Slurry Storage on Scottish Farms – A Feasibility Study

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Executive summary

This work assessed the relative value of slurry management options for climate change mitigation. There is a need to mitigate greenhouse gas (GHG) emissions at a national level, with appropriate focus on sectors where there are significant emissions and/or there are opportunities to mitigate.

Key findings

Slurry management in Scotland

- The total quantity of slurry produced in Scotland has been estimated at 6.35 Mt per annum.
- The dairy sector produces nearly half of slurry in Scotland, but occupies only 3.3% of the area of livestock farms producing slurry.
- Examples of best practice include:
  - cover slurry stores,
  - apply slurry to land using low-emission techniques, and
  - apply slurry to land when there is low risk of leaching.
- Current uptake of best practices is highly uncertain. For example, survey data[1] show that 62% of farms with slurry had covered storage, but the available data do not indicate the percentage of stores that are covered, or the percentage slurry quantity that is covered. The same survey suggests that around 88% of slurry in Scotland is already spread using low-emission techniques, but expert knowledge from farm advisers supports our view that the percentage of slurry spread using low-emission techniques is much lower than 88%.

Emissions of greenhouse gases

- Emissions of GHGs from slurry management are 1.3% of the Scotland total GHG emissions and contribute 7% to the Scottish agriculture emissions. Approximately 92% of GHG emissions from slurry management are from housing and storage, and approximately 8% are from field application.

The value of improved slurry management

- We have estimated that covering slurry stores can save 180 kt CO_2e per annum, approximately 2% of Scotland's agriculture GHG emissions. This is the largest single GHG mitigation opportunity.
- In general, climate change mitigation measures have costs to the farmer that are greater than the benefits to the farmer.

Potential to change farm practices

- Good practices that lead to abated emissions of GHGs and ammonia have, to some extent, already been adopted by farmers.
- Adoption of improved slurry management is driven by practical and commercial advantages (e.g. use of store covers excludes rainfall, leaving less slurry to handle and spread), and by the need to comply with regulations (e.g. minimum storage capacity requirements in nitrate vulnerable zones).
- Further implementation of good practice, with concomitant GHG mitigation, may require incentives or further regulation.
- For some measures (e.g. covering of stores) uptake could be increased by knowledge exchange activities to explain the benefits.

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[1] Scottish Survey of Farm Structure and Methods, 2016.

Discussion

Best practice for slurry management can be summarised as management that minimises loss of nitrogen from the slurry, and maximises nutrient uptake by a crop following application. The current level of best practice adoption is not well characterised, and could be improved by better survey data.

The savings in GHG emissions from improved slurry management are modest relative to the emissions from Scotland's agriculture sector (<3%). However, seizing opportunities to reduce emissions from multiple sources can make a larger, collective contribution to tackle emissions from agriculture.

GHG emissions mitigation from slurry management should be considered alongside ammonia emission mitigation, as there are co-benefits. Total UK ammonia emission is close to the ceiling set by the National Emissions Ceilings Directive (NECD).

1 Introduction

1.1 Slurry management and greenhouse gas emissions

Slurry is excreta produced by livestock while in a yard or building, including excreta mixed with bedding, rainwater and washings, and that have a consistency that allows them to be pumped or discharged by gravity[2].

Slurry management is a sequence of activities on farms including removal of slurry from livestock houses and yards, storage, transport, and application to land. Slurry management may also include processing activities such as anaerobic digestion (AD). Slurry management is regulated, primarily to limit water pollution (see section 1.2). During the chain of management activities, from excretion to soil application, slurries also emit methane (CH_4) and nitrous oxide (N_2O), which are greenhouse gases (GHGs). Ammonia (NH_3) is also volatilised from slurry and is deposited elsewhere, from the atmosphere to land, with consequent, further emissions of nitrous oxide. Slurry management also influences GHG emissions outside of the agriculture sector: for example, maximising the nitrogen (N) fertilisation value of slurry for crop production may decrease the use of manufactured nitrogen fertiliser and subsequently reduce the GHG emissions during manufacture.

Data from the UK Greenhouse Gas Inventory[3] show that manure management leads to 1.3% of Scotland's GHG emissions, and just over 7% of Scotland's agricultural GHG emission. The Climate Change (Scotland) Act 2009 includes targets for the reduction of GHG emissions and the Scottish Government has prioritised the reduction of emissions from the use and storage of manure and slurry. Greenhouse gas emissions may also be mitigated in other places (including other countries) and in other sectors of industry as an indirect consequence of changes in slurry management in Scotland's agriculture industry.

This project was designed to assess the relative value of slurry storage/management options for their potential to mitigate GHG emissions.

1.2 Relationship of the issue to the policy agenda

The Climate Change (Scotland) Act 2009 includes targets for the reduction of GHG emissions in Scotland. Furthermore, the draft Climate Change Plan (January 2017, http://www.gov.scot/Resource/0051/00513102.pdf) gives proposals and policies that are designed to meet the targets. The Scottish Government, in the draft Climate Change Plan, has prioritised the reduction of emissions from the use and storage of manure and slurry.

Slurry storage and management is subject to regulation. The introduction of Nitrate Vulnerable Zones (NVZs) in Scotland has resulted in the upgrading and increased capacity of slurry and manure storage across five areas[4]:

- Lower Nithsdale,
- Lothian and Borders,
- Strathmore and Fife (including Finavon, added 2016),
- Moray, Aberdeenshire/Banff and Buchan,
- Stranraer Lowlands (added 2016).

The NVZ rules require 5 – 6 months' storage of slurry on farms which leads to application timings that are appropriate for crops to use the available nutrients. A major added benefit of timely application is that this partially offsets applications to crops of inorganic nitrogen fertilisers. Decreased use of inorganic nitrogen fertilisers reduces associated nitrous oxide emissions, and other GHG emissions from fertiliser manufacture.

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[2] Based on a definition given in: Guidance for farmers in nitrate vulnerable zones, Booklet 3, http://www.gov.scot/Topics/farmingrural/Agriculture/Environment/NVZintro/NVZGuidanceforFarmers Last accessed 03 November 2017.

[3] http://naei.beis.gov.uk/reports/reports?report_id=929 Last accessed 03 November 2017.

[4] For more details of NVZs in Scotland see http://www.gov.scot/Topics/farmingrural/Agriculture/Environment/NVZintro Last accessed 03 November 2017.

For areas outside NVZs, there is a grant available for slurry storage facilities areas through the Agri-Environment and Climate Scheme (AECS) and this is an additional catalyst for change.

There is further regulation of slurry management through The Control of Pollution (Silage, Slurry and Agricultural Fuel Oil, SSAFO) (Scotland) Regulations 2003. These regulations protect water by ensuring that slurry is properly contained and that there is adequate storage capacity for the likely quantities of slurry produced.

Farm assurance schemes can provide further controls on manure (including slurry) management practices, for example, The Red Tractor Scheme.

The need for this research falls outside the policy environment outlined above, particularly the policy around GHG emissions mitigation, and the focus on slurry management. The need for this research was reinforced by the ClimateXChange "Review of options for reducing GHG emissions via cattle slurry management in Scotland[5]", which concluded that there are challenges in realising the benefits of improved slurry storage, and that there is a need for more evidence.

1.3 Aim of project

The research aim of this project is to assess the relative value of slurry storage options within the wider livestock management system and determine, the potential for GHG emissions mitigation.

To meet this aim, the research requirements can be summarised as follows.

- A characterisation of the total slurry management process in terms of both current farm business practice and market ready technological solutions, providing the framing of results from the project (section 2.1 and Appendix 1).
- An assessment of available evidence for GHG emissions from slurry management (section 2.2 and Appendix 2).
- An analysis of farm business receptiveness for slurry management options (section 2.3 and Appendix 3).
- An analysis of the strengths, weaknesses, opportunities and threats for the use of different forms of storage/management, including a comparative analysis of the results (section 3.5 and Appendix 4).

2 Findings and implications

2.1 Background: slurry management in Scotland

2.1.1 Slurry production in Scotland

Slurry arises on farms that keep beef cattle, dairy cattle, pigs or sheep in livestock housing; some slurry is also produced when livestock are on yards. The total quantity of slurry produced in Scotland has been estimated at 6.35 Mt per annum[6], and is split between the main types of livestock as shown in Table 1. These data are from a 2017 study completed by Ricardo Energy & Environment for Zero Waste Scotland, which estimated the total quantity of slurry produced in Scotland in 2015 (based on the 2015 census), split by type of slurry and Local Authority (LA). Slurry production is dominated by cattle farming systems.

Although the dairy sector accounts for around half of the total slurry produced in Scotland, 4.3% of livestock farms that could produce slurry (pig, dairy, sheep and cattle production systems) have a dairy component, and dairy farms occupy 3.3% of the area of these livestock farms.

Many farms that produce slurry from housed livestock, house the livestock for only part of the year. This is the case for many dairy, beef and sheep farms (although most sheep farms do not produce

[5] Michael MacLeod, Bob Rees, Christine Watson, Steven Thomson, Iain Boyd and Julian Bell (2016). Review of options for reducing greenhouse gas emissions via cattle slurry management in Scotland. ClimateXChange, Edinburgh, 24 November 2016. http://www.climatexchange.org.uk/files/3114/8120/1143/Review_of_options_for_reducing_greenhouse_gas_emissions_via_cattle_slurry_management_in_Scotland.pdf Last accessed 03 November 2017

[6] From data held by Ricardo Energy & Environment, prepared for a 2017 study for Zero Waste Scotland. To estimate slurry quantity, this data set uses animal population data, knowledge of manure production per animal, and local knowledge of livestock housing types and periods of usage.

slurry). Most pig farms that produce slurry have their pigs in buildings or on hard standings all the time.

Table 1: Total slurry production in Scotland, 2015.

Slurry type	Quantity produced (million tonnes, Mt)
Beef	2.57
Dairy	2.99
Pig	0.73
Sheep	0.06

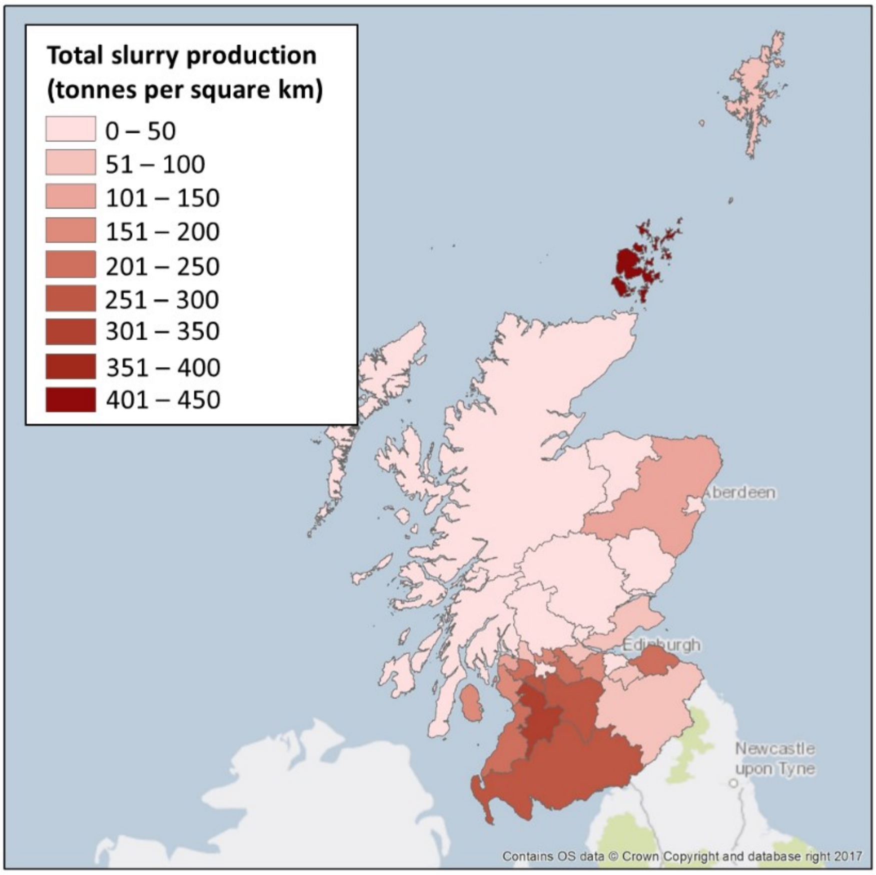
Slurry is applied to land, often following storage, and provides nutrients for crops in arable, field horticulture and grassland farming systems.

Emissions of GHGs (methane and nitrous oxide) occur during the management of slurry, as a result of microbial activity. Good practice in slurry management can minimise the emissions of these GHGs.

Emission of ammonia also occurs during the management of slurry, and leads to indirect emission of the GHG nitrous oxide following deposition to soil. Good practice in slurry management can minimise emission of ammonia with benefits for indirect GHG emissions. There are also benefits from avoiding loss of nitrogen, as nitrogen supply from slurry to soil and crop is maximised. This can increase crop yield and also reduce the need for manufactured fertiliser, avoiding the GHG emissions from the manufacturing process.

The geographic distribution of slurry production is shown in Figure 1, in tonnes per square km. There is high production of slurry in south-west Scotland, in East Lothian, Aberdeenshire, and in Orkney where the production density is greatest. Some areas of Scotland, especially south-west Scotland, has relatively little arable crop production, so here, slurry applications to land are mainly to grassland and forage crops.

Figure 1: Total slurry production by land area, 2015.



2.1.2 Slurry management practices and benefits of best practice

The type of animal housing can influence emissions of ammonia and therefore nitrogen loss from the slurry. Housing types that minimise contact between the slurry and the atmosphere, by rapid removal and covering of slurry, minimise loss of nitrogen. This can have a small impact on the need for fertiliser following application of the slurry to land. However, housing type is expected to have little direct impact on GHG emissions.

The oxygen status of stored slurry is important because it influences microbial activity in slurry and the extent to which associated chemical reactions lead to release of nitrous oxide (an important greenhouse gas). During storage, the slurry will remain largely free of oxygen (anaerobic) unless deliberately introduced as part of a treatment process or in the event of windy conditions when there is minimal surface cover. When the slurry is not anaerobic, emissions of nitrous oxide will be negligible (Sommer et al., 2000). Greenhouse gas emissions are likely to increase if a surface layer of straw is used or a crust forms, as this causes anaerobic conditions, allowing nitrification to occur. The encouragement of natural crusting on slurry stores has been advocated as a means of reducing emissions of ammonia by 50%, but emissions of nitrous oxide during slurry storage are estimated by IPCC methods (tier 1, the simplest method within the IPCC guidelines, using default emission factors) to be 1.0% of slurry nitrogen for slurry stored under a natural crust, but zero for slurries stored without a natural crust[7]. In a similar way to crusting, store covers are used to mitigate ammonia emissions, but also can result in increased emissions of nitrous oxide (Berg et al., 2006). This illustrates a potential conflict between efforts to reduce ammonia emissions during slurry storage and reducing emissions of GHGs (nitrous oxide in this case). Details of how the IPCC methods are applied for the UK and the Scotland devolved administration inventories, are given in section 2.2.1.

[7] The UK national inventory of greenhouse gases (2017 submission) uses a tier 2 method, with country specific data for nitrogen excretion and manure management systems, and IPCC default emission factors for N2O.

Slurry separation has also been found to result in increased emissions of nitrous oxide during storage due to heightened emissions from the solid fraction.

Acidification of slurry is a management practice that is used in Denmark to minimise ammonia emission. Acidification can also influence emission of the GHG methane. However, slurry acidification is not market ready in Scotland or other parts of the UK. Implementation would require a network of support services to distribute, install and maintain the necessary equipment for safe handling of sulphuric acid. Furthermore, there are concerns in the agriculture industry about safety associated with the use of a concentrated acid (usually sulphuric acid) and the potential for increased emission of hydrogen sulphide.

Anaerobic digestion (AD) can be used to process slurry, usually mixed with other feedstocks because slurry has a low energy content compared with feedstocks such as waste food or grass silage. There is little direct impact of AD on GHG emissions, but there are indirect savings in emissions through displacement of fossil fuels by biogas, and increased availability of nitrogen to crops in AD digestate compared with untreated slurry, displacing some inorganic fertiliser.

Slurry transport practices have little impact on GHG emissions from slurry management, aside from very minor differences in energy use.

The methods by which the slurry is applied influences emissions of ammonia and therefore on nitrogen loss and subsequent inorganic nitrogen requirement. The use of broadcast spreaders has been estimated to result in a loss in ammoniacal-nitrogen of between 20 – 40% (Nyord et al., 2008), whereas injection of slurry into the soil can minimise losses to 2% of nitrogen (Huijsmans et al., 2003).

