrient management plans can reduce the risk of over application of N to cropland. Most fertilizer recommendation systems use tables of standard values for N contents of manure, however it is recognized that there is a large degree of variability among manure samples. Testing of manure, ideally immediately before its use in the field, is the one way to ensure that N contents in manure are accurately accounted for in nutrient management plans.

Other considerations

On farms where feed sources and livestock characteristics and management are very consistent across the years, manure testing may not be required so frequently. After implementing a manure testing programme, the farmer may find that variability is very low, and be able to reduce the frequency of testing.
6. Strategies for irrigated land

Irrigated systems of crop production present special challenges for the management of nitrogen. The prevention of N losses to water in these systems is tightly linked to the management of irrigation water. Excessive applications of water can lead to the leaching of nitrates down below the root zone where they become groundwater pollutants. Even when water management is optimum, nitrate leaching can occur in the winter if rainfall is high and there is residual nitrate in the upper soil horizons. For this reason, it is important to combine these strategies with the balanced N application rates (see Section 4) and efficient N cycling at the field level (see Section 7). The use of catch crops after the main crop harvest is particularly appropriate in irrigated areas. Listed below in order of efficacy and cost-effectiveness, are the top strategies that we recommend for irrigated land.

Irrigated maize in Spain; Image courtesy of Miguel Quemada.
6.1 Adjust the quantity of water applied to match crop needs

The strategy

Water supplied through irrigation should be optimized to avoid decreased yields or increased drainage. This can be accomplished through using proper irrigation scheduling according to crop evapotranspiration and by applying irrigation water in smaller amounts more frequently (e.g. split applications of irrigation water to more closely coincide with crop needs). The installation of flow meters is also essential so that amounts of water supplied can be properly monitored.

How it works

The main cause of N leaching from irrigated areas is the movement of excess water down below the root zone of the crop. This water carries nitrates with it and leads to contamination of groundwater. It is therefore essential that only sufficient water to meet the crop needs is used. If this is done correctly, then all irrigation water should be used by the growing crop before it can leach below the root zone.

Tools

This is a knowledge-intensive strategy which requires a high degree of management expertise. In some locations advisory services are available to assist farmers with decision making, for example, in Denmark farmers can use an internet-based decision support tool: PlantelInfo, which provides advice on when to irrigate based on soil type and local meteorological data. Other Danish farmers collect their own environmental data and submit it to a remotely located advisory service which recommends when to irrigate.

In Spain, the internet-based decision support tool SIAR is widely used by farmers and provides detailed information (crop evapotranspiration) and advice to adapt water application to crop needs. In addition, the software provides recommendations for N fertilizer application based on water application and a simple balance method.
An example of the web-based decision support tool available to farmers using irrigation in Spain.

Another farmer tool that has proven effective in Spain is to use the “full stop” device, which provides a visual indication to the farmer of when irrigation water has infiltrated below a certain depth in the field. This is to prevent over-watering with irrigation.
Installation of a full stop device in an irrigated field in Spain, showing the below-ground reservoir where water collects during irrigation; image courtesy of Miguel Quemada.

**Regions and systems of applicability**

Applicable to all regions where irrigation is used.

**Cost**

There may be some management-related costs, especially if an advisory service must be employed to provide direction on timing and amounts of irrigation water to use. Even if the farmer is making the decisions on his/her own, there will be an additional input of time by the farmer to monitor evapotranspiration and calculate when and how much water to apply.

Flow meters are an essential component of a water-efficient irrigation system. Installation of these will also result in a one-time cost to the farmer.

Costs for pumping irrigation water will be lower if amounts of water used are reduced, as well as costs for water (in areas where there is charge for water use).
Optimal irrigation should not result in a yield decrease; therefore crop revenues should not be affected by this strategy.

**Effectiveness**

There have been numerous studies on the effects of improved water use efficiency on N leaching. In general, losses of nitrate by leaching during the cropped period can be reduced by 50% if volumes of irrigation water are reduced to better match crop needs.

Our estimates indicate that for an irrigated maize crop in Spain, reductions in water use of 20% (through adjustments to match crop needs) could reduce N leaching by 25-35 kg N/ha.

