NITRATES ACTION PROGRAMME: IMPACTS ON GREENHOUSE GAS EMISSIONS AND DIFFUSE NITROGEN POLLUTION

Report for Defra Project: WT0932 (additional work package)

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1 EXECUTIVE SUMMARY

The overall objective of this work package was to assess the effect of six methods that aim to increase manure nitrogen (N) use efficiency on nitrous oxide (N_2O-N), methane (CH_4) and ammonia (NH_3-N) emissions to air, and nitrate (NO_3-N) leaching losses to water. The six methods which are *additional* to those included in the current NVZ-AP (2009-12) were:

1. Extending the spring 'closed spreading periods' for high readily available N manures (i.e. pig and cattle slurry and poultry manures) and associated increases in slurry storage capacity
2. Rapid soil incorporation of manures
3. Increased slurry bandspreading and shallow injection
4. Increased use of slurry separation technologies
5. Storing solid manures on an impermeable base
6. Stipulating a higher figure for manure N use efficiency

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. Estimates of manure N loadings for England were calculated from figures for England and Wales, using pro-rata adjustments for animal numbers based on 2009 Agricultural Census data. Model runs were carried out for 4 scenarios:

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
4. *Month 2* – extending the 'closed spreading periods' for high readily available N manures by 2 months in spring

MANNER-*NPK* was used to estimate manure N efficiency, 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-N 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 costs associated with the different management practices (e.g. extra manure storage, use of improved slurry spreading equipment) were quantified for the current NVZ area (i.e. 62% of England and *c.*3% of Wales), England and Wales and England, using standard industry figures taking into account capital costs, amortised costs (capital repayment and interest) over the life span of the investment and extra operational costs. The economic benefits of the different management practices were quantified in terms of reduced manufactured fertiliser N use (resulting from improved manure N use efficiency) and reductions in ecosystem damage costs resulting from abated ammonia-N (£2,100/tonne), nitrous oxide (£60/tonne CO_2e) emissions and nitrate leaching (£670/tonne NO_3-N) losses (See Tables 63, 64 and 65 for detailed cost summaries).

1.1 Impact of measures on manure N efficiency, nitrous oxide, ammonia and nitrate leaching losses

(i) Current NVZ-AP

The measures included in the current NVZ-AP were predicted to increase manure N 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 manufactured fertiliser N requirement by 3,000 tonnes in the NVZ area, 5,200 tonnes in England and Wales and 4,600 tonnes in England.

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 efficiency (and resultant reductions in manufactured fertiliser N use) led to an 8% reduction in overall GHG emissions (allowing for reuctions in manufactured N fertiliser use) - equivalent to annual GHG reductions of 37,000 tonnes CO_2e for current NVZ areas, 68,000 tonnes CO_2e for England and Wales, and 59,000 tonnes CO_2e for England, 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 the current NVZ areas, 17,000 tonnes CO_2e for England and Wales and 14,000 tonnes CO_2e for England. However, extending the closed periods by 2 months was predicted to *increase* GHG emissions by 11,000 tonnes CO_2e for the NVZ areas, 17,000 tonnes CO_2e for England and Wales, and 15,000 tonnes CO_2e for England, 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, 2,800 tonnes NH_3-N for England and Wales and 2,700 tonnes NH_3-N for England 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 the NVZ area, 600 tonnes NH_3-N for England and Wales and 500 tonnes NH_3-N for England compared with the current NVZ-AP. Extending the closed period by 2 months was predicted to further *increase* ammonia emissions by 300 tonnes NH_3-N for NVZ areas, 900 tonnes NH_3-N for England and Wales, and 700 tonnes NH_3-N for England, compared with the 1 month extension.

The higher ammonia emissions from the extended closed periods were mainly a reflection of the estimated increases in 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, 2,900 tonnes NO_3-N for England and Wales, and 2,500 tonnes NO_3-N for England 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, 1,100 tonnes NO_3-N for England and Wales, and 900 tonnes NO_3-N for England, compared to the 2007 baseline. However, extending the closed period by 2 months was predicted to *increase* nitrate leaching losses by 300 tonnes NO_3-N for NVZ areas, England and Wales and England, 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.

(ii) Rapid soil incorporation

For pig slurry and poultry manures, rapid soil incorporation (within 4-6 hours) increased manure N efficiencies by *c.*5% compared with incorporation within 12-24 hours, largely due to reductions in ammonia emissions. Rapid soil incorporation had little impact on cattle slurry N efficiency because of the relatively small amount of cattle slurry (7% of total) applied to arable land. Rapid soil incorporation was predicted to increase direct nitrous oxide-N emissions by *c.*10,000 tonnes CO_2e, but reduced indirect emissions and manufactured fertiliser N use balanced these emissions. Overall, the rapid soil incorporation of slurries and poultry manures had a *neutral* effect on GHG emissions. Rapid soil incorporation of slurries and poultry manure was predicted to *reduce* annual ammonia emissions by 2,200 tonnes NH_3-N in current NVZ areas, 3,300 tonnes NH_3-N in England and Wales, and 2,900 tonnes NH_3-N in England, compared with the current NVZ-AP. The reductions in ammonia losses were predicted to increase annual nitrate leaching losses by 400 tonnes NO_3-N in current NVZ areas, 700 tonnes NO_3-N in England and Wales, and 600 tonnes NO_3-N in England (an example of pollution swapping).

(iii) Bandspreading/shallow injection

Spreading all slurry with bandspreading and shallow injection equipment was predicted to increase cattle slurry N efficiency by *c.*20% (i.e. 6-7% of total N applied) and pig slurry by *c.*5% (i.e. 3-4% of total N applied) compared with current practice. These improvements were largely due to reductions in ammonia emissions (from 13% to 5% of total N applied for cattle slurry and from 14% to 10% of total N applied for pig slurry).

Bandspreading/shallow injection was predicted to increase direct nitrous oxide-N emissions by *c.*25,000 tonnes CO_2e for NVZ areas, *c.*50,000 tonnes CO_2e for England and Wales, and *c.*45,000 tonnes CO_2e for England (mainly as a result of reductions in ammonia loss). However, these increases were offset by reductions in indirect emissions and manufactured fertiliser N use. Overall, slurry bandspreading/shallow injection was predicted to *reduce* annual GHG emissions by 20,000 tonnes CO_2e for current NVZ areas, 37,000 tonnes CO_2e for England and Wales, and 31,000 tonnes for England. Bandspreading/shallow injection of all slurry was predicted to reduce annual ammonia emissions by 3,900 tonnes NH_3-N in current NVZ areas, 8,500 tonnes NH_3-N in England and Wales, and 7,100 tonnes NH_3-N in England, and to largely have a neutral effect on nitrate leaching losses.

(iv) Slurry separation
The use of slurry separation technologies was *assessed* to increase the N efficiency of the liquid fraction from 30% to 36% of total N applied for cattle slurry and from 49% to 54% of total N applied for pig slurry, due to the increased proportion of readily available N and lower dry matter content of the separated liquid. However, as the N use efficiency of the solid fraction was assessed to be lower than the 'whole' slurry, overall slurry separation was assessed to have a *neutral* effect on N use efficiency, and GHG emissions and ammonia and nitrate losses.

(v) Storing solid manure on an impermeable base
Storing all solid manures on an impermeable base was predicted to increase the quantity of N applied to land in slurry and poultry manures by *c.*2%, and increase annual fertiliser N savings by 400 tonnes. The additional N applied was predicted to result in an associated small increase in ammonia emissions and nitrate leaching losses. GHG emissions were estimated to *increase* by 5,000 tonnes CO_2e in current NVZ areas, 10,000 tonnes CO_2e for England and Wales and 9,000 tonnes CO_2e for England compared with the current NVZ-AP.

(vi) Higher (theoretical manure N efficiencies)
Stipulating the (theoretical) use of higher manure N use efficiency coefficients in the next NVZ-AP i.e. cattle slurry (40% of total N applied), pig slurry (55% of total N applied) and poultry manure (35% of total N applied) was predicted to *reduce* overall GHG emissions by *c.*12% (equivalent to *c.*40,000 tonnes CO_2e in current NVZ areas, *c.*90,000 tonnes CO_2e for England and Wales, and 80,000 tonnes CO_2e for England), compared with the current NVZ-AP. However, these (theoretical) improvements in N use efficiency would need to be achieved in operational practice, for example, through applying greater amounts of manure in spring, use of bandspeading/shallow injection technologies for slurry application etc.

1.2 Costs and benefits

(i) Slurry storage capacity
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), £555 million for England and Wales and £460 million for England. It should be noted that estimates of existing on-farm slurry storage capacities are *uncertain.* The costs estimates assume that on average an additional 2 months storage capacity is required to comply with the current NVZ-AP. If only one month extra storage was required the capital cost of additional storage would be £145 million for the current NVZ areas, £278 million for England and Wales and £230 million for England. 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. In contrast, other farms may already have adequate storage

capacity to comply with the current NVZ-AP, in which case additional cost would be negligible.

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) in current NVZ areas, 104,000 tonnes (£104 million) in England and Wales and 92,000 tonnes (£92 million) in England, compared with the 2007 baseline. The 20 year savings in ecosystem damage costs (from reductions in GHG, ammonia and nitrate losses) resulting from the measures included in the current NVZ-AP were estimated at £143 million for current NVZ areas, £239 million for England and Wales and £218 million for England. The 20 year cost-benefit ratio of implementing the current NVZ-AP was 1.4:1 compared with 1.6:1 across England and Wales and 1.5:1 across England

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, £250 million and £430 million for England and Wales and £210 million and £365 million for England. The cost-benefit ratio of extending the storage periods by 1 and 2 months increased to 2.2:1 and 3.7:1 for current NVZ areas, 2.3:1 and 3.9:1 for England and Wales and 2.1:1 and 3.5:1 for England, 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.

(ii) Rapid soil incorporation

Incorporating high readily available N manures into the soil within 6 hours of application, in addition to the measures included in the current NVZ-AP, was estimated to have extra annual operational (staff and equipment) costs of £4 million for current NVZ areas, £7 million for England and Wales and £6 million for England. The reductions in fertiliser N use and ecosystem damage costs (mainly resulting from reductions in ammonia loss) were reflected in lower 20 year cost-benefit ratios (at 1.2:1 for current NVZ areas, 1.4:1 for England and Wales and 1.3:1 for England) than for the current NVZ-AP. Note: The cost estimates assume that additional staff resource was required to achieve soil incorporation within 4-6 hours. On some farms, it may be possible to accommodate the additional work within existing staff resources, thereby reducing the cost of implementing this measure.

(iii) Slurry bandspreading/shallow injection

Bandspreading and shallow injecting all slurry, in addition to the measures included in the current NVZ-AP, was predicted to reduce 20 year fertiliser N use by an additional 68,000 tonnes in current NVZ areas, 138,000 tonnes in England and Wales and 118,000 tonnes across England. Ammonia emissions were predicted to be reduced by a further 78,000 tonnes in the current NVZ area, 170,000 tonnes in England and Wales and 142,000 in England. The increased application costs, compared with surface broadcasting (£25 million/year in the NVZ areas, £50 million/year in England and Wales and £45 million/year in England) were reflected in higher cost-benefit ratios (1.7:1 for the current NVZ area, 1.8:1 for England and Wales and 1.8:1 for England) than for the current NVZ-AP.

(iv) Slurry separation

Slurry separation was predicted to reduce NVZ-AP storage costs by £142 million for current NVZ areas, £270 million for England and Wales and £230 million for England. However, additional annual operational costs estimated at £17 million for current NVZ areas, £35 million for England and Wales and £30 million for England, gave total capital and 20 year operational costs of £488 million for the current NVZ area, £985 million for England and Wales and £830 million for England. Overall there was *assessed* to be no reduction in fertiliser N use or ecosystem damage costs compared with the measures included in the current NVZ-AP.

(v) Storing solid manures on an impermeable base

Storing all solid manures on an impermeable base was estimated to have a capital cost of £255 million for the current NVZ area, £515 million for England and Wales and £440 million for England. Overall this method had little effect on manufactured fertiliser N use and ecosystem damage costs.

1.3 Conclusions

- For the current NVZ areas (62% of England and *c.*3% of Wales), the measures in the existing NVZ-AP 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 and nitrate leaching losses by 1,400 tonnes NO_3-N (compared with the 2007 baseline) 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 and nitrate leaching losses by 2,900 tonnes NO_3-N (compared with the 2007 baseline) at a capital cost of £555 million
- Applying the current NVZ-AP across England was predicted to reduce annual fertiliser N use by 4,600 tonnes, GHG emissions by 59,000 tonnes CO_2e , ammonia emissions by 2,700 tonnes NH_3-N and nitrate leaching losses by 2,500 tonnes NO_3-N (compared with the 2007 baseline) at a capital cost of £460 million
- The costs of extending the storage periods for high readily available N manures by 1 and 2 months, slurry separation and storing solid manures on an impermeable base were *not* reflected in proportional reductions in fertiliser N use or ecosystem damage costs.
- *Soil incorporation* of high readily available N manures (within 6 hours of application) and the use of *bandspreading/shallow injection slurry application techniques* were the most cost-effective techniques to reduce fertiliser N use and ecosystem damage costs.

2. INTRODUCTION

The atmospheric abundance of the greenhouse gases (GHG) carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) has increased considerably over recent years as a result of human activity. Emissions of N_2O and CH_4 are particularly important, as their respective global warming potentials are 310 and 21 times greater than CO_2 (IPCC, 2007). As a signatory to the Kyoto Protocol, the UK has agreed to achieve a reduction in GHG emissions of 12.5% of 1990 levels by 2008-2012. Furthermore, GHG emission reductions are required from agriculture (in common with all other sectors) in order to meet the reduction targets set by the UK Climate Change Act 2008, as detailed in the Low Carbon Transition Plan recently published by DECC. It has therefore been necessary to establish a national inventory of GHGs, which aims to accurately assess all anthropogenic sources, including N_2O, CH_4 and CO_2. Currently, the UK GHG Inventory is calculated annually using the default 1996 Intergovernmental Panel on Climate Change (IPCC) methodology (IPCC, 1997).