The timing of slurry application to land has consequences for the risk of nitrogen loss by leaching. Times of high leaching risk include:

- periods of excess rainfall (when rainfall exceeds evaporation);
- when there is soil drainage occurring (i.e. when the soil is saturated, at ‘field capacity’); and
- when there is not rapid crop uptake.

To minimise leaching, application should be avoided at these times, which typically occur during the months September to February.

Best practice for slurry management can be summarised as management that minimises loss of nitrogen from the slurry, and maximises nutrient uptake by a crop following application. Best practice must also properly account for the nitrogen content of slurry applied to land so that there is not over-supply of nutrients to crops, especially nitrogen, and so that application of inorganic nitrogen is minimised. Examples of best practice include:

- covering slurry stores, especially for pig slurry, which tends not to form a crust,
- apply slurry to land using low-emission techniques, and
- apply slurry to land when there is low risk of leaching.

2.1.3 Current practice and scope for improvement

The Scottish Survey of Farm Structure and Methods (2016), received responses from 9,900 holdings across Scotland. This found 9% of all agricultural facilities stored slurry onsite, of which 62% had covered storage, with most using tanks rather than lagoons. The percentage of slurry storage that is covered is uncertain and likely to be lower than 62%, as the data indicate the percentage of respondents with covered storage, but do not indicate the percentage of stores that are covered, or the percentage slurry quantity that is covered. Some farms may have some covered storage and some uncovered storage, but would be included in the 62% of farms with covered storage. The UK and Scotland National Inventory of Greenhouse Gases calculations for the latest inventory submission (2015 emissions) assume 24% of pig slurry stores are covered in Scotland, and that all other slurry stores (dairy and beef systems) are uncovered. This means that there is scope to improve implementation of best practice against the baseline assumptions used for the GHG inventory.

In terms of application to land, the 2016 survey reported that 12 Mt of manure (including solid manure) was broadcast, 5 Mt of slurry was applied via a band spreader and 600,000 tonnes of slurry was injected. Of holdings that reported the application of slurry, 7% tested the nutrient value. Of those holdings using a band spreader, the majority used a trailing hose, and the majority of injection was shallow/open slot.

Further studies of slurry management practices within Scottish NVZs found that the majority of these farms have made no investment or expansion in slurry storage facilities, following the instigation of legislation relating to NVZs (Barnes et al., 2009)[8]. Feliciano et al. (2014)[9] reported that although farms located within NVZs are likely to use all slurry produced on the farm as fertiliser, the covering of slurry tanks or lagoons was found to be amongst the least popular measures for adoption. Furthermore, the cost of precision farming was viewed as inhibitory.

The 2016 survey report does not give the percentage of holdings that produce slurry, and subsequently apply this slurry to land. Nor does it confirm how management practices differ between NVZ and non-NVZ areas. However, based on the Barnes et al. and Feliciano et al. studies, it is reasonable to assume that in both regions there is significant room for improvement in terms of covering slurry stores and methods of application that limit emissions to air and ensure efficient nutrient use.

The management practices adopted by a farm are influenced by the characteristics of the farm, including the size, type, location and (in particular) whether the farm is within a nitrate vulnerable zone (NVZ). Nitrate vulnerable zones were introduced in response to the Nitrates Directive (91/676/EEC). This requires all EU member states to limit nitrate in drinking water to a maximum of 50 mg/l. Farmers within NVZs must comply with strict requirements concerning the timing and application of nitrogen from organic and inorganic sources, including slurries. As of the 1st January 2016, there were five designated NVZs in Scotland[10].

- Lower Nithsdale,
- Lothian and Borders,
- Strathmore and Fife (including Finavon, added 2016),
- Moray, Aberdeenshire/Banff and Buchan,
- Stranraer Lowlands (added 2016).

Key rules for the management of slurry within NVZs in Scotland include requirements for record keeping, farm and field limits for the quantity of nitrogen than can be applied, closed periods when organic manure must not be applied, and minimum storage capacity.

The distribution of slurry production, and its concentration is some areas, especially south-west Scotland, suggests that management solutions could be focussed on a local scale. However, the specific consideration of local solutions was not within the scope of this study.

2.1.4 Summary of implications

Emissions of GHGs from slurry management are a small proportion of the Scotland total GHG emissions (1.3%), and also a small proportion of Scotland's agriculture emissions (7%); savings in GHG emissions in Scotland will be less than this percentage. Despite this relatively small potential for mitigation, best practices that mitigate GHG emissions from slurry management generally have benefits for farmers (mainly through improved crop yields and savings in use of manufactured fertilisers. Therefore, best practices should be encouraged.

There will also be further savings in GHG emissions outwith Scotland, from avoided manufacture of fertiliser that is displaced by nutrients in slurry. However, some this potential, indirect mitigation is already occurring, since all slurry is already applied to land (even when processed first by anaerobic digestion) and providing a nutrient benefit on farms.

[8] Barnes AP, Willock J, Hall C, Toma L (2009). Farmer perspectives and practices regarding water pollution control programmes in Scotland. Agricultural Water Management, 96: 1715–1722.

[9] Feliciano D, Hunter C, Slee B, Smith, P (2014). Climate change mitigation options in the rural land use sector: Stakeholders' perspectives on barriers, enablers and the role of policy in North East Scotland. Environmental Science & Policy, 44: 26-39.

[10] Scottish Government (2017c) Nitrate Vulnerable Zones [online]. Available at http://www.gov.scot/Topics/farmingrural/Agriculture/Environment/NVZintro Accessed 05 October 2017.

2.2 Emissions of GHGs

2.2.1 Methodology used in the UK GHG Inventory to calculate GHG emissions from slurry management

2.2.1.1 Methane

Methane emissions from manure management are calculated following IPCC Tier 2 methodology using:

- default IPCC data for volatile solids (VS) and methane producing potential (Bo) parameters for each livestock type (except for dairy and beef cows, where a Tier 2 calculation (IPCC 2006, Equation 10.24) is used to determine VS, and deer for which the Tier 1 IPCC default methodology and emission factor are used);
- country-specific data for the proportion of manure from each livestock type handled as slurry or solid and IPCC default methane conversion factors (MCF) for slurry and solid manures (IPCC 2006, Table 10.17).

There are some important limitations of the IPCC default approach. First, the default methane producing potential parameters have a large degree of uncertainty, based on the findings of Safley et al. (1992; cited in Amon et al. (2006)[11], who summarised the results of several different experiments. There is also evidence from several studies[12] that the use of the IPCC default values for MCF of slurry stored in cool climates is greater than is appropriate for slurry stored in Scotland. Furthermore, the MCFs cited by IPCC have been based on expert judgement, not on experimental data.

Emissions of methane following application of slurry to land are considered to be negligible (IPCC, 2006, paragraph 10.4) and do not appear to be calculated, although we did not find any explicit confirmation of this in the UK Inventory report.

2.2.1.2 Nitrous oxide

Nitrous oxide emissions from manures during storage are calculated for different storage systems as defined by IPCC. Calculation follows IPCC (2006) (equation 10.25) for each livestock category and subcategory, using country-specific data for nitrogen excretion by the different livestock categories and for the proportion of manure managed liquid slurry, and default emission factors (EF) for the different systems.

Emissions from the following storage systems are reported under the Manure Management IPCC category:

- Uncovered anaerobic lagoons. These are assumed not to be in use in the UK;
- Liquid/slurry;
- Deep bedding (previously deep litter); and
- Poultry manure with/without bedding or destined for incineration; IPCC (2006).

Indirect nitrous oxide emissions from manure management comprise nitrogen volatilisation from manure management systems calculated using Equation 10.27 (IPCC 2006 guidelines), along with country-specific fractions ($Frac_{GasMS}$), derived directly from the UK agriculture ammonia emission inventory, for nitrogen loss due to volatilisation of ammonia and NOx, disaggregated by manure management system.

Nitrous oxide emissions following slurry application to land are calculated using IPCC Tier 2 methodology, with country-specific EFs and country-specific data for the amount of manure-nitrogen applied to the land.

Indirect emissions of nitrous oxide from leaching and runoff following slurry application to land are estimated according the 2006 IPCC guidelines using equation 11.10 and the default nitrogen

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[11] Amon, B. Kryvoruchko, V. Amon, T. Zechmeister-Boltenstern, S. (2006). Methane, nitrous oxide and ammonia emissions during storage and after application of dairy cattle slurry and influence of slurry treatment. Agriculture, Ecosystems and Environment 112, 153-162.

[12] Park, K.H. Thompson, A.G. Marinier, M. Clark, Wagner-Riddle, C. 2006. Greenhouse gas emissions from stored liquid swine manure in a cold climate. Atmospheric Environment 40, 618–627.
Rodhe, L. Ascue, J. Nordberg, Å. Emissions of greenhouse gases (methane and nitrous oxide) from cattle slurry storage in Northern Europe. 2009. Earth and Environmental Science 8

leaching/runoff factor (EF5). The fraction of nitrogen that is leached ($Frac_{LEACH}$) is a country specific value (0.1).

2.2.2 Proportions of GHG emissions from Scotland accounted for by slurry management

Greenhouse gas emissions arising from the storage and spreading of livestock manures (slurry and solid manures) account for just under 2% of all GHG emissions in Scotland and just under 10% of GHG emissions from Scottish agriculture (Table 14).

Table 2: Greenhouse gas emissions from manure management in Scotland.

Category code and description	Emissions (kt CO_2e)	GHG emissions as a percentage of Scotland total	GHG emissions as a percentage of Scotland agriculture total
3B1 Dairy cattle	163.4	0.4%	2.0%
3B1 Non dairy cattle	434.6	1.0%	5.2%
3B2 Sheep	40.6	0.1%	0.5%
3B3 Pigs	49.1	0.1%	0.6%
3B4 Deer	0.2	0.0%	0.0%
3B4 Goats	0.1	0.0%	0.0%
3B4 Horses	3.0	0.0%	0.0%
3B4 Poultry	10.5	0.0%	0.1%
3B4 Other	44.9	0.1%	0.5%
3D Manure application	119.2	0.3%	1.4%
Total from manure storage and application	820.6	1.8%	9.8%
Total from slurry storage and application	580.6	1.3%	7.0%

Of these emissions from the storage and application of manures, percentages arising from slurry are:

- 82% of methane emissions and 67% of nitrous oxide emissions during storage, and
- 40% of nitrous oxide emissions following spreading.

The storage and application of slurry to land account for 1.3% of all GHG emissions in Scotland and just over 7% of agricultural GHG emissions.

2.2.3 Abatement options to reduce GHG emissions during slurry management

Greenhouse gas emissions from slurry management can be most effectively abated by reducing methane emissions during slurry storage[13].

The results of studies that have measured the impacts of slurry treatments and store covers on GHG emissions have shown that:

- methane emissions were reduced, on average, by 38% with surface covers (natural crust, leca pebbles (light, expanded clay aggregate) or straw)[14];

[13] Amon, B. Kryvoruchko, V. Amon, T. Zechmeister-Boltenstern, S. (2006). Methane, nitrous oxide and ammonia emissions during storage and after application of dairy cattle slurry and influence of slurry treatment. Agriculture, Ecosystems and Environment 112, 153-162.

[14] Petersen, S.O., Amon, B. and Gattinger, A. (2005) Methane Oxidation in Slurry Storage Surface Crusts. Journal of Environmental Quality, 34, 455-461.

- flexible synthetic sheet reduced GHG from stored pig slurry by 90%; polystyrene balls increased GHG emissions from stored pig slurry in summer; peat (used as a floating barrier between the slurry and the air above) increased GHG emissions from stored pig slurry[15];
- a solid cover can reduce GHG emissions by significantly reducing methane emissions by c. 13% in winter and c. 16% in summer; separation, anaerobic digestion (AD), and aeration all reduced methane emissions during slurry management; however, both separation and aeration gave large increases in total ammonia emissions and therefore may conflict with other environmental objectives[16].

2.2.4 Impact of adopting techniques to reduce ammonia emissions during slurry management on GHG emissions

Slurry injection has been shown to reduce ammonia emissions by an average of 70% (Webb et al., 2010)[17]. Slurry application techniques that reduce ammonia emissions might be expected to increase direct emissions of nitrous oxide because more nitrogen enters the soil. However, the reduction of ammonia emissions will reduce indirect emissions of nitrous oxide arising from the deposition of ammonia. Since the current IPCC default EFs for direct and indirect nitrous oxide emissions following the application of slurry to land are the same (0.01 kg N_2O-N/kg N input) there would appear to be no net change in total nitrous oxide emissions arising from slurry spreading.

In their review of emissions arising from the application of manures by reduced-ammonia emission spreading techniques Webb et al. (2010) found that injection of slurry does not axiomatically increase direct nitrous oxide emissions. For example, injection of slurry may either increase or have no impact on direct emissions of nitrous oxide.

Based on these considerations we conclude that concerns over increasing emissions of nitrous oxide should not inhibit the adoption of reduced-ammonia emission spreading techniques. Smith et al. (2008)[18] had earlier concluded that under conditions that did not enhance nitrous oxide emissions, there is no trade-off between ammonia and nitrous oxide production and more attention should be placed on controlling and reducing odour and ammonia emissions.

2.2.5 Conclusions

- Greenhouse gas emissions from slurry management are only a small proportion (c 7%) of GHG emissions from agriculture in Scotland and a very small proportion (1.3%) of total Scottish GHG emissions.
- Greenhouse gas emissions from slurry management arise mainly as: methane during slurry storage; nitrous oxide during slurry storage; and nitrous oxide following application of slurry to land.
- There are data from Sweden and Canada that suggest the use of the IPCC default values for the methane conversion factors (MCF) of slurry stored in cool climates is greater than is appropriate for slurry stored in Scotland. This may have caused an over-estimate of the GHG emissions from slurry stored in Scotland.
- Large reductions in methane emissions during slurry storage (relative to emissions during storage) can be obtained by subjecting the slurry to anaerobic digestion or by covering the store with a rigid or flexible cover.
- Although concerns have been expressed that measures to reduce emissions of ammonia may increase emissions of nitrous oxide, these concerns have not been substantiated.

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[15] Loyon, L., Guiziou, F., Picard, S. and Saint-Cast, P. (2016) Farm-Scale Applicability of Three Covers (Peat, Polystyrene Balls and Synthetic Sheet Roof) to Reduce Ammonia Emissions from Pig Slurry Storage. Agricultural Sciences, 7, 396-406.

[16] Amon, B. Kryvoruchko, V. Amon, T. (2007). Influence of different levels of covering on greenhouse gas and ammonia emissions from slurry stores. Sustainable Organic Waste Management for Environmental Protection and Food Safety.

[17] Webb J, Pain B, Bittman S, Morgan J. (2010). The impacts of manure application methods on emissions of ammonia, nitrous oxide and on crop response - A review. Agriculture Ecosystems and Environment 137, 39-46.

[18] Smith E, Gordon R, Bourque C, Campbell A (2008) Management strategies to simultaneously reduce ammonia, nitrous oxide and odour emissions from surface-applied swine manure. Can J Soil Sci 88: 571–584.

- It is not proven that reducing emissions of ammonia following slurry spreading generally increases direct nitrous oxide emissions; but it does reduce indirect nitrous oxide emissions.
- The conservation of slurry-nitrogen by reducing ammonia emissions reduces the requirement for nitrogen fertiliser thereby making some reduction in the GHG emissions arising from the manufacture, distribution and application of nitrogen fertiliser.

2.3 Business receptiveness of GHG mitigation measures

2.3.1 Introduction

Here we present an analysis of the potential for change on farms in Scotland, from a farm business perspective. The measures considered in this analysis are listed in Table 3. We have reviewed the costs, benefits and wider impacts of each of the actions to determine how beneficial they could be to the farmer. The quantitative assessment will be supported by expert judgement on the likelihood of change.

Table 3: Measures considered in this analysis.