**Other considerations**

This method should be used in conjunction with more water use efficient irrigation systems (see 6.3 Install more water use efficient irrigation systems) to maximize reductions in N losses to water from irrigated systems.

Improved WUE will result in more retention of mineral N in the topsoil. This method must be combined with proper nutrient management so that maximum uptake of mineral N by the crop is ensured. The goal needs to be to minimize residual soil nitrate at the end of the growing season, otherwise, there will be a higher risk of leaching during the winter when rainfall is high.
6.2 Fertigation

The strategy

Supply crop nutrients directly with the irrigation water, rather than applied to the soil.

How it works

Fertilizer is mixed with the irrigation water before application. This allows more precise and frequent application of nutrients to coincide with crop needs. The result is lower total application rates of fertilizers which reduces costs and reduces the risk of N leaching.

Tools

Fertigation cannot be used with flood irrigation systems; therefore a centre pivot or drip irrigation system will need to be installed. In addition, specialized equipment such as a fertilizer tank, dispenser system, shaker and filtering equipment, will be required.

Access to good nutrient management planning advice is necessary to ensure appropriate quantities and timing of fertilizer applications.

Irrigation system adapted for fertigation in Spain; Image: Universidad Polytechnica de Madrid

Regions and systems of applicability

Applicable to all regions where irrigation is used.
Cost

In Spain we have estimated that net margins (without farmer’s wages included) will increase by €343/ha (29% compared to a baseline scenario) and reduce N leaching by 53 kg N/ha, if a fertigation system is adopted on a farm that already has the fertilizer mixing equipment and a centre pivot irrigation system in place.

For farms that do not have the equipment in place, we estimate that costs of installing the complete system (including fertilizers tank, dispenser system, shaker and filtering equipment) will be 3395€.

Effectiveness

In the same analysis described above, we have estimated that N leaching will be reduced from 85 kg N/ha at a site in Spain with a centre pivot irrigation system, to 32 kg N/ha, through adoption of a fertigation system. At another site with a flood irrigation system, adoption of a centre pivot irrigation system in combination with fertigation, would reduce N leaching from 171 kg N/ha to 24 kg N/ha.
**6.3 Install more water use efficient irrigation systems**

The strategy

Install more water use efficient irrigation systems

**How it works**

When water use efficiency is improved, nitrates are much less likely to leach down below the root zone. The water use efficiency of irrigation systems can be ranked from highest to lowest as follows:

1. subsurface trickle irrigation systems
2. trickle irrigation
3. mini-sprinklers
4. sprinklers mounted on a bar
5. long-range sprinklers
6. flooding systems

Any improvement in water use efficiency should reduce losses of N below the root zone. When combined with fertigation (the addition of crop nutrients to the irrigation water) efficiency of fertilizer N use can be further improved.

**Regions and systems of applicability**

Applicable to all regions where irrigation is used.

**Cost**

Costs of installation for improved systems will vary depending on the existing system and the upgraded system. For example, it has been estimated that it would cost €4000/ha to upgrade a flood irrigation system in Spain to a centre-pivot (sprinkler) system.

In regions where water use is metered, improved water use efficiency should lead to reductions in costs in the long-term.

**Effectiveness**

The use of drip fertigation systems have been shown to be superior to conventional irrigation methods both in terms of water use efficiency and nitrogen use efficiency (which translates into reductions in N losses to water).

In one experiment, a furrow irrigation system left 128 kg residual NO\(_3\) in the soil profile at the end of the cropping system compared with 211 kg residual NO\(_3\) when drip irrigation was used. This demonstrates that less N was lost by leaching; however, it also highlights the need to manage the soil after crop harvest so that residual N is not lost during the winter. The use of winter cover crops (see section 7.3 Use a catch crop) is one strategy that can minimize this risk.
Other considerations

Improved WUE will result in more retention of mineral N in the topsoil. This method must be combined with proper nutrient management so that maximum uptake of mineral N by the crop is ensured. The goal needs to be to minimize residual soil nitrate at the end of the growing season, otherwise, there will be a higher risk of leaching during the winter when rainfall is high.
Closely linked to balanced N application rates are strategies to ensure the most efficient use and cycling of N in the field, once N application rates have been optimized. Here we acknowledge that even when N applications have been calculated to closely match crop needs, there is still some risk of N losses to water after the fertilizer or manure-N has been applied in the field. In addition, N can be lost from the field during the periods when crops are not actively growing. Listed below in order of efficacy and cost-effectiveness, are the top strategies that we recommend to ensure that applied N is cycled efficiently in the field, with minimal losses to water.

