POLLUTANT LOSSES FOLLOWING ORGANIC MANURE APPLICATIONS IN THE MONTH FOLLOWING THE END OF THE CLOSED PERIOD

Report for Defra Project: WT0932

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1 EXECUTIVE SUMMARY

The overall objective of this project was to assess the effect of the current Nitrate Vulnerable Zone (NVZ) ‘closed spreading periods’ in England and Wales for reducing nitrate leaching losses to ground and surface waters, and the implications of extending the ‘closed periods’ on losses of nitrate and other pollutants (i.e. ammonia and nitrous oxide emissions to air, and ammonium, phosphorus and microbial pathogen losses to water) and associated socio-economic costs to farm businesses.

Data synthesis. A review of recently completed and ongoing UK research projects, where the effects of manure application timing on pollutant losses to water and air were studied, has confirmed that autumn manure applications present the greatest risk of nitrate losses in drainage waters. However, the magnitude of the losses depended both on the readily available N content of the applied manures, soil type, crop N uptake in the autumn period and over-winter rainfall volumes following application.

On medium/heavy (i.e. poorly drained) soils, the risks of ammonium-N, phosphorus and microbial pathogen contamination of drainflow and surface runoff waters was highest when slurry applications were made to soils with a soil moisture deficit of less than 20 mm and sufficient rainfall occurred in the 10-20 days after application to initiate drainflow. In most situations, autumn, late spring and summer application timings are likely to pose the lowest risk of ammonium-N, phosphorus and microbial pathogen contamination of drainflow and surface runoff waters.

Ammonia emissions to air following slurry applications were dependent on soil and weather conditions at the time of application, rather than the time of year *per se*. Spring applications to ‘capped’ or ‘slumped’ arable soils, and summer applications to ‘dry’ grassland soils can result in reduced slurry infiltration rates and elevated ammonia emissions. However, where slurries rapidly infiltrate into soils (e.g. following applications to arable stubbles with an open structure) ammonia losses are usually lower. Similarly, direct nitrous oxide emissions following slurry applications reflected differences in soil moisture conditions and temperature, with the greatest losses measured where soil conditions were warm and moist, and crop N uptake in the weeks/months after application was low.

Pollution impacts of extending the closed spreading periods. MANURES-*GIS* outputs were combined with soil and average annual rainfall data to estimate the quantities of manure N applied to each soil type and agro-climatic zone in NVZ areas (i.e. 62% of England and *c.*3% of Wales), and for the whole of England and Wales. Assessments were carried out for 4 scenarios; *viz:*

1. *Baseline* – using manure application timing data from the 2007 British Survey of Fertiliser Practice
2. *Current NVZ Action Plan (AP)* – based on predicted changes in manure application timings as a result of the ‘closed spreading periods’ for high readily available N manures
3. *Month 1* – extending the ‘closed spreading periods’ for high readily available N manures by 1 month in spring (i.e. to 31 January on sandy and shallow soils, and 15 February on all other soils)

4. *Month 2* – extending the ‘closed spreading periods’ for high readily available N manures by 2 months in spring (i.e. to 28 February on sandy and shallow soils, and 15 March on all other soils)

MANNER-*NPK* was used to estimate manure N use efficiencies, ammonia volatilisation and nitrate leaching losses following contrasting pig slurry, cattle slurry, layer manure and broiler litter applications to arable and grassland crops. Both direct and indirect nitrous oxide emissions following the contrasting slurry and poultry manure applications were estimated, using the revised 1996 IPCC inventory methodology. The effects of the contrasting manure management practices on manufactured fertiliser N use (as a result of changes to manure N use efficiency) were also quantified.

The measures included in the current NVZ-AP were predicted to increase manure N use efficiency, compared with the 2007 baseline, by *c.*10%. For cattle and pig slurry, the improved manure N efficiency (3% of total N applied for cattle slurry and 4-5% for pig slurry) was largely as a result of reductions in nitrate leaching losses. For poultry manures, the increased manure N efficiency (4% of total N applied) was mainly due to reductions in ammonia losses as a result of soil incorporation within 24 hours of application. The measures included in the current NVZ-AP were predicted to reduce annual use of manufactured N fertiliser by 3,000 tonnes in current NVZ areas and by 5,200 tonnes for England and Wales.

Total direct and indirect nitrous oxide-N emissions following slurry and poultry manure applications were reduced by 3%, compared with the 2007 baseline, mainly as a result of lower nitrate leaching losses. The lower nitrous oxide-N emissions coupled with increased manure N use efficiency (and resultant reductions in manufactured fertiliser N use) led to an 8% reduction in overall greenhouse gas (GHG) emissions (allowing for savings in manufactured N fertiliser use) - equivalent to annual GHG reductions of 37,000 tonnes CO_2e for current NVZ areas, and 68,000 tonnes CO_2e for England and Wales, compared with the 2007 baseline. Extending the closed periods by 1 month was predicted to further *reduce* annual GHG emissions by 5,000 tonnes CO_2e for current NVZ areas, and 17,000 tonnes CO_2e for England and Wales. However, extending the closed periods by 2 months was predicted to *increase* GHG emissions by 11,000 tCO_2e for NVZ areas, and 17,000 tonnes CO_2e for England and Wales, compared with the 1 month extension. *Note*: any reductions in GHG emissions resulting from extended storage periods and associated improvements in manure N efficiency are likely to be reduced (to a greater or lesser extent) by increases in methane and nitrous oxide emissions during the extended storage period.

The current NVZ-AP was predicted to reduce annual ammonia (NH_3) emissions by 1,900 tonnes NH_3-N for current NVZ areas, and 2,800 tonnes NH_3-N for England and Wales, compared with the 2007 baseline. The emission reductions were mainly a result of the requirement to incorporate slurry and poultry manure applications to bare soil or stubble within 24 hours of application. Extending the closed periods by 1 month was predicted to *increase* ammonia emissions by 400 tonnes NH_3-N for NVZ areas, and 600 tonnes NH_3-N for England and Wales, compared with the 2007 baseline. Extending the closed periods by 2 months was predicted to further *increase* ammonia emissions by 300 tonnes NH_3-N for NVZ areas and 900 tonnes NH_3-N for

England and Wales, compared with the 1 month extension. The higher ammonia emissions from the extended closed periods were mainly a reflection of the estimated increase in the amount of cattle slurry applied to grassland in summer.

The current NVZ-AP was predicted to reduce annual nitrate (NO_3) leaching losses by 1,400 tonnes NO_3-N for NVZ areas, and 2,900 tonnes NO_3-N for England and Wales, compared with the 2007 baseline. Extending the closed periods by 1 month was predicted to further *reduce* nitrate losses by 400 tonnes NO_3-N for NVZ areas, and 1,100 tonnes NO_3-N for England and Wales. However, extending the closed period by 2 months was predicted to *increase* nitrate losses by 300 tonnes NO_3-N for NVZ areas and England and Wales, compared with the 1 month extension. This increase was because of the limited opportunities to spread manures before the establishment of arable crops in spring, which would increase the proportion spread in the autumn.

The current NVZ-AP was predicted to reduce annual P losses by 12 tonnes for current NVZ areas and 28 tonnes for England and Wales, compared with baseline values. Extending the closed periods by 1 month was predicted to reduce P losses by 5% for cattle slurry and 2% for pig slurry applications compared with the current NVZ-AP. Extending the closed periods by 2 months, was predicted to reduce P losses by 7% from cattle slurry and 4%, from cattle slurry applications compared with the current NVZ-AP.

Summary of estimated reductions in GHG, ammonia, nitrate and phosphorus losses for current NVZ areas (62% of England and *c.*3% of Wales) - compared with 2007 baseline

	Current NVZ-AP	Current NVZ-AP closed periods + 1 month	Current NVZ-AP closed periods + 2 months
GHG (t CO_2e)	37,000	42,000	31,000
Ammonia-N (t)	1,900	1,500	1,200
Nitrate-N (t)	1,400	1,800	1,500
Phosphorus (t)	12	22	25
Manufactured fertiliser N (t N)	3,000	2,900	1,700

Summary of reductions in GHG, ammonia, nitrate and phosphorus losses for England and Wales - compared with 2007 baseline

	Current NVZ-AP	Current NVZ-AP closed periods + 1 month	Current NVZ-AP closed periods + 2 months
GHG (t CO_2e)	68,000	85,000	68,000
Ammonia-N (t)	2,800	2,200	1,300
Nitrate-N (t)	2,900	4,000	3,700
Phosphorus (t)	28	45	53
Manufactured fertiliser N (t N)	5,200	5,300	3,300

Economic impacts of extending the closed periods. The costs associated with extra slurry storage capacity were quantified for small, medium and large dairy and pig farms for current NVZ areas, and the whole of England and Wales, using standard industry figures taking into account capital costs and amortised (capital repayment and interest) costs over the life span of the investment. The economic benefits of the current NVZ-AP were compared with 2007 baseline practices for current NVZ areas and for England and Wales, and were quantified in terms of reduced manufactured fertiliser N use (resulting from improved manure nutrient efficiency) and reductions in ecosystem damage costs resulting from abated ammonia-N (£2,100/tonne) and nitrous oxide (£60/tonne CO_2e) emissions, nitrate leaching (£670/tonne nitrate-N) and P (£35,000/tonne P) losses. Baseline storage capacity estimates were based on data from the literature and assumed to be 3 months for cattle slurry and 4 months for pig slurry. *Note:* Baseline estimates of slurry storage capacity are uncertain and at a farm level there will be wide variation in the costs associated with increasing slurry storage capacity.

The capital cost of extending the slurry storage capacity from baseline (i.e. 3 months capacity for cattle and 4 months for pig farms) to comply with the current NVZ-AP was estimated at £290 million for current NVZ areas, and £555 million for England and Wales. Over a 20 year period, improved manure nutrient use efficiency, resulting from the measures included in the current NVZ-AP, was predicted to save 60,000 tonnes of manufactured fertiliser N (worth £60 million) across current NVZ areas. Extending the NVZ-AP to cover England and Wales, was predicted to save 104,000 tonnes (£104 million) of manufactured fertiliser N over a 20 year period. The 20 year savings in ecosystem damage costs (from reductions in GHG, ammonia, nitrate and phosphorus losses) resulting from the measures included in the current NVZ-AP were estimated at £151 million for current NVZ areas, and £259 million for England and Wales. The 20 year cost-benefit ratio of implementing the current NVZ-AP was 1.4:1, compared with 1.5:1 across England and Wales. At a farm level there will be wide variation in the costs associated with increasing slurry storage capacity. For some farms the cost of upgrading slurry storage would be for the whole storage period (i.e. 5 months for cattle slurry and 6 months for pig slurry), as they have little or no existing storage capacity, whereas other farms may already have adequate storage capacity to comply with the current NVZ-AP.

Extending the current NVZ-AP storage periods by a further 1 and 2 months increased capital costs by £135 million and £225 million for current NVZ areas, and £250 million and £430 million for England and Wales, respectively. The cost-benefit ratio of extending the storage periods by 1 and 2 months increased to 2.0:1 and 3.3:1 for current NVZ areas, and 2.1:1 and 3.4:1 for England and Wales, respectively. The additional costs of extending the current NVZ-AP storage periods were *not* reflected in proportional reductions in manufactured fertiliser N use and ecosystem damage costs.

Conclusions

- The measures included in the current NVZ-AP (which cover 62% of England and *c.*3% of Wales) were predicted to reduce annual fertiliser N use by 3,000 tonnes, GHG emissions by 37,000 tonnes CO_2e, ammonia emissions by 1,900 tonnes NH_3-N, nitrate leaching losses by 1,400 tonnes NO_3-N and phosphorus losses by 12 tonnes P (compared with the 2007 baseline) in the current NVZ areas at a capital cost of £290 million.

- Applying the current NVZ-AP across England and Wales was predicted to reduce annual fertiliser N use by 5,200 tonnes, GHG emissions by 68,000 tonnes CO_2e, ammonia emissions by 2,800 tonnes NH_3-N, nitrate leaching losses by 2,900 tonnes NO_3-N and phosphorus losses by 28 tonnes (compared with the 2007 baseline) at a capital cost of £ 555 million.

- The costs of extending the storage periods for high readily available N manures by 1 and 2 months were *not* reflected in proportional reductions in fertiliser N use or ecosystem damage costs.

- Autumn (i.e. August to October) manure application timings present the greatest risk of nitrate leaching losses on all soil types. Applications to drained soils with moisture deficits of less than 20 mm (i.e. typically during winter/early spring) are likely to increase the risks of ammonium-N, P and microbial pathogen losses in drainage and surface runoff waters. Ammonia emissions were highest when soil conditions restricted slurry infiltration into the soil (e.g. ‘wet’ slumped arable soils in spring and ‘dry’ grassland soils in summer). The effects of manure application timing on direct nitrous oxide emissions following slurry application are currently uncertain because of the influence of soil and weather conditions and crop N uptake in the weeks/months after application; on going Defra-funded research is seeking to address this knowledge gap.

2 INTRODUCTION

2.1 Background

In the region of 90 million tonnes of farm manures, supplying 450,000 tonnes of nitrogen (N) and 119,000 tonnes of phosphorus (P) are applied to agricultural land in the UK each year (Williams *et al.,* 2000; Chambers *et al.,* 2000). These applications are a valuable source of plant available nutrients, however, they also pose a significant risk of diffuse pollution of the water (nitrate, ammonium, P and microbial pathogens) and air (ammonia – NH_3 and nitrous oxide – N_2O) environments. The land application of farm manures (particularly slurry) is recognised by the EU Commission as the *main cause of controllable diffuse pollution* in present day farming systems.

The 2008 Nitrate Vulnerable Zone Action Programme; NVZ-AP (SI, 2008; WSI, 2008) which covers *c.*62% and *c.*3% of agricultural land in England and Wales, respectively, restricts the application of manures with readily available N contents greater than 30% of total N (i.e. pig/cattle slurries and poultry manures) on all soil types in the late autumn-winter period. The ‘closed spreading periods’ are designed to minimise nitrate leaching (and other nutrient) losses following manure applications, with the length of the ‘closed period’ varying according to soil type and land use (Table 1).

Table 1. ‘Closed periods’ for spreading manures with readily available N contents greater than 30% of total N

	Grassland	Tillage land
Sandy or shallow soils	1 September to 31 December	1 August to 31 December*
All other soils	15 October to 15 January	1 October to 15 January

*Application is permitted between 1 August and 15 September inclusive, provided a crop is sown on or before 15 September.

It is noteworthy that the end of the ‘closed spreading period’ on free draining (sandy/shallow) soils in England and Wales is 31 December compared with 31 January in the Netherlands and 14 February in Belgium, which are in a similar agro-climatic zone. Moreover, the end of the closed period on poorly drained (medium/clay) soils is 15 January compared with 31 January in Northern Ireland which is in a similar agro-climatic zone. Importantly in an EU context, England and Wales (and Ireland) are dominated by poorly drained soils compared to the predominance of free draining soils in Central Europe.

From a soil and farm management perspective the best time to spread manures, especially on medium and clay soils, is when they are dry and can carry the weight of heavy application machinery (e.g. in summer and autumn) without causing compaction and damage to soil structure, which would be contrary to cross-compliance objectives of maintaining land in Good Agricultural and Environmental Condition.

2.2 Losses to water

The processes controlling nutrient (and microbial pathogen) losses to water are known to vary according to soil type:

Free draining, sandy and shallow soils - drainage occurs slowly over-winter by piston displacement in the unsaturated phase, with wetting fronts moving to depth at rates of a few metres a year depending on drainage volumes and the pore volume of the soil and base rock.

Poorly drained, medium and clay soils - surface runoff is likely to occur in rapid response to rainfall events, because of the impermeable nature of the soil matrix. Where an effective drainage system is present, much of the water that would otherwise be lost as surface runoff, will move rapidly from the soil surface through macropores that have developed naturally or have been created through the installation of pipe drains, mole drains or subsoiling fissures, with transit times influenced by rainfall volume and intensity.

Autumn application timings are likely to increase the risk of nitrate leaching losses on *all* soil types, because crop N uptake during the autumn/winter period is generally low and there is sufficient over-winter rainfall to wash manure derived nitrate beyond crop rooting depth. Targeting manure applications before the establishment of crops that have an autumn N requirement (e.g. oilseed rape) can limit leaching losses, because crop N uptake before the onset of winter drainage will reduce the amount of soil N at risk of leaching.

On soils where water moves slowly to depth (i.e. free draining sandy and shallow soils), the risks of ammonium and P contamination of ground waters is low because the ammonium and phosphorus (P) ions will be adsorbed onto soil surfaces, and in the case of ammonium will be converted to nitrate (and other nitrogen compounds) in the soil profile. On poorly drained medium and clay soils, the risks of ammonium and phosphorus contamination of surface runoff and drainage waters is much greater because of rapid response pathways (e.g. via cracks and drain channels), Plate 1.

Plate 1. Cracks and fissures in clay soils.

Previous research as part of Defra project ES0106 showed that the time period between manure application and the onset of surface runoff/drainage largely controlled the degree of water contamination by nutrients (and microbial pathogens), with factors such as the soil moisture deficit at the time of application and rainfall volumes following application also important (Sagoo *et al.,* 2006; Williams *et al.*, 2007a; Williams *et al.,* 2008).

2.3 Losses to air

Manure application timing has a significant impact on NH_3 volatilisation and N_2O emissions to air (Williams *et al.,* 2007b; Thorman *et al.,* 2007).

Ammonia losses usually occur within a few hours/days of application with soil conditions, slurry dry matter content and weather conditions (i.e. rainfall, windspeed and temperature) all influencing the rate and pattern of losses. On tillage land, autumn slurry application to stubble encourages rapid infiltration into the soil, thereby reducing the potential for NH_3 loss (Williams *et al.,* 2007b). In addition, applications to stubble can be rapidly incorporated into the soil. However, this will increase the pool of mineral N in the soil at risk of nitrate leaching loss. In spring, slurry application to 'capped' tillage soils where infiltration is restricted can lead to elevated NH_3 losses (Williams *et al*., 2005a). On grassland, summer application timings generally present the greatest risks of NH_3 loss because of reduced slurry infiltration rates under 'dry' soil conditions and warmer temperatures, compared with other application timings (Williams *et al.,* 2005b). However, the use of slurry bandspreading / shallow injection techniques can mitigate NH_3 losses to some extent.

Direct N_2O emissions from soil are predominately produced via the microbially mediated processes of nitrification and denitrification. These processes are largely controlled by the soil mineral N content (which is effected by crop N uptake), temperature and moisture conditions. Manure application timing will have a significant impact on both *direct* and *indirect* (i.e. as a result of nitrate leaching and NH_3 losses) N_2O emissions. In autumn, soils are generally warm and dry and crop N uptake following application is likely to be low (except for example where oilseed rape is grown). In spring, soils are generally colder and wetter than in autumn and the potential for crop N uptake will be higher as crop growth commences. These contrasting soil and crop growth conditions will influence the balance of N_2O emissions between autumn and spring application timings. Importantly, to fully quantify N_2O emissions following the application of organic manures it is necessary to consider not just *direct* losses, but also *indirect* losses that occur when N is lost via NH_3 volatilisation or nitrate leaching is subsequently converted to N_2O.

2.4 Farm system implications

On many farms, extending the 'closed spreading periods' will require significant financial investment in extra manure (slurry) storage capacity (Plate 2) with the typical capital cost of a slurry store ranging between £40-£100k (typical slurry storage costs of £40-£50/m^3).

Plate 2. Above ground ‘tin tank’ slurry store.

In addition, investment in slurry bandspreading (e.g. trailing hose and trailing shoe machines; Plate 3) or shallow injection equipment is likely to be required to apply slurry evenly to growing arable and grassland crops in spring/summer, without causing damage to soils and reducing crop quality, and in the case of grassland minimising sward contamination

Plate 3. Trailing hose slurry application to winter wheat (left) and trailing shoe slurry application on grassland (right)

The cost of these financial investments will however be partly offset by increased manure fertiliser N replacement values (resulting from reduced nitrate losses) and increased spreading opportunities for slurry throughout the cropping season. However, the greater slurry storage capacity may also increase NH_3 and methane losses during storage, which needs to be taken into consideration at a whole farm level.

3 OBJECTIVES

The overall objective of this study was to assess the effect of the current NVZ ‘closed spreading periods’ in England and Wales for reducing nitrate leaching to ground and surface waters, and the implications of extending the ‘closed periods’ by 1 or 2 months on losses of nitrate and other pollutants (i.e. NH_3 and N_2O emissions to air and ammonium, P and microbial pathogen losses to water) and associated socio-economic costs to farm businesses.

In more detail, the objectives were:

1. To review data from UK experiments investigating the effects of contrasting manure *application timings* on nitrate, ammonium, P and microbial pathogen losses to ground and surface waters, and NH_3 and N_2O emissions to air.

2. To assess the impact of extending the ‘closed spreading periods’ on water and air emissions from *free draining* (i.e. sandy/shallow) soils and from *poorly drained* (i.e. medium/clay) soils at a farm and national level.

3. To assess the *socio-economic effects* of extending the ‘closed spreading periods’ on typical livestock farms in terms of manure (slurry) storage requirements and benefits to improved manure nutrient utilisation.

4 DATA SYNTHESIS

4.1 Introduction

Data were drawn from current (e.g. ‘Cracking Clays-Water’, ‘Cracking Clays-Air’) and recently completed Defra-funded projects (e.g. OPTi-N) where the effects of application timing on nutrient and microbial pathogen losses to water, and NH_3 and N_2O emissions to air were measured. The synthesis focussed on integrated studies where multiple pollutants and loss processes and pathways (Figure 1) were from both free draining (sandy/shallow) and poorly drained (medium/clay soils). This enabled the implications of different timing strategies for pollutant loss pathways to water and air to be comprehensively assessed.

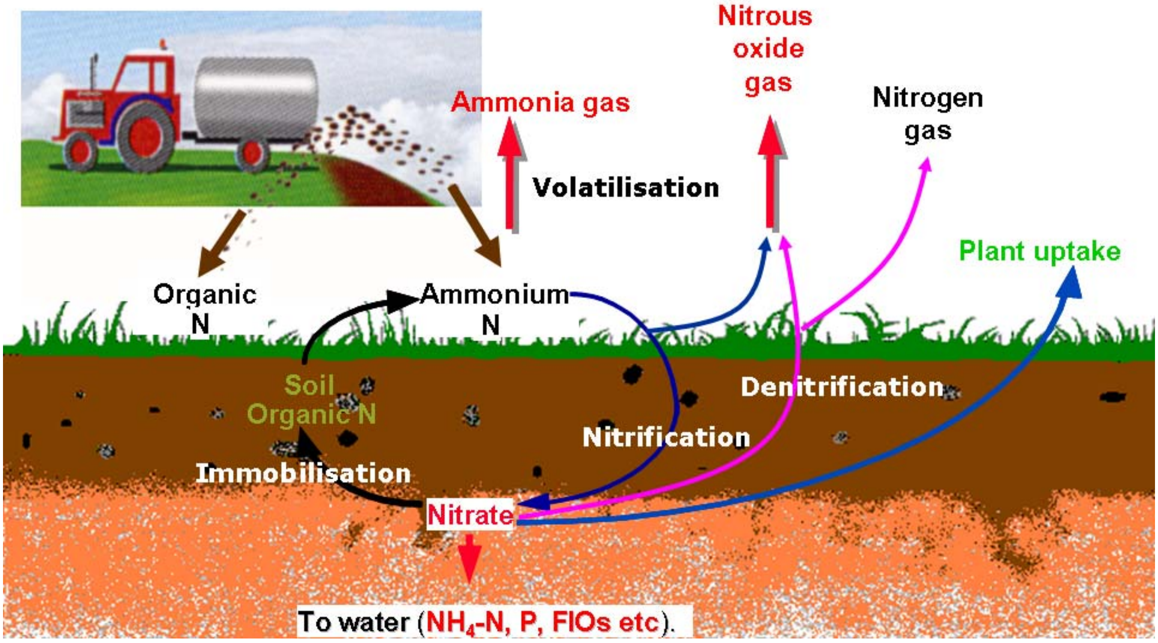

Figure 1. Pollutant loss pathways following organic manure applications

4.2 Key projects

The following projects were key sources of reference:

4.2.1 Defra projects WQ0118 and AC0111 – ‘Cracking Clays-Water’ and ‘Cracking Clays-Air’

Replicated field-scale farming system studies are being carried out (2007 – 2012) at the Faringdon (Oxon.), ADAS Boxworth (Cambs.) and North Wyke Rowden (Devon) Cracking Clays experimental platforms (Figure 2).

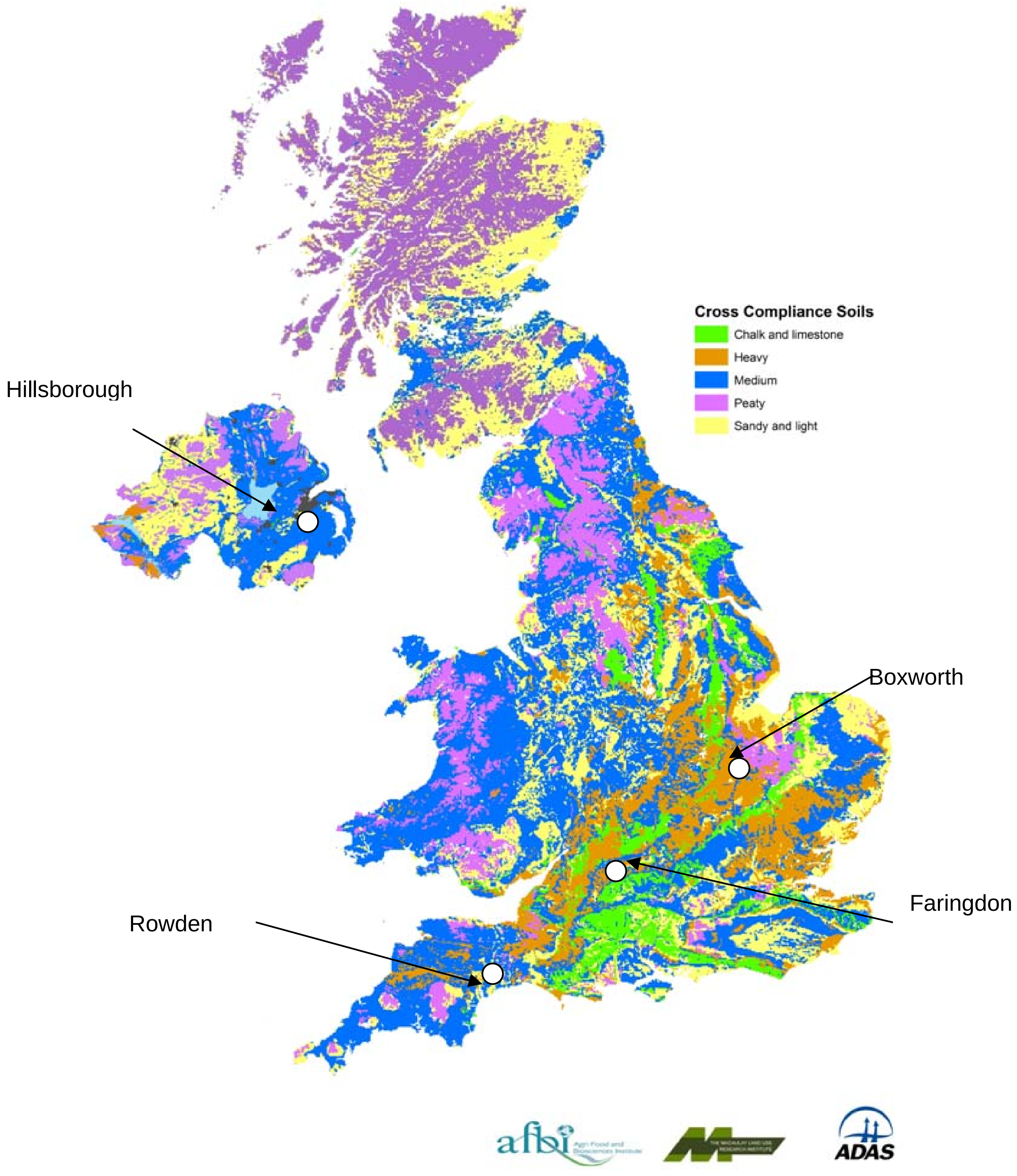

Figure 2. Location of experimental sites on poorly drained (clay) soils

Faringdon (Oxon). At Faringdon, the effects of contrasting cattle slurry application timings on nitrate, ammonium, P, microbial pathogen and sediment losses to water, and NH_3 and N_2O emissions to air are being studied on arable land and grassland in a medium rainfall agro-climatic zone. The site consists of 18 plots (40m x 48 m) on heavy clay soils of the Denchworth Association (54% clay). The site was in continuous arable production for 20+ years, before grass was established on 9 of the plots in 2001.