Measure	Short Description
Slurry store covers and slurry bags	Fixed or floating covers on slurry tanks and lagoons. Slurry bags are enclosed strong bags for storage of slurry within a bunded area.
Transfer of slurry and manures	The transfer of slurry and manures between farms to optimise the nutrient use efficiency
Anaerobic digestion	The capture of methane from the decomposition of slurry (and usually other materials)
Slurry acidification	The addition of acid to slurry to reduce volatilisation
Rapid incorporation	Applications timed to match crop requirement to reduce nutrients losses
Timing of slurry application	Utilising slurry at the optimum time of the growing season to offset fertiliser cost and emissions
Precision application techniques (injection or trailing shoe)	Use of application techniques that apply slurry directly to the soil or injected in to the soil

The receptiveness of a farm business to any change is determined by the drivers. Based on our research into agricultural advisory services[19] for Defra (Defra ref FF0202; Martineau, 2010), drivers for change fit broadly in to three categories:

- Improve profitability and business efficiency
- Legislative compliance
- Incentives such as grants and subsidies

In addition, and linked to each of these points, are the increasing demands in the supply chain from buyers or quality assurance schemes. In terms of the receptiveness to slurry management options, farming businesses will be influenced strongly by the access to capital, benefit to their farm system, payback time, and risks associated with non-compliance. All of these factors influence the decisions of farmers relating to slurry management systems, but the most important factor is whether an

[19] http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&ProjectID=17292&FromSearch=Y&Publisher=1&SearchText=ff0202&SortString=ProjectCode&SortOrder=Asc&Paging=10#Description

upgrade to the existing system is required. Slurry storage systems tend to have a 20-30 year return on investment.

In this analysis we have built on our recent (May 2017) work for Defra on ammonia from livestock production, which included an analysis of ammonia mitigation actions, mainly related to slurry management. Included were assessments of barriers to uptake, and wider business impacts on farmers. The following sections provide a summary of the results of our analysis (Table 4 and Table 5). More detail is given in Appendix 3.

2.3.2 Manure storage and management

Table 4: Summary of business receptiveness for manure storage measures.

Slurry covers and Slurry Bags	
Brief description:	Cover floating on the surface of the store or lagoon. Often a plastic cover resting on the surface that rises and falls with the slurry volume. Rain water is usually collected and pumped away keeping it separate from the slurry. Large, strong bags, placed within a bundled area, are used to store the slurry. Slurry is pumped in to the bag. Slurry bags come in a range of sizes up to 7000m^3 (This capacity is used for a dairy herd or 220 at Harper Adams[20])
Summary of business receptiveness:	Cost: as with any investment, the payback or return on investment is key to the receptiveness of the business to introducing slurry covers or slurry bags. All farms have a different set of circumstances and challenges that will affect the receptiveness to new technology or business changes. The receptiveness to slurry bags is likely to be low due to the cost and availability of less costly alternatives. Based on farm practices survey data, the current usage of slurry bags is less than 1% of holdings (handling slurry) The use of slurry covers is likely to be far more attractive due to the opportunity to reduce costs associated with storage and application. The main driver for this is the ability to divert rain water from the store. In Nitrate Vulnerable Zones this likely to be even more attractive with additional pressure on storage capacity (22-week storage for cattle slurry systems) and closed periods for applications. The Scottish Survey of Farm Structure and Methods for 2016 states that, of the 3007 holdings with storage of slurry, 62.3% are covered. This does not detail where all stores on a holding were covered. It would not be prudent to assume that 62.3% of slurry in Scotland is covered. The recent Farm Ammonia Grant (FARG) scheme provides a good measure for the receptiveness to covering stores. The scheme provided a grant of £11.20m^2 of are covered for floating covers and £61.00m^2 for self-supporting covers.
Transfer of Slurry and Manures	
Brief description:	The transfer of slurry and manures between farms to optimise the nutrient use efficiency

[20] http://www.harper-adams.ac.uk/sustainability/doc/Kirby_S_Slurry_Management.pdf

Summary of business receptiveness:	Starting with the logistical challenges: The geographic occurrence of farming enterprises tends to follow the limitations of the geographical circumstances. For example, generally, the south west of Scotland has a high proportion of dairy farms compared to the rest of the country due to there being good conditions for growing grass (high rain fall and warm climate) the east of the country tends to be suited for arable systems where the land quality is good. In the east, there are livestock and mixed farming systems do benefit from the incorporation of organic manures. The reality is that to get the benefit of slurry and manure transfer, it would likely to have to move greater distances than is economically or practically feasible. The movement of manure and slurry to where it can be utilised more effectively does already happen and the movement of livestock from the east to west of the country also happens (many store animals move east to be finished). Businesses are receptive to bringing in slurry and manures and there is trading that occurs at a local level. Some farmers will provide straw to livestock farmers and in return they get manure back. To increase activity, there could be local trading structures established to promote the transfer of slurry and manure (machinery rings could be a good broker)
Anaerobic Digestion	
Brief description:	Anaerobic digestion (AD) is the biological breakdown of organic matter into a gas (biogas), water and residual matter. The AD process can be undertaken on wet material capable of flowing and being pumped, or dry material that does not flow. Slurry is a more common feedstock in UK AD processes than FYM. AD facilities consist of tanks from which biogas is harvested. These tanks can act as storage facilities for farms. For more detail, please see the ClimateXChange report on Practical Application of AD for manure management in Scotland [add full reference when available].

<table>
<tr><td>Summary of business receptiveness:</td><td>The receptiveness of farmers to adopting AD technologies on farm are likely to be linked closely to the capital investment and the return on that investment. This very quickly reduces the likelihood of any slurry only systems. The challenge with Slurry only systems is that they are working with pre-digested material and the yield of biogas is relatively small. Slurry is generally a useful base feedstock but requires other material for co-digestion. Co-digestion with food waste, animal by-products (ABP) or crop materials (whole crop or grass silage mainly) is most common but increases costs and complexity.

For AD sites to be successful – they require many factors to be correct:

• Market/use for biogas – proximity to the gas grid or heat demanding facility.

• Access to reliable source of feedstock – Assuming co-digestion, there are risks associated with needing feedstocks such as crop materials when the price is linked to global commodity prices. Longer term contracts with waste processors are required to secure the investment and these can be difficult to negotiate.

• Access to land for digestate – this can be challenging and will often require agreements with neighbouring farmers transportation costs.

Planning and feasibility is crucial to the success of an AD facility and can take time and a large investment without any guarantees of returns. Fluctuating incentive payments can be a deterrent as they can change during the planning phase and have a significant impact on the feasibility of a project.

In summary, the combination of specific requirements and associated financial risks contribute to a low level of business receptiveness for on-farm AD.</td></tr>
<tr><th colspan="2">Acidification</th></tr>
<tr><td>Brief description:</td><td>The acidification of slurry has been found to reduce emissions to air of ammonia and greenhouse gases. It involves the addition of acid to lower the pH either in the store or during application of slurry.</td></tr>
<tr><td>Summary of business receptiveness:</td><td>It is understood that the technology is not market ready in the UK as there is not a sales and servicing network, and the on-farm knowledge that is needed has not been developed. Furthermore, there are concerns in the agriculture industry about safety associated with the use of a concentrated acid (usually sulphuric acid) and the potential for increased emission of hydrogen sulphide.

Likely considerations for receptiveness would be legislative or market drivers. Negligible benefits to farm productivity and significant additional costs mean that voluntary uptake is unlikely.

In Denmark, uptake has been achieved by government restrictions on agricultural developments that would emit ammonia. By abating ammonia emissions, farmers can expand their capacity, allowing them to increase production.</td></tr>
</table>

2.3.3 Manure Application

Table 5: Summary of business receptiveness for manure application measures.

Slurry application – rapid incorporation	
Brief description:	Partial incorporation of manures with 12 hours of application applied via low trajectory systems to arable land. Not applicable for growing crops and no-till systems.
Summary of receptiveness:	Uptake potential and receptiveness is good where the circumstances are right. The main barrier to this is the lack of understanding of the benefits.
Timing of slurry application	
Brief description:	Applying slurry and manure at optimum times to ensure that the nutrient content can be utilised by the crop when it is in a growth and development stage. Optimum timings tend to be in the spring and early summer but timings do vary depending on the development stage of the plant.
Summary of receptiveness:	This approach is common place and is good practice. Understanding the value of slurry and manure should be part of the basics of farm operations but often logistical or practical barriers exist such as adequate storage facilities and legitimate concerns over sward contamination on silage ground.
Trailing Shoe, Trailing Hose and Shallow Injection	
Brief description:	**Shoe**: Delivers slurry to soil surface below the crop canopy in narrow bands (20-30 cm apart) reducing the emitting surface area. This technique is mainly applicable to grassland and arable crops with widely spaced rows. The machine working width is typically limited to 6 – 8 m. **Hose**: The trailing hose This technique discharges slurry at or just above ground level through a series of hanging or trailing pipes or flexible hoses, which either hang a short distance (<150 mm) above the soil or are dragged along the soil surface. The working width is typically between 6 and 12 m, although larger units of up to 24 m width are commercially available. Suitable for grass and some crops. **Injection**: (not currently shortlisted) The Slurry is injected below the soil surface into slots created by discs.
Summary of receptiveness:	Voluntary uptake is likely to remain low as the financial benefit is not clear enough to make the change. Perceptions of difficulties on stony ground and the additional cost and reduced work rate are negative factors for farmers.

3 Conclusions

3.1 Slurry management in Scotland

The total quantity of slurry produced in Scotland has been estimated at 6.35 Mt per annum. The dairy sector produces nearly half of this total, but dairy farms occupy only 3.3% of the area of these livestock farms. Dairy slurry production is heavily concentrated in the south-west, especially Dumfries and Galloway, pig slurry production is mainly in Aberdeenshire; and beef slurry production is more widely distributed, but with greatest production in Dumfries and Galloway.

Best practice for slurry management can be summarised as management that minimises loss of nitrogen from the slurry, and maximises nutrient uptake by a crop following application. Best practice must also properly account for the nitrogen content of slurry applied to land so that there is not over-supply of nutrients to crops, especially nitrogen, and so that application of inorganic nitrogen is minimised. Examples of best practice include:

- covering slurry stores,
- apply slurry to land using low-emission techniques, and
- apply slurry to land when there is low risk of leaching.

Survey data show that, of all farms with stored slurry onsite, 62% had covered storage[21], with most using tanks rather than lagoons. For application to land, 5 Mt was applied via a band spreader and 600,000 tonnes was injected. This suggests that around 88% of slurry in Scotland is already spread using low-emission techniques. The figures used are based on the results from the Farm Structures and Methods 2016 survey. Discussions with farm advisers, have supported our view that the percentage of slurry spread using low-emission techniques is much lower than 88%. Further data collection would be needed to confirm this.

3.2 Emissions of greenhouse gases

Emissions of GHGs from slurry management are a relatively small proportion of the Scotland total GHG emissions (1.3%), but contribute 7% to the Scottish agriculture emissions.

Greenhouse gas emissions from slurry management arise mainly as: methane during slurry storage; and nitrous oxide during slurry storage and following application of slurry to land. Approximately 92% of GHG emissions from slurry management are from storage, and approximately 8% are from field application.

There are data from Sweden and Canada that suggest the use of the IPCC default values for the methane conversion factors (MCF) of slurry stored in cool climates is greater than is appropriate for slurry stored in Scotland. This may have caused an over-estimate of the GHG emissions from slurry.

Although concerns have been expressed that measures to reduce emissions of ammonia may increase emissions of nitrous oxide, these concerns have not been substantiated.

Reducing emissions of ammonia following slurry spreading does not axiomatically increase direct nitrous oxide emissions and will reduce indirect nitrous oxide emissions.

The conservation of slurry-nitrogen by reducing ammonia emissions reduces the requirement for nitrogen fertiliser thereby making some reduction in the GHG emissions arising from the manufacture, distribution and application of nitrogen fertiliser. However, these savings occur outside of Scotland (and therefore are not part of the Devolved Administration GHG inventory for Scotland) are estimated to be small

3.3 The value of improved slurry management

The value of improved slurry management can be judged as value to the farmer (the total costs net of savings) and as wider value to the environment and to society. In general, mitigation measures have costs to the farmer that are greater than the benefits.

The savings in GHG emissions from improved slurry management may be thought of as modest relative to the emissions from Scotland’s agriculture sector. However, it is essential that we seize the opportunities to reduce emissions from every source to make a collective contribution to tackle emissions from agriculture.

There are also co-benefits; an important aspect of the value of improved slurry management is the mitigation of ammonia, which leads to GHG and commercial benefits. Some improved techniques for slurry management do not mitigate GHG emissions directly, but do have an indirect effect on GHG emissions (e.g. improved spreading techniques). The UK has ammonia emissions that are close to the ceiling set by the National Emissions Ceilings Directive (NECD). Ammonia emission also has wider costs, and these have been estimates as damage costs, which generally exceed the cost of

[21] The percentage of slurry storage that is covered is uncertain and likely to be lower than 62%, as the data indicate the percentage of respondents with covered storage, but do not indicate the percentage of stores that are covered, or the percentage slurry quantity that is covered.

mitigation[22]. Because of the importance of ammonia emission from slurry management, we excluded some management measures from our analysis because they increase ammonia emission.

We conclude that GHG emissions mitigation from slurry management should be considered alongside ammonia emission mitigation, as there are co-benefits.

3.4 Potential for uptake by farmers

Good practices that lead to abated emissions of GHGs and ammonia have, to some extent, already been adopted by farmers. This abatement has been driven by practical and commercial advantages (e.g. use of store covers excludes rainfall, leaving less slurry to handle and spread), and by the need to comply with regulations (e.g. minimum storage capacity requirements of NVZ regulation allows farmers to better manage application timing).

Further implementation of god practice, with concomitant GHG mitigation, may require incentives or further regulation. For example, adoption of slurry acidification has been success in Denmark, where the Danish government limits the scale of agricultural developments on the basis of ammonia emissions. Therefore, by abating these emissions, farmers can expand their capacity, allowing them to increase production.

Some measures (e.g. covering of stores) uptake could be increased by knowledge exchange activities to explain the benefits, and by financial incentives.

3.5 Analysis of potential for mitigation

A summary of a SWOT (strengths, weaknesses, opportunities and threats) analysis is given in Table 6. More detailed SWOT analysis outputs and a more detailed comparative analysis is provided in Appendix 4.

The colour coding for overall assessment of potential is an indication of the potential for successful implementation, leading to some GHG mitigation. This is an expert judgement taking into account the results of the SWOT analysis and other results presented in this report.

Table 6: Summary of SWOT analysis.

Management option and overall assessment	**Assessment summary (highlights from SWOT analysis in Appendix 4)**			
Low potential Medium potential High potential	**Strengths**	**Weaknesses**	**Opportunities**	**Threats**
Store covers (e.g. floating, rigid)	Well understood, reduces nitrogen loss, excludes rain water, widely applicable	Capital cost, GHG saving smaller for stores that crust, poor data on existing uptake	Aids compliance with NVZ rules for storage, some methane mitigation	Some increase in nitrous oxide emission
Store type (bags)	Reduces nitrogen loss, excludes rain water	High capital cost, uptake will be slow, poor technical understanding	Aids compliance with NVZ rules for storage	End-of-life disposal impact

[22] https://www.gov.uk/guidance/air-quality-economic-analysis (accessed 24 October 2017).