An annual ryegrass catch-crop growing in the Nafferton Factorial Systems Comparison trial, Newcastle University, in March 2008; Image: Nafferton Ecological Farming Group
### 7.1 Split fertilizer / manure applications

#### The strategy

The required amount of fertilizer/manure is applied in several doses to more closely coincide with periods of crop demand.

#### How it works

Splitting manure or fertilizer applications into several doses allows better matching of N supply with crop demand. The growing crop has the chance to use the added N more efficiently, since at any given time, it is less likely that large pools of mineral (ammonium or nitrate) N are present in the soil. This reduces the risk of losing large proportions of the total amount of fertilizer or manure-N that has been applied.

In addition, splitting the N application allows the second N application to be adjusted based on crop N status (see section 4.2 Use in season estimates of crop N status to determine N application rates).

#### Regions and systems of applicability

This approach is applicable across a broad range of regions.

#### Cost

This strategy will entail some additional labour and management costs. In the UK we have estimated that an additional trip to spread fertilizer costs approximately £9/ha with minimal additional management costs on a per hectare basis.

#### Effectiveness

The benefits of splitting manure and fertilizer N applications vary depending on the crop and environmental conditions. In principle, splitting N applications should allow better synchronization of N supply with crop demands; however, there are economic tradeoffs that limit the number of applications that it is practical to make.
7.2 Cultivate land for crop establishment in spring rather than autumn

The strategy

In arable systems: Cultivate arable land for spring crops in the spring instead of in the autumn.

In ley/grassland systems: Plough out the grassland in the spring instead of in the autumn.

How it works

Tillage stimulates N mineralization from organic matter and crop residues. If tillage takes place in autumn, N will be released at a time when there is no or little crop N uptake. This will increase the risk of N being lost during the winter period. Tillage in spring on the other hand will reduce the amount of time inorganic N is present in the soil prior to crop N uptake.

Regions and systems of applicability

This approach is applicable across a broad range of regions, but especially in regions where the soil conditions in the autumn are warm and moist since the rates of mineralization will be higher there. The strategy can be used in rotations that include spring crops or in grassland systems where grass leys are ploughed out and re-seeded. The strategy may be less applicable in soils with medium to heavy texture as delayed cultivations may result in the spring crop being drilled into a drying seedbed which may negatively affect crop yield.

Cost

It has been assumed that this method will reduce crop yields due to delays in spring seeding created by the need to do all cultivations during a narrow window of time. Yields may be reduced by up to 25%.

Effectiveness

This strategy can be reasonably effective although it may not always work as mineralization depends on a range of different factors. It is estimated that N leaching could be reduced by about 10 and 15 kg N ha\(^{-1}\) in systems without and with manure application respectively.

Other considerations

This strategy will prevent the early establishment of spring crops as well as the breakdown of soil clods during winter by frost action and wetting and drying. Delaying the time at which tillage takes place may also have implications for the control of some weeds. In addition, cultivation during a wet spring may negatively impact the soil structure. In the case of grassland systems, reseeding is less reliable in spring compared to autumn.
7.3 Use a catch crop

The strategy

Catch crops are cover crops grown to catch available N in the soil and thereby prevent N leaching losses. They are usually planted after harvest of the main, commercial crop and left to grow during the non-growing season instead of leaving the land fallow.

How it works

By covering the land with a growing crop, nitrogen can be taken up instead of being lost through leaching during rainfall events. The crop will not only take up nitrogen but also water, reducing the amount of drainage occurring and hence reducing the amount of potential N leaching. The cover crop increases the retention of surplus inorganic N left in the soil after harvest of the main crop as well as capturing N released through on-going mineralization. In this way it can potentially reduce overwinter N leaching.

Regions and systems of applicability

Applicable in regions where there is a high amount of rainfall during the non-growing season i.e. where the main drainage occurs during the non-growing season. Especially applicable in temperate regions with mild winters as this will entail a high winter N mineralization and a longer growing season. It is also applicable in regions where irrigation is used during the dry months of the year, as this can result in an accumulation of inorganic N that is susceptible to leaching during the winter.