Boxworth (Cambs). At Boxworth, the effect of contrasting pig and cattle slurry application timings on nitrate, ammonium, P, microbial pathogen and sediment losses to water and NH_3 emissions to air are being studied on arable land in a low rainfall agro-climatic zone. Also, the effect cattle slurry application timing on N_2O emissions is being quantified. The site consists of 27 arable plots (12 m x 48 m) on drained clay soils of the Hanslope Association (35% clay), which have been in arable crop rotation for over 50 years.

Rowden (Devon). At Rowden, the effects of contrasting cattle slurry application timings on drained and undrained grassland on nitrate, ammonium, P, microbial pathogen and sediment losses in drainage and surface runoff waters, and on NH_3 and N_2O emissions to air are being studied in a high rainfall agro-climatic zone. The site consists of twelve 1 ha grassland plots on clay loam soils of the Hallsworth Association, which is typical of much of the permanent grassland in south-west England. Six of the plots are un-drained and six are drained. A slope of between 5-10% allows surface runoff/interflow to be collected in 30 cm deep gravel filled channels from both the drained and undrained plots.

4.2.2 Northern Ireland projects (poorly drained soils)

AFBI Project 0303*:* Hydrological characterisation of a typical drained grassland soil.

This study is investigating factors controlling the initiation of surface runoff from grassland and whether soil moisture deficit (SMD) can be used as an accurate predictor of the occurrence of surface runoff. Detailed measurements of soil moisture, rainfall and surface runoff have been carried out since 2003 at AFBI Hillsborough (Figure 2), where the soil is a slightly gleyed sandy clay-loam.

The experiment consists of six hydrologically isolated 143 x 14 m grassland plots located on a drumlin hillslope with tile drainage (Watson *et al.,* 2000), offering a facility to measure and sample overland flow and subsurface flow. The data reported here were collected from Plot 6, where fine scale monitoring of soil moisture, rainfall, and overland flow was carried out between 2003 and 2006. Surface runoff was recorded at 5 minute intervals (Watson *et al*., 2007) and volumetric soil moisture (VSM) in the root zone was measured at 30 minute intervals at a depth of 6 cm at six locations 20 m apart along the drumlin hill-slope, with continuous measurements of VSM at 10, 20, 30, and 40 cm depths in the soil profile at 30 minute intervals also recorded.

AFBI Project 0351: Interactions between the phosphorus content of cattle manure and losses of phosphorus in surface runoff following manure applications to grassland.

This project investigated how P losses in surface runoff from grassland respond to variations in manure P content, and the timing and seasonality of manure applications. Manure P contents and P concentrations in surface runoff were measured over a range of weather and antecedent soil moisture conditions. Rainfall simulation was used to ensure that runoff was generated at standardised intervals after manure application.

Four slurries were obtained with a range of total P contents. Twenty-five 0.5 m^2 overland flow plots were established on a grassland hillslope (slightly gleyed sandy clay loam soil), with five replicates of each slurry treatment (applied at a rate equivalent to 50 m^3/ha) and an untreated control. Surface runoff was generated by applying simulated rainfall at 40 mm/h, simulating a storm event with a return period of greater than 50 yr.

Immediately before each rainfall simulation, soil temperature and moisture were recorded at five random locations within each plot. Rainfall simulations were conducted for a 30 minute period, and all runoff was collected and analysed for N and P fractions. The experiment was undertaken on three occasions in 2006 and 2007, with successive surface runoff events generated 2, 9, 28, and 49 days after manure application.

4.2.3 Defra project ES0115 – OPTi-N (free draining soils)

The objective of this project was to develop practical slurry application timing strategies to minimise N losses to the air and water environments. Experiments were carried out on four commercial farms: Horsewold Farm, East Yorkshire (pig slurry on arable crops); Grange Farm, Cheshire (cattle slurry on grassland and arable crops); Berrowsfield Farm, Worcestershire (cattle slurry on grassland) and Holt Farm, Somerset (cattle slurry on grassland), covering a range of soil and climatic conditions, and over 3 cropping seasons (2003-2005, Figure 3). Slurry was applied at different timings using commercially available trailing hose (arable crops and grassland), trailing shoe (grassland) and shallow injection (grassland) equipment. At each site, there were 3 replicates of each application timing and an untreated control, arranged in a randomised block design. Plot sizes were either 24 m x 24 m or 21 m x 21m to fit the width of the application machinery at each farm.

Ammonia emissions (all treatments) were measured using the micrometeorological mass balance technique and N_2O emissions (selected treatments) using the static chamber technique. Nitrate leaching losses were measured using porous ceramic cups, following autumn/winter slurry application timings on the free draining soils at Horsewold, Grange and Holt Farms.

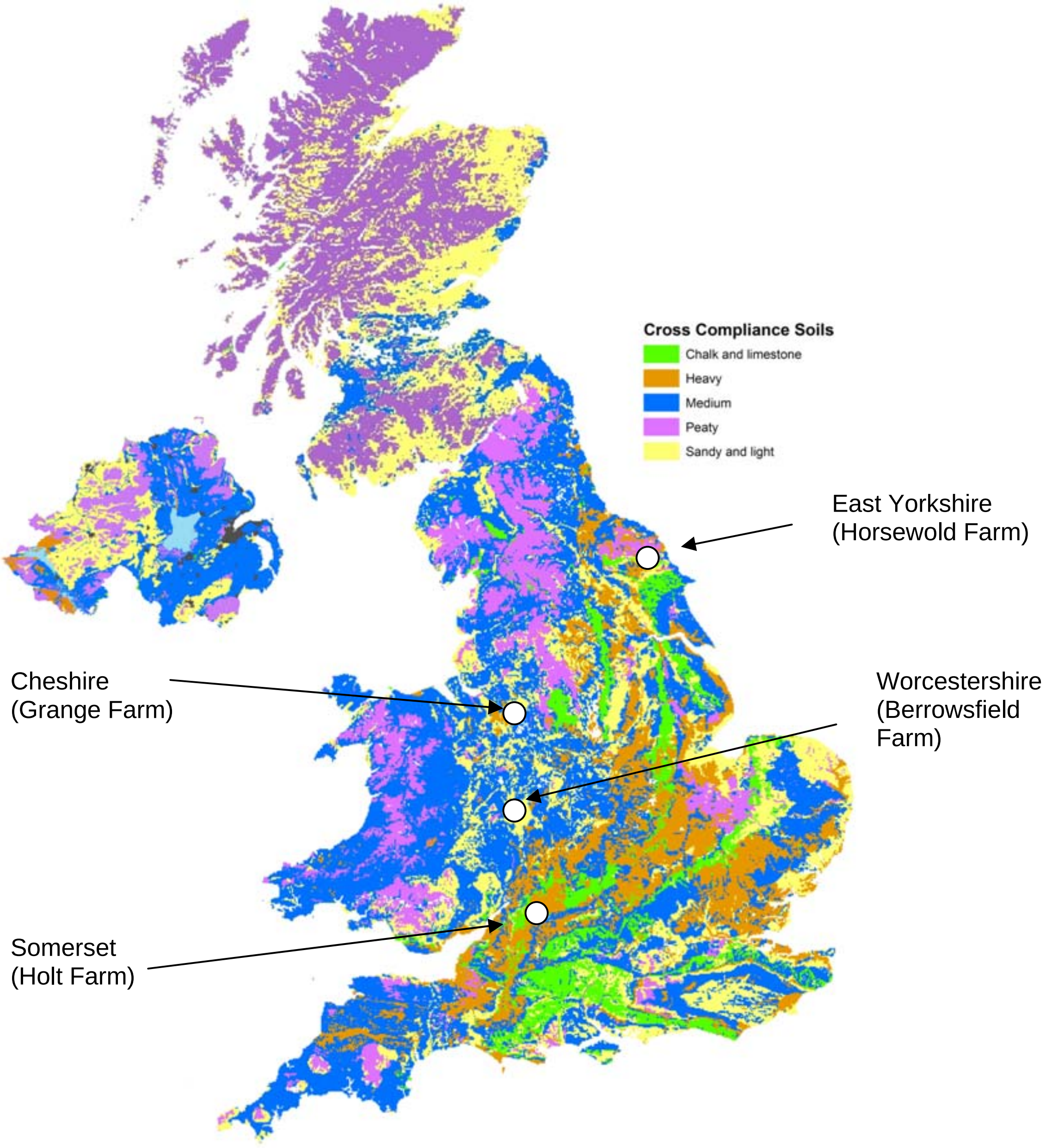

Figure 3. Location of OPTi-N experimental sites (free-draining soils)

4.2.4 Other projects

Other projects referred to in the data synthesis include:

- ES0106: Developing integrated land use and manure management strategies to control diffuse nutrient losses from drained clay soils: *BRIMSTONE-NPS*

4.3 Losses to water

4.3.1 Poorly drained soils

i) Nitrate leaching losses

Defra Project ES0106 (Brimstone-*NPS*). Initial studies from 2002 to 2006 at Brimstone Farm showed that nitrate losses from the arable plots were greatest ($P<0.05$) following the autumn slurry application timings (equivalent to 8-11% of total slurry N applied) compared with the winter timings (2-6% of total N applied). On the arable reversion grassland plots, mean NO_3-N concentrations were significantly lower ($P<0.05$) than from the arable plots, with slurry application timing having no effect ($P>0.05$) on nitrate losses, which was most probably a reflection of grass N uptake in the autumn and the accumulation of N in soil organic matter reserves.

Defra project WQ0118 (Cracking Clays-Water) - arable. At ADAS Boxworth in 2007/8, drainage water nitrate-N concentrations from the winter wheat crop peaked at the start of drainage (mid-October 2007) at *c*.50 mg/l NO_3-N on the autumn pig slurry and broiler litter treatments, compared with 10-20 mg/l NO_3-N on the other treatments (including the autumn cattle slurry and FYM treatments), reflecting the higher readily available N content of the pig slurry and broiler litter treatments. Drainage water nitrate concentrations from the autumn applied pig slurry were generally higher than those from the early and late spring applications, although concentrations from the early and late spring applications did exceed the EC limit of 11.3 mg/l NO_3-N where there was a rainfall event shortly after application (Figures 4 and 5).

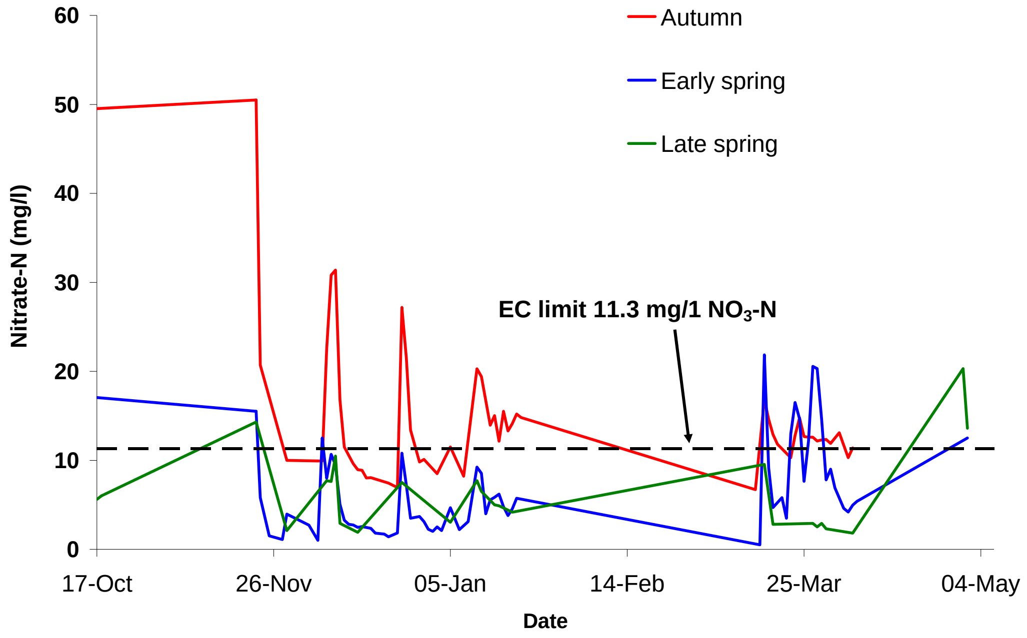

Figure 4. Nitrate-N concentrations in drainflow following pig slurry applications to winter wheat (Boxworth 2007/08)

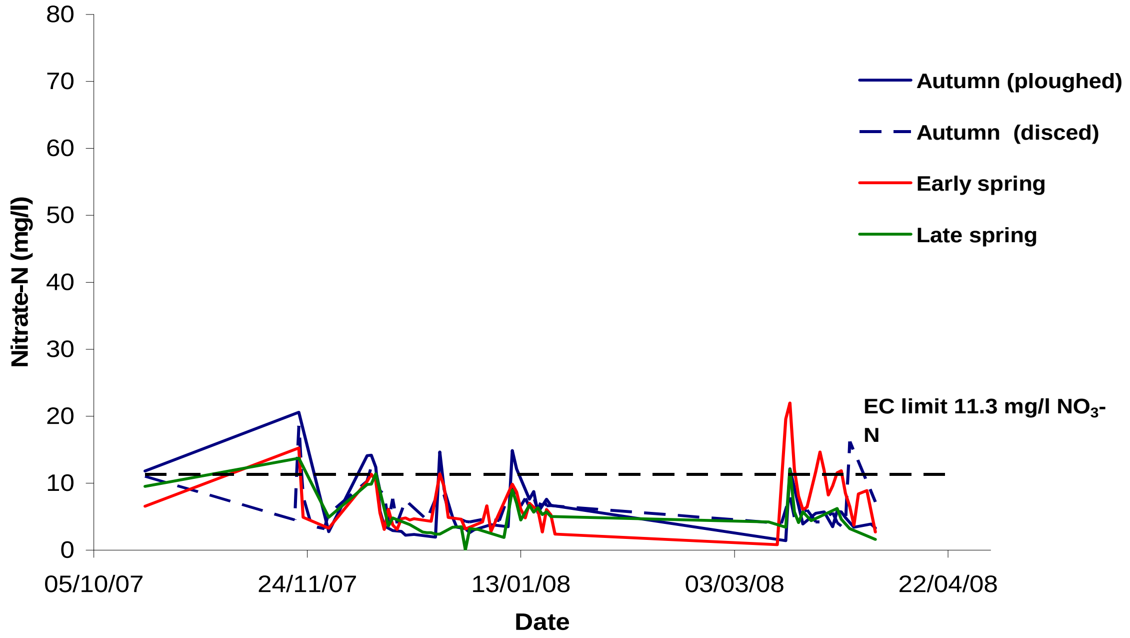

Figure 5. Nitrate-N concentrations in drainflow following cattle slurry applications to winter wheat (Boxworth 2007/08)

At ADAS Boxworth in 2008/9, nitrate-N concentrations in drainage waters following pig slurry, cattle slurry, broiler litter and cattle FYM applications to stubble, prior to the establishment of oilseed rape, and following the post-emergence cattle slurry application, were all below the EC limit of 11.3 mg/l NO_3-N. The post-emergence pig slurry application resulted in elevated nitrate-N concentrations of up to 20 mg/l NO_3-N (Figure 6). However, drainage water nitrate concentrations on all autumn treatments were considerably lower than in 2007/8 (when autumn manure applications were made before the establishment of winter wheat), reflecting N uptake during the autumn/winter period by the oilseed rape crop (Plate 4).

Plate 4. Establishment of oilseed rape at ADAS Boxworth on 21st November 2008 showing the autumn applied pig slurry (left) and nil nitrogen (right) treatments.

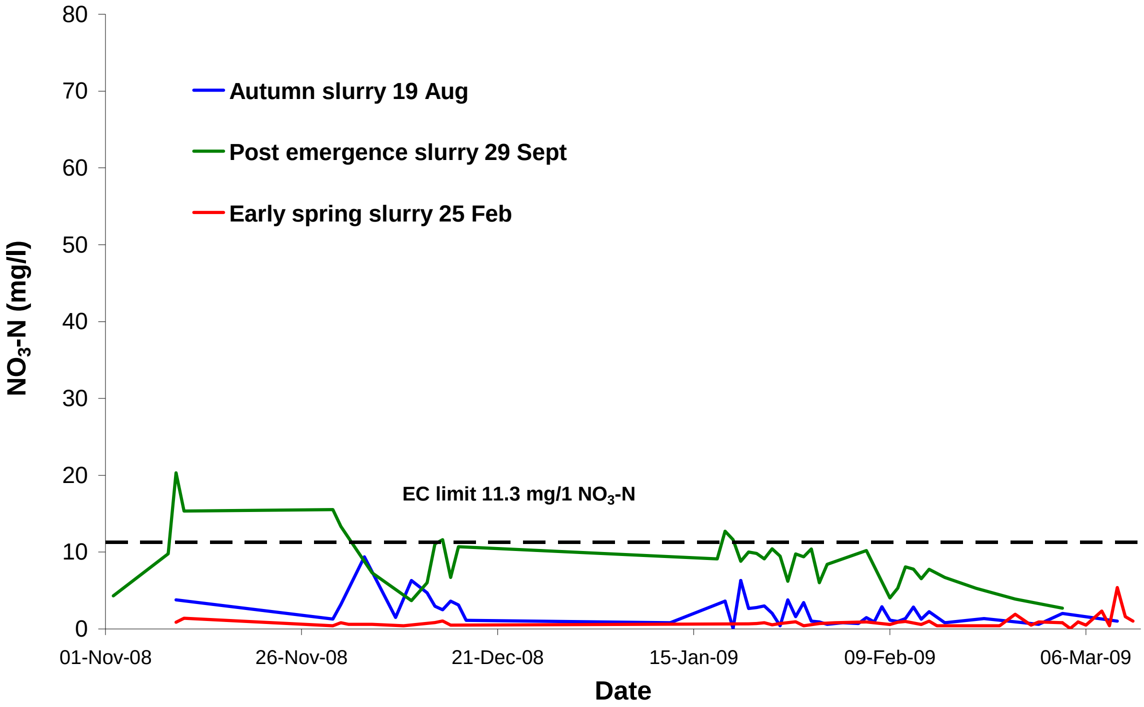

Figure 6. Nitrate-N concentrations in drainflow following pig slurry applications to oilseed rape (Boxworth 2008/09)

In 2009/10 at Faringdon, peak nitrate concentrations in drainage waters following cattle slurry applications in August (on stubble) and in late September (top dressed to the growing crop) ranged between 90mg/l NO_3-N and 75 mg/l NO_3-N, compared with 65 mg/l NO_3-N on the untreated control (Figure 7). The results contrasted with those from the previous harvest season (2008/09) at Boxworth, when nitrate concentrations in drainage waters following August and September cattle slurry applications to oilseed rape were less than 5 mg/l NO_3-N. The high nitrate concentrations at Faringdon probably reflected elevated soil mineral nitrogen contents at the start of winter drainage (115 kg/ha N and 138 kg/ha N on the August and September treatments, respectively). Dry weather during September and October resulted in slow germination and reduced growth of the oilseed rape crop which limited crop N uptake before drainage began, leaving a large pool of mineral N in the soil at risk of leaching. In contrast, oilseed rape establishment at Boxworth in 2008/09 was good and crop N uptake was sufficient to limit the soil mineral N content at the start of drainage to *c.*40kg/ha N following the autumn cattle slurry applications.

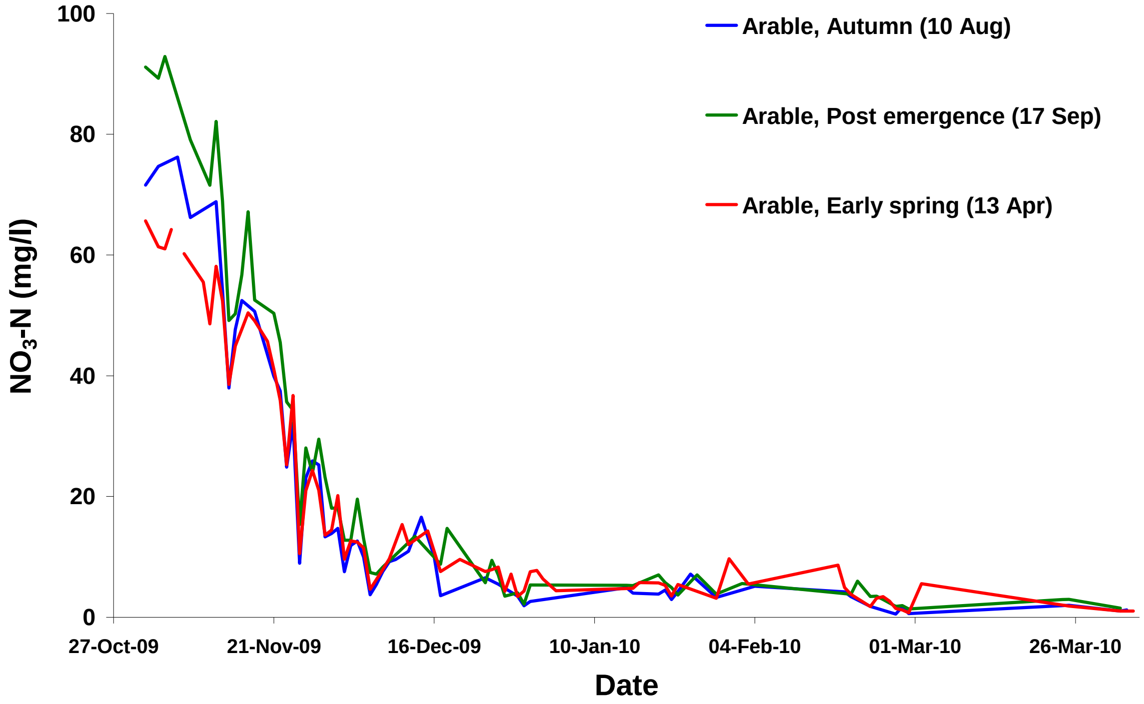

Figure 7. Nitrate-N concentrations in drainage water following cattle slurry applications to winter oilseed rape at Faringdon 2009/10

Defra project WQ0118 (Cracking Clays-Water) – grassland. In 2007/8 at Faringdon, nitrate-N concentrations from the grassland plots peaked at the start of drainage (early October 2007) at *c.*15 mg/l NO_3-N on the autumn slurry treated grassland plots (Figure 8). By early December 2007, nitrate-N concentrations had declined to <1 mg/l NO_3-N. The July 2008 cattle slurry application had no effect on nitrate-N concentrations in drainage water despite 62 mm of rain, and *c.*10 mm of drainage, occurring during the 7 days after application.

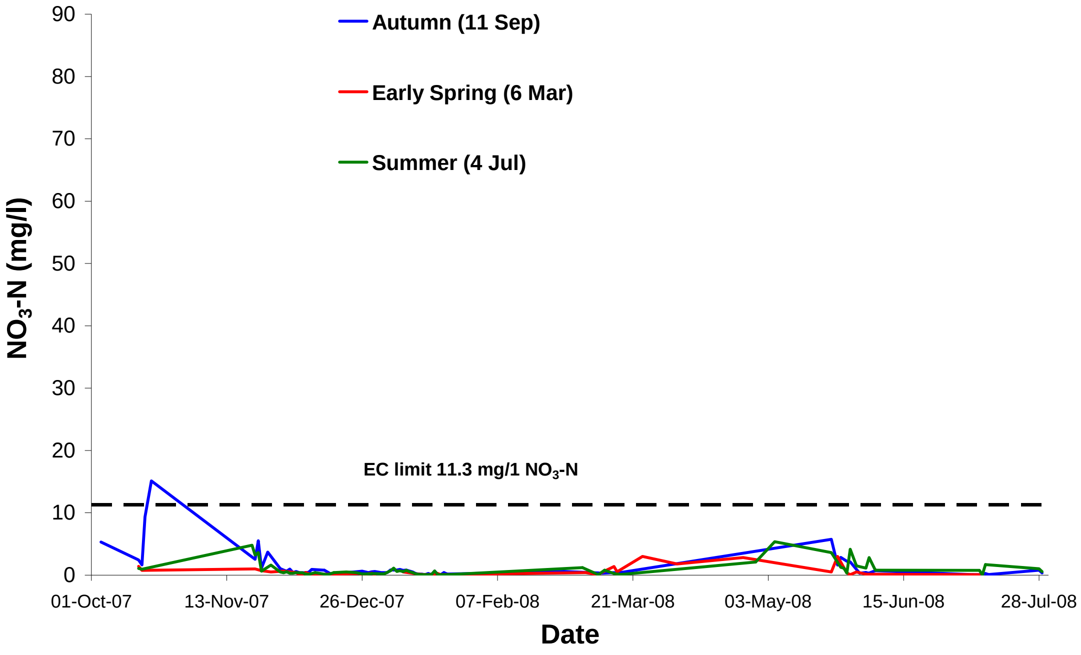

Figure 8. Nitrate-N concentrations in drainage water following contrasting cattle slurry applications to grassland (Faringdon 2007/08)

At Rowden, concentrations of nitrate-N were elevated at the start of drainflow (16-17 October 2007, 1 week following slurry application), and during the first large drainage event in mid-November 2007 (Figure 9). Nitrate-N concentrations in drainflow were higher on the slurry treatments (peak concentration of 14 mg/l NO_3-N) compared with the untreated control (peak concentration of 7 mg/l NO_3-N). Autumn slurry application had no effect on nitrate-N concentrations in surface runoff waters from both the drained and undrained treatments, with concentrations in the range 1-4 mg/l NO_3-N (Figure 9).

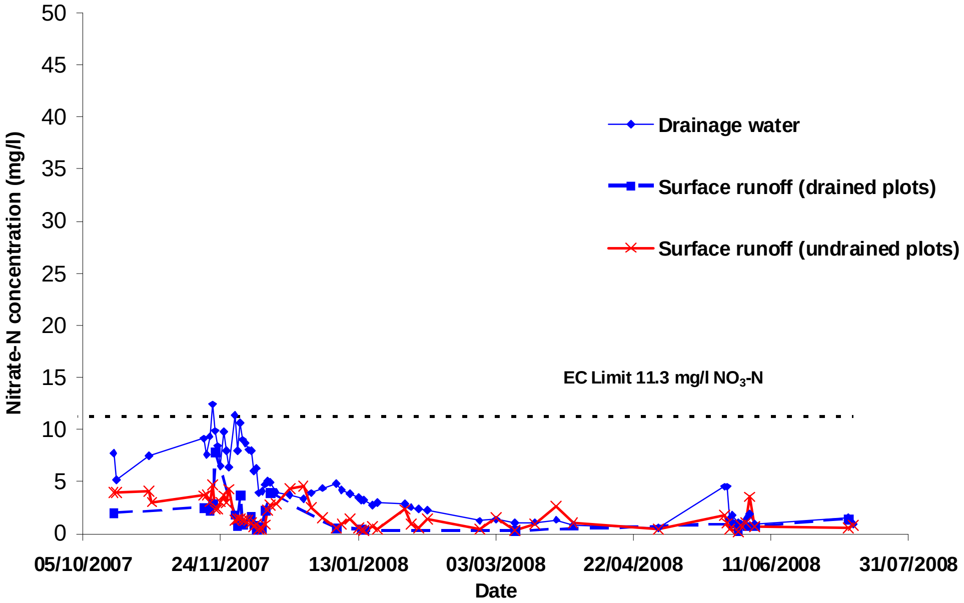

Figure 9. Nitrate-N concentrations following autumn cattle slurry application to grassland (Rowden 2007/08)

ii) Other pollutant losses

Defra Project ES0106 (Brimstone-*NPS*). Work undertaken between 2002 and 2006 at Brimstone Farm showed that autumn slurry application timings had no effect on NH_4-N and TDP concentrations in drainage waters from either the arable or grassland plots, with the exception of elevated NH_4-N concentrations from the grassland plots in autumn 2004. However, elevated NH_4-N and TDP concentrations were measured in drainage waters when slurry applications were made to 'wet' soils (soil moisture deficit <20mm) in winter and spring, and rain (>10 mm) occurred within 10-20 days of application. Mean slurry NH_4-N losses were highest at 0.4 kg/ha NH_4-N (*c.*4-fold greater than background losses) following the winter slurry applications and 0.2 kg/ha NH_4-N following the spring slurry applications to grassland. In contrast, slurry NH_4-N losses from all the arable treatment plots and autumn applications to the grassland were <0.1 kg/ha NH_4-N.