Management option and overall assessment	Assessment summary (highlights from SWOT analysis in Appendix 4)			
Low potential Medium potential High potential	**Strengths**	**Weaknesses**	**Opportunities**	**Threats**
Transfer to other farms/areas	Improves nutrient use with fertiliser savings	Cost of transport, not suitable for long distances	Aids compliance with NVZ rules for N-max, GHG benefit through soil carbon maintenance and fertiliser savings	Risk of spillage in transport, GHG emissions from transport
Anaerobic digestion of slurry	Low odour, nutrient benefits	High costs	GHG savings	Feedstock availability for co-digestion with slurry, fluctuating incentives
Slurry acidification	Reduces nitrogen loss, widely applicable Danish experience demonstrates safe operation	Not yet market ready Costs greater than benefits to farm	GHG savings, ammonia savings	Perceived and potential health and safety risks associated with handling strong acid, and emission of H_2S Small risk of soil acidification if lime inputs are not adjusted
Spreading timing (seasonal timing)	Improves nutrient use with fertiliser savings, widely applicable	Greater requirement for storage and spreading equipment	Protection of water through decreased leaching	No major threats
Spreading methods (e.g. trailing hose, trailing shoe, shallow injection)	Improves nutrient use with fertiliser savings	Increased costs, field operation more technically-demanding	GHG savings, ammonia savings	No major threats

Abbreviations

AD	Anaerobic digestion
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	CO_2 equivalent
DM	Dry matter
EF	Emission factor
GHG	Greenhouse gas
IPCC	Inter-governmental panel on climate change
LA	Local authority
LFA	Less Favoured Area
MCF	methane conversion factor
N	Nitrogen
N_2O	Nitrous oxide
NH_3	Ammonia
NOx	Oxides of nitrogen (NO and NO_2)
nLFA	Non Less Favoured Area
NVZ	Nitrate vulnerable zone
SWOT	Strengths, weaknesses, opportunities, threats

Appendix 1: slurry production and management in Scotland

Introduction

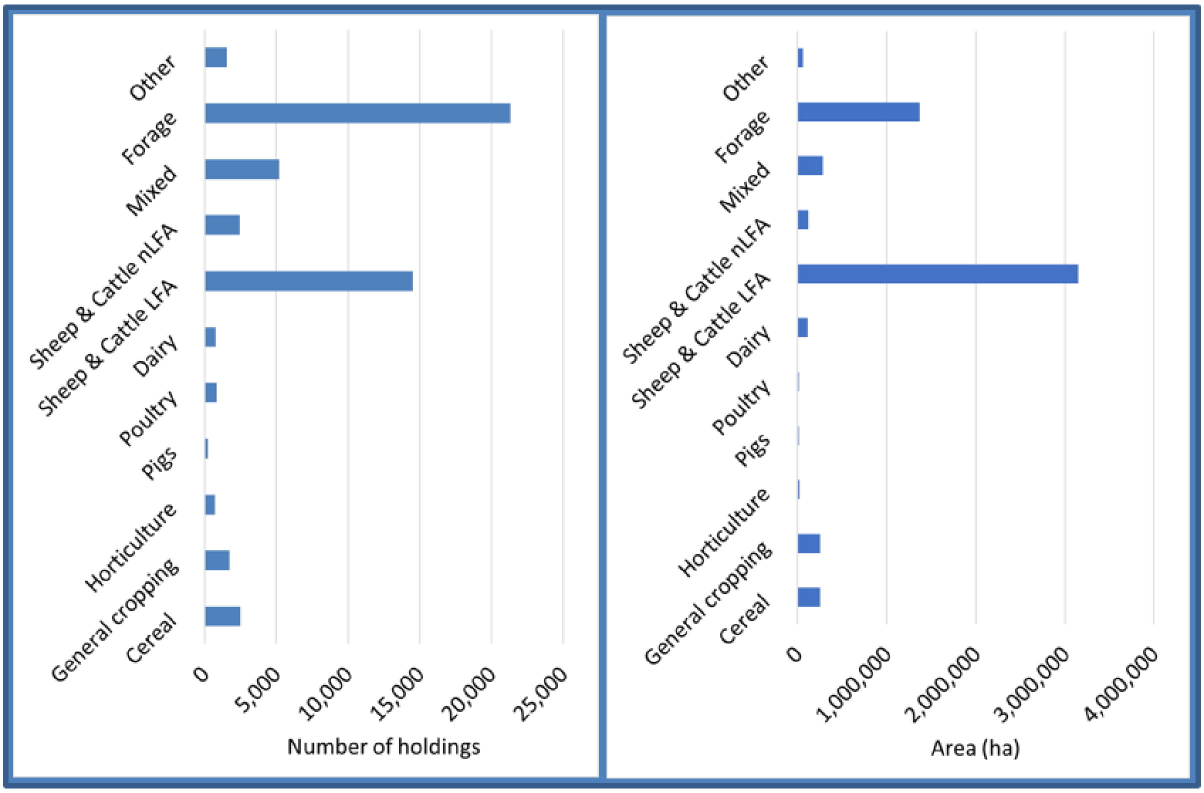
Agricultural slurries are the liquid fraction of excreta produced by livestock in a building or yard. They are often mixed with wash and rainwater, waste bedding and feed, and are collected through either the use of pumps or by gravity. The appropriate management of slurry can result in several benefits, both environmental and economic. The application of slurry, and manure, contributes to crop nutrient requirements and helps to build up reserves of nitrogen, phosphorus and potassium, as well as organic matter, in agricultural soils. However, inappropriate application can have detrimental impacts, including water pollution, emissions to air and loss of crop yield.

The information presented in this Appendix is based on data provided by the Economic Report on Scottish Agriculture (2017), the Scottish Survey of Farm Structure and Methods (2016), other published sources, including peer-reviewed studies and grey literature, and the expertise of the project team.

Slurry production

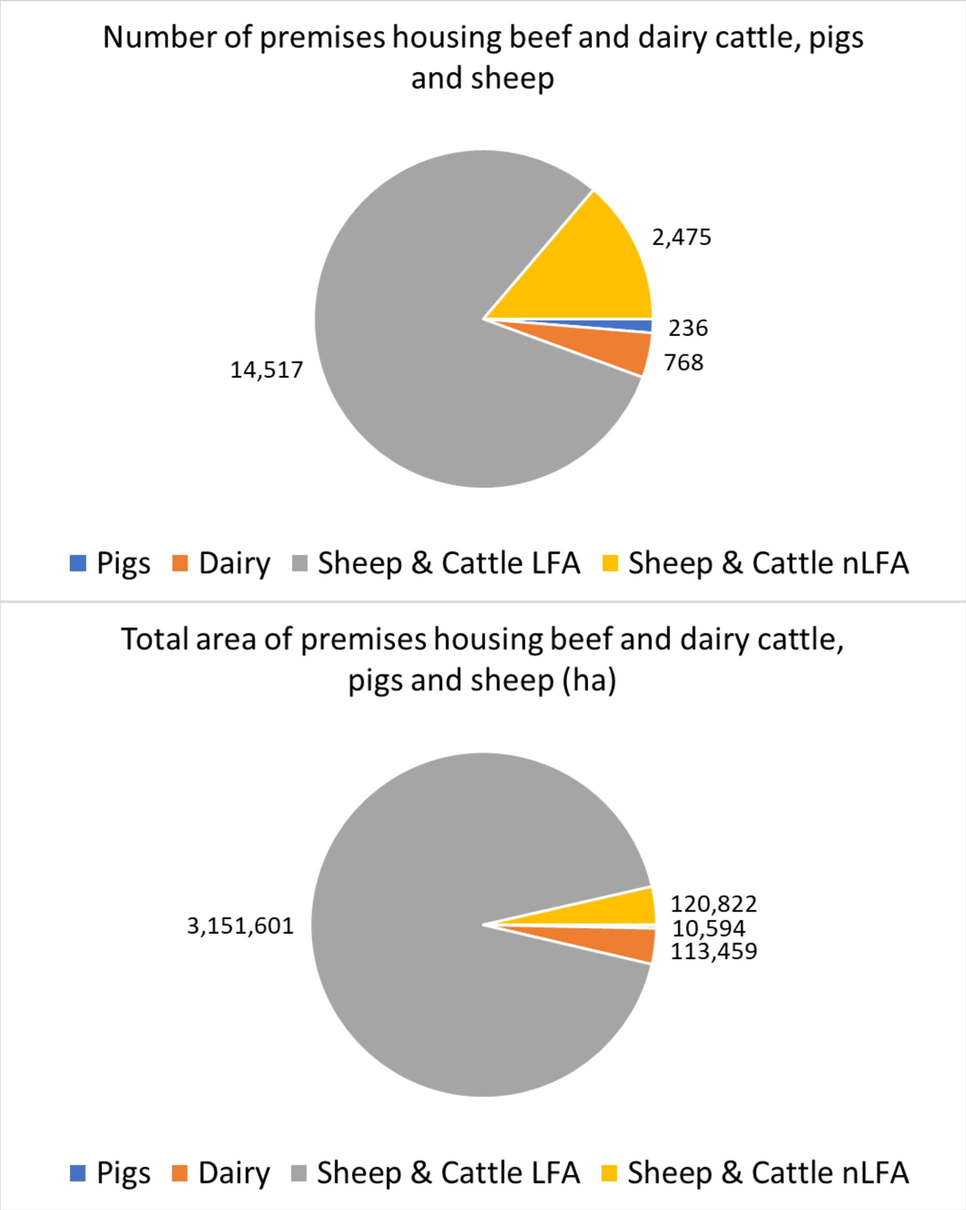
The current profile of the Scottish farming industry is characterised in the Economic Report on Scottish Agriculture, 2017 Edition (Scottish Government, 2017). This provides the following estimations (Figure 2) of the types of agricultural holdings operating in Scotland in 2016, based on number of holdings and land area in hectares.

Figure 2: Scottish agricultural holdings by number and land area, 2016. An individual holding may be represented in more than one farm type. LFA = Less Favoured Area; nLFA = Non Less Favoured Area.



As illustrated in Figure 2, the agricultural industry in Scotland is dominated by 'forage' and 'sheep & cattle LFA' farms. Agricultural slurry is generated at premises housing beef and dairy cattle, pigs and sheep. Therefore, assuming all sheep & cattle, dairy and pig farms could generate slurry, production could occur at approximately 35 % of all agricultural holdings in Scotland. The total number of holdings and land area for these premises in Scotland in 2016 is presented in Figure 3. This illustrates that premises housing beef and dairy cattle, pigs and sheep cover approximately 60 % of the total agricultural land area in Scotland.

Figure 3: Number and total area of Scottish agricultural premises housing beef and dairy cattle, pigs and sheep in 2016.



A 2017 study completed by Ricardo Energy & Environment for Zero Waste Scotland estimated the total quantity of slurry produced in Scotland in 2015 (based on the 2015 census), split by type of slurry and Local Authority (LA), excluding dirty water, effluent, yard washings etc. (Table 7).

Table 7: Total slurry production in Scotland, 2015.

Slurry type	Quantity produced (million tonnes, Mt)
Beef	2.57
Dairy	2.99
Pig	0.73
Sheep	0.06

The estimated split in slurry production by Scottish LAs, derived from the 2015 census, is presented in Figure 4. A total of 28 LAs were estimated to produce agricultural slurry in 2015 with four producing none: Dundee City, Glasgow City, City of Edinburgh and Eilean Siar (these have been excluded from Figure 4). The greatest quantity of slurry was produced in Dumfries and Galloway, at a rate of approximately 1.8 Mt per annum. Farms in Dumfries and Galloway also produced the greatest quantity of dairy and beef slurry, at 1.25 Mt and 0.5 Mt respectively. The greatest quantities of pig and sheep slurry were reported in Aberdeenshire (0.375 Mt) and the Shetland Islands (0.057 Mt), respectively.

Figure 4: Slurry production by Scottish Local Authority.

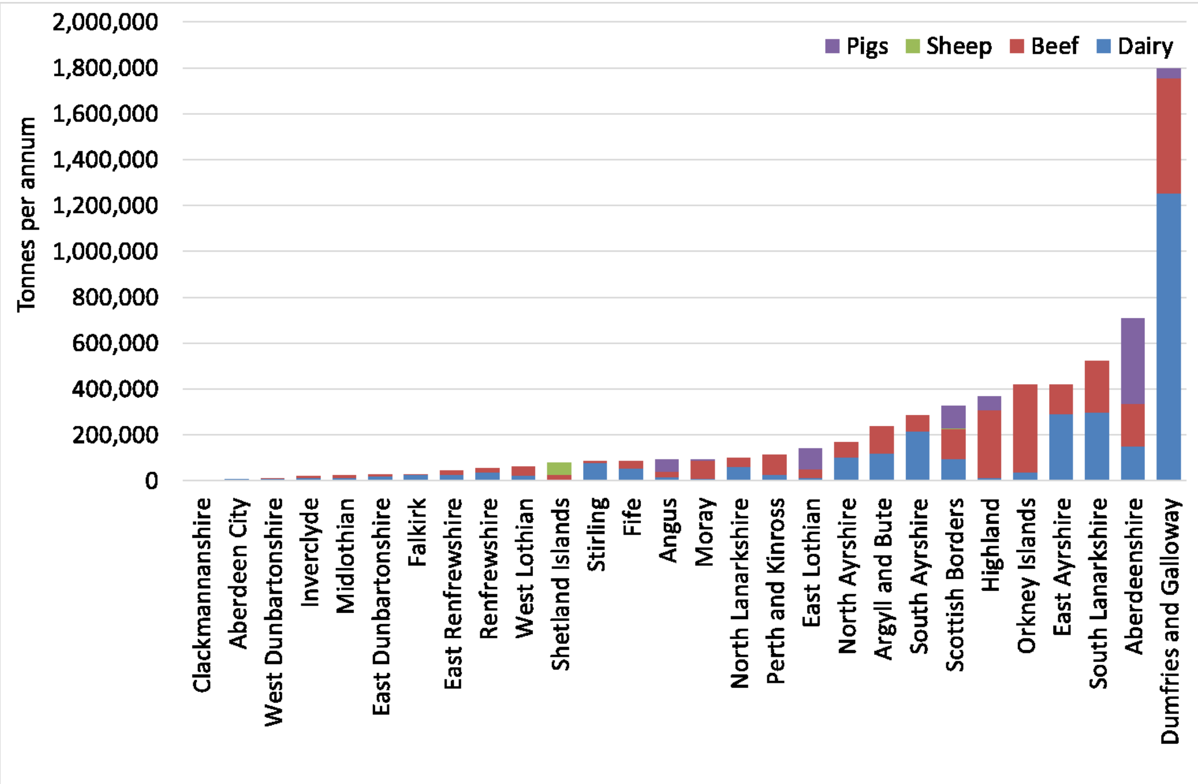
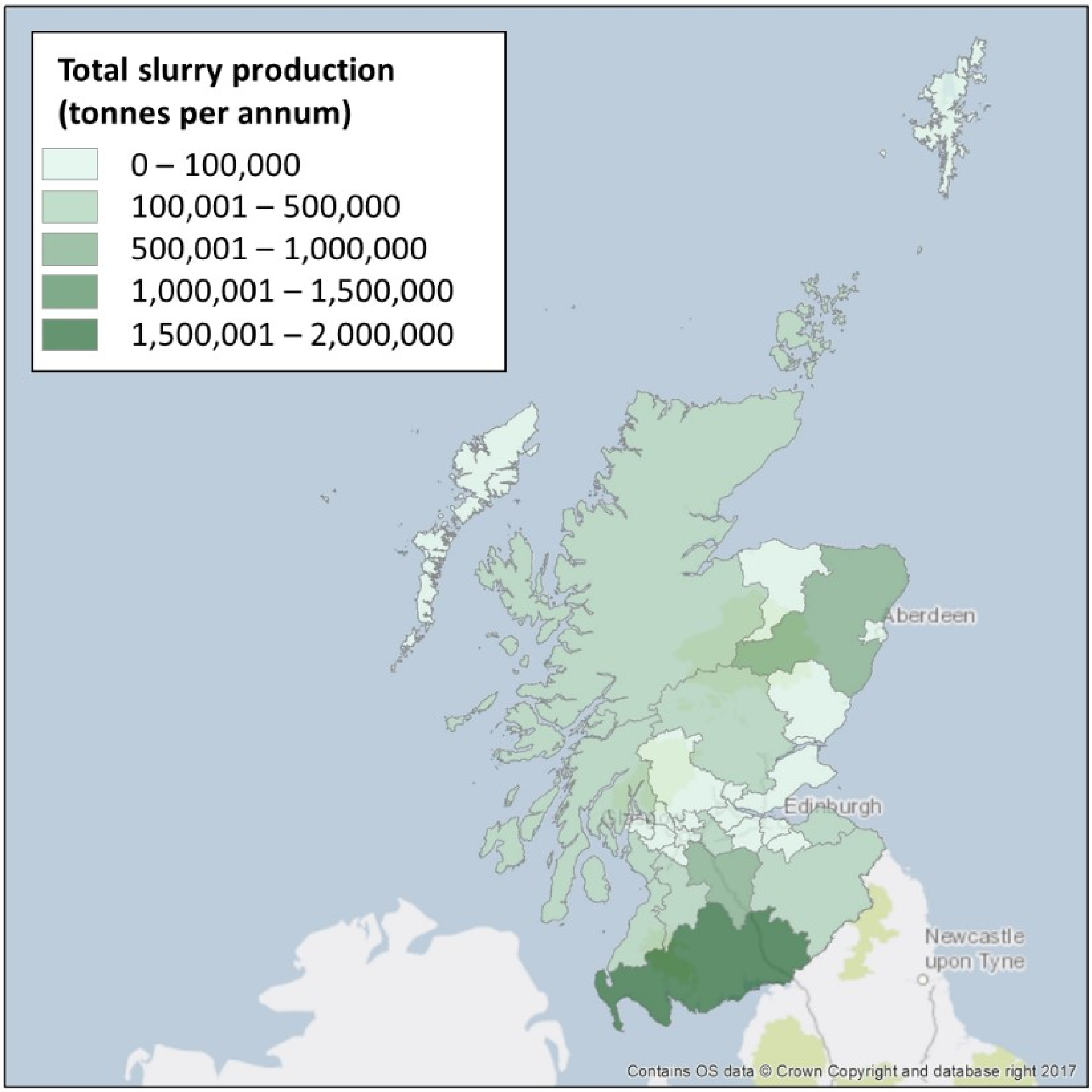


Figure 5 illustrates the distribution of total slurry production across Scottish LAs, whilst Figure 6 illustrates the distribution of Beef, Dairy, Sheep and Pig slurry. Beef slurry arisings are greatest in south-west Scotland and Orkney, and there is also significant activity in the Highlands. Slurry production from dairy systems is mainly in south-west Scotland. Slurry production from pig production is mainly in the east of Scotland where there is arable farming. Arable and horticultural field crops tend to be concentrated in eastern Scotland and pig slurry is used in these systems. Slurry produced

on farms in south west Scotland and the Highlands is likely to be applied mainly to pasture and forage crops.