Cost

This strategy will require more labour during the non-growing season, equipment and fuel for seedbed establishment, and seed costs, as well as increased management time hence there will be on-going costs.

We have estimated that net margins per hectare can be increased by up to 180 €/ha in irrigated maize systems in Spain, depending on the type of catch crop planted, when there is also a market for the harvested catch crop. If the catch crop is not harvested for sale, net margins will be lower and may at times result in a net loss, due to the added cost of seed and establishment.

Effectiveness

There have been numerous studies which have documented varying degrees of reductions in over-winter N leaching when catch crops are grown. This will depend on levels of residual N after crop harvest, over-winter temperatures and rainfall, and the growth and vigour of the catch crop. As an example we have estimated that in irrigated systems of maize production in Spain, nitrate leaching could be reduced by as much as 111 kg N/ha if a barley crop is grown during the winter months. Other studies have shown that winter cover crops can reduce nitrate leaching by 40-70% compared to bare fallow.
A cover crop of winter barley in experimental plots in Spain. Photo Nafferton Ecological Farming Group.

Other considerations

The incorporation of the catch crop may lead to a proportion of the captured N being lost due to rapid mineralization of green plant materials, especially if some time elapses between incorporation and planting of the following crop. It is important to time catch crop incorporation to occur as closely as possible to the planting of the subsequent crop.

N leaching may increase in the long term (after approximately 10 years) in systems which continuously use catch crops, if fertilizer N is not reduced or the crop rotation is not changed. Therefore, catch crops should always be used in conjunction with balanced N application rates i.e. using an optimum N rate that includes an accurate estimate of soil N supply.

In the short term, yields of crops grown after catch crops can potentially decrease, especially if a legume catch crop is relied on as the sole source of N for the subsequent crop. This problem is worse if the C:N ratio of the catch crop is relatively high, resulting in immobilization of soil mineral N. In the first years artificial fertilization might be needed; however, in the long-term catch crops may benefit subsequent crops through soil organic N accumulation.
7.4 Incorporation of high C:N ratio residues to promote immobilization of mineral N

The strategy

Straw or other high C:N ratio residues are incorporated into the soil after crop harvest to act as a “sponge” that holds inorganic N in the soil during the season when no crop growth is occurring.

How it works

Residues that are high in C and low in N can “immobilize” inorganic N in the soil. This means that the inorganic N in the soil is converted by soil microorganisms into a more stable organic form that is not so susceptible to leaching. In subsequent seasons, this immobilized N will be converted back to inorganic N through the process of mineralization, and become available for crop uptake.

This is a strategy for situations where there is a high risk of N leaching due to high levels of residual mineral N in the soil following crop harvest. It is particularly applicable in cases where a crop failure has occurred resulting in minimal uptake of applied fertilizer N.

Regions and systems of applicability

This method is applicable in any regions of Europe where residues (crop or industrial) are available at minimal cost to the farmer.

Cost

Ideally, a waste material should be used in this strategy. In many cases crop residues such as straw have a high market value and would not be appropriate. Industrial wastes such as paper mill waste or compactor waste (the final product from the recycling of cardboard) have been used effectively in the past. These materials may be available at no charge or for a minimal cost.

The spreading and incorporation of the residues will result in additional costs being incurred.

In subsequent years, with effective soil testing and nutrient management planning, it should be possible to reduce fertilizer N inputs since this method will increase the soil organic N pool in the long-term.

Effectiveness

Reductions in N leaching of as high as 25% have been reported; however, in other cases no reductions in N leaching after incorporation of a residue have been reported.

This may be related to the composition of the residues. The amounts of soil mineral N in the spring and subsequent yields of a first cereal crop were significantly correlated to the lignin and cellulose contents of the residue materials i.e. residues containing high levels of lignin and cellulose are most effective.
Other considerations

In most cases, there is no negative impact on the subsequent crop; however, the use of dynamic simulation models that include soil C turnover would improve predictions of the dynamics of soil mineral N in systems that include residue incorporation. This will allow the N needs of the subsequent crop to be better estimated. In some cases the subsequent crop may be N-limited if the incorporated residues have not fully broken down before planting of the next crop.