Total dissolved phosphorus (TDP) losses were higher ($P<0.05$) from the grassland than the arable plots in all three study years. Also, TDP losses from the grassland plots were highest ($P<0.05$) following the winter slurry timings compared with the autumn and spring timings. There was no effect ($P>0.05$) of slurry application timing on sediment losses

Defra project WQ0118 (Cracking Clays-Water) – arable. In 2007/8 at Faringdon, rainfall (13 mm) 4 days after slurry application to the arable plots in spring resulted in peak NH_4-N concentrations of 3.3 mg/l (Figure 10) and peak TDP concentrations of 1.2 mg/l (Figure 11).

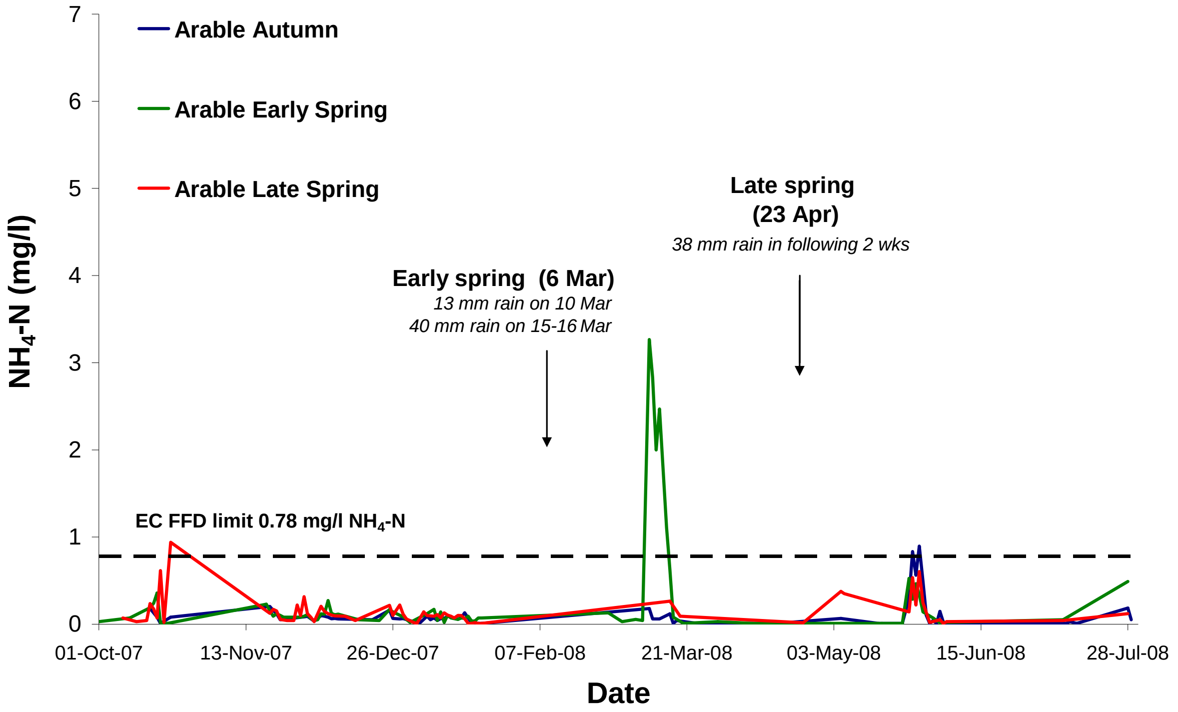

Figure 10. Ammonium-N concentrations in drainage water following contrasting cattle slurry application timings to winter cereals (Faringdon 2007/08)

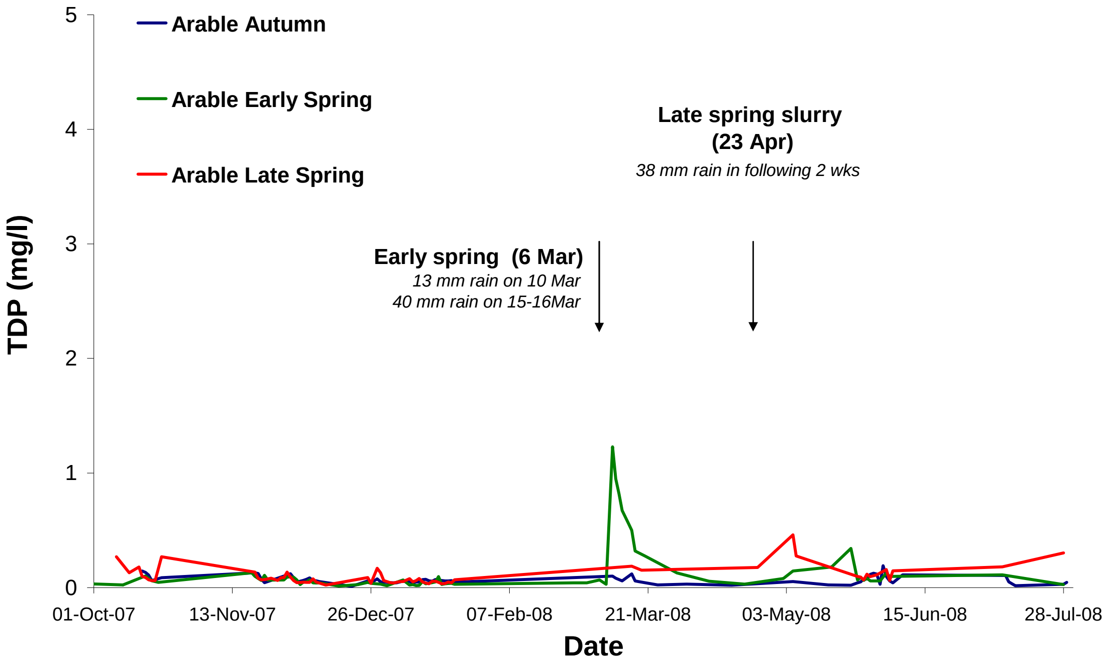

Figure 11. TDP concentrations in drainage water following contrasting cattle slurry application timings to winter wheat (Faringdon 2007/08)

At Boxworth, autumn slurry and solid manure applications had little effect on NH_4-N (Figures 12 and 13), P or *E.coli* drainage water concentrations reflecting the delay between application and the start of drainage. However, the spring pig slurry application increased drainage water NH_4-N concentrations (up to 6.1 mg/l NH_4-N) reflecting the high (*c.*80% of total N) readily available N content of the applied slurry (Figure 12).

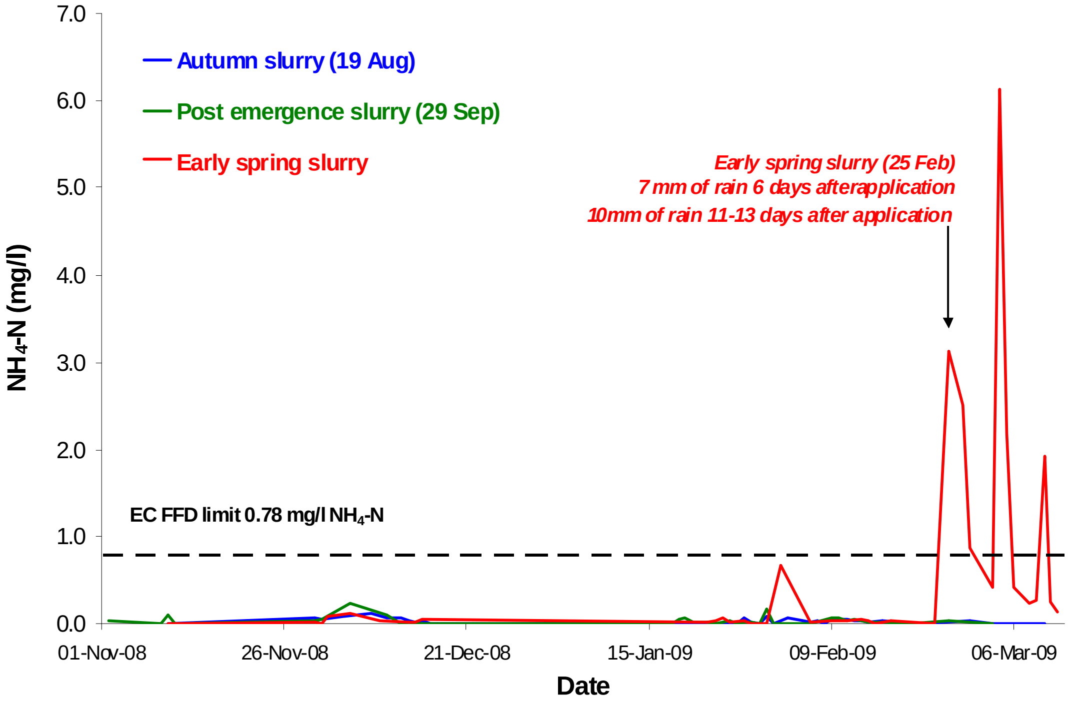

Figure 12. Ammonium-N concentrations in drainflow following pig slurry applications to oilseed rape (Boxworth 2008/09)

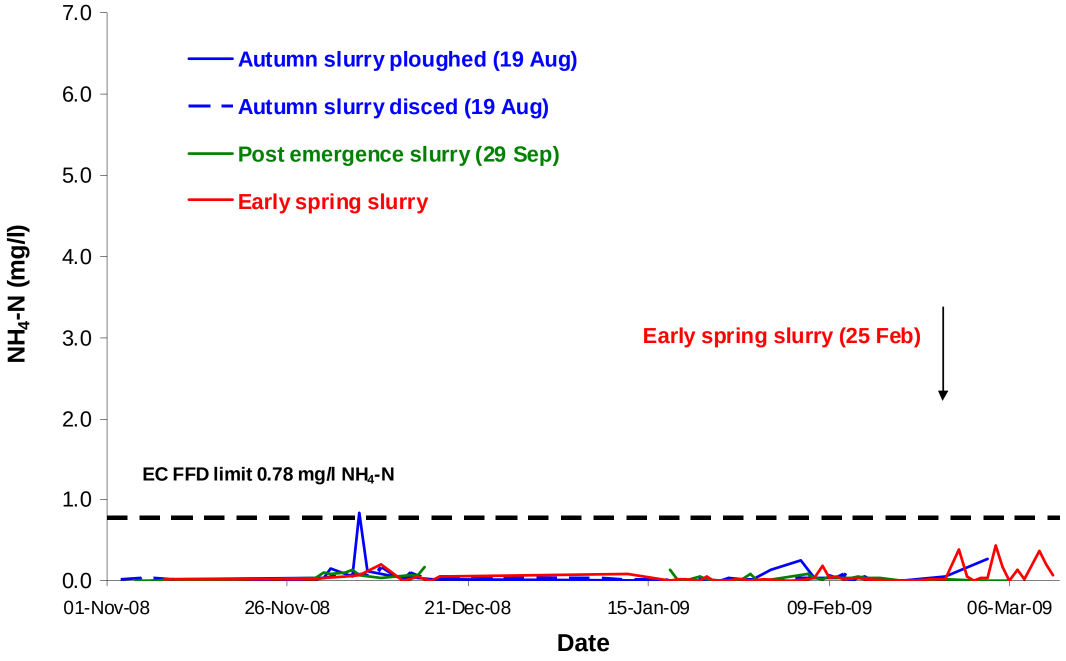

Figure 13. Ammonium-N concentrations in drainflow following cattle slurry applications to oilseed rape (Boxworth 2008/09)

Defra project WQ0118 (Cracking Clays-Water) – grassland. In 2007/8 at Faringdon, rainfall (13 mm) 4 days after slurry application to the grassland plots in the spring resulted in peak NH_4-N concentrations of 5.9 mg/l (Figure 14) and peak TDP concentrations of 4.7 mg/l (Figure 15). Following further rainfall (i.e. 40 mm within 10 days of slurry application) drainage water flows were ‘coloured’ (Plate 5) and had peak NH_4-N concentrations of 2.3 mg/l and peak TDP concentrations of 3.0 mg/l. Higher NH_4-N and TDP concentrations were measured in drainage waters from the grassland than from the cultivated arable plots, which was most probably a reflection of greater connectivity between the soil surface and drains, as a results of ‘by-pass’ flow in cracks/mole channels.

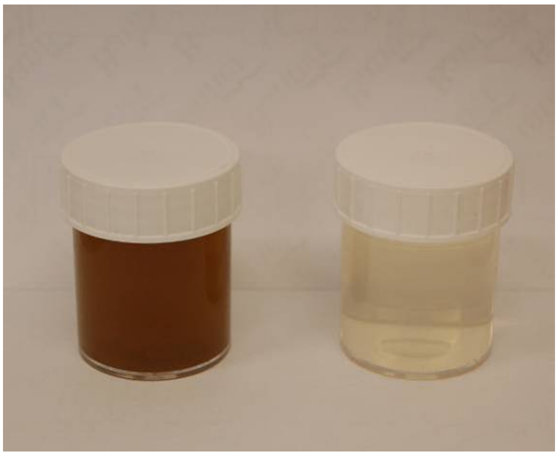

Plate 5. Drainage water samples 10 days after spring slurry application from grassland slurry treated (left) and untreated (right) plots at Faringdon

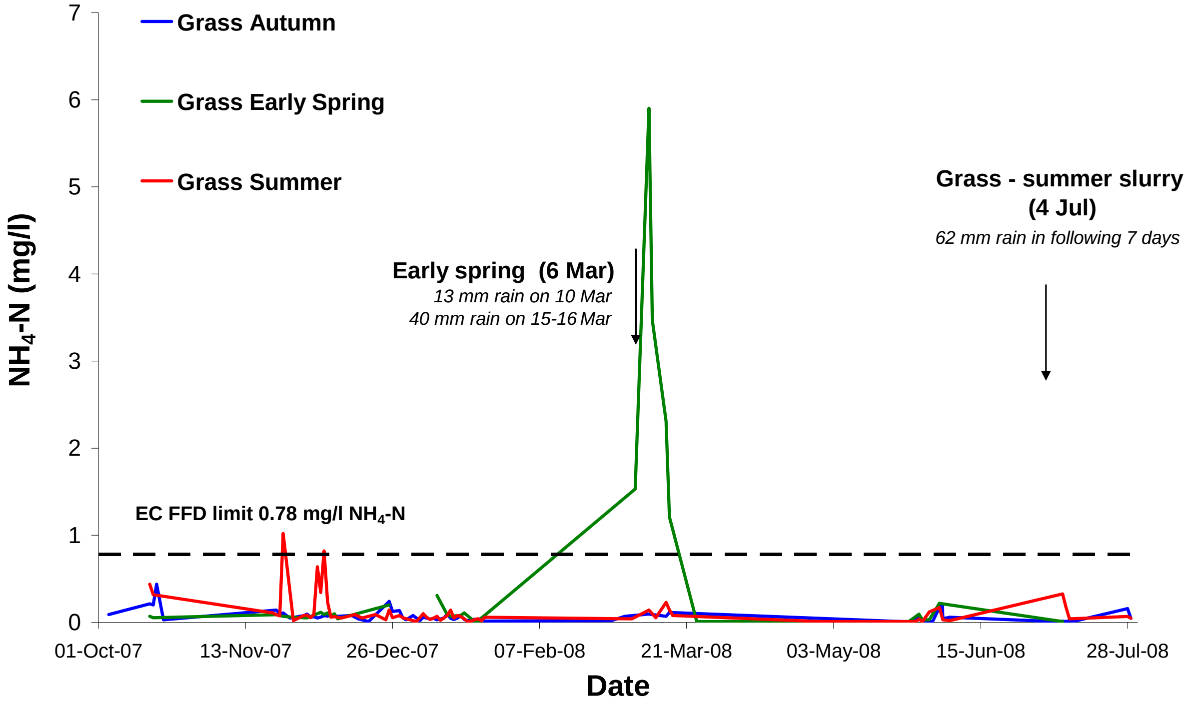

Figure 14. Ammonium-N concentrations in drainage water following contrasting cattle slurry applications to grassland (Faringdon 2007/08)

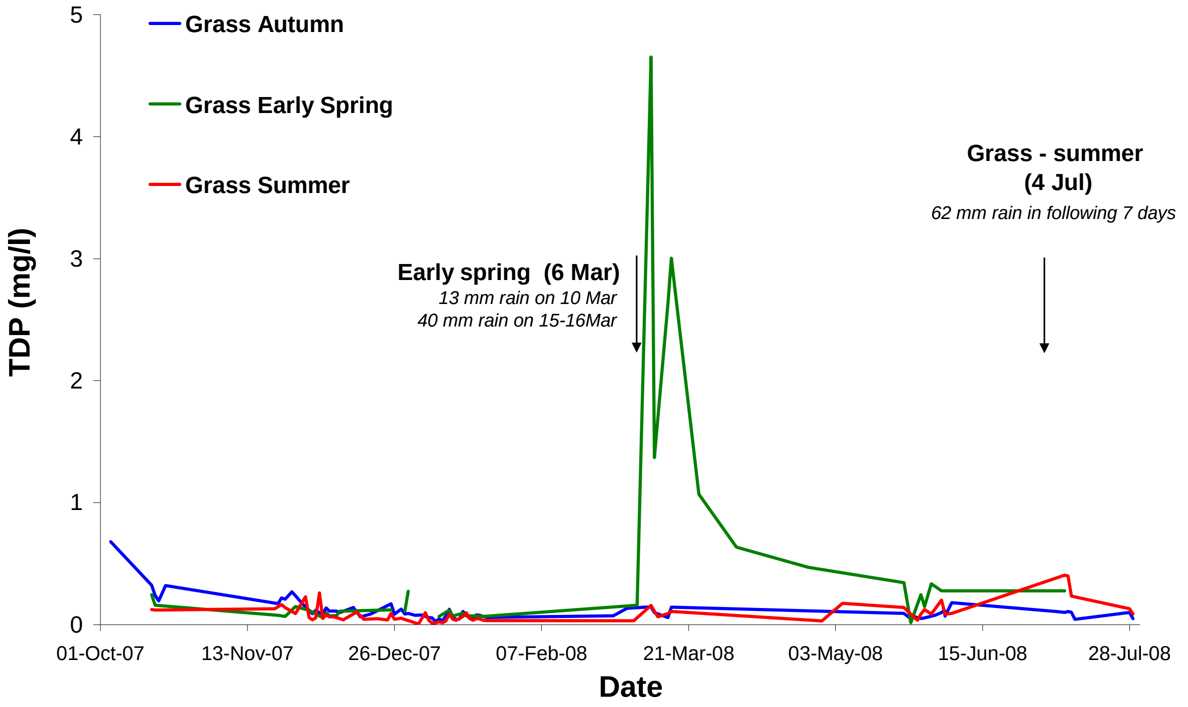

Figure 15. TDP concentrations in drainage water following cattle slurry applications to grassland (Faringdon 2007/08)

At Faringdon in autumn 2008, slurry was applied on 25th September, over 1 month before the start of drainflow and E.coli concentrations in all drainage water samples were generally low (<4 $\log_{10}$ colony forming units-CFU/100ml), Figure 16. This was most probably due to E.coli die off in soil in the month following slurry spreading. In contrast in spring 2008 at Faringdon, where slurry was applied only 4 days before the start of drainflow, E.coli concentrations in drainage water samples from the slurry treated plots were *c.*5 $\log_{10}$CFU/100ml and were higher than those from the untreated control plots (<3 $\log_{10}$CFU/100ml), Figure 17. Drainflow collected 10 days after slurry application had lower E.coli concentrations (<3 $\log_{10}$CFU/100ml).

Previous work has shown that pathogenic micro-organisms (e.g. *E.coli* O157, *Salmonella* and *Campylobacter*) generally survive in soils for up to one month following manure application, with soil concentrations declining over time (Nicholson *et al.*, 2005). Thus, if drainflow occurs soon after slurry or manure application, concentrations of *E.coli* in drainage waters are likely to be higher than if drainflow was delayed, because there will have been less time for die-off in the soil environment.

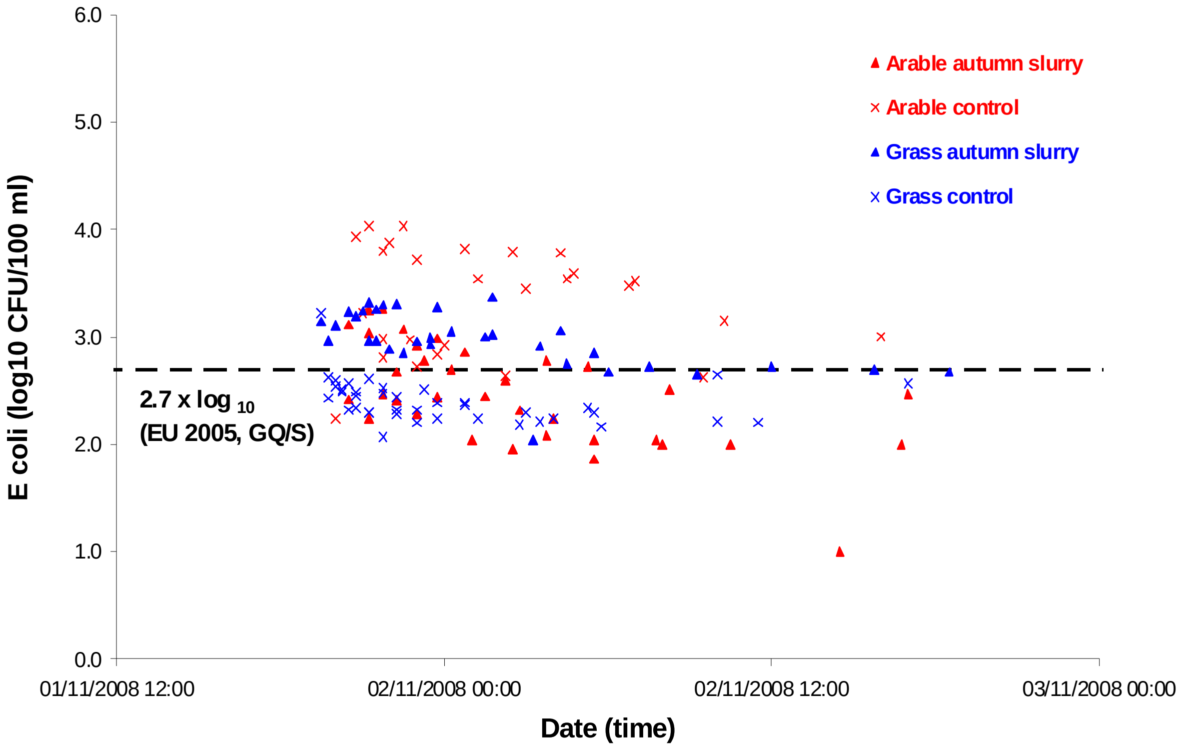

Figure 16. *E. coli* concentrations in drainflow - Faringdon (start of drainflow, 1 November 2008; slurry applied 25 September 2008)

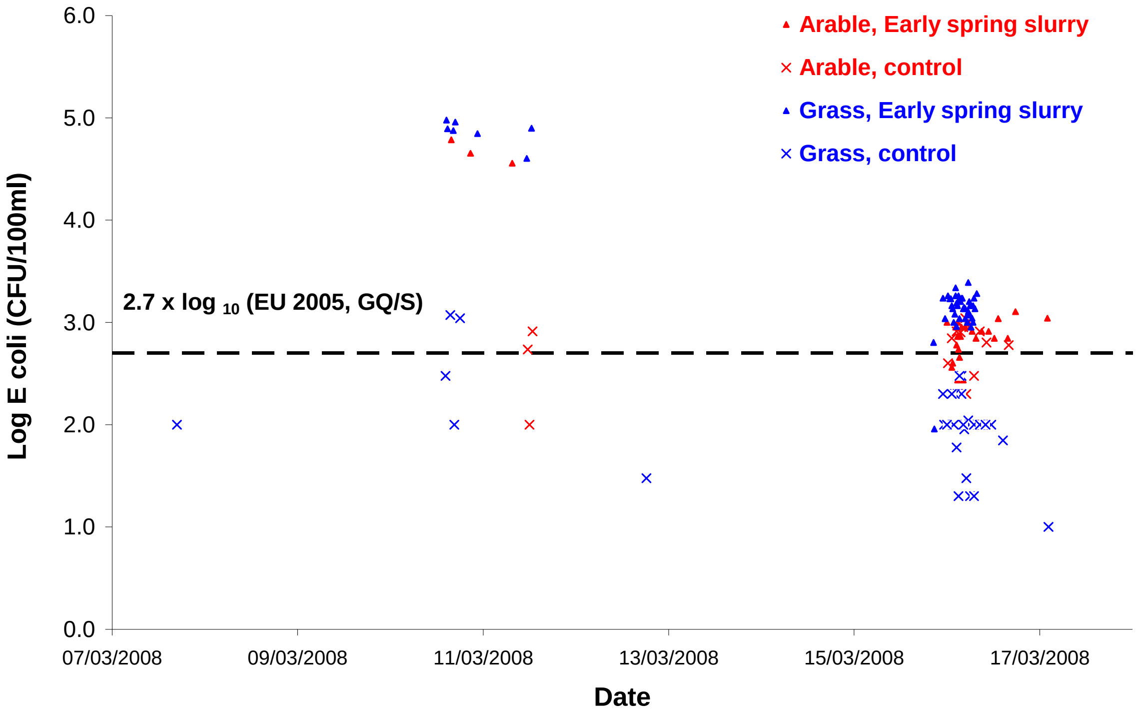

Figure 17. *E. coli* concentrations in drainflow - Faringdon (drainflow, 10 March 2008; slurry applied 6 March 2008)

AFBI Project 0351. The results from this grassland study showed that for all three slurry application timings there was a significant difference between surface runoff total P (TP) concentrations from the slurry treatments and the control (no slurry) treatment when rainfall was applied 9 days after slurry application, although after 28 days there was no longer a significant difference (Figure 18). The decline in P concentrations over time was best described by an exponential relationship, with both the slope and the intercept of the relationship varying between slurry application dates, probably due to variations in the P content of the slurries, soil moisture content on the day of application and antecedent ‘natural’ rainfall.

The results also suggested that surface runoff TP concentrations were higher from slurry applied in October (TP up to *c.*14 mg/l two days after application) and May (TP up to *c.*10 mg/l two days after application) compared with slurry applied in March (TP up to *c.*7 mg/l 2 days after application).

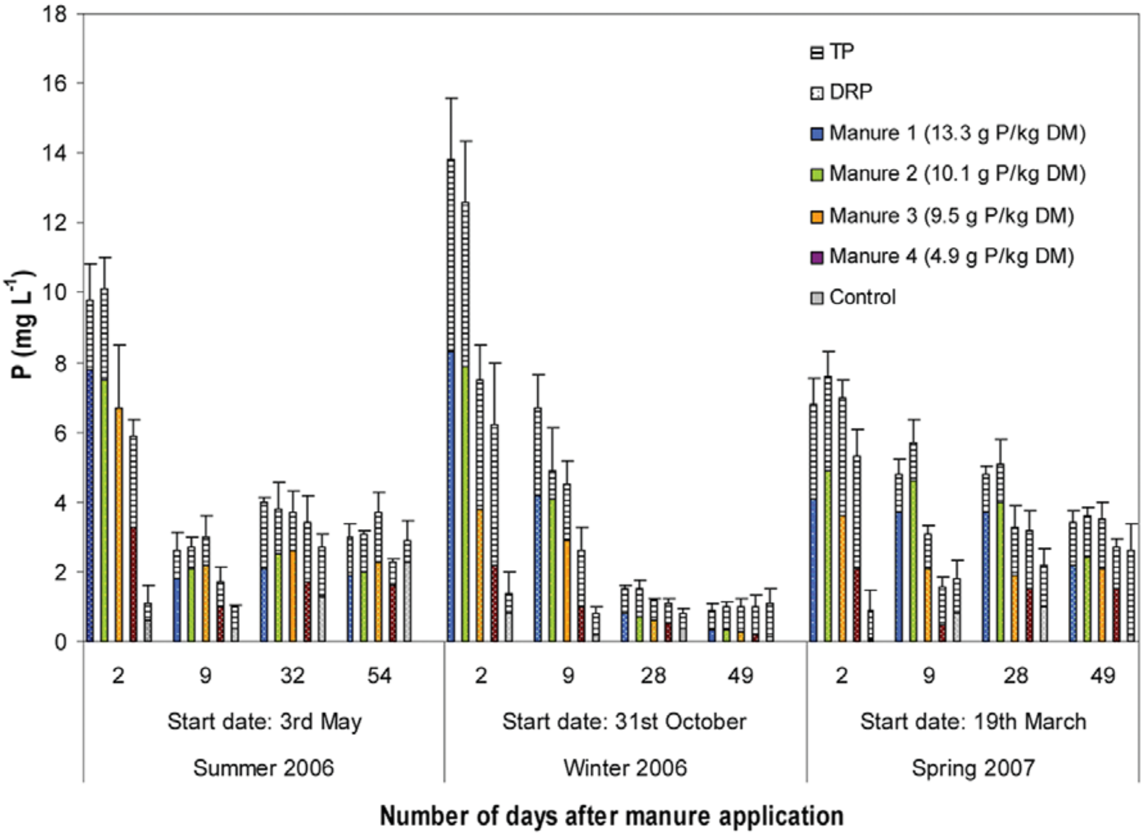

Figure 18. Flow-weighted P concentrations over successive rainfall events in summer, winter and spring following applications of manure with varying P concentrations (O' Rourke *et al.* 2010)

4.3.2 Assessing the risk of pollutant losses to water from poorly drained soils

i) Drainage water

Defra Projects WQ0118 (Cracking Clays-Water) and ES0106 (Brimstone-*NPS*). Data from these two projects were combined to assess the relationship between pollutant concentrations in drainage waters and the time since slurry application. Figures 19 and 20 show that the risks of NH_4-N and P contamination of drainage waters was reduced where drainflow occurred more than 10-20 days after slurry was applied.