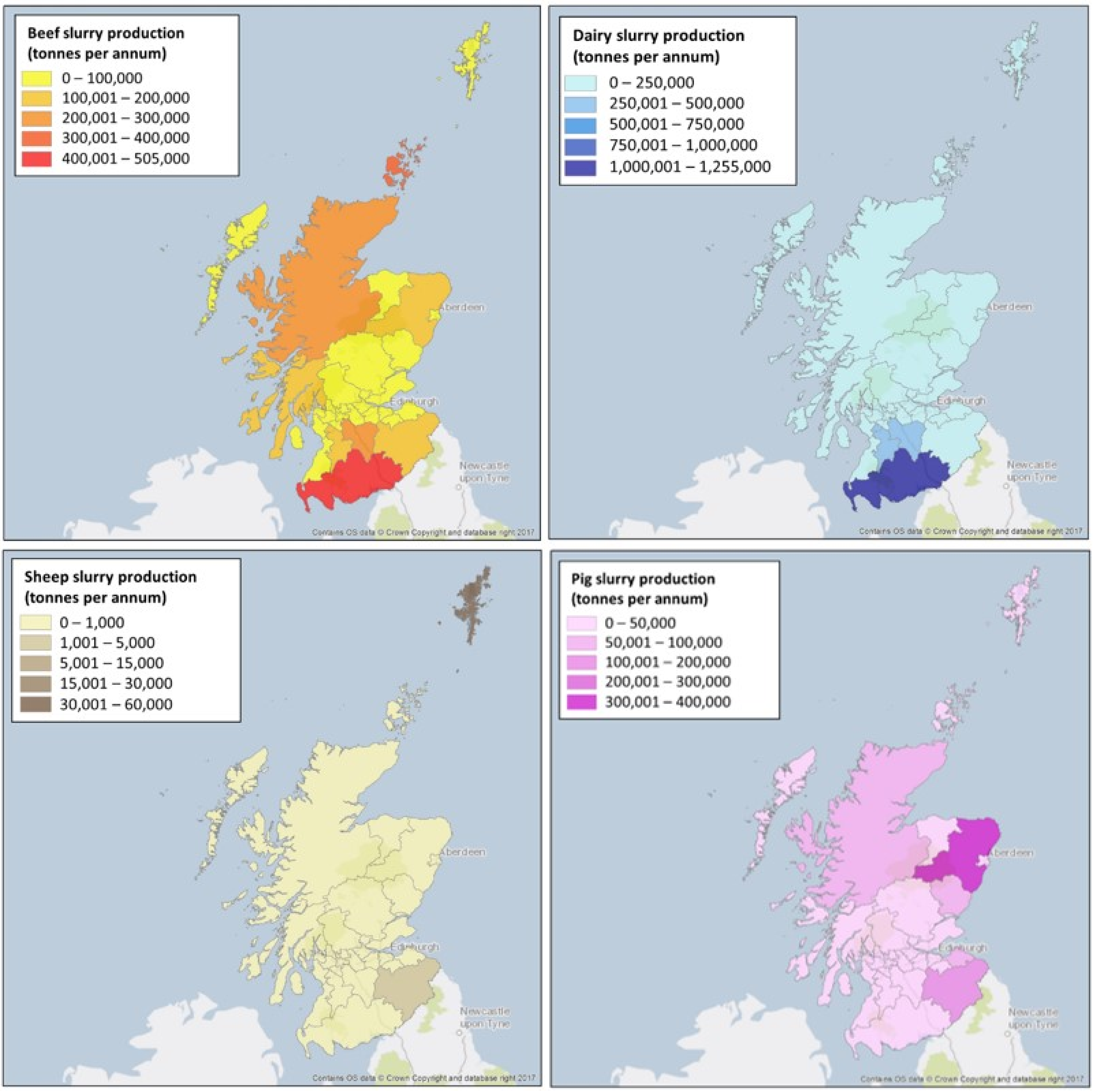
There is some sheep slurry production in the Scottish Borders and Shetland, but the quantities are small and uncertain[23]. The data used for compilation of the national inventory of GHGs does not show any sheep slurry production. Sheep slurry production in Shetland is related to the scarcity and high price of straw, with the result that when sheep are housed for lambing they are on a slurry system rather than a straw system.

Figure 5: Total slurry production in Scotland in 2015, by Local Authority (tonnes per annum).



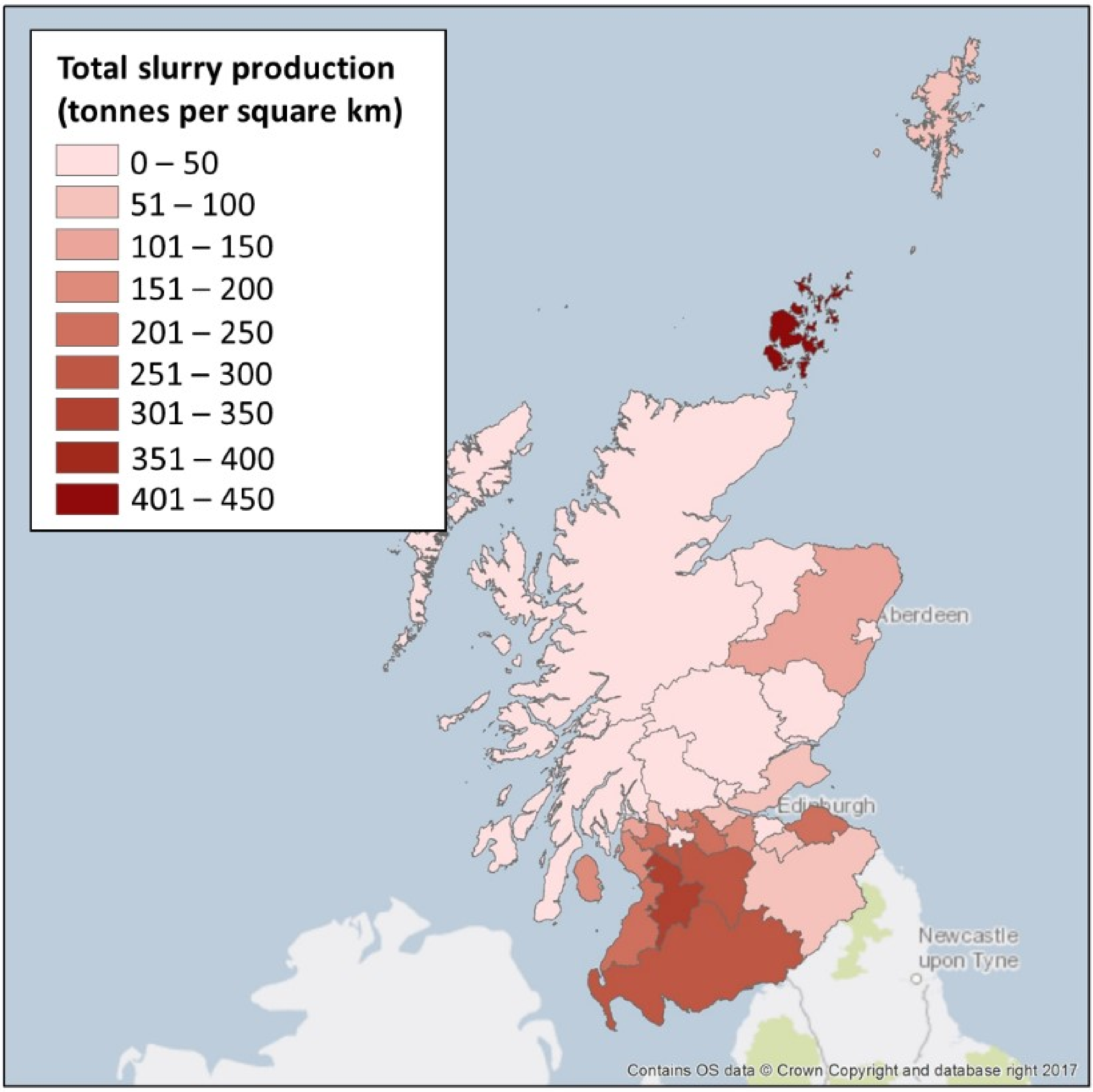
[23] In Shetland, straw is scarce and expensive, so when sheep are housed they are often on sheep slats. However, although the manure is collected beneath the slats in a similar way to slurry for other livestock, it is often managed as a solid material. Often it is neither the same as slurry from other species, nor the same as straw-based farm yard manure.

Figure 6: Beef, Dairy, Sheep and Pig slurry production in Scotland in 2015, by Local Authority (tonnes per annum). The scales are different for each map because of the large variation in quantities between systems.



The distribution of slurry production illustrated in the maps above does not take account of the land area in each LA. Data on agricultural land area per LA was not available for this study, however the following map provides an estimation of slurry production per square kilometre, based on the total land area of each LA. This shows the Orkney islands to have the greatest slurry production per square kilometre, at 423 t/km^2, followed by East Ayrshire (332 t/km^2) and South Lanarkshire (295 t/km^2). The LA with the greatest slurry production, Dumfries and Galloway, has 280 t/km^2 of slurry production.

Figure 7: Total slurry production by land area, 2015.



This review confirms that forage and 'sheep & cattle LFA' holdings are the predominant farm type in Scotland.

Data on the generation of slurry in Scotland confirms Dumfries and Galloway to be the LA with greatest production of slurry, with 1.8 Mt in 2016, the majority of which was generated at dairy and beef farms.

The Orkney islands were found to have the greatest rate of slurry production per square kilometre, which is also dominated by beef and dairy farms.

Slurry management

Management practices

The three key stages in the management of slurry are the storage, transport and application to land.

Slurry can be stored in above-ground stores, below-ground pits, or earth-banked lagoons. Stores can include an agitation system and may either be covered or uncovered.

There are four primary methods of transporting slurry: vacuum tanker, pumped tanker, umbilical hose and irrigator. Descriptions of these methods and a summary of their relative performance in terms of slurry dry matter range, requirement for separation and chopping, work rate, accuracy of application, soil compaction, capital costs and labour requirements, is provided in Table 8.

Table 8: Slurry transport systems. Ticks indicate a score from 1 to 5, with 1 being the least and 5 the greatest. Source: ADAS, IGER & Silsoe (2001).

Slurry transport system	Vacuum tanker	Pumped tanker	Umbilical hose	Irrigator
Description	An air pump is used to create a vacuum which sucks the slurry into a tanker. The slurry is evacuated by pressurising the tanker. This a versatile system which can be used for most slurry transport jobs.	The slurry is pumped into and out of the tanker using either a centrifugal or positive displacement pump. This has a higher precision than vacuum tankers, but requires more maintenance.	The distribution system is fitted to a tractor, which is fed by a drag hose which is supplied from a slurry store. This system may cause crop damage due to the trailing hose.	A centrifugal or positive displacement pump, situated near the slurry store, is attached to a network of underground pipes which feed a self-travelling machine with flexible or reeled-in hoses. This system is suitable for semi-automatic operations, however safeguards against pollution may be required.
Range of slurry dry matter	up to 12 %	up to 12 %	up to 8 %	up to 3 %
Requires separation or chopping	No	No (centrifugal) Yes (PD pump)	No (centrifugal) Yes (PD pump)	Yes
Work rate	✓✓✓	✓✓	✓✓✓✓✓	✓✓ (depends on the field size / shape)
Accuracy of application	✓	✓✓ (centrifugal) ✓✓✓ (PD pump)	✓✓ (centrifugal) ✓✓✓ (PD pump)	✓✓
Soil compaction	✓✓✓	✓✓✓	✓✓	✓
Capital costs	✓	✓ (centrifugal) ✓✓ (PD pump)	✓✓✓	✓✓
Labour requirement per m³	✓✓✓	✓✓✓	✓✓	✓

There are several methods for application to land, including direct application at surface level or incorporation into the soil. Table 9 summarises the key application methods for slurry, and outlines some of the potential pros and cons of their use.

Table 9: Methods of slurry application. Ticks indicate a score from 1 to 5, with 1 being the least and 5 the greatest. Source: ADAS, IGER & Silsoe (2001)

Slurry distribution system	Broadcast spreader	Band spreader	Trailing shoe spreader	Injector (shallow)	Injector (deep)
Description	Pressurised slurry is forced onto an inclined plate to increase the sideways spread (NB. there are restrictions on the use of high trajectory splash plates in NVZs).	The slurry is distributed close to the ground in narrow strips or bands via a number of hoses connected to the boom of the spreader. The slurry is connected fed into the system via a single pipe, with advanced systems using rotary distributors to ensure the slurry is evenly distributed between each outlet.	The addition of a shoe to each hose allows slurry to be deposited beneath the crop canopy onto the soil.	An injector system injects the slurry under the soil surface, either up to 50 mm deep (open slot shallow injection) or over 150 mm deep (deep injection).	
Typical range of dry matter	Up to 12 %	Up to 9 %	Up to 6 %	Up to 6 %	Up to 6 %
Requires separation or chopping	No	No - Up to 6 % Yes - Over 6 %	Yes	Yes	Yes
Relative work rate	✓✓✓✓	✓✓✓	✓✓✓	✓✓	✓
Uniformity across spread width	✓	✓ (simple) ✓✓✓ (advanced)	✓✓✓	✓✓✓	✓✓✓
Ease of bout matching	✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓
Crop damage	✓✓	✓	✓	✓✓	✓✓✓
Relative level of odours and ammonia emissions	✓✓✓✓	✓✓✓	✓✓	✓✓	✓
Capital costs	✓	✓✓	✓✓✓	✓✓✓	✓✓✓✓

As illustrated in Table 9, there are advantages and disadvantages with all of these systems. For example, the use of band spreaders or injectors can reduce emissions of odour and ammonia, and the potential for surface run off, but are likely to incur increased costs compared with surface broadcast spreaders. In contrast broadcast spreaders risk variable application rates, as well as increasing (compared with other spreading methods) the time between spreading and cutting/grazing, because of sward contamination (Defra, 2011).

Besides the storage, transport and spreading of slurry, farmers may conduct additional management practices, including the analysis of soil and slurry samples. It is considered good practice to conduct an analysis of the slurry, either during storage or at application. It is recommended at least two samples are collected per year to coincide with the main spreading periods (SRUC, 2013). The analysis should include dry matter content, total N, ammonium-N, P, K, S and Mg (ADAS, IGER & Silsoe, 2001).

Requirements for slurry management in nitrate vulnerable zones

The management practices adopted by a farm are influenced the characteristics of the farm, including the size, type and location and, in particular, whether the farm is within a NVZ.

Nitrate vulnerable zones were introduced in response to the Nitrates Directive (91/676/EEC). This requires all EU member states to limit nitrate in drinking water to a maximum of 50 mg/l. Farmers within NVZs must comply with strict requirements concerning the timing and application of nitrogen from organic and inorganic sources, including slurries.

As of the 1st January 2016, there were five designated NVZs in Scotland (Scottish Government, 2017c):

- Lower Nithsdale,
- Lothian and Borders,
- Strathmore and Fife (including Finavon, added 2016),
- Moray, Aberdeenshire/Banff and Buchan,
- Stranraer Lowlands (added 2016).

The following is a summary of some key rules for the management of slurry within NVZs in Scotland:

- **Record keeping**
    - Records must be kept annually on the use of all organic and inorganic (chemical) nitrogen (N) fertilisers, on a field-by-field basis.
    - A fertiliser and manure plan must be prepared and implemented each year.
- **Nitrogen application limits**
    - There are farm and field limits for the quantity of N than can be applied in the form of organic manure.
    - N from organic and inorganic sources must not exceed the crop or grassland requirement.
- **Closed periods**
    - For slurry, closed periods cover sandy and shallow soils during the times when nitrate leaching is most likely. Actual dates vary by NVZ and type of land, within the months September to February.
- **Other application restrictions**
    - Organic manure must NOT be applied: when the soil is waterlogged, flooded, frozen hard or snow covered; to steeply sloping fields; to uncropped areas, within 10 m of watercourses; within 50 m of a well, borehole or other water supply; unevenly and inaccurately.
- **Storage of slurry/poultry manure and farmyard manure**
    - The capacity of storage facilities must be sufficient to hold all the slurry / poultry manure that cannot be applied due to closed periods, with 26 weeks minimum storage requirement for pig enterprises and 22 weeks minimum storage requirement for cattle enterprises.