Special equipment to incorporate residues into the soil may be required; in some cases it may be useful for the residues to be chopped before incorporation so that they breakdown more quickly.
Include N fixing green manures in the rotation as an alternative to manufactured N fertilizers

The strategy
Include an N fixing green manure crop in the rotation to reduce the need for artificial fertilizers.

How it works
The use of N fixing green manure crops in the rotation should reduce the reliance of the farm on artificial N fertilizers. N fixing green manures (like crimson clover, vetch, alfalfa) not only take up excess mineral N from the soil, but also fix N from the air and convert it into plant N. When the green manure is ploughed into the soil the plant N becomes part of the soil organic N pool and will be eventually be released to future crops, through the process of mineralization. Mineralization of N from organic pools in the soil is a gradual process which is less likely to result in excess build up of nitrates in the soil solution. Thus the risk of N leaching is reduced if N fixing green manures are included in the rotation as an alternative to manufactured N fertilizers.

Regions and systems of applicability
This method is applicable in any system where there is a crop rotation in place. Legumes (N fixing green manures) that are adapted to the environment and climate of the region should be selected.

Cost
There will be additional costs associated with this strategy, specifically: the cost of seed and fuel and labour for crop planting.

Fertilizer use should be reduced to account for the N supplied by the green manure, so this should represent a reduction in input costs.

Crop yields may be about 10% lower if the leguminous green manure is relied upon for all the subsequent crop’s N needs.

Effectiveness
A recent meta-analysis comparing diversified legume-based rotations with conventional fertilizer-based systems reported that on average nitrate leaching is reduced by 40% by using legume-based rotations.

Other considerations
There is an assumption that average cash crop yields will decline if legumes are included in the rotation because of a reduction in the number of cash crop years within the rotational cycle. However, rotations can be modified to include legume crops during periods when
fields are normally in a bare fallow, so that cash crops can still be grown every year. This can improve the economics of using N fixing green manures as an N source.

A good nutrient management planning service (e.g. software package, advisor, or handbook) will be necessary to effectively account for the N supplied by the incorporated green manure. This should result in a reduction in the need for purchased fertilizer.

*Field beans planted in an arable crop rotation in the UK; Image: Nafferton Ecological Farming Group.*
7.6 Use slow- or controlled-release fertilizers

The strategy

Use a slow-release or controlled-release conventional soluble fertilizer material that has been given a protective coating or encapsulation which controls water entry and rate of dissolution, and/or may contain a nitrification inhibitor.

How it works

Slow- and controlled-release fertilizers (SCFs) are a type of N fertilizer that delays or extends N availability for plant uptake compared to normal N fertilizers. This allows the release of nutrients to be more synchronized with plant uptake, thus reducing the risk of N losses from the soil by denitrification or leaching. Efficiency of N fertilizer use (e.g. crop N uptake per kg of N fertilizer) may also be increased.

SCFs include sulphur-coated urea, which is widely used in the turf industry. The sulphur coating slows down the conversion of urea to ammonium, thereby delaying its release in a plant-available form.

More recently, urea fertilizers that are coated and also contain a nitrification inhibitor have become available. These fertilizers not only release plant-available N at a slower rate, but also inhibit the conversion of ammonium-N to nitrate-N.

Ammonium nitrate fertilizers that are treated with a nitrification inhibitor are also available commercially.

Regions and systems of applicability

Applicable across the EU, depending on the availability of the product. SCFs have proven to be particularly useful on grasslands where fertilizers cannot be incorporated into the soil.

Cost

SCFs typically cost about 20% more per kg N than normal fertilizers; however crop responses to them are variable. This means that the farmer cannot necessarily reduce his/her fertilizer rates when using these more expensive inputs. Therefore, there may be a net reduction in revenues when SCFs are used.

Effectiveness

In many cases the use of SCFs has been associated with reduced losses of N to the environment. A meta-analysis of experimental data on nitrapyrin (a common nitrification inhibitor) showed that on average, crop yields increased (relative to N fertilization without nitrapyrin) 7% and soil N retention increased by 28%, while N leaching decreased by 16%,
when nitrapyrin was used. In more than 75% of individual comparisons, use of a nitrification inhibitor increased soil N retention and crop yield, and decreased N leaching and volatilization.