In order to minimise the risks of diffuse water pollution, farmers will need to ensure that they have sufficient over-winter slurry storage capacity to provide the flexibility to spread slurry when soils have dried out sufficiently in spring i.e. when the soil moisture deficit (SMD) is >10mm and ideally >20mm (Table 2). The soil moisture deficit is the amount of excess rainfall (i.e. rainfall – evapotranspiration) required to return the soil to field capacity.

Table 2. Risk management guidelines for slurry application timing

Soil moisture deficit (mm)	Risk
>20	Low
10-20	Moderate
<10	High

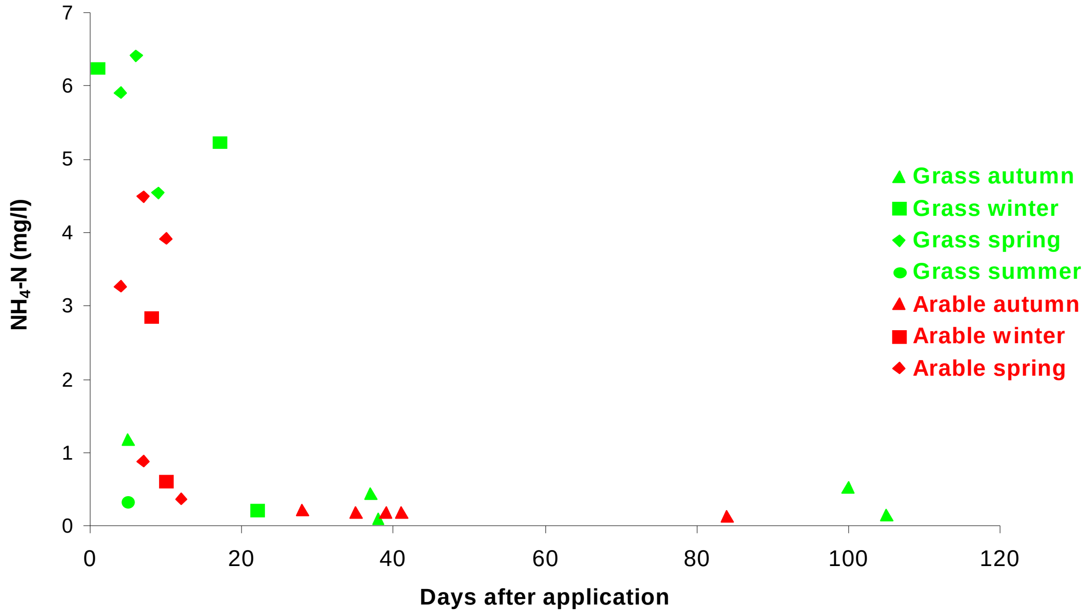

Figure 19. Delay between slurry application and peak ammonium-N concentrations (Defra projects ES0106 and WQ0118)

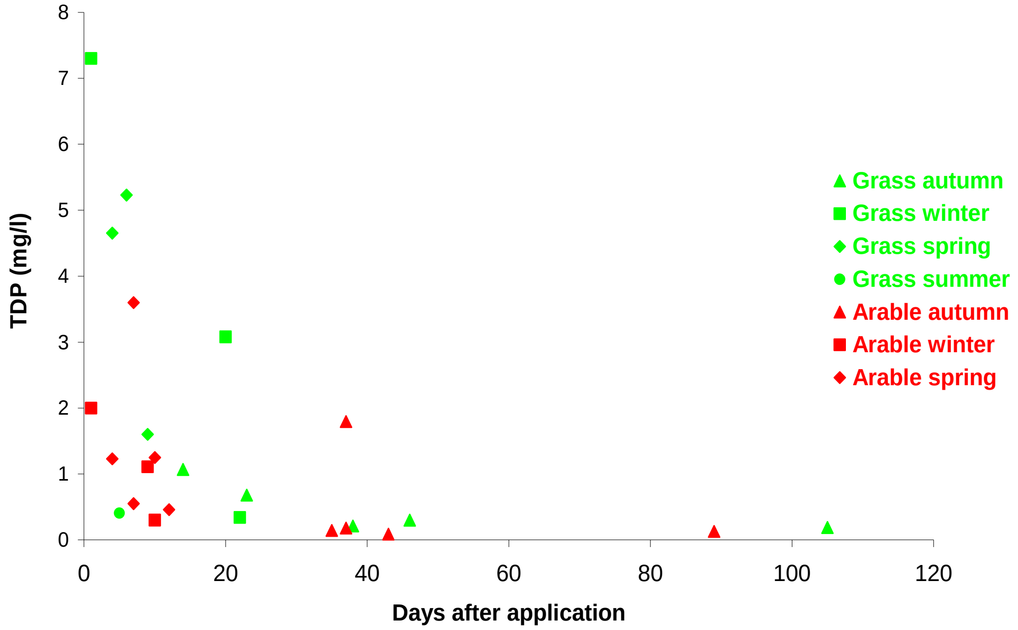

Figure 20. Delay between slurry application and peak TDP concentrations (Defra projects ES0106 and WQ0118)

Typical SMD profiles (Figures 21, 22, 23, 24 and 25), based on 23 years of data from the Irriguide model (Bailey and Spackman, 1996) for Rowden, Faringdon and Boxworth show that there is likely to be a high risk of elevated pollutant concentrations in drainage waters (i.e. the SMD <10mm) between 24th October and 8th April at Rowden (grassland); 2nd December and 24 March at Faringdon (grassland), 3rd November and 6th April at Faringdon (winter cereals) and 31st December and 17th March at Boxworth (winter cereals). Extending the closed spreading period in spring would reduce the opportunity for manure to be applied during the high risk period and the associated risks of diffuse water pollution from elevated ammonium-N, TDP and *E.coli* losses.

ii) Surface runoff

AFBI Project 0303. Of the total volume of surface runoff recorded from this drained grassland soil, 59% occurred during periods when the volumetric soil moisture (VSM) was below field capacity (56%), demonstrating that for poorly drained soils, surface runoff frequently occurs even when the soils are not fully saturated. Volumetric soil moisture content is defined as the volume of soil water as a percentage of the soil volume.

Generally, surface runoff occurred on a higher percentage of days in winter and autumn than in spring and summer. However, surface runoff occurred on average on 14% of days in February compared to 33% of days in May (Table 3). This indicates that whilst the October to January period poses the greatest risk of surface runoff, there is also a significant risk for much of the rest of the year due to high antecedent soil moisture conditions and the unpredictable timing of rainfall events. Although surface runoff occurred on only 14% of days in February, January and February pose the biggest risk of surface runoff, considering the number of days that the soil is close to field capacity. Figure 25 shows that the soil was close to field capacity (i.e. VSM >55%) on *c.*40% of the days in both January and February.

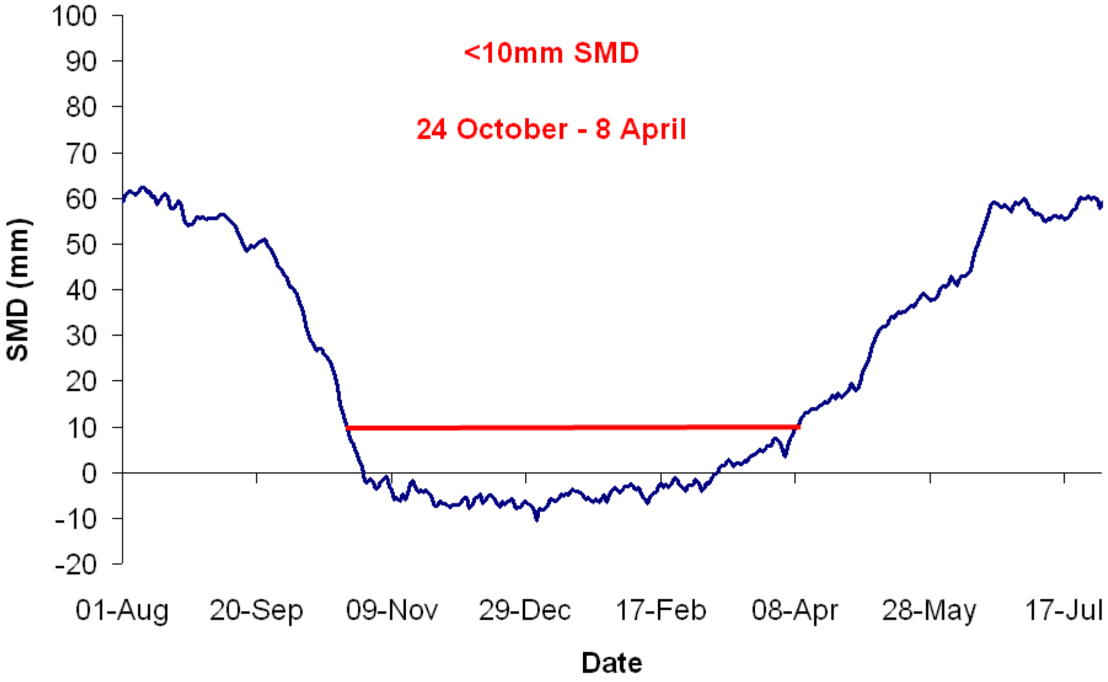

Figure 21. Typical SMD profile – Rowden grass (NVZ closed period end date 15 January)

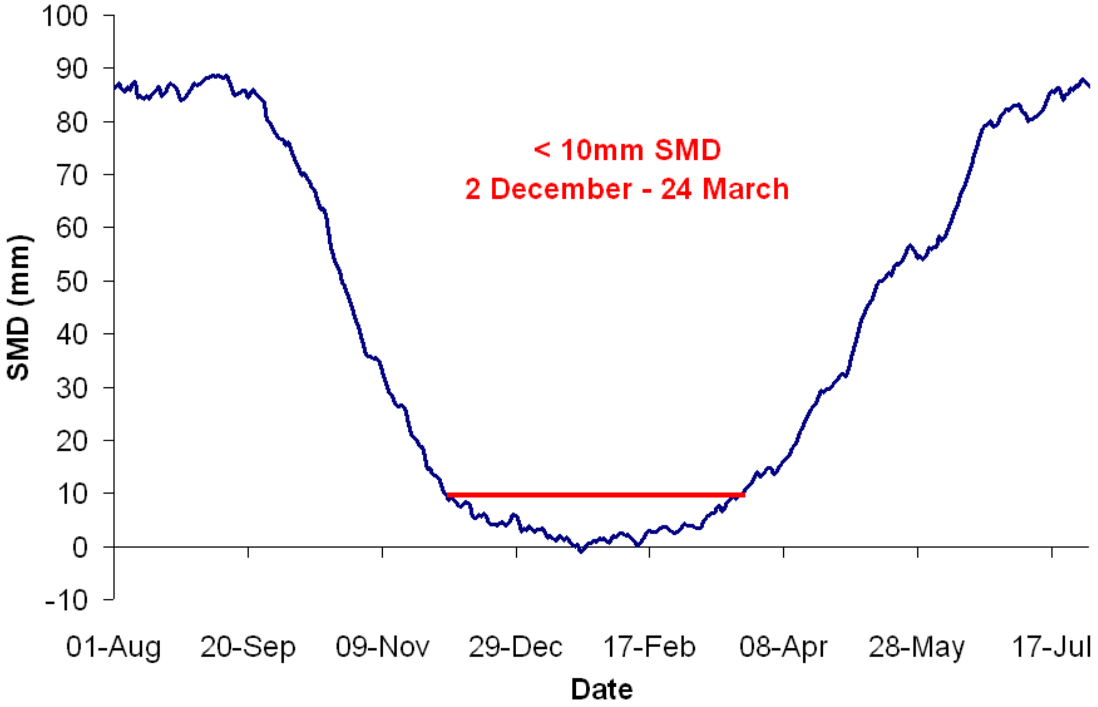

Figure 22. Typical SMD profile – Faringdon grass (NVZ closed period end date 15 January)

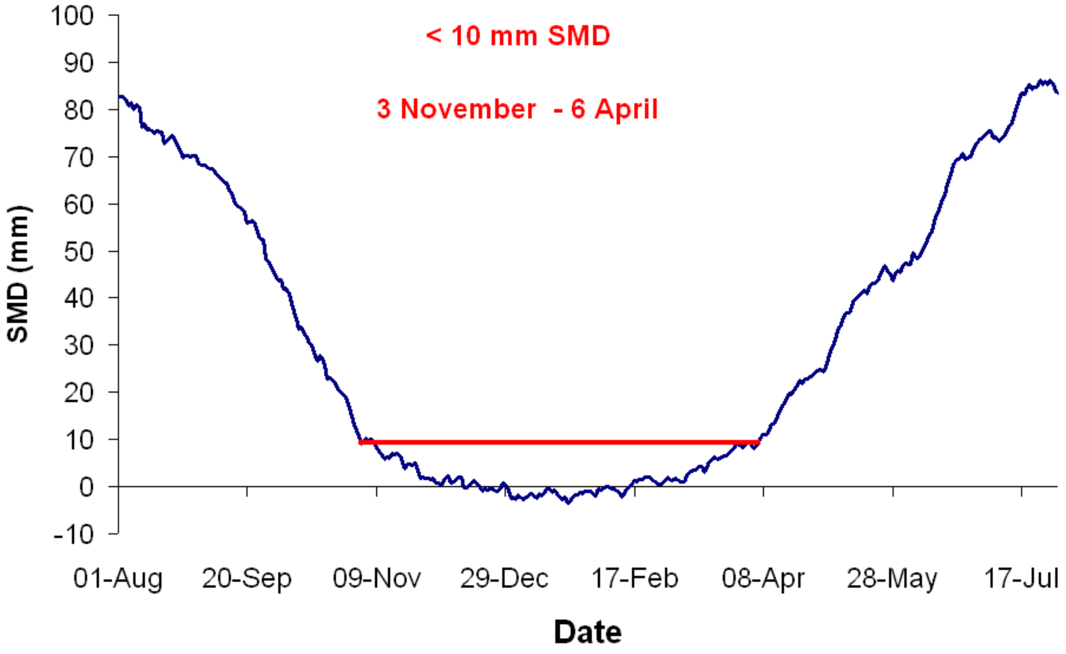

Figure 23. Typical SMD profile – Faringdon winter cereals (NVZ closed period end date 15 January)

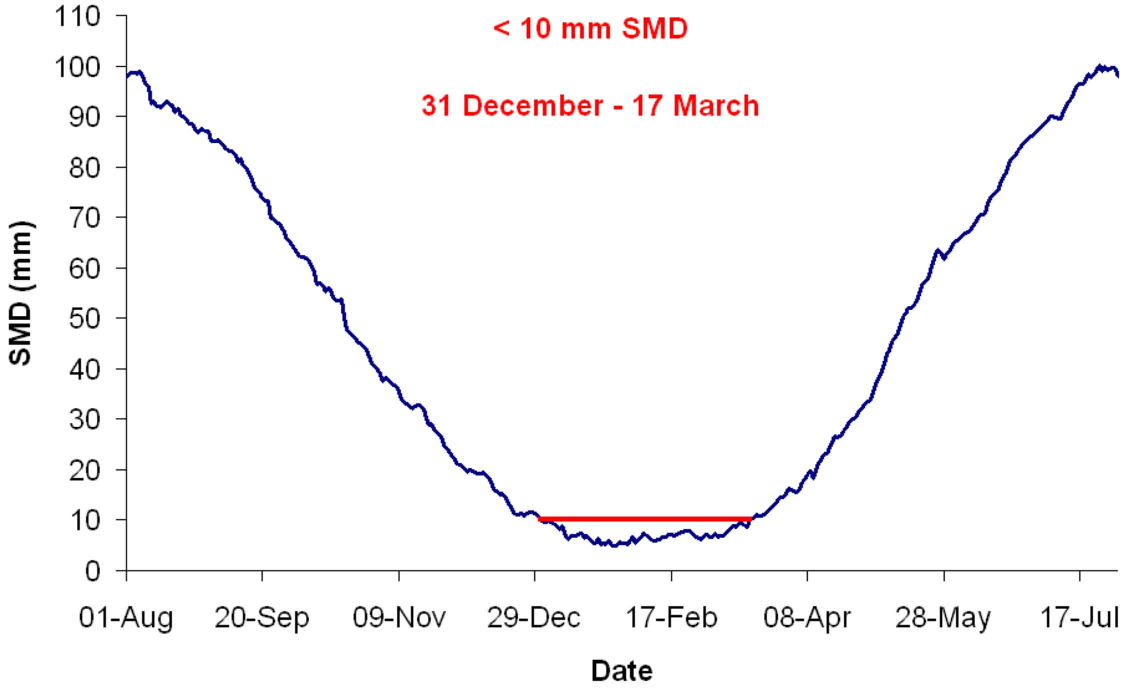

Figure 24. Typical SMD profile – Boxworth winter cereals (NVZ closed period end date 15 January)

Table 3. Average days per month (%) on which surface runoff was recorded between 2003-2006 at Hillsborough (Doody *et al.* 2010).

Month	Days surface runoff occurred (%)
October	28.2
November	25.0
December	37.1
January	32.6
February	14.3
March	26.6
April	18.3
May	33.1
June	5.8
July	8.1
August	12.1
September	14.2

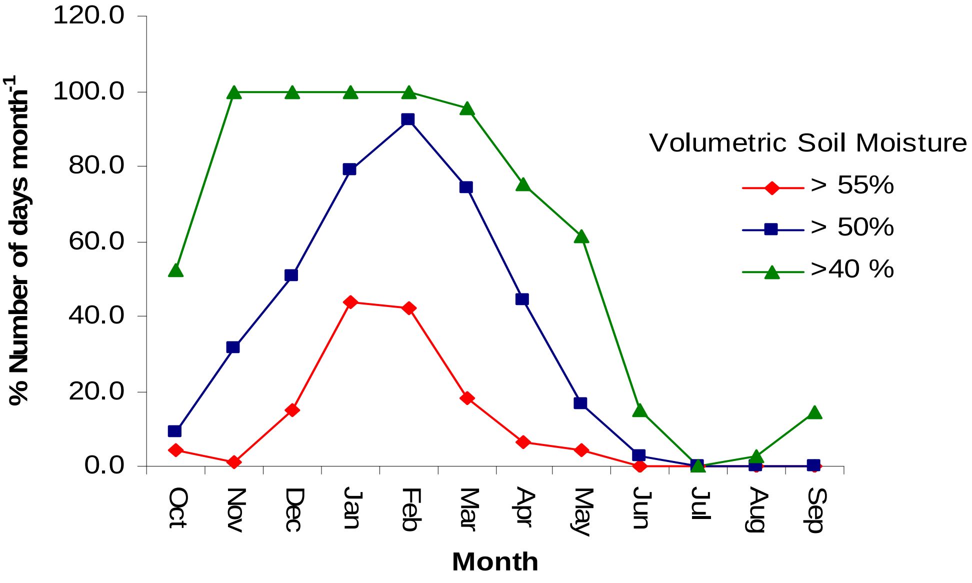

Figure 25. Average monthly distribution of high volumetric soil moisture measurements at Hillsborough 2003-2006.

4.3.3 Freely drained soils

A large body of research was undertaken in the UK on nitrate leaching from freely draining 'leaky' soils, which underpinned the establishment of Nitrate Vulnerable Zones and over-winter closed periods for high readily available N manures (Chambers *et al.,* 2000). In terms of high readily manure application timings, N losses were generally greatest following applications in September, October and November, whilst N losses following applications in December or January were not greatly elevated above those from untreated controls (Beckwith *et al*., 1998).

Defra project ES0115 – OPTi-N. Nitrate leaching losses following autumn/winter slurry application timings before winter cereals at Horsewold and Grange Farms were equivalent to 19-20% of slurry total N applied. In contrast at Horsewold Farm, nitrate leaching losses following the application of pig slurry, before the establishment of oilseed rape were not different (P>0.05) from the untreated control. The lower losses following slurry application before oilseed rape reflected greater crop N uptake (*c.*80 kg/ha N) between application and the onset of winter drainage, compared with winter cereal crop N uptake (*c.*5 kg/ha N).

On grassland at Holt Farm, nitrate leaching losses following autumn slurry application timings were increased (P<0.05) where drainage volumes after application exceeded 300mm (losses equivalent to 47% of total slurry N applied), Figure 26.

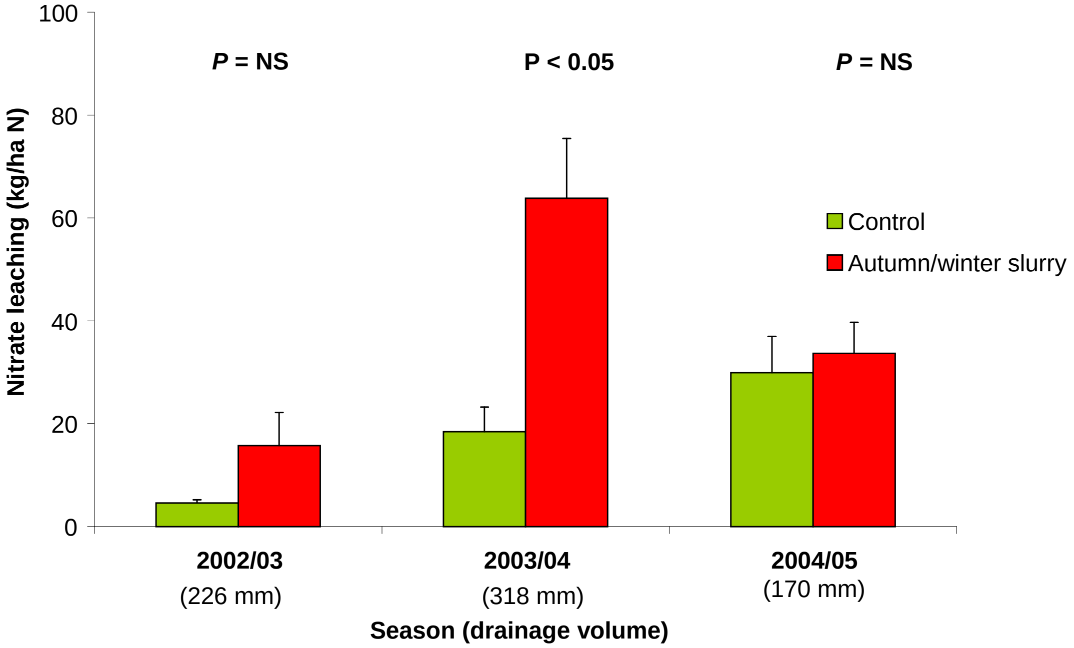

Figure 26. Nitrate leaching losses following shallow injected cattle slurry applications to grassland at Holt Farm

4.3.4 Summary of losses to water

i) Poorly drained soils

Nitrate. On drained clay soils, Defra project ES0106 showed that on the arable plots spring slurry application timings presented the lowest risk and autumn timings the highest risk of nitrate leaching loss. On the grassland plots, slurry application timings had no effect on nitrate losses.

Findings to date from Defra Project WQ0118 indicate that nitrate-N losses to water from autumn slurry applications were higher from winter cereal cropped land than from oilseed rape/grassland. Drainage water nitrate concentrations following autumn applications to arable land depended both on the manure type (with higher losses from pig slurry than from cattle slurry) and on crop establishment (with higher losses from crops with a low N uptake potential in autumn). There was some evidence that late-spring slurry applications to winter cereals could lead to elevated drainage water nitrate-N concentrations. In contrast on grassland, summer manure applications did not increase nitrate-N concentrations in drainage water even when heavy rainfall followed application.

Other pollutants. Defra project ES0106 showed that slurry applications to ‘wet’ soils in spring (and winter) were likely to result in lower nitrate but elevated NH_4-N and P concentrations in drainage waters (an example of ‘pollution swapping’). More recent findings from Defra Project WQ0118 supported these conclusions in that losses of NH_4-N, soluble P and *E.coli* were low from autumn applied slurries on both arable and grassland. In contrast, spring slurry applications lead to elevated NH_4-N, soluble P and *E.coli* losses from both arable and grassland.

Ammonium-N is usually strongly adsorbed on to soil colloids and is relatively immobile within soils. Following the autumn slurry applications, there was generally sufficient time for ammonium-N to have been adsorbed onto the soil matrix and transformed within days/weeks to nitrate-N, via the microbially mediated process of nitrification. The high NH_4-N concentrations in drainage waters following slurry application to ‘wet’ soils in winter and spring, were a result of NH_4-N moving rapidly from the soil surface to field drains via cracks/mole drains, with little interaction with the soil matrix. The higher NH_4-N and TDP concentrations and losses in drainage waters from the grassland plots most probably reflected greater connectivity between the soil surface and drains, as a result of ‘by-pass’ flow in cracks/mole channels, than on the annually cultivated arable plots.

The evidence so far indicates that slurry applied in summer to grassland has little effect on NH_4-N, soluble P and *E.coli* losses.

Assessing the risks. Data from Defra Projects WQ0118 and ES0106 showed that the risks of NH_4-N and P contamination of drainage waters was reduced where drainflow occurred more than 10-20 days after slurry was applied. In order to minimise the risks of diffuse water pollution, sufficient over-winter slurry storage capacity is required to provide the flexibility to spread slurry when soils have dried out in spring i.e. ideally when the soil moisture deficit (SMD) is >20mm.

Typical SMD profiles highlighted the periods where there was likely to be a high risk of elevated pollutant concentrations in drainage waters (i.e. SMD <10mm). Extending the closed spreading periods would reduce the opportunity for manure to be applied during the ‘high’ risk periods and hence the risks of diffuse water pollution from ammonium-N, TDP and *E.coli* losses would be reduced.

AFBI Project 0303 found that 59% of surface runoff from a drained grassland soil was generated during periods when volumetric soil moisture (VSM) was below field capacity, demonstrating that surface runoff frequently occurs even when the soils are not fully saturated. Generally, there was surface runoff on a higher percentage of days in winter and autumn than in spring and summer. January and February posed the biggest risk as the soil was close to field capacity on *c.*40% of the days. However, surface runoff also occurred on 33% of days in May, indicating that whilst the winter/autumn period poses the greatest risk of surface runoff, there is also a significant risk for much of the rest of the year.

ii) Freely drained soils

From the large body of research undertaken in the UK on nitrate leaching from freely draining ‘leaky’ soils, N losses from arable soils were generally found to be greatest following manure applications in autumn compared with winter and spring. More recently, Defra project ES0115 found that on grassland, nitrate leaching losses following autumn slurry applications were increased ($P<0.05$) where drainage volumes after application exceeded 300mm.