Current practice

The current practices adopted for the management of slurry in Scotland were characterised by the Scottish Survey of Farm Structure and Methods, published in 2016 (referred to here as the '2016 survey'). The survey was conducted across a sample of approximately 15,100 holdings, with returns received from 9,900 holdings. The results of the most recent survey were also compared with the Farm Structure Surveys, conducted in 2013 (referred to here as the '2013 survey'), to provide an illustration of recent developments in management practices. The results of the 2016 survey represent larger holdings, which account for 96% of agricultural land in Scotland.

Regarding the storage of slurry, the 2016 survey found 9% of farms used storage facilities for slurry, of which 62% were covered (an increase of 1% from the 2013 survey). However, the percentage of slurry storage that is covered is uncertain and likely to be lower than 62%, as the data indicate the percentage of respondents with covered storage, but do not indicate the percentage of stores that are covered, or the percentage slurry quantity that is covered. Some farms may have some covered storage and some uncovered storage, but would be included in the 62% of farms with covered storage. The UK and Scotland National Inventory of Greenhouse Gases calculations for the latest inventory submission (2015 emissions) assume 24% of pig slurry stores are covered in Scotland, and that all other slurry stores (dairy and beef systems) are uncovered. This means that there is scope to improve implementation of best practice against the baseline assumptions used for the GHG inventory. Table 10 details the number of holdings reporting the storage of slurry in both tanks and lagoons, during 2013 and 2016.

Table 10: Reported slurry storage in Scotland, 2013 and 2016.

<table>
<tr><th>Year</th><th colspan="2">Criteria</th><th>Storage facilities for slurry in a tank</th><th>Storage facilities for slurry in a lagoon</th></tr>
<tr><td rowspan="4">2013</td><td colspan="2">Number of holdings</td><td>3487</td><td>641</td></tr>
<tr><td colspan="2">Percentage of all holdings</td><td>10.5</td><td>1.9</td></tr>
<tr><td rowspan="2">… of which are covered</td><td>Number of holdings</td><td colspan="2">2354</td></tr>
<tr><td>As a percentage of holdings with storage</td><td colspan="2">61.3</td></tr>
<tr><td rowspan="4">2016</td><td colspan="2">Number of holdings</td><td>2739</td><td>571</td></tr>
<tr><td colspan="2">Percentage of all holdings</td><td>8.5</td><td>1.8</td></tr>
<tr><td rowspan="2">… of which are covered</td><td>Number of holdings</td><td colspan="2">1872</td></tr>
<tr><td>As a percentage of holdings with storage</td><td colspan="2">62.3</td></tr>
</table>

The application of slurry or manure to land was reported at 29% of all holdings with cultivable land. A total of 12 Mt of slurry was reported as being broadcast, with 3% being ploughed in within a 4-hour period. An additional 5 Mt were applied with a band spreader, and a further 600,000 tonnes injected. Of those holdings that applied manure or slurry, 7% had tested the nutrient value. 74% reported to separate applications of slurry and/or mineral fertiliser by at least five days. The results of the 2016 survey relating to manure and slurry application are presented in Table 11.

Table 11: Methods of manure and slurry application by tonnage in Scotland, 2016.

	Holdings	Tonnes
Broadcast		
Ploughed in or injected within four hours	920	385,842
Ploughed in after four hours	5,146	2,117,346
Not ploughed in or injected	4,957	9,322,483
Band spread		
Trailing hose	550	4,178,295
Trailing shoe	294	602,161
Injection		
Shallow/open slot	63	576,821
Deep/closed slot	11	31,043
Total applied	9,246	1,721,3991

The survey did not indicate how management practices differ between farming systems, nor did it specify how the uptake of slurry management practices differs depending on whether the holding is located within a NVZ or not. A study by Barnes et al. (2009), which assessed farmer behaviour and attitudes towards NVZs, found farmers typically held a negative view of the perceived environmental benefits, water management practices and compliance requirements associated with NVZs. This was attributed to concerns regarding the scientific basis for the designations, and a belief that the restrictions were too inflexible.

In their survey of farmers operating within NVZs, Barnes et al. found:

- 51% of farmers conducted a soil analysis every 1 - 5 years.
- A further 25% conducted a soil analysis at least once a year.
- 62% of farmers stated they prepare a nutrient management plan.
- The majority kept records of fertiliser and manure application for individual fields, and approximately 40% of all farming types invested in obtaining farming or agronomic advice for improved record keeping. Dairy producers were found to be the most proactive in terms of investment in record keeping, with 60 % claiming to have made improvements to record keeping since 2003.
- 86% of livestock and 73% of mixed farm types claimed to have made no investment or expansion in slurry storage facilities since 2003.

A 2014 study conducted by Feliciano et al. into the barriers, enablers and the role of policy for GHG mitigation from land-use in north-east Scotland, which consulted with scientists, land-owners, consultants and other representatives from the farming sector, found the top three mitigation measures for the reduction of GHG emissions, associated with the application of manure and slurry, adopted by farmers in north-east Scotland to be:

- Using all the manure or slurry produced on the farm as fertiliser;
- Matching the timing of mineral fertiliser application to time of rapid crop nutrient uptake; and
- Using biological fixation to provide nitrogen inputs.

In contrast, covering slurry tanks or lagoons was found to be amongst the least popular measures for adoption.

Stakeholders also identified precision farming as being one of the most suitable measures for implementation in north-east Scotland, however the extra costs associated with the practice and a lack of understanding of how to apply precision farming, were identified as being potential barriers to its adoption. It was also stated that precision farming would only be applicable to larger holdings.

This variability in the uptake of slurry management practices that minimise potential environmental impacts was also found in a study conducted by Macgregor & Warren in 2005. They conducted a qualitative assessment of the motivations and management practices of 30 farmers, situated in the Strathmore and Fife NVZ. They found that farmers rarely considered environmental issues beyond the boundary of their farms, unless the economic viability and productive capacity of the farms were put at risk. The farmers were not convinced of any link between their activities and water quality problems.

Studies have also indicated that the manipulation of the diet of farm animals can be used to mitigate GHG emissions from slurry (Sanchez-Martin et al., 2017).

Summary of current practice

The 2016 survey received responses from 9,900 holdings across Scotland. This found 9% of all agricultural facilities stored slurry onsite, of which 62% were covered[24], with most using tanks rather than lagoons. In terms of application to land, the 2016 survey reported that 12 Mt was broadcast, 5 Mt was applied via a band spreader and 600,000 tonnes was injected. Of holdings that reported the application of slurry, 7% tested the nutrient value. Of those holdings using a band spreader, the majority used a trailing hose, and the majority of injection was shallow/open slot

Further studies of slurry management practices within Scottish NVZs found that the majority of these farms have made no investment or expansion in slurry storage facilities, following the instigation of legislation relating to NVZs (Barnes et al., 2009). Feliciano et al. (2014) reported that although farms located within NVZs are likely to use all slurry produced on the farm as fertiliser, the covering of slurry tanks or lagoons was found to be amongst the least popular measures for adoption. Furthermore, the cost of precision farming was viewed as inhibitory.

The 2016 survey report does not give the percentage of holdings that produce slurry, and subsequently apply this slurry to land. Nor does it confirm how management practices differ between NVZ and non-NVZ areas. However, based on the Barnes et al. and Feliciano et al. studies, it is reasonable to assume that in both regions there is significant room for improvement in terms of covering slurry stores and methods of application that limit emissions to air and ensure efficient nutrient use.

Benefits of good practice

Storage practices

The effective storage and application of agricultural slurries can have the benefit of maximising nutrient uptake by crops, and partially displacing the requirement for manufactured N fertiliser. Good management can also minimise emissions to air and water, limiting environmental impacts. Conversely, inappropriate management can have the opposite effect.

Gaseous emissions from slurry, including NH_3 and GHGs (CH_4 and N_2O), arise through microbial processes within the slurry, which in turn are affected by its composition and oxygen status. Slurry management can be used to create unfavourable conditions to inhibit the activities of these microorganisms, and thus mitigate emissions to air (Owusu-Twum et al., 2017). Some slurry management actions, e.g. allowing crust formation on the surface of stored slurry, provide a physical barrier to inhibit emission of NH_3.

The storage of slurry allows the timing of spreading to be managed in order to maximise crop uptake, reducing the requirement for synthetic fertiliser and minimising emissions. The ability to choose application timing can also have some practical benefits for farmers, such as avoidance of soil compaction through spreading onto wet soil; compaction can limit crop yield and can be expensive to correct.

[24] The percentage of slurry storage that is covered is uncertain and likely to be lower than 62%, as the data indicate the percentage of respondents with covered storage, but do not indicate the percentage of stores that are covered, or the percentage slurry quantity that is covered.

Conflict between benefits of N retention and GHG emissions

During storage slurry will remain largely anaerobic unless oxygen is introduced as part of a treatment process or there are windy conditions with minimal surface cover. When the slurry is not anaerobic, emissions of N_2O will be negligible (Sommer et al., 2000). Greenhouse gas emissions are likely to increase if a surface layer of straw is used or a crust forms, as this causes anaerobic conditions, allowing nitrification to occur. The encouragement of natural crusting on slurry stores has been advocated as a means of reducing emissions of NH_3 by 50%, but emissions of N_2O during slurry storage are estimated by IPCC methods to be 1.0% of slurry N for slurry stored under a natural crust, but zero for slurries stored without a natural crust. In a similar way to crusting, store covers are used to mitigate NH_3 emissions, but also can result in increased emissions of N_2O (Berg et al., 2006). There is therefore a potential conflict, in this case, between efforts to reduce NH_3 emissions during slurry storage and reducing emissions of GHGs (N_2O in this case).

Slurry separation has also been found to result in increased emissions of N_2O during storage due to heightened emissions from the solid fraction.

Application practices

The methods by which the slurry is applied influences emissions of NH_3. The use of broadcast spreaders has been estimated to result in a loss in ammoniacal-N of between 20 – 40% (Nyord et al., 2008), whereas injection of slurry into the soil can minimise losses to 2% of N (Huijsmans et al., 2003). However, where injection occurs to a depth of ~20 cm below the surface, anaerobic conditions result in higher rates of denitrification, which may increase N_2O emissions (Boeckx and Van Cleemput, 2001).

Nutrient management

The adoption of effective nutrient planning can help to avoid the potential for exceeding the N requirements of soil, regardless of the method application, which will subsequently have a beneficial impact on N_2O emissions.

By taking account of the N content of slurry applied to crops (including grass), and thereby decreasing application of inorganic N fertiliser, the GHG emissions from fertiliser manufacture are avoided. This emissions avoidance occurs outside of the agriculture sector and outside of Scotland, as there are no N fertiliser production facilities in Scotland.

Other benefits

Although NH_3 is not a GHG, emission of NH_3 is a major concern, because of health impacts and effects on ecosystems.

Emission of NH_3 contributes to particulate matter (PM) air pollution through the reaction of NH_3 with other pollutants, leading to particle formation.

Good slurry management to limit NH_3 emission, and therefore N loss to air, can benefit sensitive ecosystems by avoiding excessive N loading through atmospheric deposition of N.

Slurry can be used to indirectly reduce emissions of GHGs through its use as a feedstock in anaerobic digestion, producing biomethane, thus displacing fossil fuel combusion (Rodhe et al., 2015).

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Appendix 2: emissions of GHGs during slurry management

Conclusions

- Greenhouse gas emissions from slurry management are only a small proportion (c 7%) of GHG emissions from agriculture in Scotland and a very small proportion (1.3%) of total Scottish GHG emissions.
- Greenhouse gas emissions from slurry management arise mainly as: methane (CH_4) during slurry storage; nitrous oxide (N_2O) during slurry storage; and N_2O following application of slurry to land.
- There are data from Sweden and Canada that suggest the use of the IPCC default values for the methane conversion factors (MCF) of slurry stored in cool climates is greater than is appropriate for slurry stored in Scotland.
- Large reductions in CH_4 emissions during slurry storage (relative to emissions total during storage) can be obtained by subjecting the slurry to anaerobic digestion or by covering the store with a rigid or flexible cover.
- Although concerns have been expressed that measures to reduce emissions of NH_3 may increase emissions of N_2O, these concerns have not been substantiated.
- Reducing emissions of NH_3 following slurry spreading does not axiomatically increase direct N_2O emissions and will reduce indirect N_2O emissions.
- The conservation of slurry-N by reducing NH_3 emissions reduces the requirement for N fertiliser thereby making some reduction in the GHG emissions arising from the manufacture, distribution and application of N fertiliser.

Methodology used in the UK GHG Inventory to calculate GHG emissions from slurry management

Methane

From slurry stores

Methane (CH_4) emissions from manure management are calculated following IPCC Tier 2 methodology using:

- default IPCC data for volatile solids (VS) and CH_4 producing potential (Bo) parameters for each livestock type (except for dairy and beef cows, where a Tier 2 calculation (IPCC 2006, Equation 10.24) is used to determine VS, and deer for which the Tier 1 IPCC default methodology and emission factor are used);
- country-specific data for the proportion of manure from each livestock type handled as slurry or solid and IPCC default methane conversion factors (MCF) for slurry and solid manures (IPCC 2006, Table 10.17).

Examples of IPCC default EFs used in the UK GHG Inventory are provided in Table 12.

Table 12: Emission factors used for stored slurry. Values for MCF are from Appendix Table A3.3.10 of the GHG Inventory report.

Store type	VS kg/hd/day	B_o m^3 CH_4/kg VS	MCF%	kg N_2O per kg N
Crusted	*5.1	*0.24	10.0	0.005
Uncrusted	*5.1	*0.24	17.0	0.0
Spread direct	*5.1	*0.24	0.1	0.0

VS, Volatile solids (IPCC, 2006).
B_o, methane producing potential (IPCC, 2006).
MCF, methane conversion factor for regions with average annual temperature <10.0°C (Table 10.17 IPCC, 2006).
N_2O EF from IPCC, 2006.
*Value for dairy cow raised in Western Europe (Table 10A-4, IPCC, 2006). No values for B_o or VS cited in the Inventory report.

Amon et al. (2006) summarised the limitations of the IPCC default approach. First, the default Bo values have a large degree of uncertainty being based on the findings of Safley et al. (1992; cited in Amon et al. (2006), who summarised the results of several different experiments). Moreover, the MCFs cited by IPCC have been based on expert judgement, not on experimental data.

Both Rodhe et al. (2009) and Park et al. (2006) have published MCFs measured in cool climates which suggest the IPCC default may overestimate CH_4 emissions from slurry stores in cool climates.

Rodhe et al. (2009) measured CH_4 emissions from cattle slurry stored under winter and summer conditions in Sweden at 3 sites with mean average temperatures <10°C. The CH_4 MCF was 2.2% in winter and 4.1% in summer from a store with a surface crust. Both these values are much less than the IPCC default value of 10% for annual average temperatures below 10°C for crusted slurry.

Park et al. (2006) measured the MCF of pig slurry stored at a mean air temperature of 8.4°C over almost 2 years in Canada. The results reported by Park et al. (2006) were reported in relation to those cited in IPCC 2000, which used different units to the percentages cited by IPCC 2006. The MCF measured by Park et al. (2006) was only 60% of the IPCC 2000 default value for cold temperatures.

It appears possible, therefore, that the use of the IPCC default values for MCF of slurry stored in cool climates is greater than is appropriate for slurry stored in Scotland.

Following application of slurry to land

Emissions of CH_4 following application of slurry to land are considered to be negligible (IPCC, 2006, paragraph 10.4) and do not appear to be calculated, although we did not find any explicit confirmation of this in the UK Inventory report. However, given that CH_4 emissions following slurry application to land are so small their calculation is not necessary. For example, Amon et al. (2006) found CH_4 emissions after spreading slurry stored after 5 storage treatments were always <1% of CH_4 emissions during storage.

Nitrous oxide

From slurry stores

Nitrous oxide (N_2O) emissions from manures during storage are calculated for different storage systems as defined by IPCC. Calculation follows IPCC (2006) (equation 10.25) for each livestock category and subcategory, using country-specific data for nitrogen (N) excretion by the different livestock categories and for the proportion of manure managed liquid slurry, and default emission factors (EF) for the different systems.