The current UK greenhouse gas emissions inventory (MacCarthy *et al.,* 2010, inventory year 2008) estimates that 75% of nitrous oxide is produced from agriculture, amounting to 82,070 t N_2O (25,443,160 t CO_2e). Less than 10% of agricultural N_2O is emitted during livestock housing and manure storage, with the majority (approximately 60%) directly emitted from agricultural soils. Emissions occur following the application of livestock manures and manufactured nitrogen (N) fertiliser to soils, and after the incorporation of crop residues. They are predominately produced via the microbially mediated processes of nitrification and denitrification (Firestone and Davidson, 1989), with the key factors controlling the magnitude of N_2O emissions including soil mineral nitrogen content (particularly soil nitrate), soil temperature and soil moisture content (Dobbie & Smith, 2001; Dobbie & Smith, 2003).

In addition, *c.*30% of agricultural N_2O is emitted indirectly from soils via two mechanisms, *viz*.: following initial N loss via ammonia (NH_3) volatilisation/NO_x emission (*c*.20%) or nitrate (NO_3) leaching (*c.*80%). Nitrogen directly lost from agricultural soils, either by NO_3 leaching or NH_3 emissions to the atmosphere, may subsequently become potentially available for loss as N_2O.

The existing Nitrate Vulnerable Zone Action Programme; (NVZ-AP; SI, 2008; and WSI, 2008) covers *c.*62% agricultural land in England and *c.*3% in Wales, and restricts the application of cattle slurry, pig slurry 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 application, with the length of the ‘closed period’ varying according to soil type and land use (Table 1).

The NVZ-AP also requires farmers to take full account of the N supplied by livestock manures when planning their manufactured fertiliser N applications.

Table 1. ‘Closed spreading 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

A range of Defra projects (including contract – WT0932 *“Pollutant Losses Following Organic Manure Applications in the Month following the End of the Closed Period”* and projects WQ0118/AC0111) are investigating the impact of NVZ-AP changes (and potential future changes) on losses of ammonium-N, phosphorus (P) and microbial pathogens to water, and NH_3 and N_2O emissions to air. However, none of these projects are making a comprehensive (national scale) estimate of the associated impacts on GHG emissions to air. Such calculations are required as part of an *integrated* approach to tackling diffuse pollution from agriculture.

3 OBJECTIVES

The objectives of this project were:

- Within existing Nitrate Vulnerable Zones – NVZs (which cover *c*.62% of the agricultural land area in England and *c*.3% in Wales), to assess the effect of each of six methods that aim to increase manure N use efficiency on N_2O, CH_4 and NH_3 emissions to air, and NO_3 leaching losses to water, viz:

    1. *'Closed spreading periods' and increased slurry (manure) storage capacity, including the effect of the current requirement (compared with a 2007 baseline) plus the effect of extending the closed-period by either an extra one or two months in spring (linked to work package 1 in Defra project WT0932, "Pollutant Losses Following Organic Manure Applications in the Month following the End of the Closed Period").*

    2. *Rapid soil incorporation of all manure types (including FYM) when they are applied to bare ground/stubbles.*

    3. *Increased use of slurry bandspreading and shallow injection equipment (presently uptake is low, but increasingly pig and leading dairy farmers are investing in these technologies).*

    4. *Increased use of slurry separation technologies (uptake is presently low, but leading dairy farmers are increasingly using this technology, particularly for umbilical slurry application).*

    5. *Storing solid manures on an impermeable base (linking to Defra project WT1006; "Pollutant Losses from Solid Manures Stored in Field Heaps").*

    6. *Stipulating a higher figure for manure N use efficiency in the next NVZ-AP (based on recommended values in Defra project WT1006; "Review and Recommendations for Minimum Livestock Manure Nitrogen Efficiency Coefficients").*

- For a whole territory approach, quantify N_2O, CH_4 and NH_3 emissions to air, and NO_3 leaching losses to water following implementation of each of the six methods.

- For a whole territory approach, with selected farms excluded, quantify N_2O, CH_4 and NH_3 emissions to air, and NO_3 leaching losses to water following implementation of each of the six methods.

- Estimate the cost of applying each of the 6 methods broken down by:
    1. Farm type
    2. Farm size
    3. NVZ area, England and Wales and England

4 METHODOLOGY

This desk-based study has evaluated the individual effect of implementing each of six methods that aim to increase manure N use efficiency on emissions of N_2O, CH_4 and NH_3 to air, and NO_3 leaching losses to water, *viz*:

- ‘Closed spreading periods’ and increased slurry (manure) storage capacity, including extending the ‘closed period’ by an extra 1 month and 2 months in spring.
- Rapid soil incorporation of all manure types when they are applied to bare ground/stubbles.
- Increased use of slurry bandspreading and shallow injection equipment.
- Increased use of slurry separation technologies.
- Storing solid manures on an impermeable base.
- Stipulating a higher figure for manure N use efficiency in the next NVZ-AP.

The study has built upon previous research (e.g. Defra project WT0757NVZ) and has drawn upon field-based studies (e.g. Defra project WQ0118) and earlier desk-based/modelling studies (e.g. Defra projects AC0101, AC0222, WQ0106, WT1006, McCleod *et al*., 2010).

4.1 Quantities of manure N applied

Estimates of the quantity of manure N applied to agricultural soils by different manure types was taken from MANURES-*GIS,* using 2004 Agricultural Census data on a 10km by 10km 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 1, 2, 3 & 4). 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 on 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. 62% of England and *c.*3% of Wales) so that the quantities of manure N applied both on whole territory (England and Wales) and within NVZ areas could be determined (Tables 2 and 4). These data showed that <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 the designated NVZ area, compared with 67% of poultry manures and 80% of pig slurry. Estimates of manure N loadings for England (Table 3) were calculated from figures for England and Wales using pro-rata adjustments for animal numbers based on 2009 Agricultural Census data.

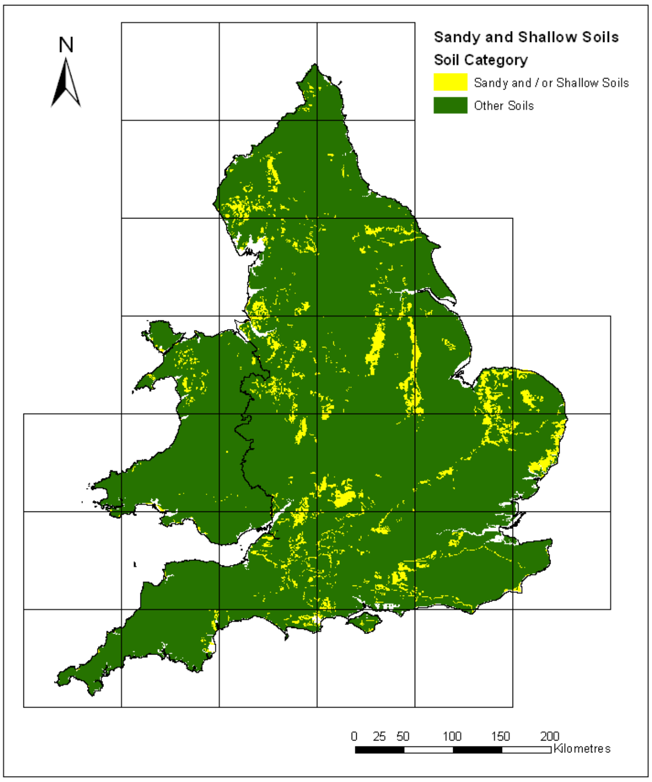


Figure 1. Location of sandy/shallow soil types within England and Wales.

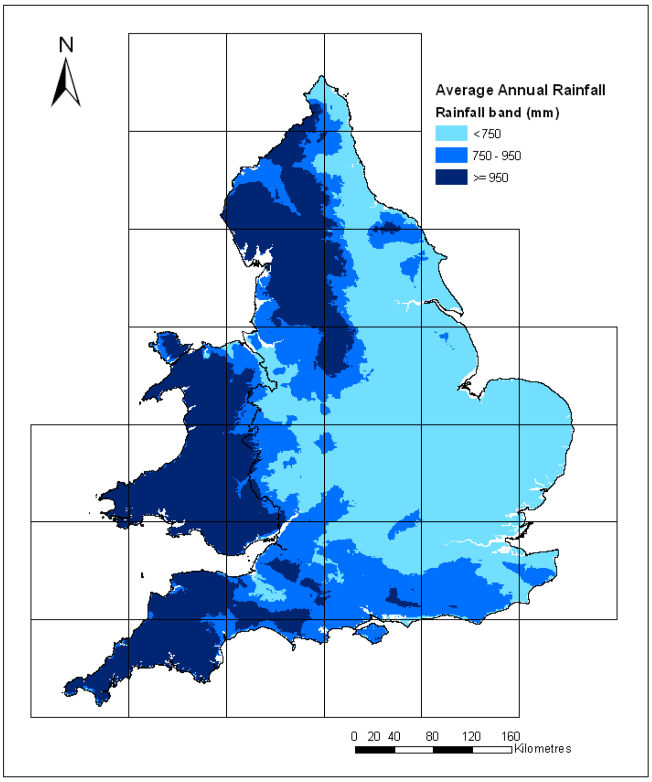


Figure 2. Areas covered by the three agro-climate zones used within this work (annual average rainfall was taken from the Met Office 1961-1990 dataset).

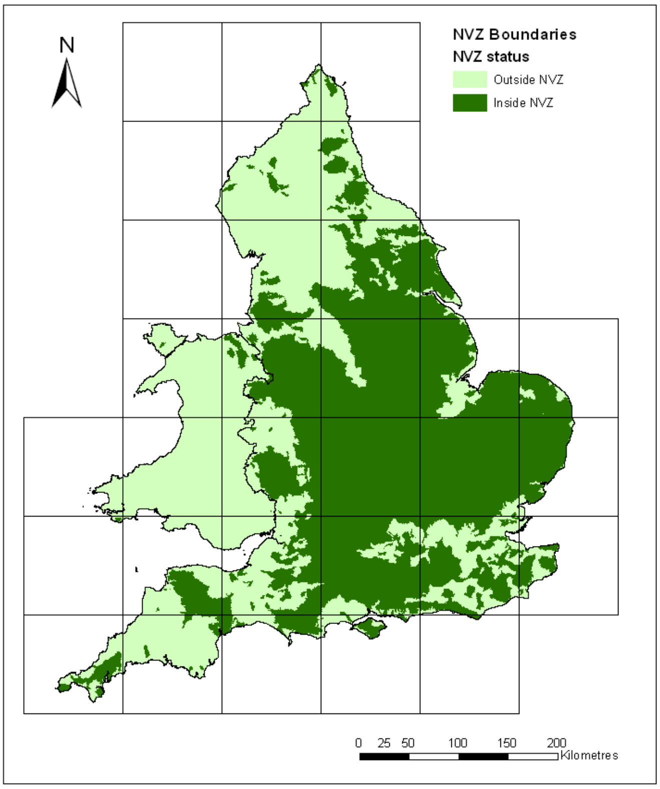


Figure 3. Spatial extent of the current NVZ areas in England and Wales (2009-12).

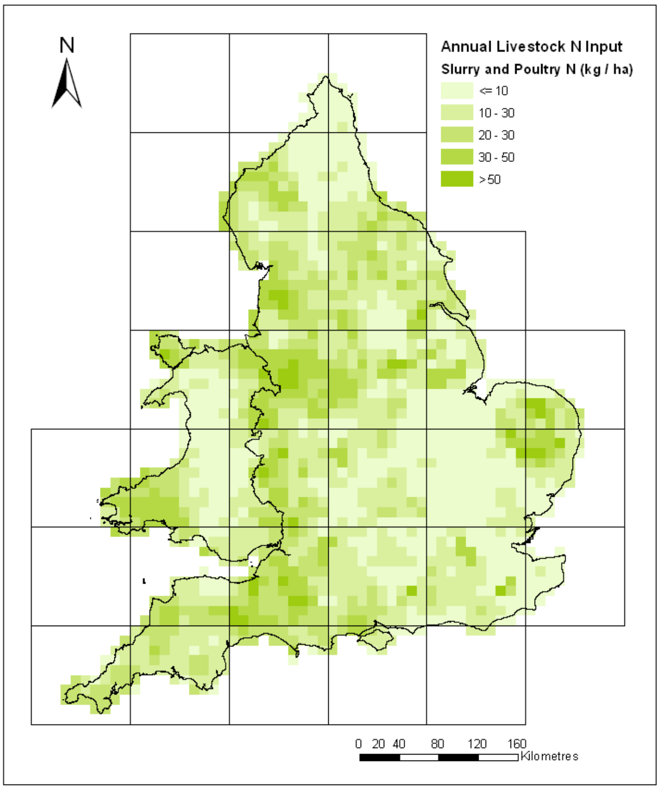


Figure 4. Total nitrogen loadings in slurry and poultry manures (kg/ha of agricultural land).

Table 2. Quantities of manure N (kt) applied in England and Wales (based on 2004 Agricultural Census data).

Soil type/ Rainfall zone[1]	**Sandy/Shallow**				**Other**				
	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 3. Quantities of manure N (kt) applied in England (calculated from England and Wales figures using pro-rata reduction in animal numbers)

Soil type/ Rainfall zone[1]	**Sandy/Shallow**				**Other**				
	High	**Medium**	**Low**	**Total (%)**	**High**	**Medium**	**Low**	**Total (%)**	**Total**
Manure type									
Cattle slurry	0.8	2.1	1.2	4.1 (5%)	31.7	24.0	19.1	74.8 (95%)	78.9
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	1.1	3.6	5.0 (9%)	9.1	13.8	29.6	52.5 (91%)	57.5

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

Table 4. Quantities of manure N (kt) applied in NVZ areas (based on 2004 Agricultural Census data and current designations).