**Other considerations**

- Nitrapyrin and dicyandiamide (DCD) are the only nitrification inhibitors available that have gained considerable practical and commercial importance in the agricultural and horticultural industry
- 3,4-dimethyl pyrazole phosphate (DMPP) has recently been recommended for large-scale adoption in Europe

It is important that the SCF selected releases its nitrogen in a plant-available form while the crop is still actively growing. An excessive delay in mineral N release could result in increased risk of N leaching after crop harvest.

As mentioned above, SCFs are more expensive than normal fertilizers and while there is a large body of evidence to suggest that they reduce losses of N to the environment, impacts on crop yields are not so clear.
7.7 Rotate N efficient and N inefficient crops

The strategy

Implement a crop rotation where crops that are very efficient at accessing soil N (e.g. deep rooted crops) are alternated with crops that are inefficient at using N and therefore leave behind high N residues in the soil.

How it works

There are a variety of ways that this strategy can be implemented. The overall goal is to diversify the crop rotation so that crops that are shallow rooted and leave behind relatively high levels of nitrate in the soil, are alternated with deep rooted crops that can capture residual nitrate from deep in the soil profile and prevent it from leaching below the root zone.

Regions and systems of applicability

This approach is applicable in any regions where crops are rotated. Currently the approach is gaining popularity in irrigated regions of Spain where a winter cash crop of wheat is rotated with a summer crop of irrigated maize.

Cost

Our economic analysis in Spain indicated that net margins were ~40% lower where wheat was rotated with maize, as opposed to continuous maize. This is due to the lower revenues generated per hectare for wheat compared with maize.

Effectiveness

Rotation of deep-rooted and shallow-rooted crops has been shown to improve the N efficiency of the crop rotation and reduce leaching from deeper layers of soil. Simulations with the NDICEA model indicated that leaching in irrigated systems in Spain would be reduced by 30-60 kg N/ha/year if continuous maize was replaced with a maize-wheat rotation. Similar results have been found in experiments in Denmark where deep-rooted brassicas were rotated with shallow-rooted crops like leeks and beets.

Other considerations

This requires a fairly major change at the cropping system level. Since economic analyses indicate that some reductions in profit will be experienced by the farmer, an economic incentive is probably necessary for this strategy to be widely accepted.
8. Runoff, drainage and wastewater management

The final category of strategy to reduce N losses to water from agriculture addresses the management of runoff, drainage and wastewater. This category is the final one because it deals largely with what we call “end of pipe” solutions to the problem of nitrate pollution. Ideally, the farming operation should be using appropriate strategies from the first 7 categories, so that imports of N to the farm are minimized, N resources on the farm are stored and used efficiently, and so that as much as possible N losses from the field and farmyard are captured and recycled. When all these strategies are in place, there is still some risk of N pollution of water from agricultural activities. This is especially the case in areas where there are periods of intense, heavy rainfall which can result in large volumes of dirty water running of farmyards and fields. Listed below are the top strategies we recommend to reduce the risk of pollution from runoff, drainage and wastewater.
### 8.1 Yardworks for clean and dirty water separation

#### The strategy
Upgrading of existing farmyard drainage water collection systems, to allow the separation of clean water and dirty water.

#### How it works
Dirty water from around farm buildings includes: rainfall mixed with manure and slurry that has been deposited in the yard as animals and vehicles pass through it and runoff from silage pits and solid manure storage areas. Rainfall from the roofs of farm buildings can add to the volume of this dirty water. In this strategy, the goal is to keep water that is “clean” i.e. rainwater from roofs, separate from the “dirty” water that runs off yards. This will reduce the overall volume of dirty water to be stored and disposed of. To accomplish this goal, clean and dirty drains may need to be re-organised and re-directed. There may need to be modifications made to the yard areas so that clean water can be directed to drains, while dirty water is diverted to collection tanks.

#### Tools
Examples of the types of improvements that may be necessary under this strategy are shown in the table below, along with the level of assistance available to farmers in the UK who are located in Catchment Sensitive Farming priority areas.