Emissions from the following storage systems are reported under the Manure Management IPCC category:

- Uncovered anaerobic lagoons. These are assumed not to be in use in the UK;
- Liquid/slurry;
- Deep bedding (previously deep litter); and
- Poultry manure with/without bedding or destined for incineration; IPCC (2006).

Indirect N_2O emissions from manure management comprise N volatilisation from manure management systems calculated using Equation 10.27 (IPCC 2006 guidelines), along with country-specific fractions ($Frac_{GasMS}$), derived directly from the UK agriculture NH_3 emission inventory, for N loss due to volatilisation of NH_3 and NOx, disaggregated by manure management system.

Following application of slurry to land

Nitrous oxide emissions following slurry application to land are calculated using IPCC Tier 2 methodology and country-specific EF (Table 13) for N_2O emissions and country-specific data for the amount of manure-N applied to the land.

Table 13: Emission factors used for slurry applied to land.

	kg N_2O-N/kg N input
Nitrous oxide	0.00601
Methane	Not estimated

Indirect emissions of N_2O from leaching and runoff following slurry application to land are estimated according the 2006 IPCC guidelines using equation 11.10 and the default nitrogen leaching/runoff factor (EF5). The fraction of N that is leached ($Frac_{LEACH}$) is a country specific value (0.1).

Proportions of GHG emissions from Scotland accounted for by slurry management

Greenhouse gas emissions arising from the storage and spreading of livestock manures (slurry and solid manures) account for just under 2% of all GHG emissions in Scotland and just under 10% of GHG emissions from Scottish agriculture (Table 14).

Table 14: Greenhouse gas emissions from manure management in Scotland.

Category code and description	Emissions (kt CO_2e)	GHG emissions as a percentage of Scotland total	GHG emissions as a percentage of Scotland agriculture total
3B1 Dairy cattle	163.4	0.4%	2.0%
3B1 Non dairy cattle	434.6	1.0%	5.2%
3B2 Sheep	40.6	0.1%	0.5%
3B3 Pigs	49.1	0.1%	0.6%
3B4 Deer	0.2	0.0%	0.0%
3B4 Goats	0.1	0.0%	0.0%
3B4 Horses	3.0	0.0%	0.0%
3B4 Poultry	10.5	0.0%	0.1%
3B4 Other	44.9	0.1%	0.5%
3D Manure application	119.2	0.3%	1.4%
Total from manure storage and application	820.6	1.8%	9.8%
Total from slurry storage and application	580.6	1.3%	7.0%

Of these emissions from the storage and application of manures, the percentages arising from slurry are:

- 82% of CH_4 emissions and 67% of N_2O emissions during storage, and
- 40% of N_2O emissions following spreading.

The storage and application of slurry to land account for 1.3% of all GHG emissions in Scotland and just over 7% of agricultural GHG emissions.

Abatement options to reduce GHG emissions during slurry management

This section summarizes the results of studies that have measured the impacts of slurry treatments and store covers on GHG emissions during slurry storage.

Loyon et al. (2016) measured the impact of three types of store cover (flexible synthetic sheet, polystyrene balls and peat) on GHG emissions from stored pig slurry. The synthetic sheet reduced GHG by 90% in all seasons. Polystyrene balls and peat increased GHG emissions in summer and all years respectively.

Amon et al. (2007) carried out a pilot scale study of different levels of cover of stored cattle slurry. A solid cover can reduce GHG emissions by significantly reducing CH_4 emissions by c. 13% in winter and c. 16% in summer. There was no significant effect on N_2O emissions.

Amon et al. (2006) evaluated four approaches to reducing GHG emissions during slurry management (separation, anaerobic digestion (AD), aeration and a straw cover) and all reduced CH_4 emissions except for the straw cover. There was no significant impact on N_2O emissions. Amon et al. (2006) concluded that GHG emissions from slurry management can be most effectively abated by reducing CH_4 emissions during slurry storage. However, both separation and aeration gave large increases in total NH_3 emissions and therefore may conflict with other environmental objectives. Therefore, AD appears the best treatment option for reducing GHG emissions without unwanted impacts on NH_3 emissions.

Petersen et al. (2005) reported that CH_4 emissions were reduced, on average, by 38% with surface covers (natural crust, leca pebbles (light, expanded clay aggregate) or straw). The reduction was probably due to CH_4 oxidation in the surface covers or in the interface between the cover and liquid in the store.

Impact of adopting techniques to reduce ammonia emissions during slurry management on GHG emissions

Slurry injection has been shown to reduce NH_3 emissions by an average of 70% (Webb et al. (2010).

Slurry application techniques that reduce NH_3 emissions would be expected to increase direct emissions of N_2O if only because more N enters the soil. However, the reduction of NH_3 emissions will reduce indirect emissions of N_2O arising from the deposition of NH_3. Since the current IPCC default EFs for direct and indirect N_2O emissions following the application of slurry to land are the same (0.01 kg N_2O-N/kg N input) there would appear to be no net change in total N_2O emissions arising from slurry spreading.

In their review of emissions arising from the application of manures by reduced-NH_3 emission spreading techniques Webb et al. (2010) found that injection of slurry does not axiomatically increase direct N_2O emissions. For example, injection of slurry may either increase (Rubaek et al., 1996, year 1; Wulf et al., 2002; cited in Webb et al., 2010) or have no impact on direct emissions of N_2O (Rubaek et al., 1996, year 2; Vallejo et al., 2005; cited in Webb et al., 2010).

There are a number of reasons why reduced-NH_3 emission application techniques would not always lead to greater direct emissions of N_2O:

- By increasing the length of the diffusion path from the site of denitrification to the soil surface injection may lead to a greater proportion of denitrified N being emitted as N_2.
- The soil moisture status following injection may not be suitable for increased N_2O production.

- In soils already well-supplied with both readily-metabolizable C and mineral N any increase in N_2O emission following slurry application may be too small to have a significant effect on total direct N_2O emissions.
- The impact of subsequent weather on soil moisture content and WFPS will also effect subsequent emissions of N_2O.

Due to the additional draught required for injection, emissions of CO_2 may also be increased by reduced-NH_3 emission techniques. Hansen et al. (2003; cited in Webb et al., 2010) made an estimate, based on the additional draught required for injection, of the impact of injection on CO_2 emissions. The estimate was an additional 0.3–0.7% to the current estimate of CO_2 emissions from agricultural field work. Hence we consider that the impacts of NH_3 abatement on emissions of N_2O will dominate the net effect of on GHG emissions arising from the application of slurry using techniques to abate NH_3 emissions.

Velthof et al. (2003; ; cited in Webb et al., 2010) postulated that the impacts of application techniques will be moderated by O_2 impacts on N_2O production, local N concentrations in soil and the length of the diffusion path of N_2O to the atmosphere. Velthof et al. (2003; cited in Webb et al., 2010) measured N_2O emissions in an incubation study from a range of manures, including cattle and pig slurry and poultry (layer) manure. Emissions of N_2O were greatest when pig manure was placed at depth of 5 cm ($P < 0.05$), least when placed at 10 cm ($P < 0.05$) and intermediate for surface application, thorough mixing and placement at 5 cm. These results suggest that while injection to 5 cm might increase emissions of N_2O, deeper injection might reduce them.

The conservation of slurry-N by injection has been shown to significantly increase apparent nitrogen recovery by crops by up to around 15% compared with surface application, with greater effects for cattle than for pig slurry. In the season of manure application, uptake of available slurry-N from cattle slurry applied by injection has been reported to be as great as from a similar amount of NH4+–N applied as fertiliser. Application rates of cattle slurry to grassland by trailing shoe, that are similar to mineral-N application rates, can give apparent nitrogen recovery by crops from manure application equivalent to that obtained by fertiliser-N at a range of application rates, timings, or seasons. These findings indicate that reduced NH_3-emission techniques can be adopted by commercial farmers to increase manure-N efficiency, thereby reducing the need for fertiliser-N and hence decreasing GHG emissions arising from both the manufacture and application of N fertiliser (Webb et al. (2013).

Based on these considerations we conclude that concerns over increasing emissions of N_2O should not inhibit the adoption of reduced-NH_3 emission spreading techniques. Smith et al. (2008) had earlier concluded that under conditions that did not enhance N_2O emissions, there is no trade-off between NH_3 and N_2O production and more attention should be placed on controlling and reducing odour and NH_3 emissions.

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Appendix 3: business receptiveness of measures to mitigate GHG emissions

Introduction

Here we present an analysis of the potential for change on farms in Scotland, from a farm business perspective. The measures considered in this analysis are listed in Table 15. We have reviewed the costs, benefits and wider impacts of each of the actions to determine how beneficial they could be to the farmer. The quantitative assessment will be supported by expert judgement on the likelihood of change.

Table 15: Measures considered in this analysis.

Measure	Short Description
Slurry store covers and slurry bags	Fixed or floating covers on slurry tanks and lagoons. Slurry bags are enclosed strong bags for storage of slurry within a bunded area.
Transfer of slurry and manures	The transfer of slurry and manures between farms to optimise the nutrient use efficiency
Anaerobic digestion	The capture of methane from the decomposition of slurry (and usually other materials)
Slurry acidification	The addition of acid to slurry to reduce volatilisation
Rapid incorporation	Applications timed to match crop requirement to reduce nutrients losses
Timing of slurry application	Utilising slurry at the optimum time of the growing season to offset fertiliser cost and emissions
Precision application techniques (injection or trailing shoe)	Use of application techniques that apply slurry directly to the soil or injected in to the soil

The receptiveness of a farm business to any change is determined by the drivers. Based on our research into agricultural advisory services[25] for Defra (Defra ref FF0202; Martineau, 2010), drivers for change fit broadly in to three categories:

- Improve profitability and business efficiency
- Legislative compliance
- Incentives such as grants and subsidies

In addition, and linked to each of these points, are the increasing demands in the supply chain from buyers or quality assurance schemes. In terms of the receptiveness to slurry management options, farming businesses will be influenced strongly by the access to capital, benefit to their farm system, payback time, and risks associated with non-compliance. All of these factors influence the decisions of farmers relating to slurry management systems, but the most important factor is whether an upgrade to the existing system is required. Slurry storage systems tend to be a 20-30 year investment.

In this analysis we have built on our recent (May 2017) work for Defra on NH_3 from livestock production, which included an analysis of NH_3 mitigation actions, mainly related to slurry

25 http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&ProjectID=17292&FromSearch=Y&Publisher=1&SearchText=ff0202&SortString=ProjectCode&SortOrder=Asc&Paging=10#Description

management. Included were assessments of barriers to uptake, and wider business impacts on farmers. The following sections provide the results of our analysis.

Manure Storage and management

Slurry covers and Slurry Bags	
Brief description:	Cover floating on the surface of the store or lagoon. Often a plastic cover resting on the surface that rises and falls with the slurry volume. Rain water is usually collected and pumped away keeping it separate from the slurry. Large, strong bags, placed within a bundled area, are used to store the slurry. Slurry is pumped in to the bag. Slurry bags come in a range of sizes up to 7000m^3 (This capacity is used for a dairy herd or 220 at Harper Adams[26])
Capital costs[27]:	Capital costs based on the EA guidance[28]. £25/m^2 of surface area of slurry Tank £33/m^2 of surface area of Lagoon Capital cost of a slurry bag system is estimated to be £29/m^3 according to a DairyCo case study or a range of £30 – £40/m^3 is provided in a report on *On-farm technologies for the reduction of greenhouse gas emissions in Scotland* (Eory et al 2016). This compares to a clay lined lagoon = £5/m^3 and HDPE (plastic) lined lagoon = £17m/^{3}. Slurry bags could be more cost effective than concrete stores (£39/m^3) and steel towers (£34/m$^{3.}$ Lifetime for depreciation in the Agriculture model is detailed at 10 years.
Running costs:	Covers: Minimal running costs. Payback from reducing rainwater contribution to the storage leading to reduced spreading costs. Slurry Bags: It is important to have the correct slurry handling system to work with the slurry bag system. A fully integrated umbilical system would be beneficial. Larger systems have a large footprint although possibly smaller than a lagoon. The Harper Adams system has a capacity of 7000m^3 and takes up approx. 0.25 ha. Running costs are not likely to be significantly different from other slurry handling systems.
Benefits:	• Benefits to the farmer is that more N is available to the plant if losses are reduced during storage (provided an appropriate application technique is used). • Reducing or separating the rainwater contribution to slurry reduces the total storage capacity required and also the volume of material required to be spread.

[26] http://www.harper-adams.ac.uk/sustainability/doc/Kirby_S_Slurry_Management.pdf

[27] https://dairy.ahdb.org.uk/resources-library/technical-information/health-welfare/cost-effective-slurry-storage-strategies/#.WL2biW-LS1s

[28] How to comply with your environmental permit for intensive farming – Appendix 9 (Environment Agency)

Slurry covers and Slurry Bags	
Barriers:	**Covers** The main barrier will be capital cost. Justifying capital expenditure is difficult with minimal benefits. The situations where this is more likely to be adopted is where there is investment required in new storage facilities or a herd expansion which puts pressure on the slurry storage facilities. In this instance, diverting rain water will be less costly than installing new facilities for slurry storage. **Slurry Bags** Farmer Perception: • From discussion with advisers working with farmers, one of the perceptions is the risk of leaks and damage and general confidence in the membrane • Slurry Management: Storage is one part of an overall slurry management system and if changing to a slurry bag storage facility then the whole system needs to be revised and renewed. • Concerns that high dry matter (DM) (over 7-8%) slurries will not be compatible with pumping slurries in and out of bags. Costs: • Slurry lagoons (especially on clay soils where no liner is required) are much cheaper to implement.
Summary of business receptiveness:	Cost: as with any investment, the payback or return on investment is key to the receptiveness of the business to introducing slurry covers or slurry bags. All farms have a different set of circumstances and challenges that will affect the receptiveness to new technology or business changes. The receptiveness to slurry bags is likely to be low due to the cost and availability of less costly alternatives. Based on farm practices survey data, the current usage of slurry bags is less than 1% of holdings (handling slurry) The use of slurry covers is likely to be far more attractive due to the opportunity to reduce costs associated with storage and application. The main driver for this is the ability to divert rain water from the store. In Nitrate Vulnerable Zones this likely to be even more attractive with additional pressure on storage capacity (22 week storage for cattle slurry systems) and closed periods for applications. The Scottish Survey of Farm Structure and Methods for 2016 states that, of the 3007 holdings with storage of slurry, 62.3% are covered. This does not detail where all stores on a holding were covered. It would not be prudent to assume that 62.3% of slurry in Scotland is covered. The recent Farm Ammonia Grant (FARG) scheme provides a good measure for the receptiveness to covering stores. The scheme provided a grant of £11.20m^2 of are covered for floating covers and £61.00m^2 for self-supporting covers.

Transfer of Slurry and Manures	
Brief description:	The transfer of slurry and manures between farms to optimise the nutrient use efficiency
Capital costs:	Capital costs are dependent on the distances and volumes being transferred. In some instances where the transfer
Running costs:	Moving slurry and manure incurs machinery (depreciation, wear and fuel) and labour costs.

Transfer of Slurry and Manures	
Benefits:	The value of Cattle slurry at 6% DM is 3.56/m^3 according to the Farm Management Handbook (2017/18). The incorporation of organic matter maintains soil organic carbon (SOC). In the correct circumstances slurry and manure applications benefit soil structure; moisture holding capacity; diversity and activity of soil organisms.
Barriers/risks:	• The costs of moving large volumes of slurry are high due to the relative bulk of the material and the value. It is still viewed as a 'waste' and thus the recipient is unlikely to pay for haulage and the producer unlikely to export unless completely necessary. • Logistically there are basic challenges (expanded on in the next section). • There are risks with transporting polluting materials via road networks due to spillages and accidents. • Application of organic materials such as cattle slurry have risks to soil and water resources if undertaken inappropriately (at the wrong time, in the wrong place)
Summary of business receptiveness:	Starting with the logistical challenges: The geographic occurrence of farming enterprises tends to follow the limitations of the geographical circumstances. For example, generally, the south west of Scotland has a high proportion of dairy farms compared to the rest of the country due to there being good conditions for growing grass (high rain fall and warm climate) the east of the country tends to be suited for arable systems where the land quality is good. In the east, there are livestock and mixed farming systems do benefit from the incorporation of organic manures. The reality is that to get the benefit of slurry and manure transfer, it would likely to have to move greater distances than is economically or practically feasible. The movement of manure and slurry to where it can be utilised more effectively does already happen and the movement of livestock from the east to west of the country also happens (many store animals move east to be finished). Businesses are receptive to bringing in slurry and manures and there is trading that occurs at a local level. Some farmers will provide straw to livestock farmers and in return they get manure back. To increase activity, there could be local trading structures established to promote the transfer of slurry and manure (machinery rings could be a good broker)

Anaerobic Digestion	
Brief description:	Anaerobic digestion (AD) is the biological breakdown of organic matter into a gas (biogas), water and residual matter. The AD process can be undertaken on wet material capable of flowing and being pumped, or dry material that does not flow. Slurry is a more common feedstock in UK AD processes than FYM. AD facilities consist of tanks from which biogas is harvested.
Capital costs:	The capital costs of AD facilities are high due to the need for multiple mechanical components and storage and processing tanks (digesters)
Running costs:	Operationally - there are ongoing servicing and mechanical costs and daily management time. The scale of these costs vary depending on the size and complexity of the facility.