Soil type/ Rainfall zone[1]	**Sandy/Shallow**				**Other**				
	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)

4.2 Manure application timings

In order to understand the effect of extending the 'closed spreading period' 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)
- EXISTING 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 5.

Table 5. '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
EXISTING 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 is shown in Tables 5-8. 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 6). Under the existing 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 5). 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).

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 effect the balance between difference N loss pathways and manure N efficiencies. 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 existing 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 existing 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.

Table 6. Percentage of manure applied by month and landuse: BASELINE (data from 2007 Survey of Fertiliser Practice).

Soil type	Manure type	Landuse	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	% manure to each landuse
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 7. Percentage of manure applied by month and landuse: CURRENT NVZ-AP (2009-2012). *Predicted values*.

Soil type	Manure type	Landuse	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	% manure to each landuse
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 8. Percentage of manure applied by month and landuse: Month 1 (1 month extension of spring closed period). *Predicted values.*

Soil type	Manure type	Landuse	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	% manure to each landuse
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 9. Percentage of manure applied by month and landuse: Month 2 (2 month extension of spring closed period). *Predicted values.*

Soil type	Manure type	Landuse	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	% manure to each landuse
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

4.3 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). MANNER-*NPK* also quantifies crop available N (P, K, Mg and S) supply, taking into account manure type, manure 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.

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/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 loam topsoil over loamy sand subsoil) and other (i.e. clay loam topsoil over clay loam subsoil). An example of the outputs for pig slurry applied in the high and low rainfall zones is shown in Figures 5 and 6. These figures illustrate how changing the timing of a manure application can effect 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 5). The effect was still apparent, but less pronounced, for applications made to the medium/heavy soil type in the high rainfall zone (Figure 5) and the low rainfall zone (Figure 6).

The outputs from MANNER-*NPK* were then combined with the quantities of manure N applied to the different soil type and agro-climate zones (Tables 2 and 4), and the manure application timings detailed in Tables 6 to 9 to provide an estimate of the quantity of manure N taken up by crops for England and Wales and the current NVZ area for each of the six methods.

Figure 5. MANNER-*NPK* predicted crop available N (% total N applied) at different application timings (slurry broadcast applied and not soil incorporated). High rainfall zone (median rainfall = 1200 mm/annum).

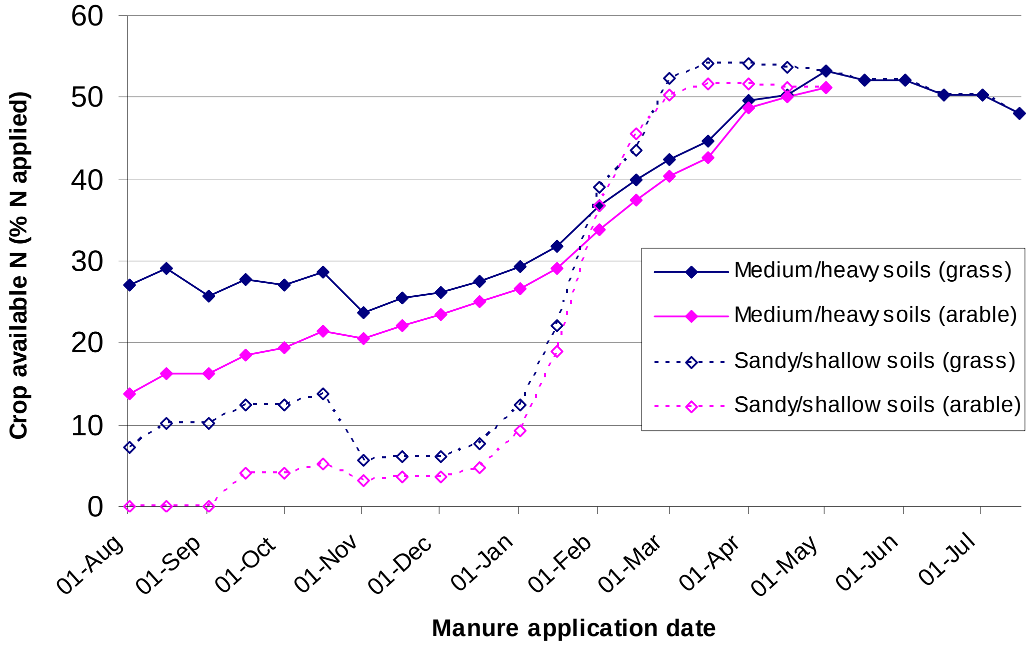
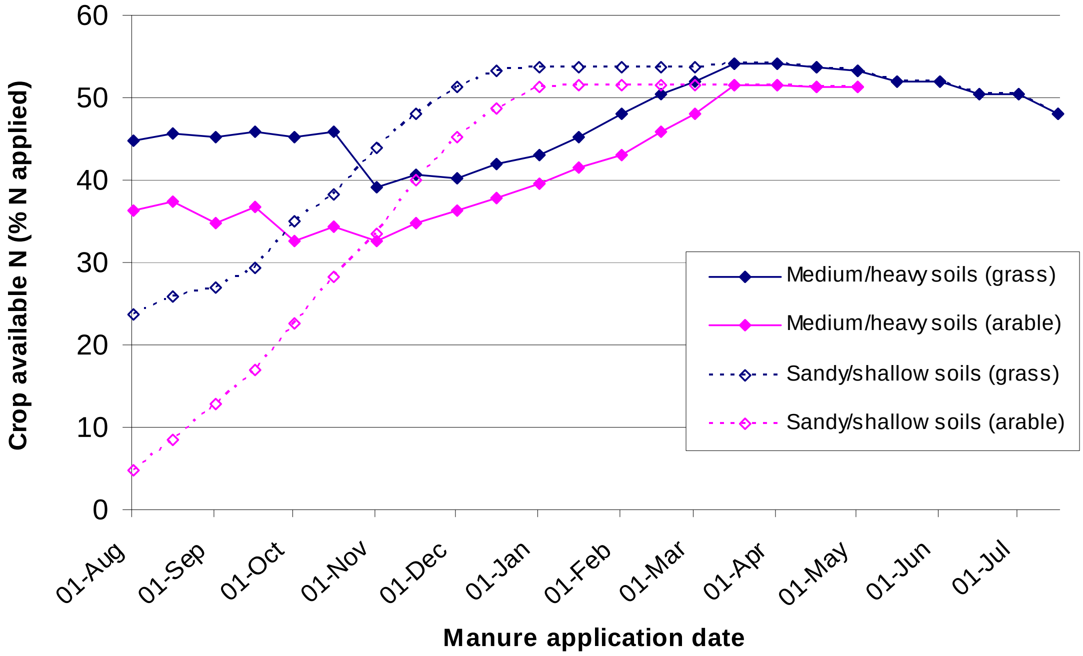


Figure 6. MANNER-*NPK* predicted crop available N (% total N applied) at different application timings (slurry broadcast applied and not soil incorporated). Low rainfall zone (median rainfall = 650 mm/annum).



4.4 Nitrate leaching losses

Outputs from MANNER-*NPK* were also used to predict nitrate leaching losses from the contrasting high readily available N manure applications. An example for pig slurry applied in the high and low rainfall zones is shown in Figures 7 and 8. These figures 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 losses decreases to *c*.2% of total N applied (Figure 7). The effect is still apparent, but less pronounced, for applications made to the medium/heavy soil type (Figure 8). In the lower rainfall zone, the change in pig slurry application timings had no effect on nitrate leaching losses (Figure 8).

As for crop N uptake, MANNER-*NPK* outputs were combined with the quantities of manure N applied to the different soil type and agro-climatic zones (Tables 2 and 3), and manure application timings (Tables 6 to 9), to provide an estimate of the quantity of manure N leached for England and Wales and the current NVZ area for each of the six methods.

Figure 7. MANNER-*NPK* predicted nitrate-N leaching (% total N applied) losses at different application timings (slurry broadcast applied and not soil incorporated). High rainfall zone (median rainfall = 1200 mm/annum).

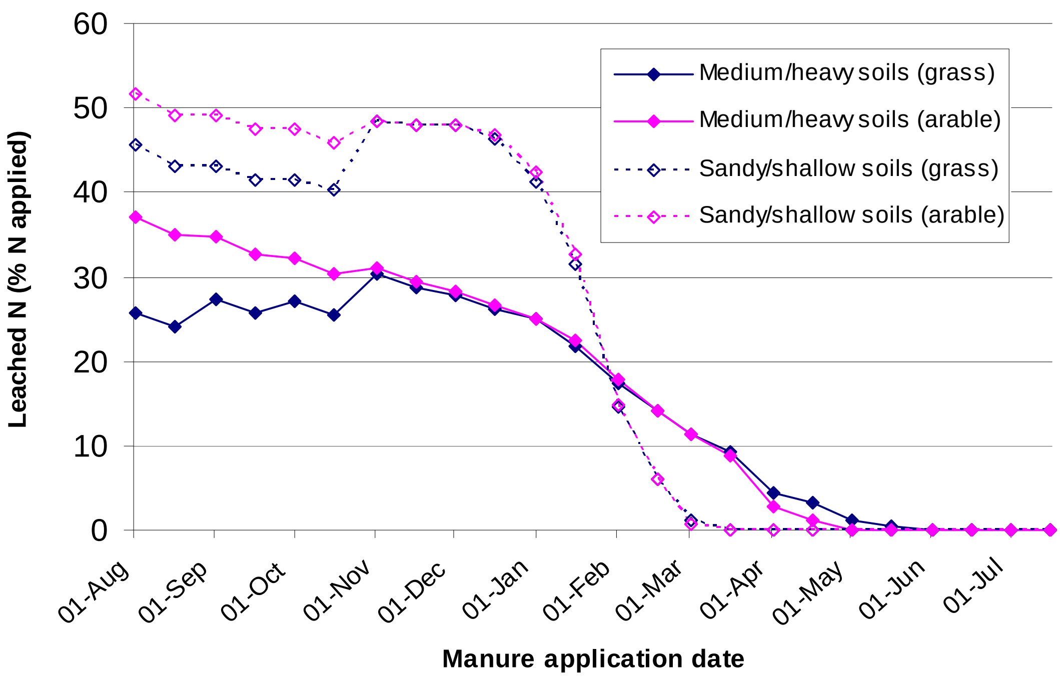
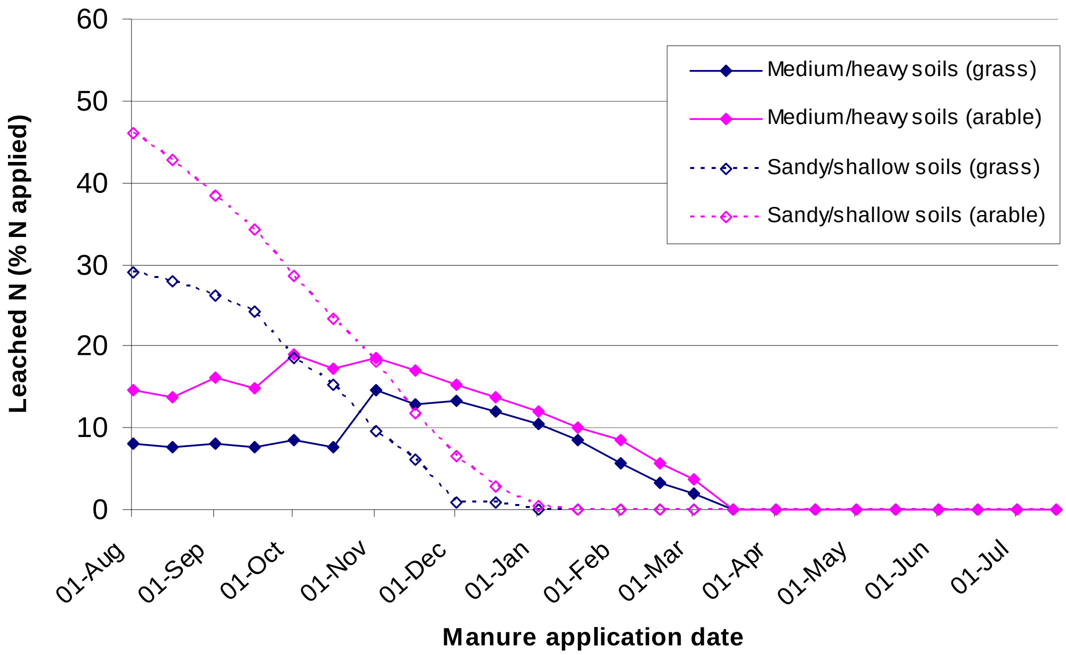


Figure 8. MANNER-*NPK* predicted nitrate-N leaching (% total N applied) losses at different application timings (slurry broadcast applied and not soil incorporated). Low rainfall zone (median rainfall = 650 mm/annum).



4.5 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 (Methods 2 and 3) on ammonia losses from August and September applications is shown in Table 10. Rapid soil incorporation (Method 2) (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 9% to 4%), 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 un-incorporated application.

Slurry bandspreading to arable crops (using a trailing hose) and shallow injection to grassland (Method 3) were also effective methods in reducing ammonia losses (from 9% to 4-6% 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 10. 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	-	-

The dry matter content of slurry can affect ammonia losses following land application, with higher dry matter content slurries having greater ammonia emission rates than lower dry matter content slurries, because they infiltrate more slowly into soils. Slurry separation technologies (e.g. weeping wall, strainer box, mechanical separation) decrease the dry matter content of the remaining liquid fraction (as well as decreasing the volume) making it easier to handle and reduce ammonia losses compared with unseparated slurry, because they move rapidly infiltrate into soils (Table 11). In addition, slurry separation increases the proportion of readily available N to total N in the liquid fraction, which also influences ammonia losses (together with nitrate leaching losses and crop N uptake).