4.4 Emissions to air

4.4.1 Ammonia emissions

Defra Project AC0111 (Cracking Clays-Air). At Rowden, ammonia emissions following cattle slurry application in September 2008 were equivalent to 9% of total N applied compared with 12% and 15% of total N applied following the May and July 2009 applications, respectively (Figure 27). The numerically higher emissions following the June application were most probably a reflection of drier soil conditions (which reduced slurry infiltration rates) and warmer soil temperatures, compared with the autumn and spring timings.

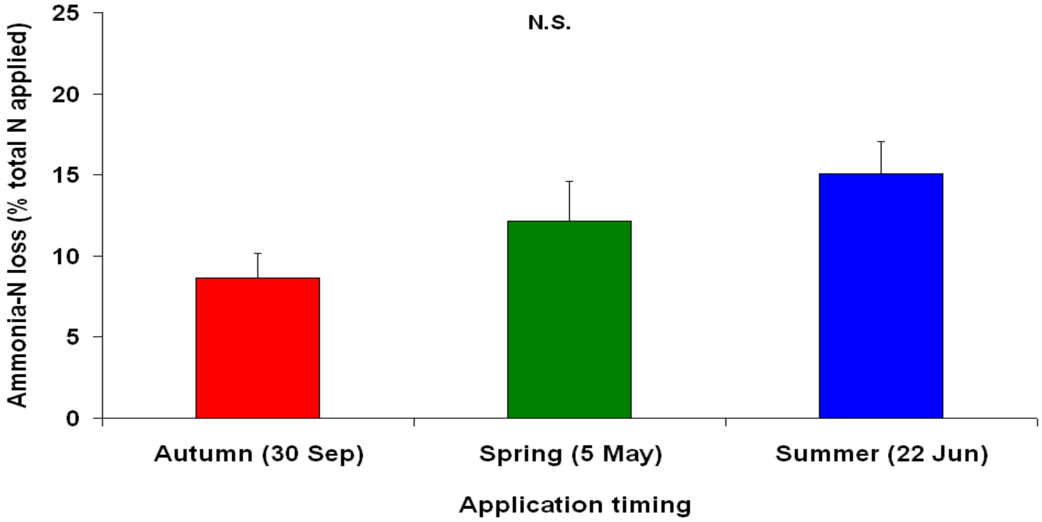

Figure 27. Ammonia emissions following contrasting cattle slurry application timings to grassland at Rowden 2008/09.

At Boxworth in 2009/10, ammonia emissions following autumn and late spring applications were higher ($P<0.05$) from cattle slurry (*c.*11% total N applied) than from pig slurry (*c.*6% total N applied); the lower emissions from pig slurry probably reflected its lower dry matter content (2.3% compared with 3.5% for cattle slurry) which enabled more rapid slurry infiltration into the soil (Figure 28). There were no differences in ammonia emissions between the early spring applied cattle and pig slurries ($P>0.05$). Higher losses from early spring application timings on arable land at Boxworth were most probably due to poor infiltration of the slurry into the soil (Plate 6).

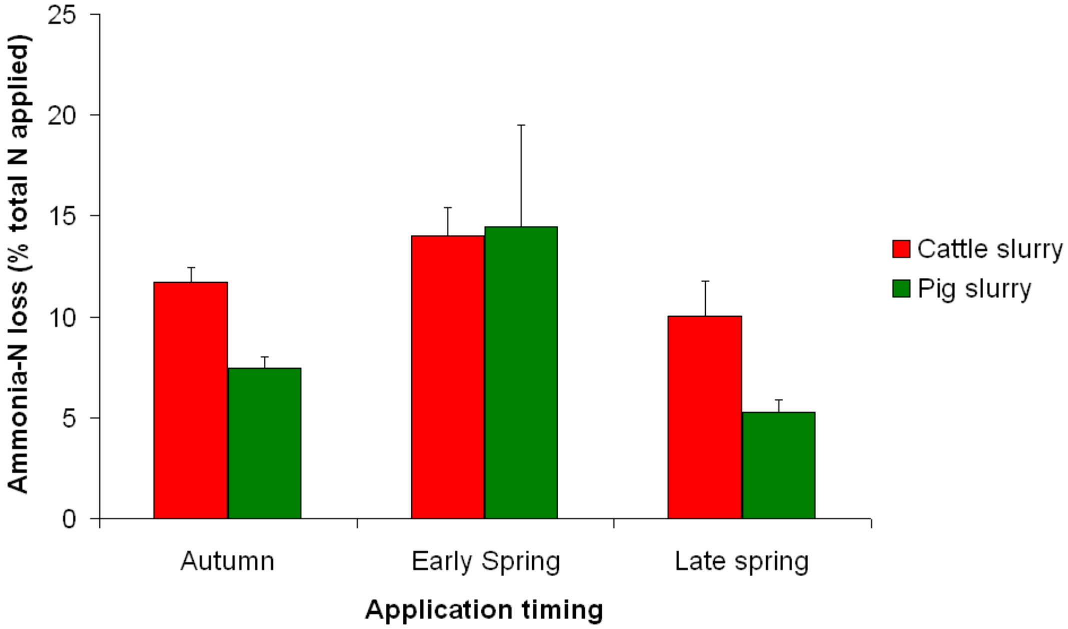

Figure 28. Ammonia emissions following autumn and spring cattle and pig slurry applications at Boxworth (harvest season 2009/10)

Plate 6. Ground conditions at Boxworth after applications of pig slurry in early spring, 11th March (left) and late spring, 5th May (right)

At Faringdon in 2010/11, there were no differences in ammonia losses from cattle slurry applied to grassland and arable land (Figure 29). Losses were lower in autumn (August) because conditions were dry and the open soil structure allowed the slurry to readily infiltrate into the soil. However by the spring (March) application timing, the soil had 'slumped' and was wet, leading to poor slurry infiltration and higher ammonia losses. In contrast at Boxworth in 2010/11 (Figure 30), ammonia losses from both pig and cattle slurry were high in August because they were applied to stubble under wet soil conditions. By September, the soil had been cultivated and oilseed rape sown improving the structure, hence ammonia losses were lower. However, in the following spring the soil had once again 'slumped' and become wet, reducing slurry infiltration rates leading to higher ammonia losses.

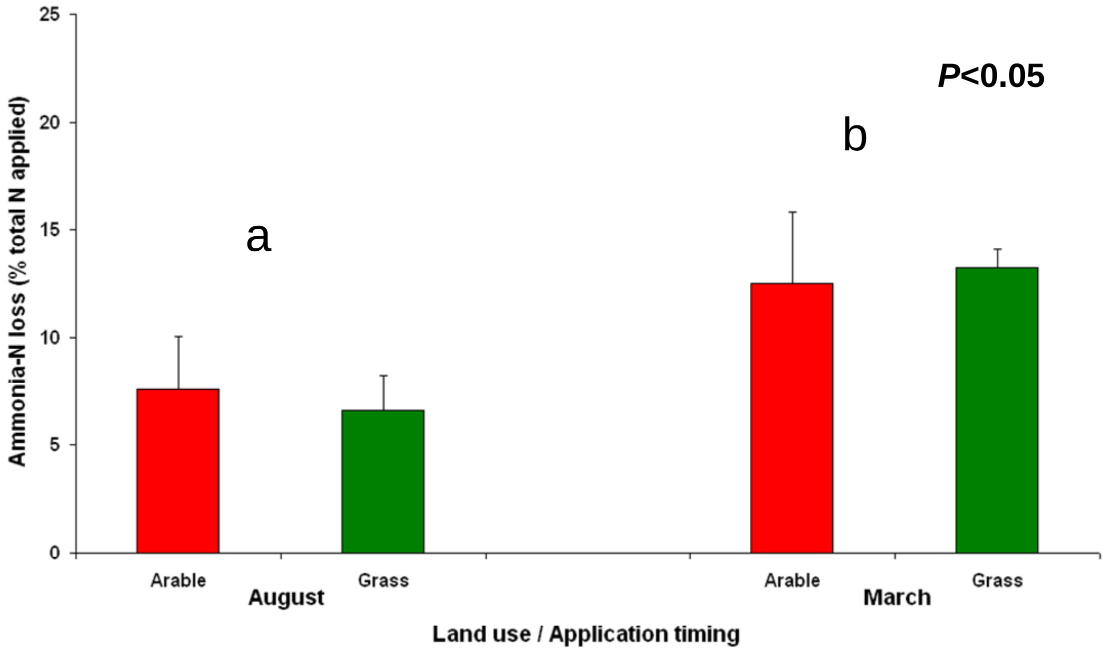

Figure 29. Ammonia emissions following cattle slurry applications to grassland and arable land at Faringdon (harvest season 2010/11)

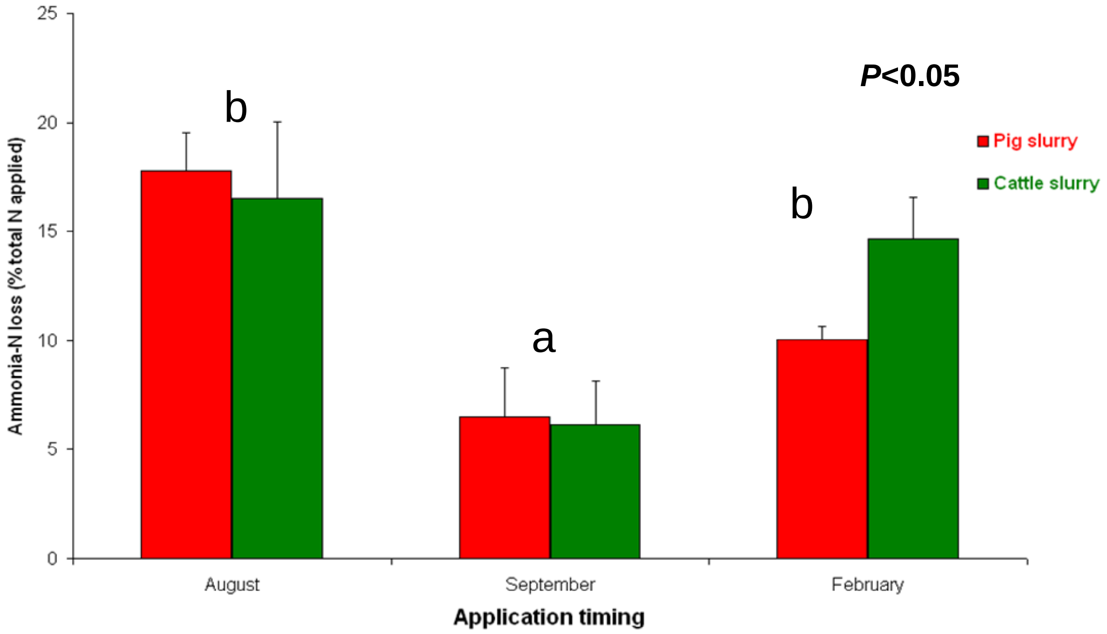

Figure 30. Ammonia emissions following cattle and pig slurry applications to winter oilseed rape at Boxworth (harvest season 2010/11)

Defra Project ES0115 (Opti-N). On winter cereal cropped land, ammonia emissions were highest following slurry applications in March/April (range 16-26% total N applied) and lowest following applications to stubble in autumn/winter (range 6-11% of total N applied), Figures 31 and 32. Also at Holt Farm, ammonia emissions were higher following slurry applications to winter wheat in March compared with the May timings. The higher emissions in spring probably reflected reduced slurry infiltration rates into 'capped' soils compared with rapid infiltration into 'permeable' cereal/maize stubbles in autumn/winter. There was no effect (*P*>0.05) of pig slurry application timing on ammonia losses following dressings to winter oilseed rape (range 7-13% of total N applied; one study year).

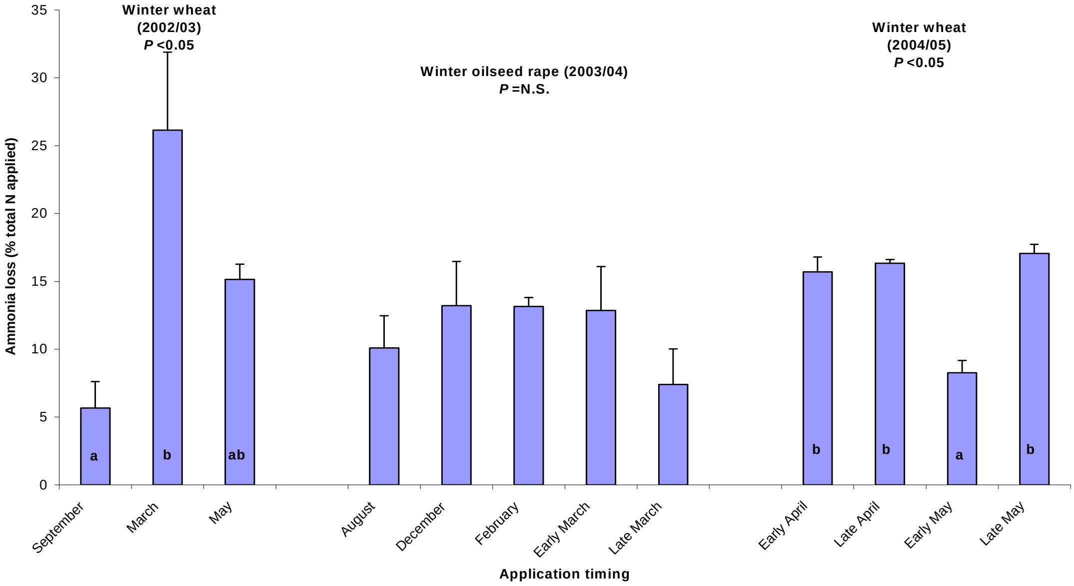

Figure 31. Ammonia emissions following contrasting pig slurry applications to arable crops at Horsewold Farm.

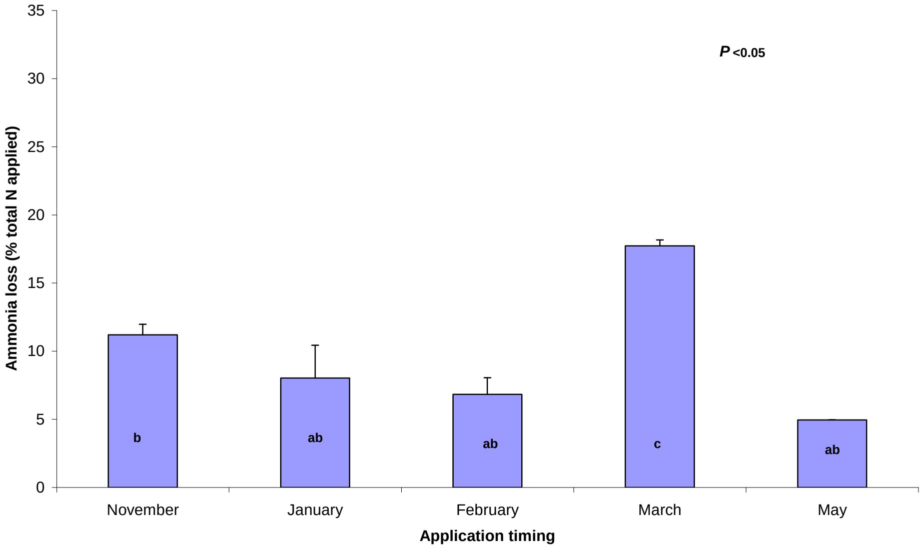

Figure 32. Ammonia emissions following contrasting cattle slurry application timings to winter wheat at Grange Farm (2004/05).

On grassland at Grange and Berrowsfield Farms, ammonia emissions following bandspread (trailing hose and trailing shoe) cattle slurry applications before second cut silage in June were 2 to 3-fold greater than following applications in the autumn to early spring period (Figures 33). Similarly on grassland at Holt Farm, ammonia emissions from shallow injected cattle slurry applications in June were 2 to 3-fold greater than from autumn and early spring applications made before first cut silage (Figure 35). At all three farms (four measurements), delaying slurry application by a fortnight before second cut silage reduced emissions from a mean of 16% of total N applied (range 9-26% of total N) to 6% of total N applied (range 3-10% of total N). The higher emissions in June reflected reduced slurry infiltration rates into ‘dry’ soils, warmer temperatures and shorter grass swards compared with the other (autumn to spring) application timings.

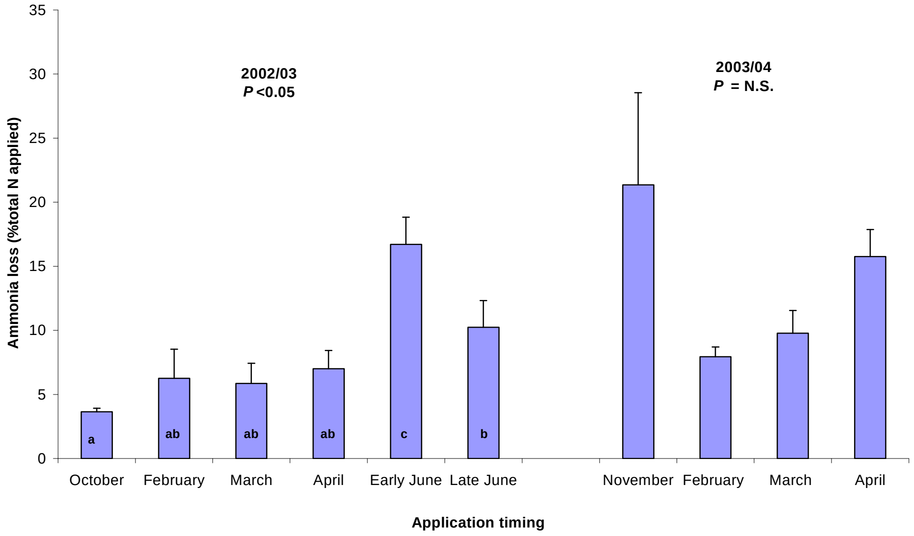

Figure 33. Ammonia emissions following contrasting trailing hose cattle slurry application timings to grassland at Grange Farm.

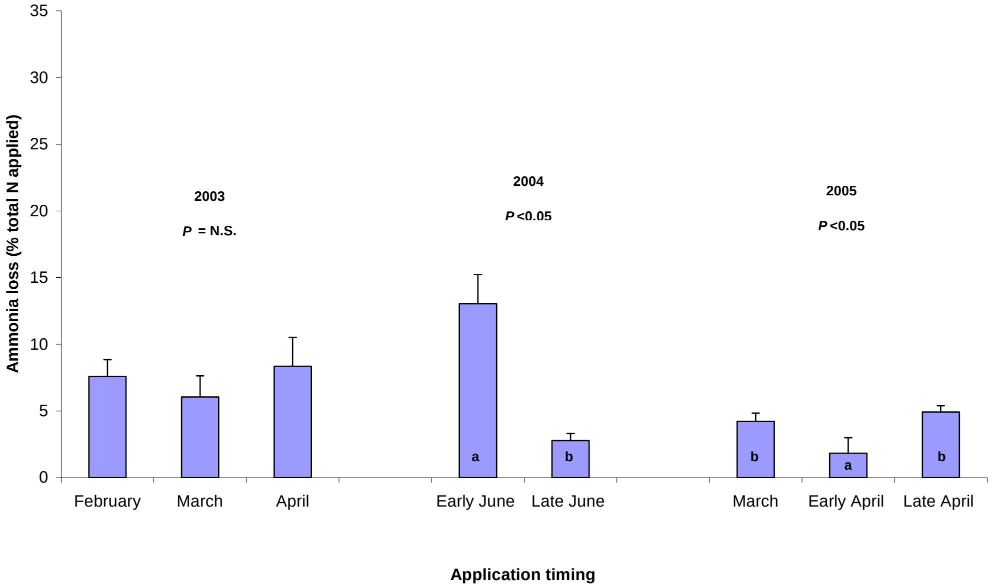

Figure 34. Ammonia emissions following contrasting trailing shoe cattle slurry application timings to grassland at Berrowsfield Farm.

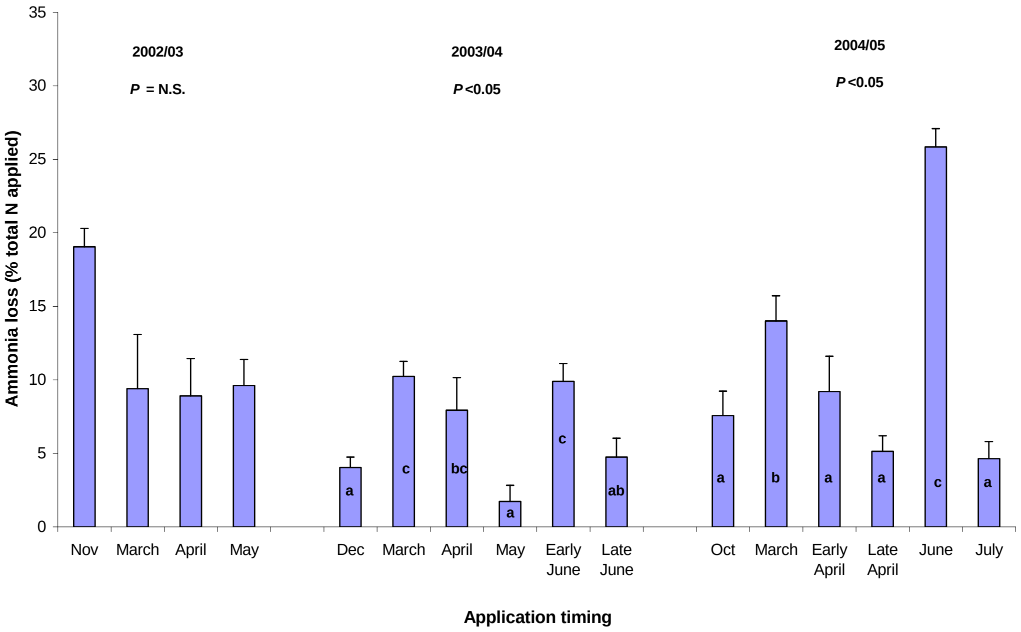

Figure 35. Ammonia emissions following contrasting shallow injected cattle slurry application timings to grassland at Holt Farm.

4.4.2 Nitrous oxide emissions

Defra Project AC0111 (Cracking Clays-Air). At Rowden in May 2009, N_2O-N emissions following cattle slurry application to the undrained soil at 2% of total N applied were *c.*10 fold-greater than following application to the drained soil (0.2% of total N applied), Figure 36. However, following the June 2009 cattle slurry application, there were no differences ($P>0.05$) in N_2O-N emissions between the drained and undrained soils. The differences in N_2O-N emissions from the contrasting cattle slurry application timings were probably a reflection of differences in soil moisture and temperature status and crop N uptake in the period after application.

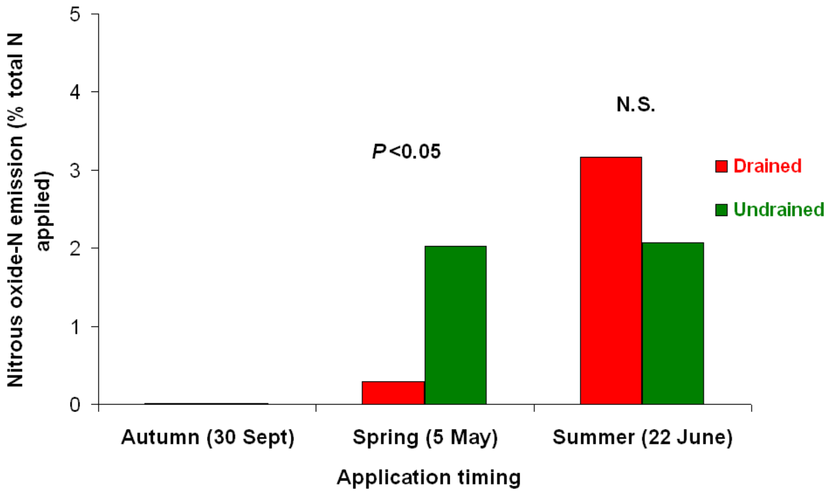

Figure 36. N_2O-N emissions following contrasting cattle slurry application timings to drained and undrained grassland soils at Rowden 2008/09.

Defra Project ES0115 (Opti-N). N_2O emissions over *c*.3 month measurement periods were greater overall (*P*<0.1) following the application of slurry to grassland (mean emission 0.73% total N applied) compared with arable land (mean emission 0.27% of total N applied). The higher emissions from grassland were most probably a reflection of the greater prevalence of anaerobic conditions in ‘compacted’ soil surface horizons leading to increased denitrification losses compared with annually cultivated arable topsoils.

Five pairs of measurements following cattle slurry applications to grassland showed that N_2O losses were greater (*P*<0.05) following late autumn/winter timings (1.10% total-N applied) than following spring (0.51% total-N applied) timings (Figure 37). The higher emissions following late autumn/winter timings were most probably a reflection on lower levels of crop N uptake in the autumn/winter compared with spring, and differences in soil moisture/temperature conditions. On grassland, N_2O production usually returned to background levels within 3 months of slurry application, largely as a result of crop N uptake depleting the soil mineral N pool available for N_2O production. The exceptions were when climatic conditions were cold and/or dry in the period after application and emissions were delayed until rainfall occurred or temperatures increased.

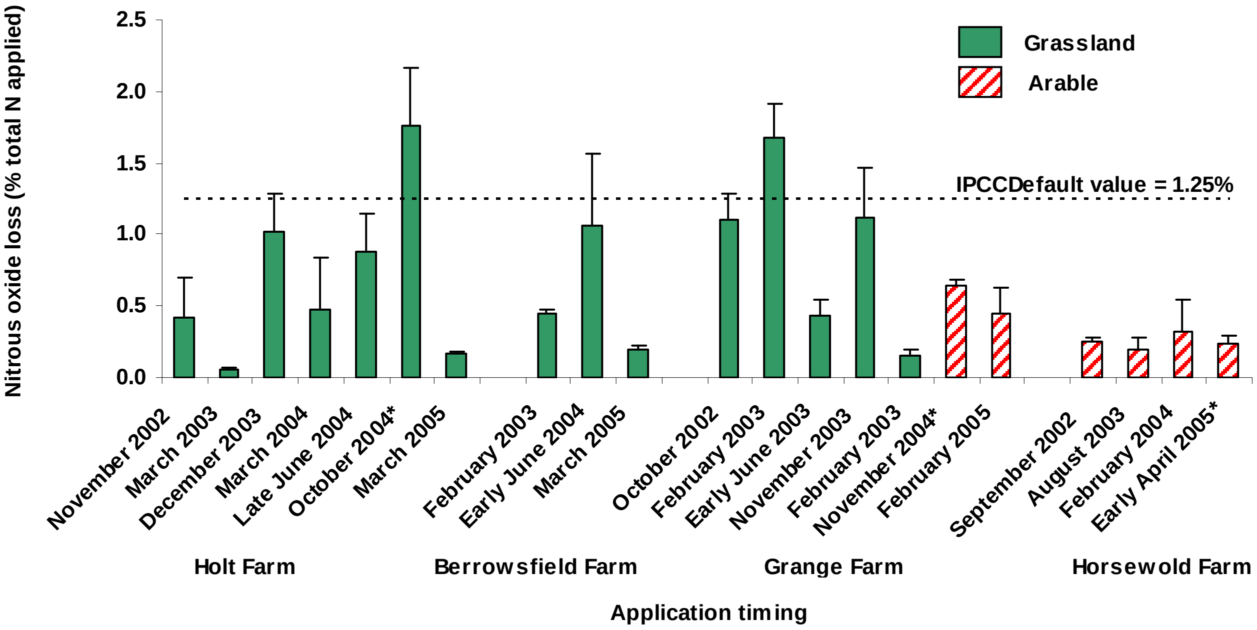

Figure 37. Nitrous oxide emissions measured over 3-12 month periods following slurry application (Error bars = one standard error of the mean; * = 9-12 month measurement periods)

4.4.3 Summary

The results from these projects have shown that ammonia losses following slurry applications are influenced by the soil and weather conditions at the time of application, rather than on the time of year *per se*. Application to soils where slurry infiltration is restricted (e.g. ‘slumped’ arable soils in spring and ‘dry’ grassland soils in summer), will increase the risks of ammonia loss. When slurries are applied to soils with an open structure (e.g. after cultivation) where the slurry can infiltrate more readily into the soil, ammonia losses will be reduced.

Similarly N_2O losses following slurry applications reflected difference in soil moisture conditions and temperature, with greater losses being recorded when soil conditions were warm and moist. Higher emissions from grassland were most probably a reflection of the greater presence of anaerobic conditions in compacted soil surface horizons leading to increased denitrification losses compared with cultivated arable topsoils. Crop N uptake also influenced N_2O losses, because an actively growing crop will deplete the soil mineral N pool available for N_2O production.