<table>
<thead>
<tr>
<th>CSF004</th>
<th>Yardworks for clean and dirty water separation</th>
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<tbody>
<tr>
<td></td>
<td>A: underground drainage pipework (per m)</td>
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<tr>
<td></td>
<td>£5.00</td>
</tr>
<tr>
<td></td>
<td>B: inspection pit (per unit)</td>
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<td></td>
<td>£361.00</td>
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<tr>
<td></td>
<td>C: concrete yard renewal (per m²)</td>
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<td></td>
<td>D: rainwater goods (per m)</td>
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<td>£438</td>
</tr>
</tbody>
</table>

*New rainwater collection pipes can be installed to divert rainfall from dirty water and slurry stores on the farm; Image: Natural England CSF Capital Grant Scheme Farmer Handbook.*
Regions and systems of applicability

This strategy is particularly applicable to areas with high levels of rainfall. Farms where livestock spend some time each day walking on hard surfaces in the yard (e.g. dairy farms) are particularly appropriate.

Cost

Capital investment may be high, however, benefits will include reductions in volumes of dirty water that must be disposed of, which will lead to reduced energy use for its disposal. The dirty water that is collected will have higher concentrations of nutrients, making it a richer nutrient source for crops.

Effectiveness

Diverting clean water away from slurry and dirty water storage tanks reduces the total volume of slurry and dirty water storage that needs to be in place on the farm. This is an indirect strategy since it reduces the risk that the slurry tank will become full during the closed period and need emptying at a time when the risk of runoff is high. Diverting clean water away from the slurry or dirty water tanks also reduces the size of tank that the farmer needs to comply with regulations.
8.2 Sedimentation ponds for treatment of surface runoff from fields

The strategy

Shallow ponds are constructed in low-lying areas of fields to intercept, store, slow and filter runoff during storm events⁴.

How it works

Sedimentation ponds are constructed in low-lying areas of arable fields, to collect runoff from the field during unusual, high rainfall events. Sediment that has been picked up as water runs off the field, settles in the pond before the overflow runs into surface drains. Sedimentation ponds, like artificial wetlands, are frequently vegetated with water plants (rushes, reeds etc.) which take up nutrients from the water, thereby purifying it. Denitrification is also facilitated in these ponds. The picture to the left shows a recently constructed sedimentation pond at Newcastle University’s Nafferton Farm.

The aerial photo below shows a plan for a proposed sedimentation pond, indicating that in addition to pond construction, there will also be a need for bunds (A & D) to divert water and prevent overflow and a structure to facilitate exit of the water into a surface drain (C)⁵.

⁴ More details on farm scale engineering solutions to control water pollution from agriculture and the development of Farm Integrated Runoff Management (FIRM) plans, can be found at: http://research.ncl.ac.uk/iq/Proactive/FIRM.html

Regions and systems of applicability

This method is suitable for all regions of Europe, but especially applicable in regions where short-term, high intensity rainfall events cause excessive surface runoff from fields. However, ponds should not be constructed on freely-drained soils as they will promote the leaching of nitrates to groundwater.

Cost

Costs for sedimentation ponds will vary, depending on the complexity of the landscape and hydrology of the area. There will be an initial cost to dig the pond, construct bunds around the edges to increase water retention, and install an exit flow structure.

Effectiveness

The effectiveness of these ponds at removing nitrates from water is not yet fully proven, however, it is assumed that reductions in nitrate concentration will occur, due to denitrification.

Other considerations

Pollution swapping is a risk with this method i.e. denitrification, if not complete, can lead to the production of nitrous oxide.

Ideally, fields should be managed so that runoff does not contain sediment (i.e. maintenance of surface cover and good soil structure) or nutrients (i.e. incorporation of fertilizers and manure soon after application). However, even when best management practices are in place, exceptional storm events can occur which result in the movement of sediment and nutrients off the field in runoff water. For this reason, the installation of a sedimentation pond is recommended.
8.3 Artificial wetlands for dirty water treatment

The strategy

Artificial, constructed wetlands physically filter dirty water and use biological processes (plant uptake, denitrification) to remove nutrients from wastewater from farmyards, milk house cleaning, and silage effluent. They may also be used to treat water that has been separated from slurry. They may include wetlands with surface (overland) flow or subsurface (percolation) flow.