Table 11. Ammonia losses (% total N applied) from unseparated slurry and the liquid fraction of separated slurries.

Manure type	Dry matter (%)	Ammonia loss*
Cattle slurry	6	12
Separated cattle slurry (liquid portion)	4	9
Pig slurry	4	18
Separated pig slurry (liquid portion)	3	14

*Slurry assumed to be surface topdressed in the autumn to spring period

4.6 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). 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 six methods. 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)

It should be noted that 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).

4.7 Economic impacts for farm businesses

The capital and annual amortised costs of implementing the six methods for improving manure N use efficiency were estimated for the livestock (dairy, pig, layer and broiler) and combinable crops farms described in the “Mitigation Methods-User Guide” (Defra Project WQ0106). For the dairy and pig farms, the costs of additional slurry storage capacity were estimated for both above ground ‘tin-tank’ and earth bank lagoon systems (Nix, 2011). Also, the costs of using bandspreading/shallow injection slurry application equipment were assessed. For the poultry farms, the costs of impermeable (concrete) base storage of solid manure (with effluent collection) were assessed.

The manure storage requirements were based on standard manure production figures for a farm with 800mm of annual rainfall and calculated using PLANET (www.planet4farmers.co.uk). It was assumed that the dairy farms used 25 litres of wash-down water per cow and that the water was collected in the slurry lagoon.

5. RESULTS

5.1 Method 1: 'closed spreading periods' and increased slurry storage

The impacts of the selected 'closed spreading period' scenarios on estimated crop N uptake, nitrate leaching losses and ammonia emissions are shown in Table 12 (England and Wales), Table 13 (England) and Table 14 (NVZ area).

For England and Wales, the measures contained in the current NVZ-AP (2008-2012) (Table 4) 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 the current NVZ area, moving from the Baseline (2007) to the current NVZ-AP (Table 4) increased cattle slurry N efficiency from 27 to 30%, pig slurry from 44 to 49% and poultry manure from 30 to 34% (Table 12). For cattle and pig slurry, the improved manure N efficiencies were largely due to reductions in overwinter 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 period' 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 period' 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).

The measures contained in the current NVZ-AP were predicted to reduce total direct and indirect nitrous oxide-N emissions following slurry and poultry manure applications by 8% 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 efficiency (and resultant reductions in manufactured fertiliser N use) were equivalent to a GHG reduction of 68,000 tCO_2e across England and Wales, 59,000 tCO_2e for England and 37,000 tCO_2e for current NVZ areas, compared with the 2007 baseline (Tables 16,17 and 18). Extending the 'closed period' by one month was predicted to reduce GHG emissions by 85,000 tCO_2e across England and Wales, 73,000 tCO_2e for England and 42,000 tCO_2e for the current NVZ areas compared with the 2007 baseline. Extending the 'closed period' 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 for England and Wales) in GHG emissions, compared with the one month extension, because of increased indirect nitrous oxide-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 nitrous oxide 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 kt CO_2e (11%) to agricultural GHG emissions. The emission factors used to estimate methane and nitrous oxide 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.

Table 12. Method 1: 'Closed spreading periods' and increased slurry storage. Impact on crop N uptake, nitrate leaching losses and ammonia emissions in England and Wales.

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

[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. Method 1: 'Closed spreading periods' and increased slurry storage. Impact on crop N uptake, nitrate leaching losses and ammonia emissions in England

	Crop N uptake		Nitrate-N leaching losses		Ammonia-N losses to air	
	Total (kt)	**% total N applied**	**Total (kt)**	**% total N applied**	**Total (kt)**	**% total N applied**
Baseline[1]						
Cattle slurry	20.4	26	7.3	9	10.3	13
Pig slurry	5.4	44	1.3	10	2.0	16
Poultry manure	16.9	29	5.3	9	11.1	19
Current NVZ-AP[2]						
Cattle slurry	22.5	29	5.1	7	10.3	13
Pig slurry	6.0	48	0.9	8	1.7	14
Poultry manure	18.8	33	5.4	9	8.7	15
1 month extension of closed period[2]						
Cattle slurry	22.8	29	4.3	6	10.8	14
Pig slurry	6.0	48	0.9	7	1.7	14
Poultry manure	18.6	32	5.3	9	8.7	15
2 month extension of closed period[2]						
Cattle slurry	22.2	28	4.3	5	11.5	15
Pig slurry	5.9	48	1.0	8	1.7	14
Poultry manure	17.5	30	5.5	9	8.7	15

[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. Method 1: 'Closed spreading periods' and increased slurry storage. Impact on crop N uptake, nitrate leaching losses and ammonia emissions in NVZ areas.

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

[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 15. Method 1: 'Closed spreading periods'. Impact on GHG emissions (ktCO_2e) in England and Wales

	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	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_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).

Table 16. Method 1: 'Closed spreading periods'. Impact on GHG emissions (ktCO_2e) in England

	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	417	50	89	**556**	144	126	**412**	430
Pig slurry	64	10	15	**88**	38	34	**50**	54
Poultry manure	283	54	65	**402**	121	105	**281**	297
Total	764	114	169	**1046**	303	265	**743**	781
Current NVZ-AP								
Cattle slurry	417	51	63	**531**	162	141	**369**	390
Pig slurry	65	8	11	**84**	41	37	**43**	47
Poultry manure	297	42	65	**404**	132	115	**272**	289
Total	776	101	139	**1019**	335	293	**684**	726
1 month extension of 'closed period'								
Cattle slurry	414	52	53	**519**	162	141	**357**	378
Pig slurry	65	8	11	**84**	43	37	**41**	47
Poultry manure	297	42	65	**404**	132	115	**272**	289
Total	776	102	129	**1007**	337	293	**670**	714
2 month extension of 'closed period'								
Cattle slurry	410	56	52	**518**	157	137	**361**	381
Pig slurry	65	8	12	**85**	42	37	**43**	48
Poultry manure	297	42	66	**405**	124	108	**281**	297
Total	772	106	130	**1008**	323	282	**685**	726

[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).

Table 17. Method 1: 'Closed spreading periods'. Impact 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).

5.2 Method 2: Rapid soil incorporation

Rapid soil incorporation, within hours of spreading, is effective in reducing ammonia emissions (odour and fly nuisance) following the land application of organic manures. However, soil incorporation is only possible when manure applications are made to uncropped tillage land before crop establishment. For autumn applied manures, any ammonia that is conserved by rapid soil incorporation is at risk of overwinter leaching loss (an example of 'pollution swapping'), unless the manure is applied before a crop with a requirement for N in the autumn (e.g. winter oilseed rape). On medium and heavy soil types, where winter arable cropping is the predominant land use, the rapid soil incorporation of manures will usually only be possible following autumn application timings.

The current NVZ-AP stipulates that surface broadcast slurry and poultry manure applications to uncropped land/stubble must be incorporated within 24 hours of application. In this study, our baseline assumption was that 20% of cattle slurry, 75% of pig slurry and 50% of poultry manure applied to tillage land was incorporated by ploughing within 24 hours. We estimated under the current NVZ-AP that this would increase to 30% of cattle slurry, 80% of pig slurry and 80% of poultry manure. The effects of more rapid soil incorporation within 4-6 hours for surface broadcast pig and cattle slurry and poultry manures on estimated crop N uptake, nitrate leaching losses and ammonia emissions are shown in Table 18 (England and Wales), Table 19 (England) and Table 20 (NVZ areas).

For pig slurry and poultry manures, soil incorporation within 4-6 hours increased manure N efficiency by *c.*5% (i.e. 2% of total N applied) for both England and Wales (Table 18) and NVZ areas (Table 20). These improvements were largely due to reductions in ammonia emissions (from 14% to 12% for pig slurry, and from 15% to 10% for poultry manure) which more than compensated for the small increases in nitrate leaching losses. Rapid soil incorporation had little impact on the cattle slurry N efficiency because of the relatively small amount of cattle slurry applied (7% of total) applied to arable land.

Rapid soil incorporation was predicted to increase total nitrous oxide-N emissions following manure application by *c.*10,000 tCO_2e, mainly as a result of increased direct nitrous oxide-N emissions following reductions in ammonia loss (Tables 21, 22 and 23). However, reductions in manufactured fertiliser N use following improvements in manure N efficiency compensated for the increase in direct emissions. Overall, the rapid soil incorporation of slurries and poultry manures had a *neutral* effect on GHG emissions.

Table 18. Method 2: Rapid soil incorporation. Impact on crop N uptake, nitrate leaching losses and ammonia emissions in England and Wales.

	Crop N uptake		Nitrate-N leaching losses		Ammonia-N losses to air	
	Total (kt)	**% total N applied**	**Total (kt)**	**% total N applied**	**Total (kt)**	**% total N applied**
Current NVZ-AP[1]						
Cattle slurry	27.2	29	6.2	7	12.4	13
Pig slurry	6.0	48	0.9	8	1.7	14
Poultry manure	20.0	33	5.7	9	9.3	15
Incorporation within 4-6 hours[2]						
Cattle slurry	27.3	29	6.2	7	12.4	13
Pig slurry	6.3	50	1.0	8	1.5	12
Poultry manure	21.6	35	6.3	10	6.2	10

[1]Assumes 30% of cattle slurry, 80% of pig slurry and 80% of poultry manure applied to arable land was incorporated by plough within 12-24 hours.

[2]Assumes 30% of cattle slurry, 80% of pig slurry and 80% of poultry manure applied to arable land was incorporated by plough within 4-6 hours.

Table 19. Method 2: Rapid soil incorporation. Impact on crop N uptake, nitrate leaching losses and ammonia emissions in England

	Crop N uptake		Nitrate-N leaching losses		Ammonia-N losses to air	
	Total (kt)	**% total N applied**	**Total (kt)**	**% total N applied**	**Total (kt)**	**% total N applied**
Current NVZ-AP[1]						
Cattle slurry	22.5	29	5.1	7	10.3	13
Pig slurry	6.0	48	0.9	8	1.7	14
Poultry manure	18.8	33	5.4	9	8.7	15
Incorporation within 4-6 hours[2]						
Cattle slurry	22.6	29	5.1	7	10.3	13
Pig slurry	6.3	50	1.0	8	1.5	12
Poultry manure	20.3	35	5.9	10	6.0	10

[1]Assumes 30% of cattle slurry, 80% of pig slurry and 80% of poultry manure applied to arable land was incorporated by plough within 12-24 hours.

[2]Assumes 30% of cattle slurry, 80% of pig slurry and 80% of poultry manure applied to arable land was incorporated by plough within 4-6 hours.

Table 20. Method 2: Rapid soil incorporation. Impact on crop N uptake, nitrate leaching losses and ammonia emissions in NVZ areas.

	Crop N uptake		Nitrate-N leaching losses		Ammonia-N losses to air	
	Total (kt)	**% total N applied**	**Total (kt)**	**% total N applied**	**Total (kt)**	**% total N applied**
Current NVZ-AP[1]						
Cattle slurry	12.7	30	2.2	5	5.5	13
Pig slurry	4.8	49	0.7	7	1.4	14
Poultry manure	13.9	34	3.4	8	6.2	15
Incorporation within 4-6 hours[2]						
Cattle slurry	12.8	30	2.2	5	5.5	13
Pig slurry	5.0	51	0.7	7	1.2	12
Poultry manure	15.0	36	3.8	9	4.2	10

[1]Assumes 30% of cattle slurry, 80% of pig slurry and 80% of poultry manure applied to arable land was incorporated by plough within 12-24 hours.

[2]Assumes 30% of cattle slurry, 80% of pig slurry and 80% of poultry manure applied to arable land was incorporated by plough within 4-6 hours.

Table 21. Method 2: Rapid soil incorporation. Impact on GHG emissions in England and Wales (ktCO_2e).

	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])
Current NVZ-AP[3]								
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
Incorporation within 4-6 hours[4]								
Cattle slurry	503	60	76	**639**	194	169	**445**	470
Pig slurry	67	7	12	**85**	44	39	**41**	46
Poultry manure	335	30	77	**442**	153	134	**289**	308
Total	905	97	165	**1166**	391	342	**775**	824

[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) and 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).

[3]Assumes 30% of cattle slurry, 80% of pig slurry and 80% of poultry manure applied to arable land was incorporated by plough within 12-24 hours.

[4]Assumes 30% of cattle slurry, 80% of pig slurry and 80% of poultry manure applied to arable land was incorporated by plough within 4-6 hours.

Table 22. Method 2: Rapid soil incorporation. Impact on GHG emissions in England ($ktCO_2e$).

	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])
Current NVZ-AP[3]								
Cattle slurry	417	51	63	**531**	162	141	**369**	390
Pig slurry	65	8	11	**84**	41	37	**43**	47
Poultry manure	297	42	65	**404**	132	115	**272**	289
Total	776	101	139	**1019**	335	293	**684**	726
Incorporation within 4-6 hours[4]								
Cattle slurry	417	50	63	**530**	161	140	**369**	390
Pig slurry	67	7	12	**86**	44	39	**41**	47
Poultry manure	315	28	72	**415**	144	126	**272**	289
Total	799	85	147	**1031**	349	305	**682**	726

[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) and 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).

[3]Assumes 30% of cattle slurry, 80% of pig slurry and 80% of poultry manure applied to arable land was incorporated by plough within 12-24 hours.

[4]Assumes 30% of cattle slurry, 80% of pig slurry and 80% of poultry manure applied to arable land was incorporated by plough within 4-6 hours.

Table 23. Method 2: Rapid soil incorporation. Impact on GHG emissions in NVZ areas (ktCO_2e).

	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])
Current NVZ-AP[3]								
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
Incorporation within 4-6 hours[4]								
Cattle slurry	224	27	27	**278**	91	79	**187**	199
Pig slurry	53	6	9	**68**	36	31	**32**	37
Poultry manure	225	20	46	**292**	106	93	**186**	199
Total	502	53	82	**638**	233	203	**405**	435

[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) and 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).