4.5 Conclusions of data synthesis

The information reviewed in this synthesis of recently completed and ongoing UK research projects has confirmed that autumn slurry (and poultry manure) applications present the greatest risk of nitrate-N losses to drainage waters on free draining and poorly drained soils. However, the magnitude of losses depends both on the manure type (with higher losses from pig slurry than from cattle slurry) and on crop establishment (with higher losses from crops with a low N uptake potential in the autumn).

On drained soils, the risk of ammonium-N, phosphorus and microbial pathogen contamination of drainage and surface waters was highest when slurry applications were made to soils with a soil moisture deficit of less than 10-20 mm. In most situations, autumn, late spring and summer application timings are likely to pose the lowest risk of ammonium-N, phosphorus and microbial pathogen contamination of drainage and surface waters.

Ammonia losses following slurry applications were dependent on soil conditions at the time of application, rather than on the time of year *per se*. Slurry applications to arable soils which are ‘capped’ or ‘slumped’ (see note below) can result in poor slurry infiltration, leading to elevated ammonia losses. However, when slurries are applied to soils with an open structure (e.g. after cultivation) where the slurry can infiltrate readily into the soil, ammonia losses are usually lower. In general, it is most likely that soil and climate conditions that encourage ammonia volatilisation following slurry application will occur in the early spring on arable land and summer on grassland. Similarly N_2O losses following slurry applications reflected differences in soil moisture conditions and temperature, with the greatest losses measured when soil conditions were warm and moist and when crop N uptake was low.

Note: Capping is the creation of a thin crust on the surface of soil, which restricts the infiltration of rainwater and increases surface runoff. Slumping is a process that can occur in sandy and silty soils, where raindrop impact and wetting causes the soil surface structure to collapse and a thin crust to develop that prevents surface water infiltration and increases runoff.

5 IMPACTS OF EXTENDING THE ‘CLOSED PERIOD’ ON THE BALANCE OF POLLUTANT LOSSES TO WATER AND AIR

5.1 Methodology

The study assessed the effect that extending the ‘closed spreading periods’ in spring by 1 month and 2 months would have on the balance of pollutant losses to the water and air environments following different slurry (i.e. cattle and pig) and poultry manure (layer manure and poultry litter) application timings, at the farm and national level.

5.1.1 Manure quantities

Estimates of the quantity of manure N applied to agricultural soils with different manure types were taken from MANURES-*GIS,* using 2004 Agricultural Census data on a 10km^2 grid cell basis (Defra project WQ0103). Using GIS techniques, these results were overlaid with 1km^2 gridded data on the dominant soil type (i.e. sandy/shallow and other) present in each grid cell (derived from Natmap1000 data) and average annual rainfall (using 1961-1990 statistics) data, to derive information on the quantity of manure N applied to the different soil type and rainfall zone combinations (Figures 38, 39, 40 and 41). This information was required as both soil type and rainfall have a strong influence on the quantity of N lost by overwinter nitrate leaching and manure N efficiency, and hence will affect GHG emissions.

Additionally, the data were overlaid with a GIS map of the current (2008) designated NVZ areas (i.e. *c.*62% of England and *c.*3% of Wales) so that the quantities of manure N applied both in England and Wales and within NVZ areas could be determined (Tables 4 and 5). These data showed that for England and Wales <10% of high readily available N manures were applied to sandy/shallow soils, with the majority being applied to ‘other’ soil types. Moreover, only 45% of cattle slurry was applied within designated NVZ areas compared with 67% of poultry manures and 80% of pig slurry.

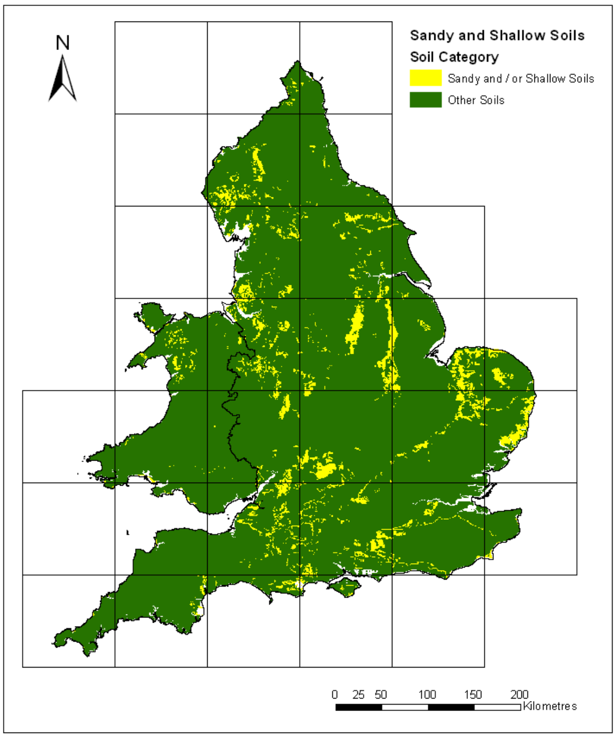

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Figure 38. Location of sandy/shallow soil types within England and Wales.

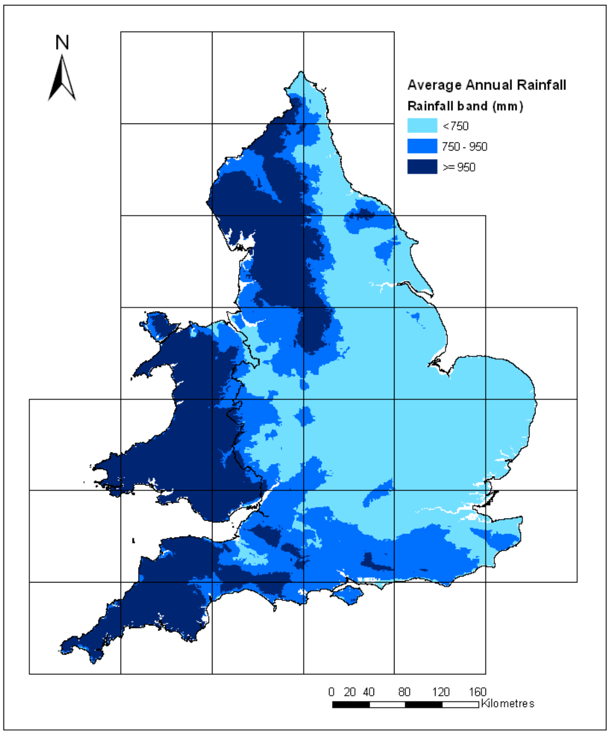

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Figure 39. Areas covered by the three agro-climate zones used within this work (annual average rainfall was taken from the Met Office 1961-1990 dataset).

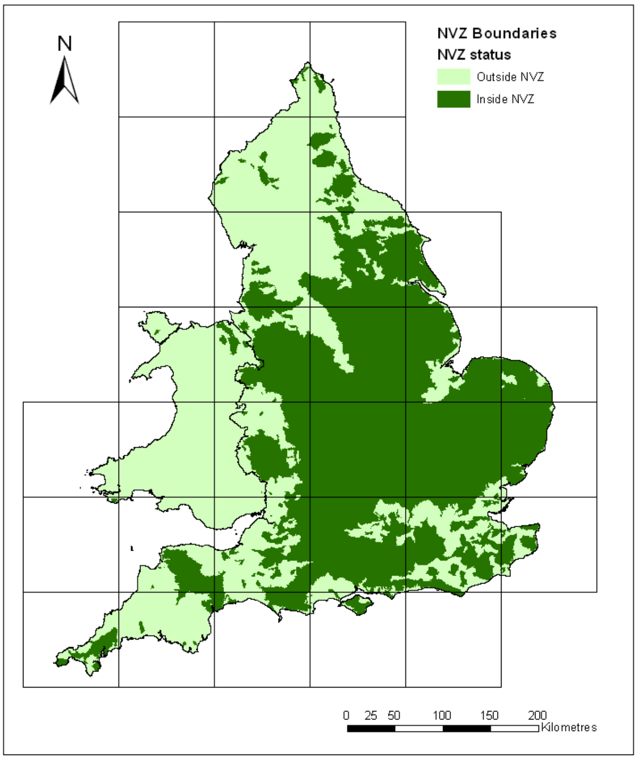

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Figure 40. Spatial extent of the current NVZ areas in England and Wales (2009-12).

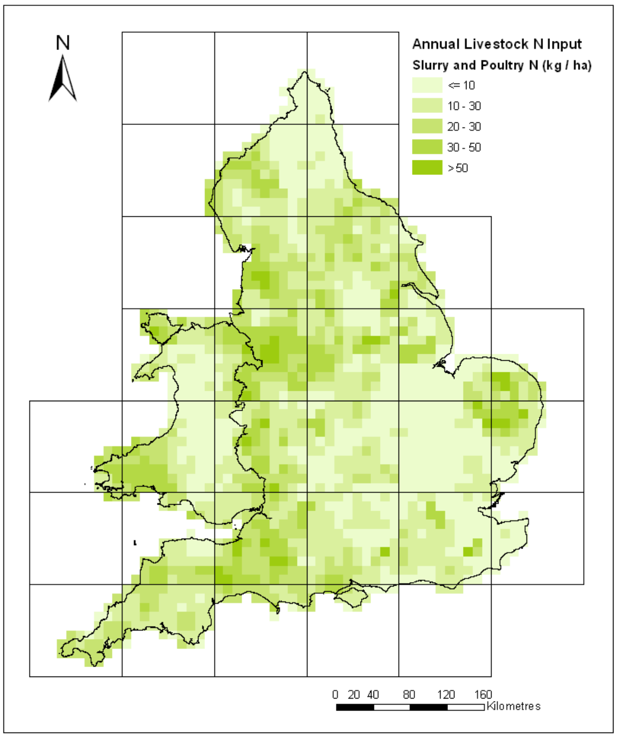

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Figure 41. Total nitrogen loadings in slurry and poultry manures (kg/ha) on agricultural land.

Table 4. Quantities of manure total N (kt) applied in England and Wales (based on 2004 Agricultural Census data).

Soil type/	Sandy/Shallow				Other				
Rainfall zone[1]	High	Medium	Low	Total (%)	High	Medium	Low	Total (%)	Total
Manure type									
Cattle slurry	1.0	2.5	1.4	4.9 (5%)	38.2	28.9	23.0	90.1 (95%)	95.0
Pig slurry	<0.1	0.2	1.0	1.2 (10%)	0.9	1.8	8.5	11.2 (90%)	12.4
Poultry manure	0.3	1.2	3.8	5.3 (9%)	9.7	14.7	31.5	55.9 (91%)	61.2

[1] High rainfall (>950 mm per annum); medium rainfall (750-950 mm per annum); low rainfall (<750 mm per annum)

Table 5. Quantities of manure total N (kt) applied in NVZ areas (based on 2004 Agricultural Census data and current designations).

Soil type/	Sandy/Shallow				Other				
Rainfall zone[1]	High	Medium	Low	Total (%)	High	Medium	Low	Total (%)	Total
Manure type									
Cattle slurry	0.2	1.8	1.3	3.3 (8%)	6.5	14.4	18.1	39.0 (92%)	42.3
Pig slurry	0.1	0.1	0.9	1.1 (11%)	0.3	1.1	7.4	8.8 (89%)	9.9
Poultry manure	0.1	0.8	3.4	4.3 (10%)	1.9	7.8	27.1	36.8 (90%)	41.1

[1] High rainfall (>950 mm per annum); medium rainfall (750-950 mm per annum); low rainfall (<750 mm per annum)

5.1.2 Manure application timings

In order to evaluate the effect of extending the 'closed spreading periods' for high readily available N manures, four scenarios were assessed, *viz*.:

- BASELINE - manure application timings prior to implementation of the 2008 NVZ-AP based on data collected in the 2007 British Survey of Fertiliser Practice (BSFP, 2008)
- CURRENT NVZ-AP - predicted manure application timings at the end of the current NVZ-AP (i.e. by 2012)
- Month 1 - extend 'closed period' by 1 month in spring
- Month 2 - extend 'closed period' by 2 months in spring

A summary of the 'closed periods' assessed for each scenario (by cropping and soil type) is given in Table 6.

Table 6. 'Closed spreading periods' applied for each scenario by cropping and soil type.

Scenario	Grassland	Tillage
BASELINE (2007)		
Sandy/shallow soils	15 Sept – 1 Nov	1 Aug – 1 Nov
All other soils	None	None
CURRENT NVZ-AP		
Sandy/shallow soils	1 Sept – 31 Dec	1 Aug – 31 Dec
All other soils	15 Oct – 15 Jan	1 Oct – 15 Jan
MONTH 1		
Sandy/shallow soils	1 Sept – 31 Jan	1 Aug – 31 Jan
All other soils	15 Oct – 15 Feb	1 Oct – 15 Feb
MONTH 2		
Sandy/shallow soils	1 Sept – 28 Feb	1 Aug – 28 Feb
All other soils	15 Oct – 15 Mar	1 Oct – 15 Mar

The proportions of high readily available N manures estimated to be applied each month (to grassland and arable land) in the four scenarios are summarised in Tables 7 to 10. For scenarios 2 to 4, manure applications that could not be made during the 'closed periods' were redistributed to other periods of the year. For example, in the Baseline (2007) scenario around 24% of cattle slurry was applied to grassland between September and December, with 52% spread between January and April (Table 7). Under the Current NVZ-AP, the spreading of cattle slurry to grassland is not permitted between 1 September and 31 December on sandy shallow soils (and 15 October to 15 January on other soil types) (Table 1). Hence, the quantity of manure spread during these times was reduced to zero, which resulted in the estimated quantity spread on sandy/shallow soils between January and April increasing to 71% (Table 8).

Table 7. Percentage of manure applied by month and land use: BASELINE (data from 2007 Survey of Fertiliser Practice).

Soil type	Manure type	Land use	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	% manure to each land use
All	Cattle slurry	Grassland	14	15	15	8	4	5	4	4	4	3	8	9	93
		Arable	<1	1	1	1	<1	<1	<1	1	1	1	1	<1	7
		Total	14	16	16	9	4	5	4	5	5	4	9	9	
All	Pig slurry	Grassland	3	6	6	3	3	4	3	5	4	0	2	2	41
		Arable	4	10	10	5	0	0	0	7	9	4	7	3	59
		Total	7	16	16	8	3	4	3	12	13	4	9	5	
All	Poultry	Grassland	1	3	3	1	<1	1	<1	1	0	<1	<1	<1	10
		Arable	1	9	9	5	2	2	2	18	38	1	2	1	90
		Total	2	12	12	6	2	2	2	19	38	2	2	1	

Table 8. Percentage of manure applied by month and land use: CURRENT NVZ-AP (2009-2012). *Predicted values*.

Soil type	Manure type	Land use	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	% manure to each land use
Sandy/shallow	Cattle slurry	Grassland	18	21	21	11	5	7	5	5	0	0	0	0	93
		Arable	1	2	2	1	<1	<1	<1	<1	1	0	0	0	7
		Total	19	23	23	12	5	7	5	5	1	0	0	0	100
Sandy/shallow	Pig slurry	Grassland	4	8	8	4	3	5	3	6	0	0	0	0	41
		Arable	6	17	18	9	0	0	0	4	5	0	0	0	59
		Total	10	25	26	13	3	5	3	10	5	0	0	0	100
Sandy/shallow	Poultry	Grassland	1	3	3	1	<1	1	<1	1	0	0	0	0	10
		Arable	2	15	16	8	3	3	4	13	26	0	0	0	90
		Total	3	18	19	9	3	4	4	14	26	0	0	0	100
Other	Cattle slurry	Grassland	10	21	22	11	5	7	5	5	5	2	0	0	93
		Arable	<1	2	2	1	<1	<1	<1	<1	2	0	0	0	7
		Total	10	23	24	12	5	7	5	5	7	2	0	0	100
Other	Pig slurry	Grassland	2	7	8	4	3	4	3	5	5	0	0	0	41
		Arable	3	14	14	7	0	0	0	10	11	0	0	0	59
		Total	5	21	22	11	3	4	3	15	16	0	0	0	100
Other	Poultry	Grassland	<1	3	3	2	<1	1	<1	1	0	<1	0	0	10
		Arable	1	11	11	5	2	2	2	18	38	0	0	0	90
		Total	1	14	14	7	2	3	2	19	38	<1	0	0	100

Table 9. Percentage of manure applied by month and land use: Month 1 (1 month extension of spring closed period). ***Predicted values.***

Soil type	Manure type	Land use	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	% manure to each land use
Sandy/shallow	Cattle slurry	Grassland	0	26	26	13	6	9	7	6	0	0	0	0	93
		Arable	0	2	2	1	<1	<1	<1	1	1	0	0	0	7
		Total	0	28	28	14	6	9	7	7	1	0	0	0	100
Sandy/shallow	Pig slurry	Grassland	0	9	9	4	4	5	4	6	0	0	0	0	41
		Arable	0	20	20	10	0	0	0	4	5	0	0	0	59
		Total	0	29	29	14	4	5	4	10	5	0	0	0	100
Sandy/shallow	Poultry	Grassland	0	3	3	2	<1	1	<1	1	0	0	0	0	10
		Arable	0	16	16	8	3	3	5	13	26	0	0	0	90
		Total	0	19	19	10	3	4	5	14	26	0	0	0	100
Other	Cattle slurry	Grassland	0	14	28	14	7	9	7	6	6	2	0	0	93
		Arable	0	1	2	1	<1	<1	<1	1	2	0	0	0	7
		Total	0	15	30	15	7	9	7	7	8	2	0	0	100
Other	Pig slurry	Grassland	0	4	8	4	4	5	4	6	6	0	0	0	41
		Arable	0	9	18	9	0	0	0	11	12	0	0	0	59
		Total	0	13	26	13	4	5	4	17	18	0	0	0	100
Other	Poultry	Grassland	0	2	4	2	<1	1	<1	1	0	<1	0	0	10
		Arable	0	6	13	7	2	2	3	19	38	0	0	0	90
		Total	0	8	17	9	2	3	3	20	38	<1	0	0	100

Table 10. Percentage of manure applied by month and land use: Month 2 (2 month extension of spring closed period). ***Predicted values.***

Soil type	Manure type	Land use	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	% manure to each land use
Sandy/shallow	Cattle slurry	Grassland	0	0	36	18	9	12	9	9	0	0	0	0	93
		Arable	0	0	3	2	<1	<1	<1	1	1	0	0	0	7
		Total	0	0	39	20	9	12	9	10	1	0	0	0	100
Sandy/shallow	Pig slurry	Grassland	0	0	11	6	5	6	5	8	0	0	0	0	41
		Arable	0	0	31	15	0	0	0	6	7	0	0	0	59
		Total	0	0	42	21	5	6	5	14	7	0	0	0	100
Sandy/shallow	Poultry	Grassland	0	0	4	2	<1	1	1	2	0	0	0	0	10
		Arable	0	0	22	11	4	4	5	14	30	0	0	0	90
		Total	0	0	26	13	5	5	6	16	30	0	0	0	100
Other	Cattle slurry	Grassland	0	0	19	19	10	13	10	9	9	4	0	0	93
		Arable	0	0	2	2	<1	<1	<1	1	2	0	0	0	7
		Total	0	0	21	21	10	13	10	10	11	4	0	0	100
Other	Pig slurry	Grassland	0	0	5	5	5	6	5	7	8	0	0	0	41
		Arable	0	0	15	16	0	0	0	13	15	0	0	0	59
		Total	0	0	20	21	5	6	5	20	23	0	0	0	100
Other	Poultry	Grassland	0	0	2	3	1	1	1	2	0	<1	0	0	10
		Arable	0	0	10	10	3	3	4	20	40	0	0	0	90
		Total	0	0	12	13	4	4	5	22	40	0	0	0	100

The delay between manure application and soil incorporation, and for slurries the method of application (i.e. surface broadcast compared with bandspread/shallow injection) will affect the balance between different N loss pathways and manure N efficiency. In this study, we assumed for the 2007 baseline scenario that 20% of cattle slurry, 75% of pig slurry and 50% of poultry manure applications to tillage land were incorporated by ploughing within 24 hours – based on data from the British Survey of Fertiliser Practice 2007 (BSFP, 2008). The current NVZ-AP stipulates that poultry manure applications and surface broadcast slurry applications to uncropped land (i.e. bare ground/stubble) must be incorporated into the soil within 24 hours of application. For the current NVZ-AP scenario, we assumed that 30% of pig slurry and 4% of cattle slurry was applied by trailing hose to arable land or shallow injected to grassland (Misselbrook *et al*., 2009). Of the remainder, we assumed that 30% of cattle slurry, 80% of pig slurry and 80% of poultry manure applied to uncropped land was incorporated by ploughing within 24 hours.

5.1.3 Manure crop N uptake and efficiency

The original version of MANNER (Chambers *et al*., 1999) and the enhanced MANNER-*NPK* software (Nicholson *et al*., 2009; Nicholson *et al*., 2010) were developed to synthesise knowledge on N transformations and losses following the land spreading of organic manures (e.g. on ammonia emissions and denitrification losses as di-nitrogen and N_2O to air, nitrate leaching losses to water and the mineralisation of manure organic N), as shown in Figure 42. MANNER-*NPK* also quantifies crop available N, P, K, Mg and S supply, taking into account manure type, total and readily available N contents, dry matter, speed and method of soil incorporation, application technique (for slurry), timing of application, soil type and moisture content, windspeed and overwinter rainfall.

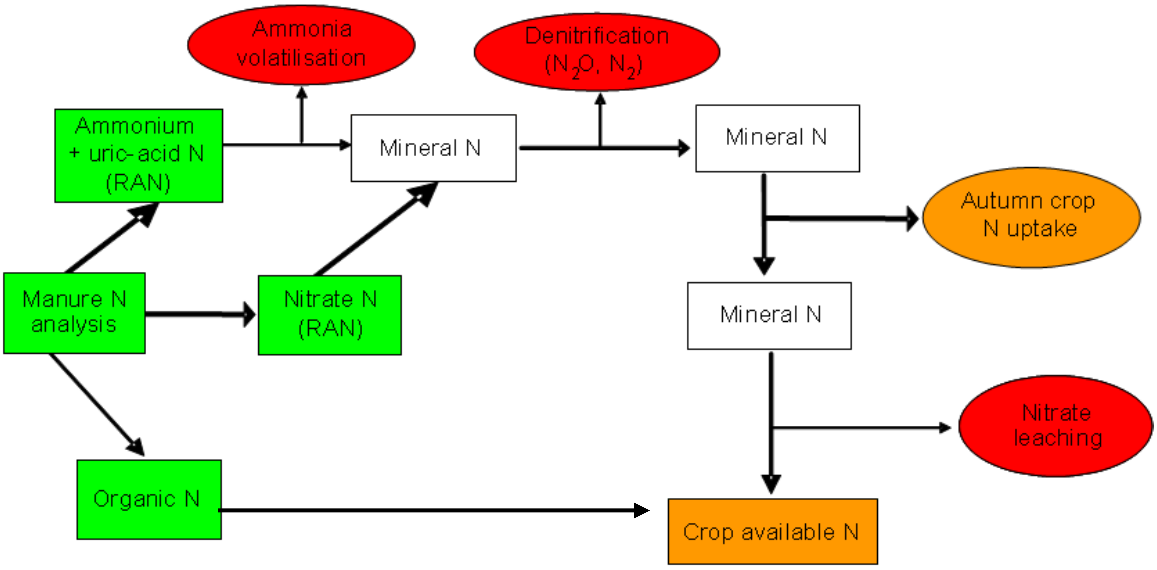

Figure 42. MANNER-*NPK* flow diagram

In this study, the MANNER-*NPK* model was used to predict manure N efficiencies where high readily available N manures (i.e. cattle slurry, pig slurry and poultry manure) were applied at 2-week intervals throughout the year to grassland and arable crops in the different soil type and agro-climate zones. Manures were assumed to be applied at rates equivalent to 250 kg total N/ha (the maximum field N rate), using 'typical' compositional data as published in the "Fertiliser Manual (RB209)" (Defra, 2010). The soil types used were sandy/shallow (i.e. sandy is sandy loam topsoil over loamy sand subsoil) and medium/heavy (i.e. clay loam topsoil over clay loam subsoil). Examples of the outputs for pig slurry applied in the high and low rainfall zones are shown in Figures 43 and 44. These figures illustrate how changing the timing of a manure application can affect the amount of manure N taken up by the crop. For example, pig slurry applied on 1 January to grassland on a sandy/shallow soil in a high rainfall zone would only have an N efficiency of *c.*10% of the total N applied. However, if the same application was made on 1 March the efficiency would increase to *c*.50% of total N applied (Figure 43). The effect was still apparent, but less pronounced, for applications made to the medium/heavy soil type in the high rainfall zone (Figure 43) and the low rainfall zone (Figure 44).

To calculate the impact of extending the closed spreading periods at a national level, the outputs from MANNER-*NPK* were then combined with the quantities of manure N applied to different soil type and agro-climate zones (Table 4 and 5), and the manure application timings detailed in Table 7 to 10 to provide an estimate of the quantity of manure N taken up by crops in England and Wales and current NVZ areas.

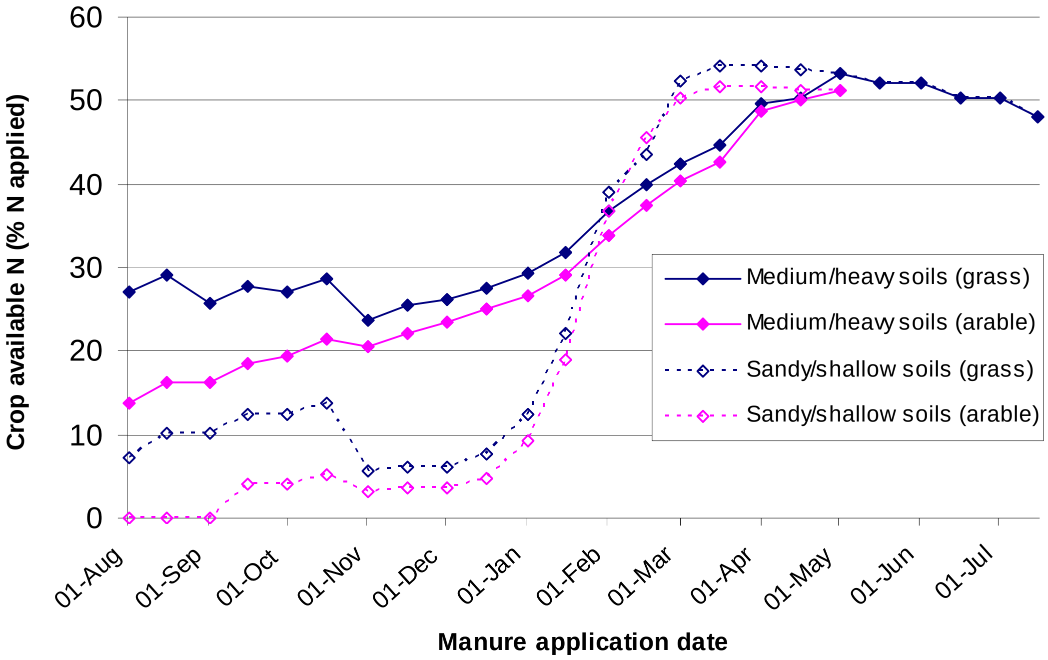

Figure 43. MANNER-*NPK* predicted crop available N (% total N applied) at different application timings (pig slurry broadcast applied and not soil incorporated). High rainfall zone (median rainfall = 1200 mm/annum).