How it works

Water flows through the wetlands slowly, allowing heavier particles to settle. Artificial wetlands are frequently vegetated with aquatic plants (*Phragmites australis*, rushes, reeds etc.) which take up nutrients from the water, thereby purifying it. Microbial communities in the wetland process plant nutrients and contribute to reductions in levels of nitrates, through denitrification.

Regions and systems of applicability

Artificial wetlands should only be constructed on soils that have moderate or poor drainage, since they could become a source of nitrate flow to groundwater if constructed on more permeable soils.

They should be applicable in all regions of Europe.

Cost

Artificial wetlands can be difficult and expensive to build. Costs for their construction were estimated in Defra’s User Manual (2007), and are shown in the table below:

<table>
<thead>
<tr>
<th>Costs for farm system</th>
<th>Arable</th>
<th>Dairy</th>
<th>Beef</th>
<th>Broilers</th>
<th>Pigs (indoor)</th>
<th>Pigs (outdoor)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital cost £/farm</td>
<td>36,100</td>
<td>18,040</td>
<td>12,030</td>
<td>52,580</td>
<td>3,540</td>
<td>n/a</td>
</tr>
<tr>
<td>Annual cost £/ha</td>
<td>13.3</td>
<td>12.8</td>
<td>12.8</td>
<td>13.3</td>
<td>13.3</td>
<td>13.3</td>
</tr>
<tr>
<td>Annual cost £/farm</td>
<td>3,880</td>
<td>1,830</td>
<td>1,280</td>
<td>5,780</td>
<td>940</td>
<td>11</td>
</tr>
</tbody>
</table>

Effectiveness

Artificial wetlands can be considered an “end of pipe” solution to water pollution from agriculture. Ideally, nutrients should be fully recycled on the farm and not treated as a waste product.

Defra’s User Manual (2007) estimates that installing an artificial wetland on an arable farm on a clay loam soil could reduce its N losses annually from 47 kg N/ha to 10 kg N/ha with even higher reductions occurring for indoor pig operations who could reduce their losses from 74 kg N/ha to 12 kg N/ha.
Other considerations

Much of the reduction in water nitrate contents in artificial wetlands occurs via the process of denitrification. Evidence suggests that wetlands can be large emitters of nitrous oxide, a by-product of the denitrification process. Therefore, the use of artificial wetlands should be seen as a last resort for removal of nitrates, when all other avenues to conserve and recycle available N on the farm have been exhausted.
8.4 Riparian buffer strips

The strategy

Establish a vegetated strip adjacent to streams and wetlands.

How it works

Riparian buffer strips slow down the rate of water runoff from the field, allowing the water to infiltrate the soil (entering subsurface flow) where it is more susceptible to uptake by plants and denitrification by soil microorganisms. Riparian buffer strips also work to a lesser extent by filtering particulate forms of nitrogen out of the surface flow. Buffer strip width is a key factor determining the efficiency of N removal from runoff water; in general, the wider the strip, the better the removal of N. Researchers in The Netherlands concluded that a 5 m wide strip was ineffective. High degrees of removal are generally associated with strips from 20 to 50 m in width. Vegetation type on the buffer is also important, with trees or mixtures of trees and grass being more effective than grass alone.

Regions and systems of applicability

This method should be applicable in all regions of the European Union, but is particularly appropriate in areas with periods of high rainfall and on land with a slope, which makes the erosion risk high.

Cost

The primary cost associated with the implementation of this measure will be the opportunity cost of the land taken out of arable crop production.

Effectiveness

Riparian buffer strips can remove very high percentages of nitrogen from inflowing water (on average over two-thirds); however, their effectiveness is dependent on a range of factors (width, vegetation type) as well as site-specific characteristics (soil type, subsurface hydrology and subsurface chemistry).

Other considerations

It is notable that while buffer strips are usually effective when new, their efficacy may decrease as they age.

Buffers should be protected against soil compaction that might inhibit infiltration or disrupt water flow patterns.

The amount of denitrification from buffer strips is still uncertain; therefore they increase the risk of pollution swapping. Buffer strips are a final defense against water pollution. Ideally, field management should be optimized so that water leaving the field contains a minimum amount of pollutants.
Fenced riparian buffer strip at Newcastle University’s Nafferton Farm; Image Nafferton Ecological Farming Group.