[3]Assumes 30% of cattle slurry, 80% of pig slurry and 80% of poultry manure applied to arable land was incorporated by plough within 12-24 hours.

[4]Assumes 30% of cattle slurry, 80% of pig slurry and 80% of poultry manure applied to arable land was incorporated by plough within 4-6 hours.

5.3 Method 3: Increased use of slurry bandspreading and shallow injection

Bandspreading (Plate 1) and shallow injection (Plate 2) technologies are the most practical methods for applying slurries to growing crops, because they spread slurry evenly, minimise ammonia emissions and odour nuisance and reduce crop (especially grass) contamination, compared with conventional surface broadcast applications.

Plate 1. Trailing hose slurry application to winter wheat

Plate 2. Shallow injection slurry application on grassland

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, respectively.

Spreading all slurries with bandspreading/ shallow injection equipment was predicted to increase N efficiency from 29% to 35% of total N applied for cattle slurry, and from 48% to 52% of total N applied for pig slurry (Table 24) across England and Wales. In NVZ areas, manure N efficiency was estimated to increase from 30% to 37% of total N applied for cattle slurry, and from 49% to 52% of total N applied for pig slurry (Table 26). These improvements were largely due to reductions in ammonia emissions (from 13% to 5% of total N applied for cattle slurry, and from 14% to 10% of total N applied for pig slurry).

The reduction in ammonia losses was predicted to increase direct nitrous oxide-N emissions compared with current NVZ-AP (Tables 27, 28 and 29). However, these increases were largely offset by reductions in indirect nitrous oxide-N emissions and increases in slurry N efficiency from bandspread/shallow injected slurry applications (and resultant reductions in manufactured fertiliser N use), which led to GHG reductions of 37,000 tonnes CO_2e across England and Wales, 31,000 tonnes CO_2e across England and 20,000 tonnes CO_2e in NVZ areas.

Table 24. Method 3: Use of bandspreading and shallow injection. Impact on crop N uptake, nitrate leaching losses and ammonia emissions in England and Wales.

	Crop N uptake		Nitrate-N leaching losses		Ammonia-N losses to air	
	Total (kt)	**% total N applied**	**Total (kt)**	**% total N applied**	**Total (kt)**	**% total N applied**
Current NVZ-AP[1]						
Cattle slurry	27.2	29	6.2	7	12.4	13
Pig slurry	6.0	48	0.9	8	1.7	14
Poultry manure	20.0	33	5.7	9	9.3	15
Bandspread/shallow injected[2]						
Cattle slurry	33.7	35	6.2	7	4.4	5
Pig slurry	6.4	52	1.0	8	1.2	10
Poultry manure	20.0	33	5.7	9	9.3	15

[1]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 12-24 hours.

[2]Assumes 100% of pig slurry and 100% of cattle slurry was applied by trailing hose to arable land or shallow injected to grassland.

Table 25. Method 3: Use of bandspreading and shallow injection. Impact on crop N uptake, nitrate leaching losses and ammonia emissions in England.

	Crop N uptake		Nitrate-N leaching losses		Ammonia-N losses to air	
	Total (kt)	**% total N applied**	**Total (kt)**	**% total N applied**	**Total (kt)**	**% total N applied**
Current NVZ-AP[1]						
Cattle slurry	22.5	29	5.1	7	10.3	13
Pig slurry	6.0	48	0.9	8	1.7	14
Poultry manure	18.8	33	5.4	9	8.7	15
Bandspread/shallow injected[2]						
Cattle slurry	28.0	35	5.2	7	3.7	5
Pig slurry	6.4	52	1.0	8	1.2	10
Poultry manure	18.8	33	5.4	9	8.7	15

[1]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 12-24 hours.

[2]Assumes 100% of pig slurry and 100% of cattle slurry was applied by trailing hose to arable land or shallow injected to grassland.

Table 26. Method 3: Use of bandspreading and shallow injection. Impact on crop N uptake, nitrate leaching losses and ammonia emissions in NVZ areas.

	Crop N uptake		Nitrate-N leaching losses		Ammonia-N losses to air	
	Total (kt)	**% total N applied**	**Total (kt)**	**% total N applied**	**Total (kt)**	**% total N applied**
Current NVZ-AP[1]						
Cattle slurry	12.7	30	2.2	5	5.5	13
Pig slurry	4.8	49	0.7	7	1.4	14
Poultry manure	13.9	34	3.4	8	6.2	15
Bandspread/shallow injected[2]						
Cattle slurry	15.7	37	2.2	5	2.0	5
Pig slurry	5.2	52	0.7	7	1.0	10
Poultry manure	13.9	34	3.4	8	6.2	15

[1]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 12-24 hours.

[2]Assumes 100% of pig slurry and 100% of cattle slurry was applied by trailing hose to arable land or shallow injected to grassland.

Table 27. Method 3: Use of bandspreading and shallow injection. Impact on GHG emissions in England and Wales ($ktCO_2e$)

	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]**)**
Current NVZ-AP[1]								
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
Bandspread/shallow injected[4]								
Cattle slurry	552	22	76	**649**	239	209	**410**	440
Pig slurry	68	6	12	**86**	45	40	**41**	46
Poultry manure	316	45	69	**431**	142	124	**289**	307
Total	936	73	157	**1166**	426	373	**740**	793

[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) and 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).

[3]Assumes 30% of pig slurry and 4% of cattle slurry was applied by trailing hose to arable land or shallow injected to grassland.

[4]Assumes 100% of pig slurry and 100% of cattle slurry was applied by trailing hose to arable land or shallow injected to grassland.

Table 28. Method 3: Use of bandspreading and shallow injection. Impact on GHG emissions in England (ktCO_2e)

	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]**)**
Current NVZ-AP[1]								
Cattle slurry	417	51	63	**531**	162	141	**369**	390
Pig slurry	65	8	11	**84**	41	37	**43**	47
Poultry manure	297	42	65	**404**	132	115	**272**	289
Total	776	101	139	**1019**	335	293	**684**	726
Bandspread/shallow injected[4]								
Cattle slurry	458	18	63	**539**	199	174	**340**	365
Pig slurry	68	6	12	**86**	45	40	**41**	46
Poultry manure	297	42	65	**404**	132	115	**272**	289
Total	823	66	140	**1029**	376	329	**653**	700

[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) and 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).

[3]Assumes 30% of pig slurry and 4% of cattle slurry was applied by trailing hose to arable land or shallow injected to grassland.

[4]Assumes 100% of pig slurry and 100% of cattle slurry was applied by trailing hose to arable land or shallow injected to grassland.

Table 29. Method 3: Use of bandspreading and shallow injection. Impact on GHG emissions in NVZ areas (ktCO_2e)

	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])
Current NVZ-AP[1]								
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
Bandspread/shallow injected[4]								
Cattle slurry	246	10	26	**281**	111	97	**170**	184
Pig slurry	54	5	9	**68**	37	32	**31**	36
Poultry manure	212	30	41	**284**	99	86	**185**	198
Total	512	45	76	**633**	247	215	**386**	418

[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) and 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).

[3]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 12-24 hours.

[4]Assumes 100% of pig slurry and 100% of cattle slurry was applied by trailing hose to arable land or shallow injected to grassland.

5.4 Method 4: Increased use of slurry separation technologies

To assess the effect of increased use of slurry separation technologies it was assumed that separation reduced the volumes of cattle and pig slurry spread to land by 20% and 10%, respectively (Defra/EA, 2008). Furthermore, the dry matter content of the liquid fraction was estimated to be reduced from 6% to 4% for cattle slurry, and from 4% to 3% for pig slurry, with corresponding changes in N composition (Table 30).

Table 30. Effects of separation on slurry dry matter and nitrogen composition

Slurry type	**Dry matter (%)**	**Total N (kg/m^3)**	**Readily available N (kg/m^3)**	**Readily available N (% total N)**
Cattle slurry:	6	2.6	1.2	46
Separated cattle slurry – liquid fraction	4	2.3	1.3	56
Separated cattle slurry – solid fraction	20	4.0	1.0	25
Pig slurry:	4	3.6	2.5	69
Separated pig slurry – liquid fraction	3	3.4	2.6	76
Separated pig slurry – solid fraction	20	5.0	1.3	25

The impact of increased use of slurry separation technologies on estimated crop N uptake is shown in Table 31 (NVZ areas). Slurry separation increased the N efficiency of the liquid fraction from 30% to 36% of total N applied for cattle slurry, and from 49% to 54% of total N applied for pig slurry. There was little change in estimated overall nitrate leaching and ammonia losses from the liquid fraction, as the N efficiency improvements were largely due to the increased proportion of readily available N in the liquid fraction compared with unseparated slurry (Table 30).

The separated solid fraction was assumed to be soil incorporated within 24 hours and to have a crop N availability of 15% (Anon, 2010). When the N efficiency of both the liquid and solid fractions was considered, there was estimated to be *no net change* in overall crop N uptake (N losses via nitrate leaching and ammonia) or GHG emission. However, there are a number of practical benefits in using slurry separation technologies (e.g. weeping wall, strainer box, mechanical separation). Slurry volume (and storage requirement) is decreased by up to *c.*20% for cattle slurry and *c.*10% for pig slurry. Also, the dry matter content of the liquid fraction is reduced making it easier to handle and pump, and the solid fraction can be easily be transported to neighbouring farmland (i.e. exported) and spread without closed-period restrictions that apply to slurry.

Table 31. Method 4: Increased use of slurry separation. Impact on crop N uptake in NVZ areas.

	Current NVZ-AP[1]			**Separated slurry - liquid fraction[2]**			**Separated slurry - solid fraction[2]**			**Separated slurry - overall[2]**		
	Total N applied (kt)	**Total crop N uptake (kt)**	**Mean crop N recovery (%)**	**Total N applied (kt)**	**Total crop N uptake (kt)**	**Mean crop N recovery (%)**	**Total N applied (kt)**	**Total crop N uptake (kt)**	**Mean crop N recovery (%)**	**Total N applied (kt)**	**Total crop N uptake (kt)**	**Mean crop N recovery (%)**
Cattle slurry	42.3	12.7	30	29.6	10.8	36	12.7	1.9	15	42.3	12.7	30
Pig slurry	9.9	4.8	49	8.4	4.6	54	1.5	0.2	15	9.9	4.8	49

[1]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 12-24 hours.

[2]Assumes all slurry is separated.

5.5 Method 5: Storing solid manures on an impermeable base

Defra project WT1006 "Review of Pollutant Losses from Solid Manures Stored in Temporary Field Heaps" concluded that 0.8–5.3% of total N in cattle/pig FYM and 0.4–8.2% of total N in poultry manure heaps was lost in leachate during storage. On a field site the leachate heap is likely to infiltrate into the soil, a proportion of the N supplied will be lost by leaching and via denitrification with the remainder available for crop N uptake.

In this study, we assumed that a mean of 3% of total N in cattle/pig FYM and poultry manure field heaps would be lost in the leachate, and that if the manures were stored on an impermeable base the leachate would be collected and added into a slurry store (cattle/pig FYM) or returned to the manure heap (poultry manure). Data from the Farm Practices Survey (Defra. 2006) showed that *c.*40% of cattle/pig FYM and *c.*30% of poultry manure is stored in field heaps (with no constructed base). It was assumed that all of these manures would in future be stored on an impermeable base; leaving *c.*30% of cattle/pig FYM and *c.*60% of poultry manures spread directly to land (Table 32). Hence, the quantity of slurry and poultry manure N spread to land would be increased by a small amount (Table 33).

Table 32. Destination of solid manures stored after removal from a building (Defra, 2006)

Manure type	**No further storage**	**Stored under cover**	**Stored in the open on a concrete (impermeable) base**	**Stored in the open on a field site (no constructed base)**
Cattle/pig FYM	28	2	26	44
Poultry manure	58	3	9	31

Table 33. Quantity of leachate N collected from solid manures stored on an impermeable base (previously stored in field heaps)

Slurry type	**N added in leachate (kt)**
Cattle slurry	0.6
Pig slurry	0.2
Poultry manure	0.4

The effects of managing previously stored field heaps on an impermeable base on estimated crop N uptake, nitrate leaching losses and ammonia emissions are shown in Table 34 (England and Wales), Table 35 (England) and Table 36 (NVZ areas). The main effect of this method was to increase by 2% the total amount of N applied. There was no effect on manure N efficiency (Tables 34 and 36). However, total crop N uptake, nitrate leaching losses and ammonia emissions were increased by a small amount due to the additional leachate N being applied to land.

The increased quantity of slurry N applied led to a small increase in direct and indirect nitrous oxide-N emissions (equivalent to 15,000 tCO_2e for England and Wales, 9,000 tCO_2e for current NVZ areas). These increases were partly offset by reductions in manufactured fertiliser N use, however, the overall effect of this method was to increase GHG emissions by 10,000 tCO_2e for England and Wales 9,000 tCO_2e for England and.5,000 tCO_2e for current NVZ areas (Tables 37, 38 and 39).

Table 34. Method 5: Storing solid manures on an impermeable base. Impact on crop N uptake, nitrate leaching losses and ammonia emissions in England and Wales.

	Crop N uptake		Nitrate-N leaching losses		Ammonia-N losses to air	
	Total (kt)	% total N applied	Total (kt)	% total N applied	Total (kt)	% total N applied
Current NVZ-AP[1]						
Cattle slurry	27.2	29	6.2	7	12.4	13
Pig slurry	6.0	48	0.9	8	1.7	14
Poultry manure	20.0	33	5.7	9	9.3	15
Solid manures stored on impermeable base[2]						
Cattle slurry	27.6	29	6.3	7	12.6	13
Pig slurry	6.1	48	1.0	8	1.8	14
Poultry manure	20.2	33	5.8	9	9.4	15

[1]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 12-24 hours.

[2]Assumes all leachate from solid manures currently stored in field heaps is collected and returned to a slurry store or poultry manure heap. The proportions incorporated and bandspread are the same as the Current NVZ-AP.