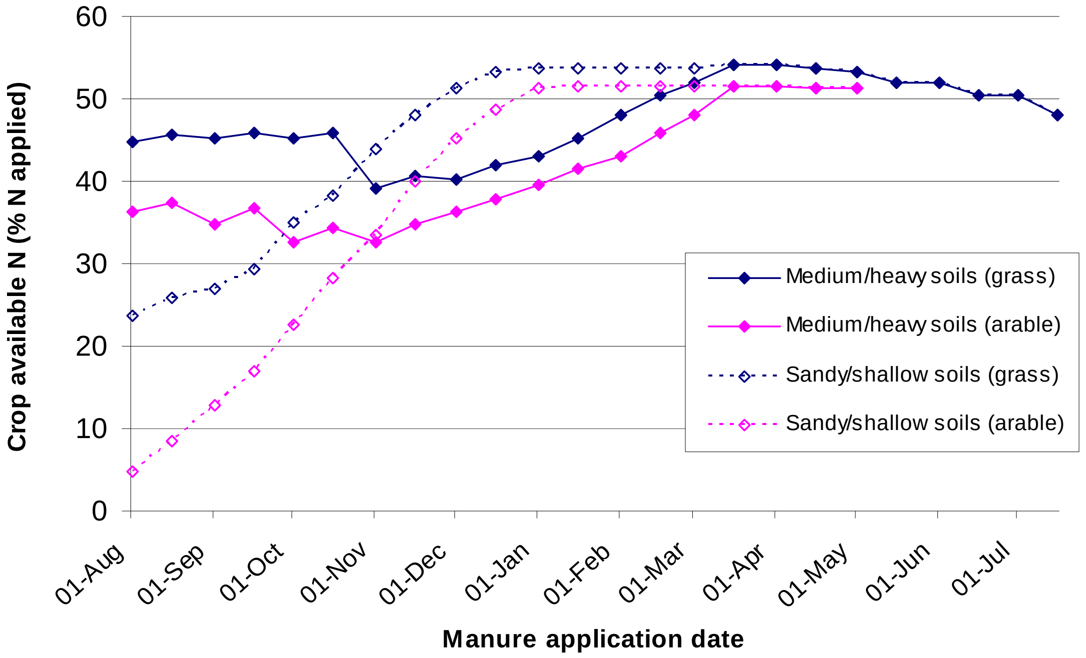

Figure 44. MANNER-*NPK* predicted crop available N (% total N applied) at different application timings (pig slurry broadcast applied and not soil incorporated). Low rainfall zone (median rainfall = 650 mm/annum).

5.1.4 Nitrate leaching losses

Outputs from MANNER-*NPK* were also used to predict nitrate leaching losses from the contrasting high readily available N manure applications. Examples for pig slurry applied in the high and low rainfall zones are shown in Figures 45 and 46. These illustrate how changing the timing of a pig slurry application can affect the amount of N lost through nitrate leaching. For example, pig slurry applied on 1 January to grassland on a sandy/shallow soil in a high rainfall zone was predicted to result in nitrate-N leaching losses equivalent to *c.*40% of the total N applied. However, if the same application was made on 1 March nitrate-N leaching decreases to *c.*2% of total N applied (Figure 45). The effect is still apparent, but less pronounced, for applications made to the medium/heavy soil type in both rainfall zones (Figures 45 and 46). In the low rainfall zone, the change in pig slurry application timing had no effect on nitrate leaching losses from sandy/shallow soils, because leaching was already predicted to have finished by the 1st January (Figure 46).

To estimate the impact of extending the closed periods at a national level, MANNER-*NPK* outputs were combined with the quantities of manure N applied to the different soil type and agro-climatic zones (Tables 4 and 5), and the manure application timings (in Tables 7 to 10) to provide an estimate of the quantity of manure N leached in England and Wales, along with current NVZ areas.

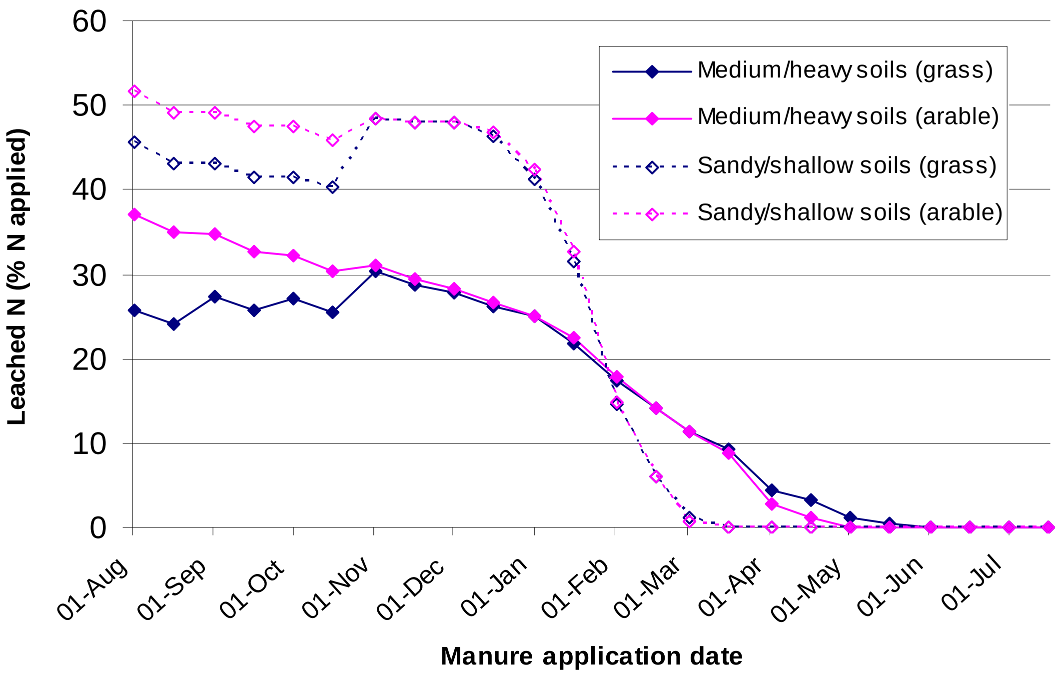

Figure 45. MANNER-*NPK* predicted nitrate-N leaching (% total N applied) losses at different application timings (pig slurry broadcast applied and not soil incorporated). High rainfall zone (median rainfall = 1200 mm/annum).

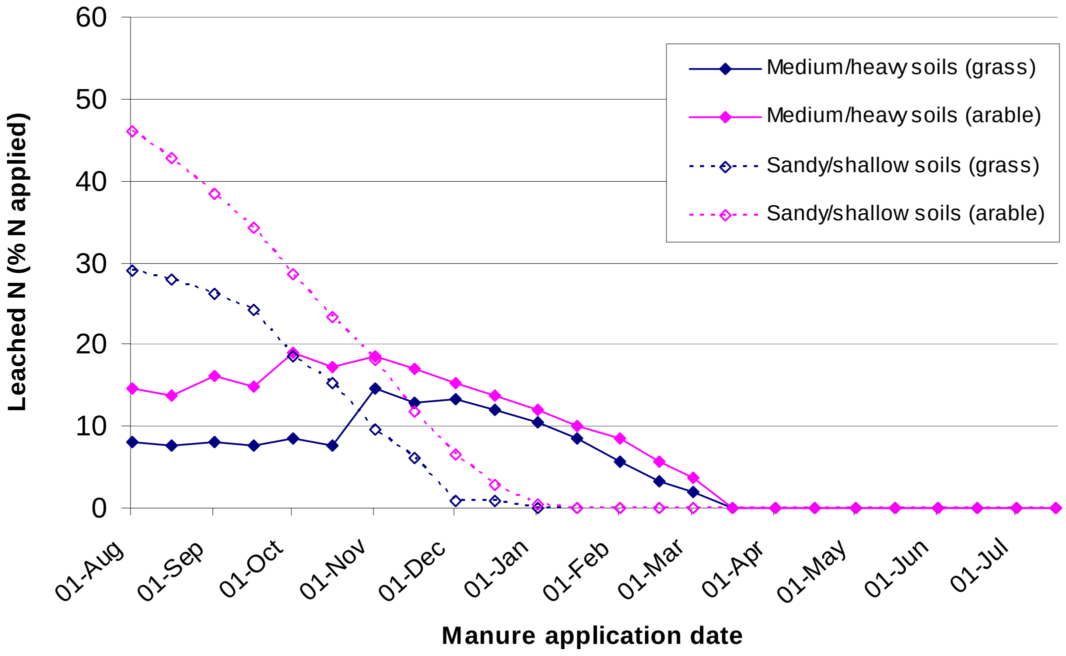

Figure 46. MANNER-*NPK* predicted nitrate-N leaching (% total N applied) losses at different application timings (pig slurry broadcast applied and not soil incorporated). Low rainfall zone (median rainfall = 650 mm/annum).

5.1.5 Ammonia losses to air

Outputs from MANNER-*NPK* were also used to predict ammonia losses to air from the contrasting high readily available N manure applications. The effect of different manure management strategies on ammonia losses from August and September applications is shown in Table 11. Rapid soil incorporation (within 4-6 hours), compared with surface un-incorporated application, was particularly effective in decreasing ammonia losses from poultry manures (from 26% to 4% of total N applied for layer manure and from 18% to 3% for broiler litter); with substantial reductions also achieved for cattle slurry (from 12% to 7%), pig slurry (from 18% to 7%), 'fresh' cattle FYM (from 14% to 5%) and 'fresh' pig FYM (from 18% to 6%). Smaller reductions were obtained if the manures were incorporated after 12-24 hours, compared with surface applied manures that were not incorporated.

Slurry bandspreading to arable crops (using a trailing hose) and shallow injection to grassland were also effective methods in reducing ammonia losses (from 12% to 4-8% of total N applied for cattle slurry, and from 18% to 5-13% for pig slurry). However, nitrogen retained in the soil by reducing ammonia losses from autumn applied manures may subsequently be lost via over-winter nitrate leaching, hence, the net impact on crop N uptake of these methods will be reduced.

Table 11. Ammonia losses (% total N applied) from manures using different management techniques.

Manure type	**Broadcast applied, not incorporated**	**Broadcast applied, incorporated by plough within 12-24 hours**	**Broadcast applied, incorporated by plough within 4-6 hours**	**Band-spread to arable**	**Shallow injected to grassland**
Cattle slurry	12	9	7	8	4
Pig slurry	18	13	7	13	5
Layer manure	26	11	4	-	-
Broiler litter	18	8	3	-	-
Cattle FYM ('fresh')	14	9	5	-	-
Cattle FYM ('old')	7	4	2	-	-
Pig FYM ('fresh')	18	11	6	-	-
Pig FYM ('old')	10	7	4	-	-

5.1.6 GHG emissions

Both *direct* and *indirect* soil N_2O emissions were estimated using IPCC default emission factors (EFs). The default EF for *direct* soil emissions, which is used in the current UK GHG inventory, states that there is a linear relationship between N applied and N_2O emitted, where 1.25% of total N applied remaining after NH_3 loss (10% of total N applied) is estimated to be emitted as N_2O-N (IPCC, 1997). As a result of new global research and scientific understanding, the 1996 (revised) IPCC inventory methodology has recently been updated, such that the default value for *direct* soil emissions has been <u>reduced</u> to 1.0% of total N applied lost as N_2O-N and no longer takes account of NH_3 loss before the N_2O EF is applied (IPCC, 2006). Furthermore, the EF used to calculate *indirect* N_2O losses following NO_3 leaching has also been reduced from 2.5% to 0.75% of leached N lost as N_2O-N (IPCC, 2006). Defra, however, has no immediate plans to use the IPCC 2006 methodology to calculate N_2O emissions from agricultural soils in the UK GHG inventory (*Pers.Comm*. L. Cardenas, North Wyke).

In this study, data from MANNER-*NPK* on crop N uptake, nitrate leaching and ammonia losses were used to estimate direct and indirect N_2O-N losses from each of the four timing scenarios (Table 6). The IPCC Tier 1 methodology (McCarthy *et al*., 2010), which is based on the revised 1996 methodology, was used to estimate direct and indirect N_2O-N emissions from soils (i.e. an EF of 1.25% after NH_3 loss for *direct* soil emissions and an EF of 2.5% of leached N lost as N_2O-N and an EF of 1% of NH_3-N lost as N_2O-N for *indirect* soil emissions).

In addition, the change in GHG emissions as a result of decreased (or increased) manufactured N fertiliser use was also assessed. It has been estimated to take 40.7 MJ of energy to produce, package and transport 1 kg of N fertiliser as ammonium nitrate (Elsayed *et al*., 2006). Total GHG emissions associated with this entire process (i.e. production, packaging and transport to point of use of manufactured N fertiliser) were estimated at 7.11 kg CO_2-e/kg N, with *c*.65% of this total arising from the emission of N_2O during nitric acid production (Elsayed *et al*., 2006). This value has recently been updated to 6.20 kg CO_2-e/kg N to take account of improved N_2O abatement practices during the manufacturing process (Brentrup & Pallière, 2008).

5.1.7 P losses to water

The PSYCHIC (Phosphorus and Sediment Yield Characterisation In Catchments) model (Collins *et al*., 2007; Davison *et al*., 2008; Stromqvist *et al*., 2008) is a process based, monthly time-step model with explicit representation of surface and drain flow hydrological pathways, particulate and solute mobilisation, and incidental losses associated with fertiliser and manure spreading, and which accounts for landscape retention between the point of mobilisation and neighbouring watercourses. Under Defra project NIT18, this model is being enhanced to utilise a daily time-step and to have a more sophisticated representation of surface runoff, which is a major pathway for P and sediment loss.

The updated PSYCHIC model was used, along with experimental data from Faringdon (Oxfordshire), ADAS Boxworth (Cambs) and ADAS Rosemaund (Herefordshire) to assess P losses per unit of P applied for a range of application timings across the year. The model was applied to the same soil categories as for the nitrate leaching assessments (i.e. sandy/shallow and medium/heavy soils).

The outputs from PSYCHIC were then combined with the quantities of manure P applied to the different soil types and agro-climate zones (Tables 4 and 5), and the manure application timings detailed in Tables 7-10 to provide an estimate of the quantity of manure P lost in surface runoff and drainflow waters.

Manure P losses are generally low from May through to September as there is little or no drainage during this period, and are related to rainfall (and drainage) volumes, with higher losses in high compared with low rainfall areas (Figure 47)

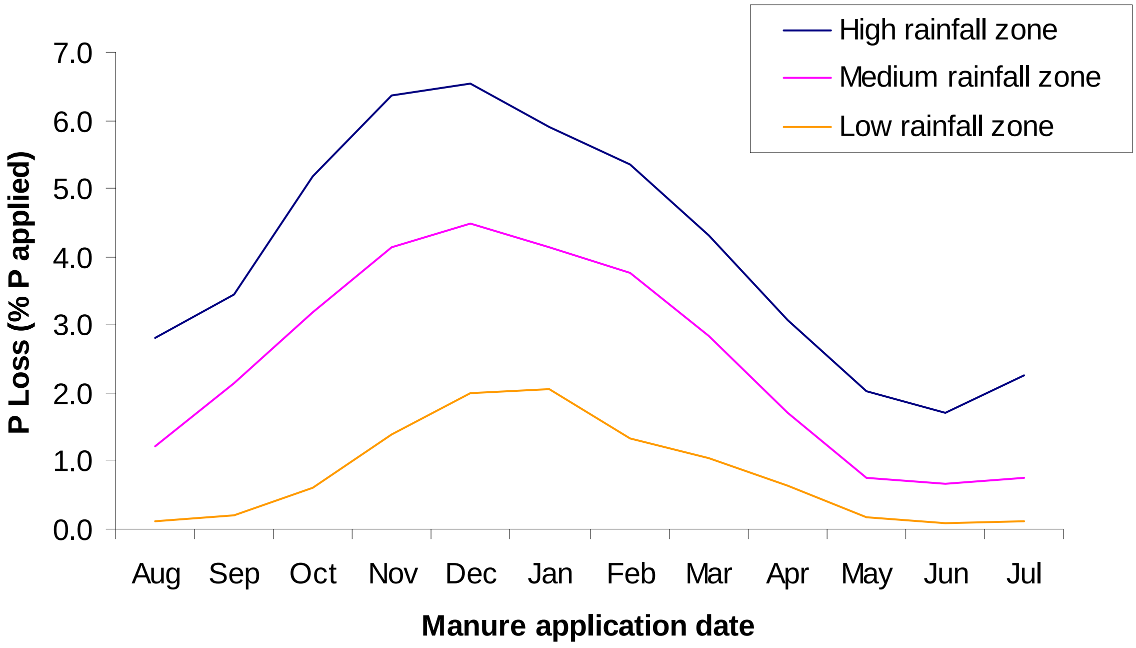

Figure 47. PSYCHIC predicted P losses (% total P applied) for different slurry application timings medium/heavy soil.

Data from Defra project ES0106 showed that mean losses following autumn (September), winter (December-February) and spring (March-April) cattle slurry applications to arable land were equivalent to 1.7%, 2.1% and 2.3% of total manure P applied, respectively (drainage seasons 2003/04 to 2005/06). Similarly on grassland P losses following autumn, winter and spring timings were equivalent to 2.2%, 4.2% and 3.7% of manure total P applied. At ADAS Boxworth (Hodgkinson *et al.,* 2002, Defra project NT1028) mean drainflow P losses following autumn pig slurry applications to arable land were equivalent to 2.0% of P applied (range nil – 3.0%; from 5 over-winter drainage seasons) following winter timings 1.1% of total P applied (range nil – 2.2%; two over-winter drainage seasons) and following spring timings 0.36% (range 0 – 0.8%; two overwinter drainage seasons). At ADAS Rosemaund (Smith et *al.*, 2001) mean P losses in surface runoff following cattle slurry applications in the December to February period were equivalent to 0.6% of total manure P applied (range <0.1 – 2.0%; two drainage seasons).

Based on these measured and modelled data, the export coefficients used to calculate P losses from the contrasting manure application timings on medium/heavy soils were 1.6% of slurry P applied for summer and autumn timings, 2.4% for winter and 1.8% for spring timings, respectively. P loss coefficients for slurry applications to light and shallow soils and solid manure applications to all soil types were based on 0.2% of total P applied.

5.1.8 Ammonium-N losses to water

Data from Defra project WQ0118 have shown that ammonium-N losses to water follow a similar pattern to P losses (see Figures 14 and 15). Hence, for this study it was assumed that the proportional change in ammonium-N losses to water due to extending the closed periods would be the same as those estimated for P.

5.2 Results

To assess the impact of proposed extensions to the closed spreading periods on pollutant losses to air and water at the farm level, it was assumed that individual farmers would broadcast apply manures at the maximum permitted rate of 250 kg/ha in NVZs and as recommended in the Code of Good Agricultural Practice (manure incorporated within 24 hours on arable cropped land in NVZs) and shift the application date forwards by 1 or 2 months in spring (i.e. from 1st January to 1st February or 1st March on sandy/shallow soils; from 16th January to 16th February or 16th March on other soils).

5.2.1 Crop N uptake and N losses via nitrate leaching and ammonia emissions

For England and Wales, the measures contained in the current NVZ-AP (2009-2012) (Table 1) were predicted to increase manure N efficiency for cattle slurry from 26 to 29%, pig slurry from 44 to 48% and poultry manure from 29 to 33% (Table 12). For current NVZ areas, moving from the Baseline (2007) to the current NVZ-AP (Table 6) increased cattle slurry N efficiency from 27 to 30%, pig slurry from 44 to 49% and poultry manure from 30 to 34% (Table 13). For cattle and pig slurry, the improved manure N efficiencies were largely due to reductions in over-winter nitrate leaching losses. For poultry manures, the improvement was mostly due to reductions in ammonia losses as a result of the NVZ-AP requirement to incorporate applications made to bare ground/stubble within 24 hours.

Extending the ‘closed spreading periods’ by a further 1 and 2 months in spring was predicted to have a relatively small impact on manure N efficiencies. For cattle slurry, the slightly lower nitrate leaching losses were balanced by an increase in ammonia emissions from the greater amount of summer (May-July) applications. For poultry manures, extending the ‘closed spreading periods’ later into spring would limit the opportunity to apply manures on stubbles (and rapid incorporation) before the establishment of spring crops. This practice is common on light/sandy soils and can be considered a ‘win-win’ management practice, as it reduces the potential for ammonia emissions and nitrate leaching losses. In many situations, top dressing poultry manures in spring to growing crops is likely to be impractical because of problems associated with soil trafficability and the potential for odour/fly nuisance. Also, it is not generally possible to spread poultry manures evenly over current arable tramline spacings (12-30m).

5.2.2 GHG emissions

The measures contained in the current NVZ-AP were predicted to reduce total direct and indirect N_2O-N emissions following slurry and poultry manure applications by 3% compared with the 2007 baseline, mainly as a result of lower nitrate leaching losses (Tables 14 and 15). The lower N_2O-N emissions coupled with increased manure N efficiency (and resultant reductions in manufactured fertiliser N use) gave overall reductions in GHG emissions equivalent to 68,000 tCO_2e across England and Wales and 37,000 tCO_2e for current NVZ areas, compared with the 2007 baseline. Extending the 'closed periods' by one month was predicted to further reduce GHG emissions by 17,000 tCO_2e across England and Wales and 5,000 tCO_2e for NVZ areas. Extending the 'closed periods' by a further month (i.e. two months more than the current NVZ-AP) was predicted to result in a small increase (*c*.15,000 tCO_2e) in GHG emissions, compared with the one month extension, because of increased indirect N_2O-N emissions from cattle slurry (through increased ammonia loss from summer applications) and poultry manures (because of increased nitrate leaching losses).

Extending the 'closed periods' is likely to increase the potential for methane and N_2O emissions during manure storage, because of the requirement to store slurry and poultry manure for longer. Methane is produced from slurry stores during the anaerobic digestion of organic materials, and the presence of anaerobic/aerobic sites in poultry manure heaps (and FYM heaps) encourages nitrous oxide production, via nitrification and denitrification of readily available N. Current estimates in the UK GHG Inventory (MacCarthy *et al.,* 2010) indicate that the handling and storage of livestock manures contributes *c.*5,000 $ktCO_2e$ (11%) to agricultural GHG emissions. The emission factors used to estimate methane and N_2O losses during the storage and handling of manures are based on animal numbers, with different emission factors used for 'stored' and 'daily spread' manures to give GHG emissions on an annual basis. Unfortunately, it was not possible to disaggregate the data to provide monthly emission factors to assess the impact of extending the closed-periods on methane and nitrous oxide emissions from manure storage. *Note*: any reductions in GHG emissions resulting from extended storage periods and associated improvements in manure N efficiency will be reduced (to a greater or lesser extent) by increased GHG emissions during the extended storage period.

5.2.3 P losses to water

For the whole of England and Wales, baseline P losses were estimated at 370 tonnes from cattle slurry, 51 tonnes from pig slurry and 38 tonnes from poultry manure applications. And baseline P losses within current NVZ areas were estimated at 162 tonnes from cattle slurry, 40 tonnes from pig slurry and 26 tonnes from poultry manure applications. The current NVZ-AP was predicted to reduce P losses by 12 tonnes for current NVZ areas (Table 13) and 28 tonnes for England and Wales (Table 12) compared with baseline values (i.e. a 6% reduction for pig slurry and 7% reduction for cattle slurry). Extending the closed periods by 1 month was predicted to further reduce P losses by 5% for cattle slurry and 2% for pig slurry applications compared with the current NVZ-AP. Extending the closed periods by 2 months was predicted to further reduce P losses by 7% from cattle slurry and 4% from pig slurry applications compared with the current NVZ-AP. It was not possible to predict the effect of the current NVZ-AP and extending the closed periods on P losses from poultry manures because of the lack of information on the effect of timing on P losses from poultry manure applications.

Table 12. Impact of 'closed spreading periods' and increased slurry storage on crop N uptake, nitrate-N leaching losses, ammonia-N emissions and total P losses in England and Wales.

	Crop N uptake		Nitrate-N leaching losses		Ammonia-N losses to air		Total P losses to water	
	Total (kt)	**% total N applied**	**Total (kt)**	**% total N applied**	**Total (kt)**	**% total N applied**	**Total (tonnes)**	**% total P applied**
Baseline[1]								
Cattle slurry	24.6	26	8.8	9	12.4	13	370	1.9
Pig slurry	5.4	44	1.3	10	2.0	16	51	1.7
Poultry manure	18.0	29	5.6	9	11.8	19	38	0.2
Current NVZ-AP[2]								
Cattle slurry	27.2	29	6.2	7	12.4	13	345	1.7
Pig slurry	6.0	48	0.9	8	1.7	14	48	1.6
Poultry manure	20.0	33	5.7	9	9.3	15	38	0.2
1 month extension of closed period[2]								
Cattle slurry	27.5	29	5.2	6	13.0	14	329	1.6
Pig slurry	6.0	48	0.9	7	1.7	14	47	1.6
Poultry manure	19.8	32	5.6	9	9.3	15	38	0.2
2 month extension of closed period[2]								
Cattle slurry	26.8	28	5.2	5	13.9	15	322	1.6
Pig slurry	5.9	48	1.0	8	1.7	14	46	1.5
Poultry manure	18.6	30	5.8	9	9.3	15	38	0.2

[1] Assumes 20% of cattle slurry, 75% of pig slurry and 50% of poultry manure was incorporated by plough within 24 hours.

[2] Assumes 30% of pig slurry and 4% of cattle slurry was applied by trailing hose to arable land or shallow injected to grassland. Of the remainder, 30% of cattle slurry, 80% of pig slurry and 80% of poultry manure applied to arable land was incorporated by plough within 24 hours.

Table 13. Impact of ‘closed spreading periods’ and increased slurry storage on crop N uptake, nitrate-N leaching losses, ammonia-N emissions and total P losses in NVZ areas.

	Crop N uptake		Nitrate-N leaching losses		Ammonia-N losses to air		Total P losses to water	
	Total (kt)	% total N applied	Total (kt)	% total N applied	Total (kt)	% total N applied	Total (tonnes)	% total P applied
Baseline[1]								
Cattle slurry	11.6	27	3.3	8	5.5	13	162	1.8
Pig slurry	4.4	44	1.0	10	1.6	16	40	1.7
Poultry manure	12.4	30	3.4	8	7.9	19	26	0.2
Current NVZ-AP[2]								
Cattle slurry	12.7	30	2.2	5	5.5	13	152	1.7
Pig slurry	4.8	49	0.7	7	1.4	14	38	1.6
Poultry manure	13.9	34	3.4	8	6.2	15	26	0.2
1 month extension of closed period[2]								
Cattle slurry	12.8	30	1.8	4	5.8	14	144	1.6
Pig slurry	4.8	49	0.7	7	1.4	14	37	1.5
Poultry manure	13.7	33	3.4	8	6.3	15	26	0.2
2 month extension of closed period[2]								
Cattle slurry	12.4	29	1.9	4	6.2	15	142	1.6
Pig slurry	4.8	48	0.8	8	1.4	14	36	1.5
Poultry manure	12.9	31	3.5	8	6.2	15	26	0.2

[1] Assumes 20% of cattle slurry, 75% of pig slurry and 50% of poultry manure was incorporated by plough within 24 hours.

[2] Assumes 30% of pig slurry and 4% of cattle slurry was applied by trailing hose to arable land or shallow injected to grassland. Of the remainder, 30% of cattle slurry, 80% of pig slurry and 80% of poultry manure applied to arable land was incorporated by plough within 24 hours.

Table 14. Impact of ‘closed spreading periods’ and increased slurry storage on GHG emissions (ktCO$_2$e) in England and Wales

	Direct N$_2$O emissions	**Indirect N$_2$O emissions from NH$_3$**	**Indirect N$_2$O emissions from NO$_3$**	**Total N$_2$O emissions following manure application**	**‘Saved’ CO$_2$e from reduced manufactured fertiliser N application[1]**	**‘Saved’ CO$_2$e from reduced manufactured fertiliser N application[2]**	**Total GHG emission (including fertiliser ‘saving’[1])**	Total GHG emission (including fertiliser ‘saving’[2])
Baseline								
Cattle slurry	503	60	107	**671**	175	153	**496**	518
Pig slurry	64	10	15	**88**	38	34	**50**	54
Poultry manure	301	57	69	**427**	128	111	**299**	316
Total	868	127	191	**1186**	341	298	**845**	888
Current NVZ-AP								
Cattle slurry	503	61	76	**639**	194	169	**445**	470
Pig slurry	65	8	11	**85**	42	37	**43**	48
Poultry manure	316	45	69	**431**	142	124	**289**	307
Total	884	114	156	**1155**	378	330	**777**	825
1 month extension of ‘closed period’								
Cattle slurry	499	63	64	**626**	196	171	**430**	455
Pig slurry	65	8	11	**84**	43	37	**41**	47
Poultry manure	316	45	69	**430**	141	123	**289**	307
Total	880	116	144	**1140**	380	331	**760**	809
2 month extension of ‘closed period’								
Cattle slurry	494	68	63	**625**	190	166	**435**	459
Pig slurry	65	8	12	**85**	42	37	**43**	48
Poultry manure	316	45	70	**431**	132	115	**299**	316
Total	875	121	145	**1141**	364	318	**777**	823

[1] Calculated using a fertiliser manufacture value of 7.11 kg CO$_2$e/kg N – including production (6.96 kg CO$_2$e/kg N), packaging (0.03 kg CO$_2$e/kg N)& transport to point of use (0.11 kg CO$_2$e/kg N) (Elsayed *et al*. 2006).