Table 35. Method 5: Storing solid manures on an impermeable base. Impact on crop N uptake, nitrate leaching losses and ammonia emissions in England

	Crop N uptake		Nitrate-N leaching losses		Ammonia-N losses to air	
	Total (kt)	% total N applied	Total (kt)	% total N applied	Total (kt)	% total N applied
Current NVZ-AP[1]						
Cattle slurry	22.5	29	5.1	7	10.3	13
Pig slurry	6.0	48	0.9	8	1.7	14
Poultry manure	18.8	33	5.4	9	8.7	15
Solid manures stored on impermeable base[2]						
Cattle slurry	22.9	29	5.2	7	10.5	13
Pig slurry	6.1	48	1.0	8	1.8	14
Poultry manure	18.9	33	5.5	9	8.8	15

[1]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 12-24 hours.

[2]Assumes all leachate from solid manures currently stored in field heaps is collected and returned to a slurry store or poultry manure heap. The proportions incorporated and bandspread are the same as the Current NVZ-AP.

Table 36. Method 5: Storing solid manures on an impermeable base. Impact on crop N uptake, nitrate leaching losses and ammonia emissions in NVZ areas.

	Crop N uptake		Nitrate-N leaching losses		Ammonia-N losses to air	
	Total (kt)	**% total N applied**	**Total (kt)**	**% total N applied**	**Total (kt)**	**% total N applied**
Current NVZ-AP[1]						
Cattle slurry	12.7	30	2.2	5	5.5	13
Pig slurry	4.8	49	0.7	7	1.4	14
Poultry manure	13.9	34	3.4	8	6.2	15
Solid manures stored on impermeable base[2]						
Cattle slurry	12.9	30	2.3	5	5.6	13
Pig slurry	4.9	49	0.7	7	1.4	14
Poultry manure	14.0	34	3.4	8	6.3	15

[1]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 12-24 hours.

[2]Assumes all leachate from solid manures currently stored in field heaps is collected and returned to a slurry store or poultry manure heap. The proportions incorporated and bandspread are the same as the Current NVZ-AP.

Table 37. Method 5: Storing solid manures on an impermeable base. Impact on GHG emissions in England and Wales (ktCO_2e)

	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])
Current NVZ-AP[1]								
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
Solid manures stored on impermeable base[2]								
Cattle slurry	510	62	77	**649**	196	171	**453**	478
Pig slurry	66	9	12	**86**	43	38	**43**	48
Poultry manure	319	46	70	**435**	144	125	**291**	310
Total	895	117	159	**1170**	383	334	**787**	836

[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) and 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).

Table 38. Method 5: Storing solid manures on an impermeable base. Impact on GHG emissions in England ($ktCO_2e$)

	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])
Current NVZ-AP[1]								
Cattle slurry	417	51	63	**531**	162	141	**369**	390
Pig slurry	65	8	11	**84**	41	37	**43**	47
Poultry manure	297	42	65	**404**	132	115	**272**	289
Total	776	101	139	**1019**	335	293	**684**	726
Solid manures stored on impermeable base[2]								
Cattle slurry	423	52	64	**538**	163	142	**376**	397
Pig slurry	66	9	12	**87**	43	38	**43**	49
Poultry manure	300	43	66	**409**	135	118	**274**	291
Total	789	104	142	**1034**	341	298	**693**	737

[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) and 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).

Table 39. Method 5: Storing solid manures on an impermeable base. Impact on GHG emissions in NVZ areas (ktCO_2e)

	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])
Current NVZ-AP[1]								
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
Solid manures stored on impermeable base[2]								
Cattle slurry	227	27	28	**282**	92	80	**190**	202
Pig slurry	53	7	9	**69**	35	30	**34**	39
Poultry manure	214	31	42	**287**	100	87	**187**	200
Total	494	65	79	**638**	227	197	**411**	441

[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) and 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).

5.6 Method 6: Higher manure N use efficiencies in the next NVZ-AP

Defra project WT1006 "Review and Recommendations for Minimum Livestock Manure Nitrogen Efficiency Coefficients" summarised the minimum manure N efficiencies stipulated in the current NVZ-AP (that must be used as part of the N max calculations) and values considered for adoption in the next NVZ-AP (Table 40).

Table 40. Estimated manure N efficiencies compared with values stipulated in the current NVZ-AP and recommended for adoption in the next NVZ-AP.

Manure type	**Current estimate within NVZ areas***	**NVZ-AP** **From 1st January 2012**	**Possible values in the next NVZ-AP**
Cattle slurry	30	35	40
Pig slurry	49	45	55
Poultry manures	34	30	35

*See Table12. Manure N efficiency currently estimated to be achieved within NVZs

In order to achieve the above values in the next NVZ-AP, a number of enhancements will need to be made to manure management practices within NVZ areas e.g. increased use of bandspreading/shallow injection equipment, greater uptake of slurry separation technologies, more manures applied in spring etc.

The theoretical impacts of stipulating higher manure N use efficiency coefficients on estimated crop N uptake, nitrate leaching losses and ammonia emissions are shown in Table 41 (England and Wales), Table 42 (England) and Table 43 (NVZ areas). *Note:* we have assumed that nitrate leaching losses and ammonia emissions would be the same as under the current NVZ-AP, as we were uncertain about how farmers would achieve the improvements in manure N use efficiency i.e. a combination of methods could be used.

Stipulating (theoretical) higher manure N use efficiency coefficients was estimated to reduce manufactured fertiliser N applications and associated overall GHG emissions by *c.*12% (equivalent to 93,000 tCO_2e for England and Wales, 79,000 tCO_2e for England and 38,000 tCO_2e for current NVZ areas) compared with the current NVZ-AP (Tables 44, 45 and 46).

Table 41. Method 6: Higher manure N use efficiency. Impact on crop N uptake, nitrate leaching losses and ammonia emissions in England and Wales.

	Crop N uptake		Nitrate-N leaching losses		Ammonia-N losses to air	
	Total (kt)	**% total N applied**	**Total (kt)**	**% total N applied**	**Total (kt)**	**% total N applied**
Current NVZ-AP[1]						
Cattle slurry	27.2	29	6.2	7	12.4	13
Pig slurry	6.0	48	0.9	8	1.7	14
Poultry manure	20.0	33	5.7	9	9.3	15
Increased manure N use efficiency[2]						
Cattle slurry	38.0	40	6.2	7	12.4	13
Pig slurry	6.8	55	0.9	8	1.7	14
Poultry manure	21.4	35	5.7	9	9.3	15

[1]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 12-24 hours.

[2]Increased manure N use efficiency. Nitrate leaching and ammonia emissions were assumed to be the same as the current NVZ-AP.

Table 42. Method 6: Higher manure N use efficiency. Impact on crop N uptake, nitrate leaching losses and ammonia emissions in England.

	Crop N uptake		**Nitrate-N leaching losses**		**Ammonia-N losses to air**	
	Total (kt)	**% total N applied**	**Total (kt)**	**% total N applied**	**Total (kt)**	**% total N applied**
Current NVZ-AP[1]						
Cattle slurry	22.5	29	5.1	7	10.3	13
Pig slurry	6.0	48	0.9	8	1.7	14
Poultry manure	18.8	33	5.4	9	8.7	15
Increased manure N use efficiency[2]						
Cattle slurry	31.5	40	5.2	7	10.3	13
Pig slurry	6.8	55	0.9	8	1.7	14
Poultry manure	20.1	35	5.4	9	8.7	15

[1]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 12-24 hours.

[2]Increased manure N use efficiency. Nitrate leaching and ammonia emissions were assumed to be the same as the Current NVZ-AP.

Table 43. Method 6: Higher manure N use efficiency. Impact on crop N uptake, nitrate leaching losses and ammonia emissions in NVZ areas.

	Crop N uptake		Nitrate-N leaching losses		Ammonia-N losses to air	
	Total (kt)	% total N applied	Total (kt)	% total N applied	Total (kt)	% total N applied
Current NVZ-AP[1]						
Cattle slurry	12.7	30	2.2	5	5.5	13
Pig slurry	4.8	49	0.7	7	1.4	14
Poultry manure	13.9	34	3.4	8	6.2	15
Increased manure N use efficiency[2]						
Cattle slurry	16.9	40	2.2	5	5.5	13
Pig slurry	5.4	55	0.7	7	1.4	14
Poultry manure	14.4	35	3.4	8	6.2	15

[1]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 12-24 hours.

[2]Increased manure N use efficiency. Nitrate leaching and ammonia emissions were assumed to be the same as the Current NVZ-AP.

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Table 44. Method 6: Higher manure N use efficiency. Impact on GHG emissions in England and Wales ($ktCO_2e$)

	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])
Current NVZ-AP[1]								
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
Increased manure N use efficiency [2]								
Cattle slurry	503	61	76	**639**	270	236	**369**	403
Pig slurry	65	8	11	**85**	48	42	**37**	43
Poultry manure	316	45	69	**431**	152	133	**279**	298
Total	884	114	156	**1155**	470	411	**684**	743

[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) and 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).

Table 45. Method 6: Higher manure N use efficiency. Impact on GHG emissions in England ($ktCO_2e$)

	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])
Current NVZ-AP[1]								
Cattle slurry	417	51	63	**531**	162	141	**369**	390
Pig slurry	65	8	11	**84**	41	37	**43**	47
Poultry manure	297	42	65	**404**	132	115	**272**	289
Total	776	101	139	**1019**	335	293	**684**	726
Increased manure N use efficiency[2]								
Cattle slurry	417	51	63	**531**	224	196	**306**	334
Pig slurry	65	8	11	**84**	48	42	**37**	43
Poultry manure	297	42	65	**404**	143	125	**262**	280
Total	776	101	139	**1019**	415	363	**605**	657

Table 46. Method 6: Higher manure N use efficiencies. Impact on GHG emissions in NVZ areas (ktCO_2e)

	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])
Current NVZ-AP[1]								
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
Increased manure N use efficiency [2]								
Cattle slurry	224	27	27	**278**	120	105	**158**	173
Pig slurry	52	7	9	**67**	39	34	**28**	33
Poultry manure	212	30	41	**284**	102	89	**182**	195
Total	489	64	77	**629**	261	228	**368**	401

[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) and 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, pig, laying hen and broiler 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.

(iii) Laying hens:

- 'Small' - 10,000 layers, 4,000 pullets
- 'Medium' - 50,000 layers, 20,000 pullets
- 'Large' - 100,000 layers, 40,000 pullets

(iv) Broilers:

- 'Small' - 56,000 broilers, 3,000 breeders
- 'Medium' - 120,000 broilers, 6,000 breeders
- 'Large' - 200,000 broilers, 12,000 breeders

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 47). In order to comply with the existing 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 current closed period by another 2 months (and therefore the storage requirement from 5 to 7 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.

Table 47. 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
Existing NVZ-AP (5 months)	830	1480	3960
1 month extension of ‘closed period’ (6 months)	970	1740	4670
2 month extension of ‘closed period’ (7 months)	1070	1930	5170

Increasing the storage capacity by 2 months i.e. from 3 to 5 months (the existing 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 (due to a 1 month extension of ‘closed-period’) 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 to 7 months (due to a 2 month extension) 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.

Extending the storage period from baseline 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 (Table 48).

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). At farm level there will be a 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 5 month period, as many existing steel tanks/concrete structures will have reached the end of their useable life. Other farms may have intended to replace storage facilities as part of planned business costs and as such the expenditure on extending slurry storage capacity may not be considered additional cost.

Table 48. 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, England and 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, England and the current NVZ area (Table 49).

Table 49. Cattle slurry storage requirement and costs for England and Wales, England and current NVZ areas

	England and Wales		England		NVZ areas	
	Volume (m m^3)	Cost (£ m)	Volume (m m^3)	Cost (£ m)	Volume (m m^3)	Cost (£ m)
3 months (baseline)	15.9	790	13.0	650	8.2	410
5 months (existing NVZ-AP)	26.3	1,315	21.6	1,080	13.5	675
6 months	31.0	1,550	25.5	1,280	16.0	800
7 months	34.4	1,720	28.2	1,410	17.6	880

These costs estimates assume that on average, an additional 2 months storage capacity is required to comply with the existing NVZ-AP.

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 50). 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 50. 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

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 51). 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).

Table 51. 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**

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). At farm level there will be a 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 6 month period, as many existing steel tanks/concrete structures will have reached the end of their useable life. Other farms may have intended to replace storage facilities as part of planned business costs and as such a proportion of the expenditure on extending slurry storage capacity may not be considered additional cost.

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 52). 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 52. Pig slurry storage requirement and costs for England and Wales Whole Territory Area and current NVZ areas

	England and Wales*		NVZ	
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 (existing NVZ-AP)	1.7	85	1.4	70
7 months	2.0	100	1.6	80
8 months	2.2	110	1.8	90

Note: Less than1% of pig production is in Wales

6.2 Rapid soil incorporation

On the dairy farm, it was assumed that all the slurry was applied to grassland and so rapid incorporation was not considered. For the pig and poultry farms, it was assumed that 58% of pig slurry and 90% of poultry manure was applied to tillage land (Farm Practice Survey; Defra, 2006). Manure application rates were assumed to be $40m^3$/ha for pig slurry, 8t/ha for broiler litter and 13 t/ha for layer manure.

Table 53. Quantities of manure spread and costs of soil incorporation within 6 hours of application.

Farm	Manure Produced (t)	Amount spread on tillage land (t)	Land area required (ha)	Extra cost required to soil incorporate within 6 hours of application (£)
Pig (slurry):				
Small	1,050	600	15	270
Medium	2,100	1,200	30	540
Large	4,100	2,400	60	1,080
Broiler:				
Small	1,040	940	118	2,120
Medium	2,240	2,020	253	4,550
Large	3,760	3,380	422	7,600
Layer:				
Small	470	420	32	580
Medium	2,360	2,130	164	2,950
Large	4,730	4,255	327	5,890

We assumed that an extra ‘rapid’ surface cultivation, using tine/disc equipment, was required to incorporate the manure into the soil within 6 hours of application. Costs assume a work rate of 1.5 ha/hour and labour of £27/hour, Nix (2011). However on some farms, it may be possible to accommodate the additional work within existing staff resources thereby reducing the cost of implementing this measure.

The extra costs of rapid soil incorporation (Table 53) were highest on the broiler farm (range £2,120-£7,600/year) reflecting the greater land areas required to apply broiler litter in compliance with the NVZ organic manure N field limit i.e. 250 kg/ha total N in any 12 month period (Defra/EA, 2008).

6.2.1 Scaling up to England and Wales, England and England and NVZ areas

Data from MANURES-*GIS* (Table 54) were used to estimate the amounts of cattle slurry, pig slurry and poultry manure applied to land in England and Wales and the proportions of manure applied in NVZ areas. Ninety three percent of cattle slurry, 41% of pig slurry and 10% of poultry manure were estimated to be applied to grassland and so were not considered for rapid incorporation. We assumed that 30% of cattle slurry, 80% of pig slurry and 80% of poultry manure applied to tillage land was applied to stubble and subject to soil incorporation (Farm Practice Survey; Defra, 2006).

Table 54. Total annual quantities of handled manures and directly deposited excreta produced in England and Wales

Sector	Livestock numbers (million)	Solid manure spread (Mt/yr fresh weight)	Slurry spread (Mt/yr fresh weight)	Excreta deposited (Mt/yr fresh weight)	Incinerated (Mt/yr fresh weight)
Dairy	2.4	9.6	25.5	16.4	-
Beef	4.5	16.0	8.7	25.8	-
Pigs	4.3	3.1	3.4	0.7	-
Laying hens	28.2	1.1	-	0.1	-
Broilers	117	2.5	-	<0.1	0.4

Table 55. Area of tillage land area receiving applications of slurry and poultry manure and costs of rapid soil incorporation.

Manure type	England and Wales		England		NVZ	
	Land area (ha)	Cost (£ m)	Land area (ha)	Cost (£ m)	Land area (ha)	Cost (£ m)
Cattle slurry	18,000	0.3	15,000	0.3	8,250	0.1
Pig slurry	40,000	0.7	40,000	0.7	32,000	0.6
Broiler litter	225,000	4.1	212,000	3.9	151,000	2.7
Layer manure	61,000	1.1	57,000	1.0	41,000	0.7
Total	343,000	6.2	324,000	5.8	232,250	4.1

The costs of rapid soil incorporation were estimated at £6.2 million per year for England and Wales, £5.8 million and £4.1 million for NVZ areas (Table 55). The highest costs were associated with the incorporation of broiler litter reflecting the greater land areas required to apply broiler litter in compliance with the NVZ organic manure N field limit i.e. 250 kg/ha total N in any 12 month period (Defra/EA, 2008).

6.3 Slurry bandspreading/shallow injection

Changing from surface broadcast slurry application to bandspreading/shallow injection requires significant investment in new spreading equipment, as retrofitting of existing equipment is generally not practical.

An 11m^3 tanker fitted with a bandspreader/shallow injection boom will typically cost £30,000 (compared with around £6,000 for a conventional 6m^3 tanker). The annual cost of bandspreading/shallow injection equipment (amortised over 10 years at an interest rate of 7%) was estimated at £4,300/year (compared with £850/year for a conventional tanker). Notably, the increased capital costs of bandspreading/shallow injection equipment is likely to encourage farmers to use contractors for slurry spreading rather than purchasing on-farm equipment, along with the need for a 'large' tractor to operate such equipment.

Trailing hose booms are typically 12-24 m wide and can be used to apply slurry to both arable and grassland crops; they are particularly suited to arable cropland because the wide booms can fit tramline spacings. Shallow injection is most suited to grassland use because of the narrow application width (4-6 m). Hence, our calculations assume that all of the slurry on the dairy farm was shallow injected (on grassland), and all of the slurry on the pig farm was bandspread on to either grassland or arable crops.

The costs of the different slurry application techniques were based on figures from Nix (2011) i.e. £2/m^3 for surface broadcasting, £3/m^3 for bandspreading and £3.50/m^3 for shallow injection. The higher costs for bandspreading and shallow injection reflect additional capital costs of the equipment, along with increased maintenance, spare parts, fuel use costs etc.

Table 56. Costs of contrasting slurry application techniques

	Volume of slurry spread*	Annual cost	
Dairy:		Broadcast	Shallow injection
'Small'	1,500	3,000	5,250
'Medium'	2,800	5,600	9,800
'Large'	7,300	14,600	25,550
Pig:		Broadcast	Bandspread
'Small'	1,050	2,100	3,150
'Medium'	2,100	4,200	6,300
'Large'	4,200	8,400	12,600

* Note: Figures include an allowance for rainwater dilution

On the small dairy farm, the additional annual cost of shallow injection was *c.*£2,250 and on the large dairy farm *c.*£11,000 (compared with conventional surface broadcast application). On the small pig farm, the additional annual cost of bandspreading was *c.*£1,000 and for the large pig farm *c.*£4,000 (compared with conventional surface broadcast application; Table 56).

6.3.1 Scaling up to England and Wales, England and NVZ areas

The volumes of slurry applied to land in England and Wales were based on data from MANURES-*GIS* (Table 57). We assumed that all slurry applied to grassland was shallow injected (93% of cattle slurry and 41% of pig slurry) and applications to arable land (7% of cattle slurry and 59% of pig slurry) were bandspread. Also, that 4% of cattle slurry and 30% of pig slurry was currently applied using bandspreading/shallow injection techniques (Farm Practice Survey; Defra, 2006).

The annual costs of slurry bandspreading/shallow injection were estimated at £52 million for England and Wales, £45 million for England and £25 million for the current NVZ area (Table 57).

Table 57. Extra volume and cost of slurry bandspreading/shallow injection.

	England and Wales		England		NVZ	
	Volume (m m^3)	Cost (£ m)	Volume (m m^3)	Cost (£ m)	Volume (m m^3)	Cost (£ m)
Cattle	32.8	49.1	27.2	41.4	14.7	22.0
Pig	2.4	3.2	2.4	3.2	1.9	2.6
Total	35.2	52.3	29.6	44.6	16.6	24.6

6.4 Slurry separation

Mechanical equipment can be used to separate slurry into solid and liquid fractions. The resulting solid fraction is usually stored on a concrete pad and under the NVZ-AP is subject to the same storage and spreading restrictions as farmyard manure. The liquid fraction is regarded as slurry and is subject to NVZ-AP storage and closed period spreading restrictions. In our calculations we assumed the capital cost of a slurry separator at £23,000 (amortised over 20 years) and that slurry storage capacity would be reduced by 20% on the dairy farm and 10% on the pig farm (Defra/EA, 2008).

6.4.1 Dairy farms

On the medium farm, capital costs were *c.*£8,000 higher for 5 months storage, £5,000 higher for 6 months storage and £4,000 higher for 7 months storage compared with the storage costs in Table 48. Notably, on the large farm, installing a slurry separator reduced capital costs by *c.*£17,000 for 5 months, £24,000 for 6 months and £29,000 for 7 months storage, respectively (Table 58).

Table 58. Costs of slurry separation and storage for small, medium and large dairy farms

Farm size	**Small**	**Medium**	**Large**	**Small**	**Medium**	**Large**
	Steel/concrete tank			**Lagoon**		
Existing NVZ-AP (5 months)						
Capital cost	55,960	82,160	181,600	49,368	70,330	149,900
Annual amortised cost	5,260	7,720	17,070	4,640	6,610	14,090
Repairs , separator running costs etc £	1,120	1,640	3,630	990	1,410	3,000
Total annual cost	**6,380**	**9,360**	**20,700**	**5,630**	**8,020**	**17,090**
1 month extension of 'closed period'						
Capital cost	61,800	92,640	209,800	54,040	78,710	172,440
Annual amortised cost	5,810	8,710	19,720	5,080	7,400	16,210
Repairs , separator running costs etc. £	1,240	1,850	4,200	1,080	1,570	3,450
Total annual cost	**7,050**	**10,560**	**23,920**	**6,160**	**8,970**	**19,660**
2 month extension of 'closed period'						
Capital cost	65,960	100,120	229,760	57,370	84,700	188,360
Annual amortised cost	6,200	9,410	21,600	5,390	7,960	17,710
Repairs , separator running costs etc. £	1,320	2,000	4,600	1,150	1,700	3,770
Total annual cost	**7,520**	**11,410**	**26,200**	**6,540**	**9,660**	**21,480**

6.4.2 Pig farms

On the small farm, investment in a slurry separator increased capital costs for 5 months storage by *c.*£20,000, on the medium farm by *c.*£18,000 and on the large farm by *c.*£13,000 (Table 59) compared with the storage costs in Table 38.

Table 59. Costs of slurry separation and storage for small, medium and large pig farms

Farm size	**Small**	**Medium**	**Large**	**Small**	**Medium**	**Large**
Capacity Type	**Steel/concrete tank**			**Lagoon**		
Current NVZ–AP (6 months)						
Capital cost	46,400	70,250	117,500	41700	60,800	98,600
Annual cost	4,380	6,600	11,040	3,940	5,710	9,260
Repairs @ 2%	930	1,400	2,350	840	1,220	1,970
Total annual cost	**5,310**	**8,000**	**13,390**	**4,780**	**6,930**	**11,230**
1 month extension of 'closed period'						
Capital cost	50,400	77,810	132,580	44,890	66,850	110,660
Annual cost	4,730	7,310	12,460	4,220	6,290	10,400
Repairs @ 2%	1,010	1,560	2,650	900	1,340	2,210
Total annual cost	**5,740**	**8,870**	**15,110**	**5,120**	**7,630**	**12,610**
2 month extension of 'closed period'						
Capital cost	54,140	85,370	147,700	47,910	72,900	122,760
Annual cost	5,090	8,030	13,890	4,500	6,850	11,540
Repairs @ 2%	1,080	1,710	2,950	960	1,460	2,460
Total annual cost	**6,170**	**9,740**	**16,840**	**5,460**	**8,310**	**14,000**

6.4.3 Scaling up to England and Wales and NVZ areas

The costs of slurry separation were estimated at £3,000 per year based on annual amortised capital repayment and running costs of the separator and slurry volumes handled on the small, medium and large farms. For the dairy farms the mean cost of separation on a volume basis was calculated at £1/m^3 and for the pig farms £1.50/m^3.

The savings in slurry storage requirement were based on the slurry volumes calculated in Section 5.1 (assuming a 20% reduction for cattle slurry and 10% for pig slurry; Defra/EA, 2008). Our baseline assumption was that 5% of cattle slurry and 10% of pig slurry was mechanically separated. Slurry separation is likely to be more economically viable for larger farms because the additional capital repayment and operational costs for the separation equipment will be more than compensated for by reductions in slurry storage costs.

The savings in slurry storage capital costs were estimated at £270 million for England and Wales, £230 million for England and £142 million for the current NVZ area (Table 60). Annual costs of slurry separation were estimated at £35 million for England and Wales, £30 million for England and £17 million for the current NVZ area

Table 60. Slurry separation annual costs and slurry storage capital savings

	England and Wales		England		NVZ	
	Storage saving	Separator cost	Storage saving	Separator cost	Storage saving	Separator cost
	£ million					
Cattle slurry	262	31	222	26	135	15
Pig slurry	8	4	8	4	7	2
Total	270	35	230	30	142	17

6.5 Storing solid manures on an impermeable base

For the laying hen and broiler farms, the baseline assumption was that 31% of the manure was stored in field heaps (Farm Practice Survey; Defra, 2006). It was assumed that broiler litter had a bulk density of 0.5 and layer manure 0.9. Stacking height was assumed to be 2m for broiler litter and 1m for layer manure. An additional floor area, equivalent to 10% of the area covered by the manure heap, was assumed to be required for turning and loading. Construction costs were based on £40/m^2 for concrete (Nix, 2011) and additional storage for leachate from the solid manure (10% of manure weight) was estimated at £50/m^3.

For the broiler farms, the additional storage costs ranged from *c.*£15,000 on the small farm to *c.*£57,000 on the large farm. For laying hens, the additional storage costs were estimated at *c.*£8,000 for the small farm and *c.*£66,000 for the large farm (Table 61).

Table 61. Extra costs of storing poultry manures* on an impermeable base for small, medium and large broiler and laying hen farms

	Farm type					
	Broiler			Laying hen		
	Small	Medium	Large	Small	Medium	Large
Additional storage requirement (t)	320	670	1,150	150	730	1,470
Concrete area required (m^2)	350	740	1,150	180	890	1,890
Leachate collection (m^3)	30	70	120	15	70	150
Capital cost (£)	15,500	33,100	56,600	7,950	39,100	66,300

*Note: 31% of poultry manures stored in field heaps (Defra, 2006)

Note: The dairy and pig farm typologies evaluated in this project were slurry based.

6.5.1 Scaling up to England and Wales and NVZ areas

Data from MANURES-*GIS* were used to quantify the amounts of cattle and pig farmyard manure, broiler litter and layer manure produced in England and Wales (Table 54). The baseline assumption was that 44% of cattle and pig FYM, and 31% of poultry manure was stored in field heaps (Farm Practice Survey; Defra, 2006). Stacking height for pig and cattle FYM was assumed to be 2m and the bulk density was assumed to be 0.7.

For England and Wales, the additional capital cost required to store all solid manures on an impermeable base was estimated at £520 million (Table 49) compared with an estimated £440 million for England and £256 million for the current NVZ areas.

Table 62. Capital costs of storing all solid manures on an impermeable base.