[2] Calculated using a fertiliser manufacture value of 6.2 kg CO$_2$e/kg N) including manufacture to the plant gate i.e. excluding transport to point of use (Brentrup & Pallière, 2008).

Table 15. Impact of ‘closed spreading periods’ and increased slurry storage on GHG emissions (ktCO_2e) in NVZ areas

	Direct N_2O emissions	**Indirect N_2O emissions from NH_3**	**Indirect N_2O emissions from NO_3**	**Total N_2O emissions following manure application**	**‘Saved’ CO_2e from reduced manufactured fertiliser N application[1]**	**‘Saved’ CO_2e from reduced manufactured fertiliser N application[2]**	**Total GHG emission (including fertiliser ‘saving’[1])**	Total GHG emission (including fertiliser ‘saving’[2])
Baseline								
Cattle slurry	224	27	41	**292**	82	72	**210**	220
Pig slurry	51	8	12	**70**	31	27	**39**	43
Poultry manure	202	39	42	**282**	88	77	**194**	205
Total	477	74	95	**644**	201	176	**443**	468
Current NVZ-AP								
Cattle slurry	224	27	27	**278**	90	79	**188**	199
Pig slurry	52	7	9	**67**	34	30	**33**	37
Poultry manure	212	30	41	**284**	99	86	**185**	198
Total	488	64	77	**629**	223	195	**406**	434
1 month extension of ‘closed period’								
Cattle slurry	222	28	23	**273**	91	79	**182**	194
Pig slurry	52	7	8	**67**	34	30	**33**	37
Poultry manure	212	31	41	**284**	98	85	**186**	199
Total	486	66	72	**624**	223	194	**401**	430
2 month extension of ‘closed period’								
Cattle slurry	220	30	23	**273**	88	77	**185**	196
Pig slurry	52	7	9	**68**	34	29	**34**	39
Poultry manure	212	30	42	**285**	92	80	**193**	205
Total	484	67	74	**626**	214	186	**412**	440

[1] Calculated using a fertiliser manufacture value of 7.11 kg CO_2e/kg N – including production (6.96 kg CO_2e/kg N), packaging (0.03 kg CO_2e/kg N)& transport to point of use (0.11 kg CO_2e/kg N) (Elsayed *et al*. 2006).

[2] Calculated using a fertiliser manufacture value of 6.2 kg CO_2e/kg N) including manufacture to the plant gate i.e. excluding transport to point of use (Brentrup & Pallière, 2008).

6 ECONOMIC IMPACTS OF IMPLEMENTING THE METHODS AT FARM AND NATIONAL SCALE

The capital and amortised (capital repayment and interest) costs of implementing the six methods of improving manure N use efficiency were estimated for ‘small’, ‘medium’ and ‘large’ dairy and pig farms; based on the farm typologies described in the “Mitigation Methods–User Guide” (Defra Project WQ0106). Details of the farm typologies are summarised below; average annual rainfall was assumed to be 800mm:

(i) Dairy:

- ‘Small’ - 60 cows; 265m^2 of concrete hard standing
- ‘Medium’ - 110 dairy cows, 486 m^2 of concrete hard standing
- ‘Large’ - 300 cows; 1,325 m^2 of concrete hard standing

It was assumed that 25 litres/day of wash-down water and half of the rainfall volume falling on the concrete yard area was collected in the slurry store. Housing occupancy was assumed to be 80% in October, 100% in November, December, January and February, 80% in March and 40% in April.

(ii) Pigs:

- ‘Small’ - 335 weaners, 160 growers, 150 finishers, 36 maiden gilts 60 sows; 140 m^2 of concrete yard
- ‘Medium’ 670 weaners, 325 growers, 300 finishers, 72 maiden gilts 120 sows; 280 m^2 of concrete yard
- ‘Large’ pig farm 1340 weaners, 650 growers, 600 finishers, 144 maiden gilts, 240 sows; 560 m^2 of dirty concrete yard

It was assumed that half of the rainfall volume falling on the concrete yard area was collected in the slurry store.

6.1 Manure storage

Livestock manure storage requirements were based on standard manure production figures (Defra/EA, 2008) and calculated using PLANET (www.planet4farmers.co.uk). For the dairy and pig farms, the baseline slurry storage capacity was assumed to be 3 months and 4 months, respectively – based on data from Smith *et al.* (2001). The costs of additional slurry storage capacity were estimated for both above ground ‘steel/concrete tank’ (£50/m^3) and earth-bank lagoon systems (£40/m^3), (Nix, 2011).

The capital repayment and interest costs for slurry storage and construction of impermeable concrete pads and leachate collection for solid manure stores were amortised over 20 years, assuming a 7% interest rate. The annual charge of servicing the interest and to repay the capital was £94 for each £1,000 borrowed (Nix, 2011). Annual repair costs were assumed to be 2% of the total capital expenditure.

On the poultry farms it was assumed that the additional solid manure was stored in field heaps, so there were no additional costs associated with the extended manure storage periods.

6.1.1 Dairy farms

The baseline (3 months) slurry storage capacity was calculated at 500 m^3 on the small, 890 m^3 on the medium and 2380 m^3 on the large dairy farm, respectively; based on October to February rainfall volumes (Table 16). In order to comply with the current NVZ-AP (i.e. a minimum of 5 months storage), a further 330 m^3 of storage would be required on the small farm, 590 m^3 on the medium and 1,580 m^3 on the large farm. Extending the closed period by another 2 months increased the baseline storage requirement for each farm type to 1070 m^3, 1,930 m^3 and 5,170 m^3 on the small, medium and large farms, respectively (i.e. to provide 7 months storage).

Table 16. Slurry storage requirement for small, medium and large dairy farms

	Storage requirement (m^3)		
Storage period	Small	Medium	Large
Baseline (3 months)	500	890	2380
Current NVZ-AP (5 months)	830	1480	3960
1 month extension of ‘closed period’	970	1740	4670
2 month extension of ‘closed period’	1070	1930	5170

Increasing the storage capacity by 2 months i.e. from 3 to 5 months (the current NVZ-AP requirement) was estimated to have a capital cost of *c*. £16,000 on the small farm and *c*. £80,000 on the large farm for steel/concrete tanks. Increasing the slurry storage requirement to 6 months was estimated to have a capital cost of *c*. £24,000 on the small farm and *c.*£115,000 on the large farms for steel/concrete tanks. Increasing the storage requirement by 2 more months (i.e. from 3 to 7 months) was estimated to have a capital cost of *c.*£29,000 on the small farm and *c.*£140,000 on the large farm. The lower monthly cost of extending the storage capacity to 6 and 7 months (compared with 5 months) reflected the smaller volumes of slurry collected at the start of the grazing season in March/ April (Table 17).

Extending the storage period from baseline (3 months) to 5 months increased annual costs to *c.* £4,700 on the small farm and *c*.£23,000 on the large farm. Extending the storage period to 6 months increased annual costs to *c.*£5,500 on the small farm and *c*.£27,000 on the large farm.

Note:

(i) Capital and annual costs for earth banked lagoon stores were *c.*20% lower than steel/concrete tanks reflecting their lower construction, material and maintenance costs.

(ii) For many farms the cost of upgrading slurry storage would be for the whole 5 month period, as many existing steel tanks/concrete structures will have reached the end of their useable life.

Table 17. Tin-tank and lagoon storage costs for small, medium and large dairy farms

Farm size	**Small**	**Medium**	**Large**	**Small**	**Medium**	**Large**
	Steel/concrete tank			**Lagoon**		
Baseline (3 months)						
Capital cost £	25,000	44,500	119,100	20,000	35,600	95,300
Annual amortised cost £	2,340	4,180	11,200	1,870	3,350	8,960
Repairs @ 2% £	500	890	2,380	400	710	1,910
Total annual cost	**2,840**	**5,070**	**13,580**	**2,270**	**4,060**	**10,860**
Existing NVZ-AP (5 months)						
Capital cost	41,500	74,000	198,200	33,200	59,200	158,600
Annual cost	3,870	6,950	18,640	3,100	5,560	14,910
Repairs @ 2%	820	1,480	3,970	660	1,180	3,170
Total annual cost	**4,690**	**8,430**	**22,610**	**3,760**	**6,740**	**18,080**
1 month extension of ‘closed period’						
Capital cost	48,500	87,100	233,500	38,800	69,600	186,800
Annual cost	4,560	8,180	21,950	3,650	6,550	17,560
Repairs @ 2%	970	1,740	4,670	780	1,390	3,740
Total annual cost	**5,530**	**9,920**	**26,620**	**4,430**	**7,940**	**21,300**
2 month extension of ‘closed period’						
Capital cost	53,700	96,400	258,500	43,000	77,100	206,700
Annual cost	5,050	9,060	24,290	4,040	7,250	19,430
Repairs @ 2%	1,070	1,930	5,170	860	1,540	4,130
Total annual cost	**6,120**	**10,990**	**29,460**	**4,900**	**8,790**	**23,560**

Scaling up to England and Wales and current NVZ areas

The mean slurry storage requirement (per cow) for each closed period scenario was combined with data on dairy cow numbers from Defra Statistics (2006) to provide estimates for the slurry storage requirement for England and Wales and the current NVZ area (Table 18).

Table 18. Cattle slurry storage requirement and costs for England and Wales and current NVZ areas

	England and Wales		NVZ area	
	Volume (m m^3)	Cost (£ m)	Volume (m m^3)	Cost (£ m)
3 months (baseline)	15.9	790	8.2	410
5 months (existing NVZ-AP)	26.3	1,315	13.5	675
6 months	31.0	1,550	16.0	800
7 months	34.4	1,720	17.6	880

6.1.2 Pig Farms

The baseline (4 month) slurry storage capacity was calculated at 350 m^3 on the small, 710 m^3 on the medium and 1,410 m^3 on the large pig farm (Table 19). In order to comply with the existing NVZ-AP (i.e. a minimum of 6 months storage), a further 170 m^3 of storage would be required on the small farm, 340 m^3 on the medium and 690 m^3 on the large farm; based on October to March rainfall volumes. Increasing the slurry storage requirement by another 2 months (to eight months) increased the slurry storage requirement to 690 m^3, 1,390 m^3 and 2,770 m^3 on the small, medium and large farms, respectively.

Table 19. Slurry storage requirement for small, medium and large pig farms

	Storage requirement (m^3)		
Storage period	Small	Medium	Large
Baseline (4 months)	350	710	1410
Existing NVZ-AP (6 months)	520	1050	2100
1 month extension of ‘closed period’	610	1220	2440
2 month extension of ‘closed period’	690	1390	2770

Table 20. Tin-tank and lagoon storage costs for small, medium and large pig farms

Farm size	**Small**	**Medium**	**Large**	**Small**	**Medium**	**Large**
Capacity Type	**Steel/concrete tank**			**Lagoon**		
Baseline (4 months)						
Capital cost £	17,500	35,300	70,500	14,100	28,400	56,400
Annual cost £	1,660	3,320	6,630	1,330	2,660	5,300
Repairs @ 2% £	350	710	1,410	280	570	1,130
Total annual cost	**2,010**	**4,330**	**8,040**	**1,610**	**3,230**	**6,430**
Existing NVZ – AP (6 months)						
Capital cost	26,200	52,450	104,900	20,960	41,960	83,920
Annual cost	2,460	4,930	9,890	1,970	3,940	7,890
Repairs @ 2%	520	1,050	2,100	420	840	1,680
Total annual cost	**2,980**	**5,980**	**11,990**	**2,390**	**4,780**	**9,570**
1 month extension of ‘closed period’						
Capital cost	30,400	60,900	121,750	24,320	48,720	97,400
Annual cost	2,860	5,730	11,450	2,290	4,580	9,160
Repairs @ 2%	610	1,220	2,440	490	970	1,950
Total annual cost	**3,470**	**6,950**	**13,890**	**2,780**	**5,550**	**11,110**
2 month extension of ‘closed period’						
Capital cost	34,600	69,300	138,550	27,680	55,440	110,840
Annual cost	3,250	6,510	13,020	2,600	5,210	10,420
Repairs @ 2%	690	1,390	2,770	550	1,110	2,220
Total annual cost	**3,940**	**7,900**	**15,790**	**3,150**	**6,320**	**12,640**

Increasing the storage capacity to 6 months (the existing NVZ-AP requirement) was estimated to have a capital cost of *c.*£9,000 on the small farm and *c.*£35,000 on the large pig farm for a steel/concrete tank (Table 20). Increasing the slurry storage requirement to 8 months was estimated to have a capital cost (above baseline) of *c.*£17,000 on the small farm and *c.*£70,000 on the large farm (for a steel/concrete tank).

Extending the storage period to six months increased annual costs by a *c.*£1,000/year on the small farm and by *c.*£4,000 a year on the large farm. Extending the closed-period to 8 months increased annual costs on the small farm by *c.*£2,000 and *c.*£8,000 on the large pig farm.

Note:

(i). Capital and annual costs for earth banked lagoons stores were *c.*20% lower than steel/concrete tanks reflecting their lower construction, material and maintenance costs.

(ii). For many pig farms the costs of upgrading slurry storage will be for the whole 6 month period, as many existing on-farm steel tank/concrete structures have reached the end of their useable life.

6.1.3 *Scaling up to England and Wales and NVZ areas*

Data from MANURES-*GIS* were used to estimate pig slurry storage requirements for England and Wales and the current NVZ area (Table 21). It was assumed that the volumes of slurry produced were consistent throughout the year (i.e. the same volume of slurry was produced each month).

Table 21. Pig slurry storage requirement and costs for England and Wales and current NVZ areas

	England and Wales		NVZ area	
Storage period	Volume (m m^3)	Cost (£ m)	Volume (m m^3)	Cost (£ m)
4 months (baseline)	1.1	55	0.9	45
6 months (current NVZ-AP)	1.7	85	1.4	70
7 months	2.0	100	1.6	80
8 months	2.2	110	1.8	90

6.2 Cost-benefit assessment

The costs of extending the closed periods in terms of improved manure N use efficiency were compared with the benefits in terms of reductions in manufactured fertiliser N use and societal benefits from reduced diffuse pollution of the air and water environments. The savings were calculated assuming a cost of £1000/tonne of fertiliser N (equivalent to £345/tonne of ammonium nitrate) and ecosystem damage costs of £60/tonne CO_2e (DECC, 2009), £2,100/tonne for NH_3-N (IGCB, 2008) £670/tonne for NO_3-N (Defra project WT0706) and £35,000/tonne of P (Defra project WT0706).

The costs and benefits were calculated over a 20 year period to reflect the typical write-off period for farm capital investment. The costs and benefits were summarised for current NVZ areas (Table 22) and England and Wales (Table 23). The cost-benefit ratios for each method were calculated using (i) capital and operational costs and (ii) the total amortised cost for repaying the capital and servicing the interest over 20 years and annual operational costs.

Overall, the capital costs of extending slurry storage capacity from the 2007 baseline estimate to comply with the existing NVZ-AP were estimated at £290 million for the current NVZ area and £555 million for England and Wales. Over 20 years, the cost of repaying the capital and servicing the interest was estimated to be £550 million for the current NVZ area and £1,040 million for England and Wales.

Note: Baseline slurry storage capacity estimates are uncertain.

Table 22. Costs and benefits of the existing NVZ-AP options OVER 20 YEARS: Current NVZ Areas (62% of England and *c.*3% of Wales)

	NVZ-AP Closed period	NVZ-AP Closed period + 1 month extra storage	NVZ-AP Closed period + 2 months extra storage
Capital costs of extra slurry storage[1]	290 million	425 million	515 million
Annual amortised costs[2]	550 million	800 million	970 million
Additional operational costs	0	0	0
Fertiliser N saving (t)	60,000	58,000	34,000
GHG savings (tCO_2e)	740,000	840,000	620,000
Ammonia-N savings (t)	38,000	30,000	24,000
Nitrate-N savings (t)	28,000	36,000	30,000
Phosphorus savings (t)	240	420	480
Fertiliser saving (£)[3]	60 million	58 million	34 million
GHG savings societal benefit (£) [4]	44 million	50 million	37 million
Ammonia N savings societal benefit (£)[5]	80 million	63 million	50 million
Nitrate-N savings societal benefit (£)[5]	19 million	24 million	20 million
Phosphorus savings societal benefit (£)	8 million	15 million	17 million
Cost benefit ratio based on capital and operation costs [5]	1.4:1	2.0:1	3.3:1
Cost benefit ratio based on amortised and operation costs[5]	2.6:1	3.8:1	6.1:1

[1] Baseline storage assumed to be 3 months for cattle slurry and 4 months for pig slurry (Smith et al., 2001). Slurry storage costs are £50/m^3 based on above ground steel/concrete structures (Nix, 2011).

[2] Capital costs amortised over 20 years at 7% interest

[3] Based on manufactured fertiliser N cost of £1,000/tonne (i.e. £345/tonne of ammonium nitrate)

[4] Based on non-traded price of CO_2e of £60/tonne and ecosystem damage costs of £2,100/tonne of NH_3-N, £670/tonne NO_3-N and £35,000/tonne of P

[5] Benefits based on fertiliser N savings and avoided GHG, ammonia-N, nitrate-N and P damage costs

Over a 20 year period improved manure N use efficiency resulting from the existing NVZ-AP was predicted to save 60,000 tonnes in manufactured fertiliser N use (worth £60 million) across current NVZ areas and 104,000 tonnes for England and Wales (worth £104 million).

The reductions in ecosystem damage costs (from lower nitrous oxide, ammonia, and nitrate and P losses) over a 20 year period resulting from the existing and NVZ-AP were estimated at £ 151 million for current NVZ areas (Table 22) and £259 million for England and Wales (Table 23). The overall cost-benefit ratio based on the initial capital cost was 1.4:1 for current NVZ areas and 1.5:1 for England and Wales, compared with a cost-benefit ratio based on capital repayment and interest charges of 2.6:1 for current NVZ areas and 2.9:1 for England and Wales.

Table 23. Costs and benefits of NVZ-AP OVER 20 YEARS: of implementing the existing NVZ-AP across England and Wales

	NVZ-AP Closed period	NVZ-AP Closed period + 1 month extra storage	NVZ-AP Closed period + 2 months extra storage
Capital costs of extra slurry storage[1]	555 million	805 million	985 million
Annual amortised costs[2]	1,040 million	1,510 million	1,850 million
Additional operational costs	0	0	0
Fertiliser N saving (t)	104,000	106,000	66,000
GHG savings (tCO_2e)	1,360,000	1,700,000	1,360,000
Ammonia-N savings (t)	56,000	44,000	26,000
Nitrate-N savings (t)	58,000	80,000	74,000
Phosphorus savings (t)	560	900	1,060
Fertiliser saving (£)[3]	104 million	106 million	66 million
GHG savings societal benefit (£)[4]	80 million	102 million	82 million
Ammonia N savings societal benefit (£)[4]	120 million	90 million	55 million
Nitrate-N savings societal benefit (£)[4]	39 million	54 million	50 million
Phosphorus savings societal benefit (£)	20 million	32 million	37 million
Cost benefit ratio based on capital and operation costs [5]	1.5:1	2.1:1	3.4:1
Cost benefit ratio based on amortised and operation costs[5]	2.9:1	3.9:1	6.4:1

[1] **Baseline storage assumed to be 3 months for cattle slurry and 4 months for pig slurry (Smith et al., 2001). Slurry storage costs are £50/m^3 based on above ground steel/concrete structures (Nix, 2011).**

[2] **Capital costs amortised over 20 years at 7% interest**

[3] **Based on manufactured fertiliser N cost of £1,000/tonne (i.e. £345/tonne of ammonium nitrate).**

[4] **Based on non-traded price of CO_2e of £60/tonne and ecosystem damage costs of £2,100/tonne of NH_3-N £670/tonne NO_3-N and £35,000/tonne of P**

[5] **Benefits based on fertiliser N savings and avoided GHG, ammonia-N, nitrate-N and P ecosystem damage costs**

Extending the current NVZ-AP storage period (4 months for cattle slurry; 5 months for pig slurry) by a further 1 and 2 months *increased* capital costs by £135 million and £225 million for current NVZ areas, compared with £250 million and £430 million for England and Wales. The cost-benefit ratio (based on capital costs) of extending the closed periods by 1 and 2 months increased to 2.0:1 and 3.3:1 for the current NVZ areas and to 2.1:1 and 3.4:1 for England and Wales, respectively. The extra costs of extending the storage periods were not matched by proportional reductions in fertiliser N use and ecosystem damage costs.

7 CONCLUSIONS

- The measures included in the current NVZ-AP were predicted to increase manure N use efficiency, compared with the 2007 baseline, by *c.*10% in NVZ areas and for the whole of England and Wales. For cattle and pig slurry, the improved manure N use efficiency (3% of total N applied for cattle slurry and 4-5% for pig slurry) was largely as a result of reductions in nitrate leaching losses. For poultry manures, the increased manure N use efficiency (4% of total N applied) was mainly due to reductions in ammonia losses as a result of soil incorporation within 24 hours of application.

- Total direct and indirect nitrous oxide-N emissions following slurry and poultry manure applications where reduced by 3%, compared with the 2007 baseline, mainly as a result of lower nitrate leaching losses. The lower nitrous oxide-N emissions coupled with increased manure N use efficiency (and resultant reductions in manufactured fertiliser N use) reduced overall GHG emissions by 8% - equivalent to reductions of 68,000 tCO_2e for England and Wales and 37,000 tCO_2e for NVZ areas, compared with the 2007 baseline. Extending the ‘closed spreading periods’ by one month was predicted to *reduce* GHG emissions by a further 17,000 t CO_2e for England and Wales and by 5,000 tCO_2e for current NVZ areas. Extending the ‘closed periods’ by a further month (i.e. two months more than the current NVZ-AP) was predicted to *increase* GHG emissions by 17,000 tonnes CO_2e for England and Wales and 11,000 tCO_2e for the NVZ area compared with the one month extension. *Note*: any reductions in GHG emissions resulting from extended storage periods and associated improvements in manure N efficiency are likely to be reduced (to a greater or lesser extent) by increases in methane and nitrous oxide emissions during the extended storage period.

- The current NVZ-AP was predicted to reduce annual ammonia emissions by 1,900 tonnes NH_3-N across current NVZ areas and 2,800 tonnes NH_3-N across England and Wales compared with the 2007 baseline. The emission reductions were mainly a result of the requirement to incorporate slurry and poultry manure applications to bare soil or stubble within 24 hours of application. Extending the closed periods by 1 month was predicted to increase ammonia emissions by 400 tonnes NH_3-N for NVZ areas and 600 tonnes NH_3-N for England and Wales. Extending the closed periods by 2 months was predicted to further increase ammonia emissions by 700 tonnes NH_3-N for NVZ areas and 1,500 tonnes NH_3-N for England and Wales, compared with the 2007 baseline. The higher ammonia emissions from the extended closed periods were mainly a reflection of the increased proportion of cattle slurry applied to grassland in summer.

- The current NVZ-AP was predicted to reduce nitrate leaching losses by 1,400 tonnes NO_3-N for NVZ areas and 2,900 tonnes NO_3-N across England and Wales, compared with the 2007 baseline levels. Extending the closed periods by 1 month was predicted to reduce nitrate losses to 1,800 tonnes NO_3-N for NVZ areas and 4,000 tonnes NO_3-N across England and Wales. However, extending the closed periods to 2 months was predicted to increase nitrate-N losses compared to the 1 month extension by 300 tonnes NO_3-N for NVZ areas and England and Wales, because of the limited opportunities to spread manure before the establishment of arable crops in spring which would increase the proportion of manure spread in the autumn.

- The current NVZ-AP was predicted to reduce P losses by 12 tonnes for current NVZ areas and 28 tonnes for England and Wales, compared with baseline values (i.e. a 6% reduction for pig slurry and 7% reduction for cattle slurry). Extending the closed periods by 1 month was predicted to reduce P losses by 5% for cattle slurry and 2% for pig slurry applications compared with the current NVZ-AP. Extending the closed periods by 2 months was predicted to reduce P losses by 7% from cattle slurry and 4% from pig cattle slurry applications compared with the current NVZ-AP. It was not possible to predict the effect of the current NVZ-AP and extending the closed periods on P losses from poultry manures, because of the lack of information on the effect of timing on P losses from poultry manure applications.
- The capital cost of extending the slurry storage capacity from baseline (3 months capacity for cattle and 4 months for pig farms) to comply with the current NVZ-AP (5 months for cattle and 6 months for pig farms) was estimated at £290 million for current NVZ areas (62% of England and *c.*3% of Wales) and £555 million for England and Wales.

- Over a 20 year period improved manure N use efficiency, resulting from the measures included in the current NVZ-AP was predicted to save 60,000 tonnes of manufactured fertiliser N (worth £60 million) across current NVZ areas. Extending the NVZ-AP to cover England and Wales was predicted to save 104,000 tonnes (£104 million) of manufactured fertiliser N over a 20 year period. The 20 year reductions in ecosystem damage costs (from reductions in GHG and ammonia, and nitrate and P losses) resulting from the measures included in the current NVZ-AP were estimated at £151 million for NVZ areas and £259 million for England and Wales. The 20 year cost-benefit ratio of implementing the existing NVZ-AP was 1.4:1 compared with 1.5:1 across England and Wales.

- Extending the existing NVZ-AP storage periods by a further 1 and 2 months increased capital costs by £135 million and £225 million for current NVZ areas, compared with £250 million and £430 million for England and Wales, respectively. The cost-benefit ratio of extending the storage periods by 1 and 2 months increased to 2.0:1 and 3.3:1 for current NVZ areas, and 2.1:1 and 3.4:1 for England and Wales, respectively. The additional costs of extending the existing NVZ-AP storage periods were *not* reflected in proportional reductions in manufactured fertiliser N use and ecosystem damage costs.

8 RECOMMENDATIONS FOR FUTURE WORK

The findings from this project have shown that measures to increase manure N efficiency (e.g. increasing slurry storage capacity to allow spring rather than autumn application timings) can reduce direct and indirect nitrous oxide emissions from soils, as long as improvements in manure N efficiency are matched by reductions in manufactured fertiliser N inputs. However, any reductions in GHG emissions from improvements in manure N efficiency (e.g. from spring compared with autumn application timings) are likely to be offset by increased GHG emissions resulting from the extended slurry storage period. The current UK GHG Inventory (which estimates that 14% of dairy slurry and *c.*7% of pig slurry is 'daily spread') indicates that the handling and storage of livestock manures contributes *c.*5,000 kt CO_2e (11%) to agricultural GHG emissions, compared with *c.*6,000 kt CO_2e (12% of agricultural GHG emissions) following manure spreading.

There is a need to carry out *integrated studies* to quantify nitrous oxide, methane and ammonia emissions during the manure management continuum (i.e. from both manure storage and land spreading) so that the impacts of strategies to minimise diffuse pollution to the air and water environments can be fully appraised. This information will be required to help ensure that measures designed to reduce one pollutant (e.g. increased slurry storage to minimise nitrate leaching losses) do not lead to increases losses of another (e.g. methane emissions from slurry stores) – so called 'pollution swapping'.

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Defra projects

AC0101: An improved inventory of greenhouse gases from agriculture.

AC0111: Nitrous oxide and ammonia emissions from multiple pollutant Cracking Clay experimental sites (adding value to Defra project WQ0118).

AC0222: Agricultural greenhouse gas mitigation feasibility study.

ES0115: OPTi-N

FF0201: Market segmentation in the agriculture sector: climate change.

KT0106: MANNER – POLICY SUPPORT MODEL (*MANNER-PSM*)

KT0105: MANURE NUTRIENT EVALUATION ROUTINE (MANNER-*NPK*)

WT1006: Management of livestock manures to meet Nitrate Directive requirements.

WQ0757NVZ: The impact on greenhouse gas emissions of the revised Action Programme for Nitrate Vulnerable Zones.

WQ0103: The National Inventory and Map of Livestock Manure Loadings to Agricultural Land: MANURES-*GIS*

WQ0106: Mitigation Methods: User-*Guide.*

WQ0118: Understanding the behaviour of livestock manure multiple pollutants through contrasting cracking clay soils – Cracking Clays: Water.

WT0706: Benefits and Pollution Swapping: Cross-cutting issues for Catchment Sensitive Farming Policy.