Manure type	England and Wales		England		NVZ	
	Concrete area (million m^2)	Capital cost (£ m)	Concrete area (million m^2)	Capital cost (£ m)	Concrete area (million m^2)	Capital cost (£ m)
Cattle FYM	8.9	412	7.3	336	3.9	180
Pig FYM	1.1	50	1.1	50	0.9	40
Broiler litter	0.9	40	0.8	36	0.5	23
Layer manure	0.4	18	0.4	18	0.3	13
Total	11.3	520	9.6	440	5.6	256

7 COST-BENEFIT ASSESSMENT

The costs of implementing the six methods to improve 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), *c.*£2,100/tonne for NH_3-N (IGCB, 2008) and £670/tonne for NO_3-N (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 the current NVZ area (Table 63), England and Wales (Table 64) and England (Table 65). 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, £555 million for England and Wales and £460 million for England. Over 20 years, the cost of repaying the capital and servicing the interest was estimated to be £550 million for the current NVZ area £1,040 million for England and Wales and £865 million for England. *Note:* Baseline slurry storage capacity estimates are uncertain.

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 the current NVZ area, 104,000 tonnes for England and Wales (worth £104 million) and 92,000 tonnes fro England (worth £92 million).

The reductions in ecosystem damage costs (from lower nitrous oxide, ammonia and nitrate losses) over a 20 year period resulting from the existing NVZ-AP were estimated at £143 million for the current NVZ Area, £239 million for England and Wales and £216 million for England. The overall cost-benefit ratio based on the initial capital cost was 1.4:1 for the current NVZ area, 1.6:1 for England and Wales and 1.5:1 for England, compared with a cost-benefit ratio based on capital repayment and interest charges of 2.7:1 for the current NVZ area, 3.0:1 for England and Wales and 2.8:1 for England.

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 the current NVZ area, £250 million and £430 million for England and Wales and £210 million and £365 million for England. The cost-benefit ratio (based on capital costs) of extending the closed period by 1 and 2 months increased to 2.2:1 and 3.7:1 for the current NVZ area, to 2.3:1 and 3.9:1 for England and Wales and 2.1:1 and 4.0:1 for England, respectively. The extra costs of extending the storage periods were not matched by proportional reductions in fertiliser N use and ecosystem damage costs.

Incorporating high readily available N manures into the soil within 6 hours of application, in addition to the measures included in the existing NVZ-AP, was estimated to have additional annual operational (staff and equipment) costs of £4 million for the current NVZ area, £7 million for England and Wales and £6 million for England. The reductions in fertiliser N use and ecosystem damage costs (mainly resulting from reductions in ammonia loss) were reflected in *lower* 20 year cost-benefit ratios (at 1.2:1 for the current NVZ area, 1.4:1 for England and Wales and 1.3:1 for England) than for the existing NVZ-AP.

Bandspreading and shallow injecting all slurry, in addition to the measures included in the existing NVZ-AP, was predicted to reduce fertiliser N use by an additional 68,000 tonnes in the current NVZ area, 138,000 tonnes across England and Wales and . Ammonia emissions were predicted to be reduced by a further 78,000 tonnes NH_3-N in the current NVZ area, 170,000 tonnes in England and Wales and 142,000 tonnes in England. The increased application costs compared with surface broadcasting (£25 million/year for the NVZ area, £50 million/year for England and Wales and £45 million for England) were reflected in *higher* cost-benefit ratios (at 1.7:1 for the current NVZ area, 1.8:1 for England and Wales and 1.8:1 for England) than for the existing NVZ-AP.

The slurry separation and storing solid manures on an impermeable base methods were assessed to have *little effect* on manure N use efficiency or ecosystem damage costs compared with the existing NVZ-AP.

Table 63. Costs and benefits of the existing NVZ-AP options OVER 20 YEARS: Current NVZ Area (62% of England and *c.*3% of Wales)

	Option						
	1a NVZ-AP Closed period	1b NVZ-AP Closed period + 1 month extra storage	1c NVZ-AP Closed period + 2 months extra storage	2 NVZ-AP Closed period + rapid incorporation[3]	3 NVZ-AP Closed period + slurry bandspreading/shallow injection [4]	4 NVZ-AP Closed period + slurry separation[5]	5 NVZ-AP Closed period + impermeable base storage for solid manures
Capital costs of extra slurry storage[1]	290 million	425 million	515 million	290 million	290 million	148 million	545 million
Annual amortised costs[2]	550 million	800 million	970 million	550 million	550 million	280 million	1,020 million
Additional operational costs	0	0	0	80 million	500 million	340 million	0
Fertiliser N saving (t)	60,000	58,000	34,000	88,000	128,000	60,000	68,000
GHG savings (tCO_2e)	740,000	840,000	620,000	760,000	1,140,000	740,000	640,000
Ammonia-N savings (t)	38,000	30,000	24,000	82,000	116,000	38,000	34,000
Nitrate-N savings (t)	28,000	36,000	30,000	20,000	26,000	28,000	26,000
Fertiliser saving (£)[6]	60 million	58 million	34 million	88 million	128 million	60 million	68 million
GHG savings societal benefit (£) [7]	44 million	50 million	37 million	46 million	68 million	44 million	38 million
Ammonia N savings societal benefit (£)[7]	80 million	63 million	50 million	172 million	244 million	80 million	71 million
Nitrate-N savings societal benefit (£)[7]	19 million	24 million	20 million	13 million	17 million	19 million	17 million
Cost benefit ratio based on capital and operation costs [8]	1.4:1	2.2:1	3.7:1	1.2:1	1.7:1	2.4:1	2.8:1
Cost benefit ratio based on amortised and operation costs[8]	2.7:1	4.1:1	6.8:1	1.9:1	2.3:1	3.1:1	5.4:1

[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] Incorporation cost £18/ha (Nix, 2011); manure application rates: slurry 40m^3/ha, layer manure 13 t/ha and broiler litter 8t/ha
[4] Spreading costs £2/m^3 for surface broadcast, £3/m^3 for bandspreading and £3.50/m^3 for shallow injection (Nix, 2011)
[5] Slurry separation assumed to reduce cattle slurry storage by 20% and pig slurry storage by 10%. Slurry separation costs assumed to be £1/m^3 for cattle slurry and £1.50/m^3 for pig slurry based on operation costs and capital cost of equipment amortised over 20 years and expressed on an annual basis.
[6] Based on manufactured fertiliser N cost of £1,000/tonne (i.e. £345/tonne of ammonium nitrate).
[7] Based on non-traded price of CO_2e of £60/tonne and ecosystem damage costs of £2,100/tonne of NH_3-N and £670/tonne NO_3-N.
[8] Benefits based on fertiliser N savings and avoided GHG/ammonia-N/nitrate-N damage costs

Table 64. Costs and benefits of NVZ-AP options OVER 20 YEARS: of implement the existing NVZ-AP across England and Wales

	Option						
	1a NVZ-AP Closed period	1b NVZ-AP Closed period + 1 month extra storage	1c NVZ-AP Closed period + 2 months extra storage	2 NVZ-AP Closed period + rapid incorporation[3]	3 NVZ-AP Closed period + slurry bandspreading/shallow injection [4]	4 NVZ-AP Closed period + slurry separation[5]	5 NVZ-AP Closed period + impermeable base storage for solid manures
Capital costs of extra slurry storage[1]	555 million	805 million	985 million	555 million	555 million	285 million	1,070 million
Annual amortised costs[2]	1,040 million	1,510 million	1,850 million	1,040 million	1,040 million	535 million	2,010 million
Additional operational costs	0	0	0	140 million	1,000 million	700 million	0
Fertiliser N saving (t)	104,000	106,000	66,000	144,000	242,000	104,000	118,000
GHG savings (tCO_2e)	1,360,000	1,700,000	1,360,000	1,400,000	2,100,000	1,360,000	1,160,000
Ammonia-N savings (t)	56,000	44,000	26,000	122,000	226,000	56,000	48,000
Nitrate-N savings (t)	58,000	80,000	74,000	44,000	56,000	58,000	52,000
Fertiliser saving (£)[6]	104 million	106 million	66 million	144 million	242 million	104 million	118 million
GHG savings societal benefit (£)[7]	80 million	102 million	82 million	84 million	126 million	80 million	70 million
Ammonia N savings societal benefit (£)[7]	120 million	90 million	55 million	255 million	475 million	120 million	100 million
Nitrate-N savings societal benefit (£)[7]	39 million	54 million	50 million	29 million	38 million	39 million	35 million
Cost benefit ratio based on capital and operation costs [8]	1.6:1	2.3:1	3.9:1	1.4:1	1.8:1	2.9:1	3.3:1
Cost benefit ratio based on amortised and operation costs[8]	3.0:1	4.3:1	7.3:1	2.3:1	2.3:1	3.6:1	6.2:1

[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] Incorporation cost £18/ha (Nix, 2011); manure application rates: slurry 40m^3/ha, layer manure 13 t/ha and broiler litter 8t/ha
[4] Spreading costs £2/m^3 for surface broadcast, £3/m^3 for bandspreading and £3.50/m^3 for shallow injection (Nix, 2011)
[5] Slurry separation assumed to reduce cattle slurry storage by 20% and pig slurry storage by 10%. Slurry separation costs assumed to be £1/m^3 for cattle slurry and £1.50/m^3 for pig slurry based on operation costs and capital cost of equipment amortised over 20 years and expressed on an annual basis
[6] Based on manufactured fertiliser N cost of £1,000/tonne (i.e. £345/tonne of ammonium nitrate).
[7] Based on non-traded price of CO_2e of £60/tonne and ecosystem damage costs of £2,100/tonne of NH_3-N and £670/tonne NO_3-N.
[8] Benefits based on fertiliser N savings and avoided GHG/ammonia-N/nitrate-N damage costs

Table 65. Costs and benefits of NVZ-AP options OVER 20 YEARS: of implementing the existing NVZ-AP across England

	Option						
	1a NVZ-AP Closed period	1b NVZ-AP Closed period + 1 month extra storage	1c NVZ-AP Closed period + 2 months extra storage	2 NVZ-AP Closed period + rapid incorporation[3]	3 NVZ-AP Closed period + slurry bandspreading/shallow injection [4]	4 NVZ-AP Closed period + slurry separation[5]	5 NVZ-AP Closed period + impermeable base storage for solid manures
Capital costs of extra slurry storage[1]	460 million	670 million	825 million	460 million	460 million	230 million	900 million
Annual amortised costs[2]	865 million	1,260 million	1,550 million	865 million	865 million	430 million	1,690 million
Additional operational costs	0	0	0	120 million	900 million	600 million	0
Fertiliser N saving (t)	92,000	94,000	58,000	130,000	210,000	92,000	104,000
GHG savings (tCO_2e)	1,180,000	1,460,000	1,160,000	1,220,000	1,800,000	1,180,000	1,000,000
Ammonia-N savings (t)	54,000	44,000	30,000	112,000	196,000	54,000	46,000
Nitrate-N savings (t)	50,000	68,000	62,000	38,000	46,000	50,000	44,000
Fertiliser saving (£)[6]	92 million	94 million	58 million	130 million	210 million	92 million	104 million
GHG savings societal benefit (£)[7]	71 million	88 million	70 million	73 million	108 million	71 million	60 million
Ammonia N savings societal benefit (£)[7]	113 million	92 million	63 million	235 million	412 million	113 million	97 million
Nitrate-N savings societal benefit (£)[7]	34 million	46 million	42 million	25 million	31 million	34 million	29 million
Cost benefit ratio based on capital and operation costs [8]	1.5:1	2.1:1	3.5:1	1.3:1	1.8:1	2.7:1	3.1:1
Cost benefit ratio based on amortised and operation costs[8]	2.8:1	3.9:1	6.6:1	2.1:1	2.3:1	3.3:1	5.8:1

[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] Incorporation cost £18/ha (Nix, 2011); manure application rates: slurry 40m^3/ha, layer manure 13 t/ha and broiler litter 8t/ha
[4] Spreading costs £2/m^3 for surface broadcast, £3/m^3 for bandspreading and £3.50/m^3 for shallow injection (Nix, 2011)
[5] Slurry separation assumed to reduce cattle slurry storage by 20% and pig slurry storage by 10%. Slurry separation costs assumed to be £1/m^3 for cattle slurry and £1.50/m^3 for pig slurry based on operation costs and capital cost of equipment amortised over 20 years and expressed on an annual basis
[6] Based on manufactured fertiliser N cost of £1,000/tonne (i.e. £345/tonne of ammonium nitrate).
[7] Based on non-traded price of CO_2e of £60/tonne and ecosystem damage costs of £2,100/tonne of NH_3-N and £670/tonne NO_3-N.
[8] Benefits based on fertiliser N savings and avoided GHG/ammonia-N/nitrate-N damage costs

8 CONCLUSIONS

- For the current NVZ area (62% of England and c.3% of Wales), the measures in the existing NVZ-AP 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 and nitrate leaching losses by 1,400 tonnes NO_3-N (compared with the 2007 baseline) at a capital cost of £290 million.
- Applying the existing 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 and nitrate leaching losses by 2,900 tonnes NO_3-N (tonnes compared with the 2007 baseline) at a capital cost of £555 million.
- Applying the existing NVZ-AP across England was predicted to reduce annual fertiliser N requirement by 4,600 tonnes, GHG emissions by 59,000 tonnes CO_2e , ammonia emissions by 2,700 tonnes NH_3-N and nitrate leaching losses by 2,500 tonnes NO_3-N (compared with the 2007 baseline) at a capital cost of £460 million.
- The costs of extending the closed spreading period by 1 and 2 months, slurry separation and storing solid manures on an impermeable base were *not* reflected in proportional reductions in fertiliser N use or ecosystem damage costs.
- *Soil incorporation* of high readily available N manures (within 6 hours of application) and the use of *bandspreading/shallow injection slurry application techniques* were the most cost-effective techniques to reduce fertiliser N use and ecosystem damage costs.

9 RECOMMENDATIONS FOR FURTHER 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.

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

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.