<table>
<tr><th colspan="2">Anaerobic Digestion</th></tr>
<tr><td>Benefits:</td><td>AD facilities provide some additional slurry storage capacity
Harvested biogas reduces methane emissions and is a source of energy (heat and/or electricity)
Improved nutrient value of digestate and less odour than raw slurry
Reduced DM content for ease of pumping and applications
Reduced Biochemical Oxygen Demand (BOD)
Eligible for Feed-in-Tariff and Renewable Heat incentive</td></tr>
<tr><td>Barriers/risks:</td><td>The significant barrier is the capital cost and lack of payback for the farmer for Slurry only AD. The economics of co-digestion are better but require more infrastructure which is a major limiting factor. Securing finance for this type of investment can be difficult.

Often overlooked are the risks associated with the transportation and application of large quantities of slurry and digestate within a relatively small area. This is especially the case with larger plants. There are costs associated with transporting slurry and digestate.

Planning and feasibility costs can be high, subject to site specific details and feedstocks. Tens of thousands of pounds may need to be spent before knowing if a project can go ahead.</td></tr>
<tr><td>Summary of business receptiveness:</td><td>The receptiveness of farmers to adopting AD technologies on farm are likely to be linked closely to the capital investment and the return on that investment. This very quickly reduces the likelihood of any slurry only systems. The challenge with slurry only systems is that they are working with pre-digested material and the yield of biogas is relatively small. Slurry is generally a useful base feedstock but requires other material for co-digestion. Co-digestion with food waste, animal by-products (ABP) or crop materials (whole crop or grass silage mainly) is most common but increases costs and complexity.

For AD sites to be successful – they require many factors to be correct:
Market/use for biogas – on-site or nearby use or proximity to gas or electricity grid.
Access to reliable source of feedstock – assuming co-digestion, there are risks associated with needing feedstocks such as crop materials when the price is linked to global commodity prices. Longer term contracts with waste processors are required to secure the investment and these can be difficult to negotiate.
Access to land for digestate – this can be challenging and will often require agreements with neighbouring farmers and transportation costs.
Planning and feasibility assessment is crucial to the success of an AD facility and can take time and require a large investment without any guarantees of returns. Fluctuating incentive payments can be a deterent as they can change during the planning phase and have a significant impact on viability.

In summary, the combination of specific requirements and associated financial risks contribute to a low level of business receptiveness for on-farm AD.</td></tr>
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Acidification	
Brief description:	The acidification of slurry has been found to reduce emissions to air of ammonia and greenhouse gases. It involves the addition of acid to lower the pH either in the store or during application of slurry.
Capital costs:	The costs of acidification are high with limited application in the UK at present. The additional cost slurry management is reported as being between £2.50/m3 (Eory et al 2015) and £4.00 (Webb et al 2017)
Running costs:	The cost above is provided on a volume base incorporating all costs including capital and running costs.
Benefits:	Reduces ammonia and GHG emissions
Barriers/risks:	Cost and market availability
Summary of business receptiveness:	It is understood that the technology is not market ready in the UK as there is not a sales and servicing network, and the on-farm knowledge that is needed has not been developed. Furthermore, there are concerns in the agriculture industry about safety associated with the use of a concentrated acid (usually sulphuric acid) and the potential for increased emission of hydrogen sulphide. Likely considerations for receptiveness would be legislative or market drivers. Negligible benefits and significant additional costs mean that voluntary uptake is unlikely. In Denmark, uptake has been achieved by government restrictions on agricultural developments that would emit NH_3. By abating NH_3 emissions, farmers can expand their capacity, allowing them to increase production.

Manure Application

Slurry application – rapid incorporation	
Brief description:	Partial incorporation of manures with 12 hours of application applied via low trajectory systems to arable land. Not applicable for growing crops and no-till systems.
Capital costs:	Minimal as there this will only occur in situations where cultivation will occur anyway.
Running costs:	As above but ensuring the timing is correct can be challenging. There may be logistical and practical constraints because of ground condition and weather.
Benefits:	Cost benefit in realising a greater proportion of the available N through rapid incorporation of manures.
Barriers/ risks:	There are limited risks. There may be a view that it is logistical difficult. Access to machinery for timely field cultivations. For example, if contractors are used. There may be a limited understanding of the benefit
Summary of receptiveness:	Uptake potential and receptiveness is good where the circumstances are right. The main barrier to this is the understanding

Timing of slurry application –	
Brief description:	Applying slurry and manure at optimum times to ensure that the nutrient content can be utilised by the crop when it is in a growth and development stage. Optimum timings tend to be in the spring and early summer but timings do vary depending on the development stage of the plant.
Capital costs:	Applications: Minimal, although specialist equipment may be required to limit crop damage or grazing can take place. For example, trailing shoe application to grass can reduce the contamination to the grass sward. Storage: additional storage may be required to be able to fully utilise the slurry in NVZ areas this is less likely to be problem as 22 weeks of storage is required but this depends on the housed period.
Running costs:	No additional cost unless using another application method – see section on running costs for precision application methods.
Benefits:	Cost benefit in realising a greater proportion of the available N the appropriate timming of application. This can reduce fertiliser costs significantly. The Farm Management handbook puts a value of 3.56/m3 Cattle slurry at 6% DM.
Barriers/ risks:	There are limited risks. Barriers might be that the application of slurry to grass at appropriate times does not fit with grazing regimes. Using a trailing shoe can reduce the exclusion times following applications. Applications to crop land can be made but require band spreaders (trailing hose)
Summary of receptiveness:	This approach is common place and is good practice. Understanding the value of slurry and manure should be part of the basics of farm operations but often logistical or practical barriers exist such as adequate storage facilities and legitimate concerns over sward contamination on silage ground.

Trailing Shoe, Trailing Hose and Shallow Injection	
Brief description:	**Shoe**: Delivers slurry to soil surface below the crop canopy in narrow bands (20-30 cm apart) reducing the emitting surface area. This technique is mainly applicable to grassland and arable crops with widely spaced rows. The machine working width is typically limited to 6 – 8 m. **Hose**: The trailing hose This technique discharges slurry at or just above ground level through a series of hanging or trailing pipes or flexible hoses, which either hang a short distance (<150 mm) above the soil or are dragged along the soil surface. The working width is typically between 6 and 12 m, although larger units of up to 24 m width are commercially available. Suitable for grass and some crops. **Injection**: (not currently shortlisted) The Slurry is injected below the soil surface into slots created by discs.
Capital costs:	Investment in the machinery is significant – as a guide splash plate based vacuum tankers may cost in the region of £12-15k with tailing shoe and injection machines ranging £25k and £40k. Most of the applications done by trailing shoe will be done by contractors. Contractors charges range from around £60 and £70 per hour for shoe, hose, injection applications in comparison to standard splash plate equipment at £40-£50/hour. With splash plate equipment the work will be done considerably more quickly.

Trailing Shoe, Trailing Hose and Shallow Injection	
Running costs:	Depreciation, parts and general wear and tear on machinery is higher on equipment that has more contact will the ground and soil and more moving parts. Running costs are much higher in with trailing shoe/hose and injection which is reflected in the contracting costs. Injection is likely to have the highest running costs.
Benefits:	More N available for uptake by the crop reducing N fertiliser applications. Indicatively, the benefit could be £5-£9 per ha benefit[29]
Barriers/risks:	The added cost is difficult to justify. Many farms still own their own tankers and see it as an easier and cheaper option to spread using their own labour and existing machinery. Advisers we have spoken to have all mentioned the difficulties in applying an inconsistent slurry through a shoe, hose or direct injection method and how they cannot handle dry matter content over 6-7%. Additional work taking a longer time for application is a barrier despite the potential additional N.
Summary of receptiveness:	Voluntary uptake is likely to remain low as the financial benefit is not clear enough to make the change. Perceptions of difficulties on stoney ground and the additional cost and reduced work rate are negative factors for farmers.

[29] http://farmnw.co.uk/factsheets/cost_effective_slurry_spreading

Appendix 4: SWOT analysis of market-ready technologies and comparative analysis

SWOT analysis

In this analysis of strengths, weaknesses, opportunities and threats (SWOT), we have drawn information from the other task outputs and also from the expert knowledge of the project team The list of management options included is as follows.

- Store covers (e.g. floating, rigid)
- Store type (bags)
- Transfer to other farms/areas
- Anaerobic digestion of slurry
- Slurry acidification (NOTE: not yet market ready in Scotland)
- Spreading timing (seasonal timing)
- Spreading methods (e.g. trailing hose, trailing shoe, shallow injection)

Some management options that were candidates for inclusion in the analysis have been excluded. These are given below with the reason for exclusion.

- Housing and slurry removal management options
  Housing emissions are not represented in the IPCC methodology for national inventory reporting. Emissions associated with livestock housing and removal of slurry to storage are not readily mitigated in existing production systems, because changes require large capital expenditure and usually are considered only when new housing is planned.

- Slurry separation
  This increases emission of NH_3, and is therefore excluded, as mitigation options that increase emission of NH_3 are not acceptable because NH_3 emissions are high nationally and close to the permitted emission ceiling. Effects on GHG emissions are highly uncertain.

- Aeration of slurry in tanks or lagoons – is this a practice we should consider?
  This option can mitigate CH_4, but emission of NH_3 is increased. Mitigation options that increase emission of NH_3 are not acceptable because NH_3 emissions are high nationally and close to the permitted emission ceiling.

- Washing systems
  Effects on GHG mitigation are expected to be minor and highly uncertain. Furthermore, verification of the adoption of the option is difficult.

Store covers (e.g. floating, rigid)

Store covers (e.g. floating, rigid)	
Strengths	Weaknesses
• Saving N loss decreases need for inorganic fertiliser, estimated at between 0.2 and 0.3 kg N per m^3 of slurry applied. • Benefits relatively well understood, considerable uptake already. Although survey data show 38% of stores are uncovered, actually this could be higher for stores that could be covered as data include all types of storage including under slatted floors for example. • Applicable to most slurry-based livestock systems; additional benefits where storage capacity is limited (rainfall excluded). • Benefit of excluding rainfall, so less transport and spreading, leads to high receptiveness. • Low requirement for technical knowledge on farm.	• Capital cost is a barrier despite the benefits • Less GHG saving if surface usually forms a crust (animal type?) • GHG saving is small relative to Scotland's agricultural GHG emissions total • Lack of understanding of possible scale of deployment because of poor survey data
Opportunities	Threats
• Compliance with NVZ rules for adequate storage is easier if rainwater is excluded, reducing capacity requirement • GHG and NH_3 emissions reduction – assuming 50% of slurry is already covered, and mitigation potential is 50%, we estimate a saving of 180 kt CO_2e per annum, approximately 2% of Scotland's agriculture GHG emissions.	• N_2O emission increases alongside decrease in NH_3 emission (check wording) •

Store type (bags)

Store type (bags)	
Strengths	Weaknesses
• Saving N loss decreases need for inorganic fertiliser, estimated at around 0.4 kg N per m^3 of slurry applied on an individual farm. • Benefit of excluding rainfall, so less transport and spreading. • With bunding, storage is more secure (less vulnerable to water contamination from leaks) than covered lagoon	• Capital cost is a barrier compared with other storage • GHG saving is small relative to Scotland's agricultural GHG emissions total • Low deployment opportunity as applied only when new storage is required and in many cases would not be selected due to cost comparison with alternatives • Will usually require new end-to-end slurry management system, adding to costs • Not suited to higher dry matter materials (over 8%% DM) • Poor technical understanding of the capability of the system (e.g. concern about leaks) • May need larger land area than a lagoon, as slurry depth is less
Opportunities	Threats
• Compliance with NVZ rules for adequate storage is easier if rainwater is excluded, reducing capacity requirement • GHG and NH_3 emissions reduction – assuming 5% uptake of slurry bags and 90% mitigation of GHGs, we estimate a saving of 32 kt CO_2e per annum, approximately 0.4% of Scotland's agriculture GHG emissions.	• End of life disposal may have greater environmental impact than materials from alternatives (e.g. lagoon lining), as there is more material to dispose of.

Transfer to other farms/areas

Transfer to other farms/areas	
Strengths	Weaknesses
• Movement of nutrient from an area in surplus to an area in deficit, results in saved application of inorganic fertilisers • Can improve soil properties (e.g. organic matter, water holding capacity, nutrient retention, soil structure, diversity of soil organisms) when applied appropriately in situations where organic materials would not otherwise be applied. • At local (5 km radius) level, high scope for deployment. • Applicable to any farm system producing slurry and close enough to an area with nutrient deficit.	• Cost of transport, machinery and staff time is a barrier. • This measure is not suitable for long distances between exporting and importing farms. • There is a perception of slurry as a waste rather than as a resource, and this is a barrier to implementation.
Opportunities	Threats
• Compliance with NVZ rules for N-max calculations is easier if N is exported from the farm. • Can maintain soil organic carbon on the importing farm, to aid compliance with GAEC 6 (maintain the level of organic matter in the soil). • GHG emissions reduction through more effective use of nutrients, partially displacing manufactured fertiliser. • Avoidance of nutrient leaching on the farm producing slurry, by reducing overall nutrient load. • Potential for larger benefits if cost barriers for longer-distance transport (e.g. from intensive livestock regions to mainly arable regions) can be overcome.	• Risk of spillage on the road network with consequences for water protection • Greater GHG emissions associated with transport energy use, especially for longer distances.

Anaerobic digestion of slurry

<table>
<tr><th colspan="2">Anaerobic digestion of slurry</th></tr>
<tr><td>Strengths</td><td>Weaknesses</td></tr>
<tr><td>Helps to minimise GHG emissions from agriculture and offsets natural gas usage
Digestate has low odour compared to raw slurry
There is evidence that the digestion process increases the availability of nutrients and reduces COD
Digestate is lower DM so easier to pump and apply to land</td><td>High planning and feasibility cost
High capital cost
Only suitable to certain farming systems
Transportation of digestate incurs costs and risks of pollution</td></tr>
<tr><td>Opportunities</td><td>Threats</td></tr>
<tr><td>Incentives could encourage the use of more slurry and manure to encourage this activity.
Landfill ban on organic waste could increase need for new AD capacity in Scotland. Opportunity to incentivise slurry/FYM inclusion and design facilities from outset to co-digest with slurry/FYM
CARES funding
Based on a scenario of 5% increase in slurry processed by AD, and and 90% mitigation of GHGs, we estimate a saving of 32 kt CO_2e per annum, approximately 0.4% of Scotland's agriculture GHG emissions.
There will also be GHG savings through through substitution of grid energy by biogas, and through displacement of fertiliser emissions. For the latter, the change in GHG emissions from current practice will be small.</td><td>Risk associated with securing adequate (quantity and price) feedstock over the lifetime of the digester
Fluctuating incentives such as feed in tariff and renewable heat incentive (RHI)
Feedstock sustainability criteria may affect crop materials</td></tr>
</table>

Slurry acidification (NOTE: not yet market ready in Scotland)[30]

Slurry acidification (NOTE: not yet market ready in Scotland)	
Strengths	Weaknesses
• Saving N loss decreases need for inorganic fertiliser. • Applicability to all farm systems where slurry is managed. • Danish experience demonstrates safe operation	• Capital and management costs will be greater than the financial benefit of increased N input to crops. • Skills for operation and maintenance are not currently developed in Scotland. • Cannot be deployed currently because the support systems are not in place in Scotland.
Opportunities	Threats
• GHG emissions reduction (CH_4) is expected (not calculated, as deployment is not expected soon)	• Perceived and potential health and safety risks associated with handling strong acid, and emission of H_2S • Small risk of soil acidification if lime inputs are not adjusted

[30] We have included slurry acidification in this analysis because there is mitigation potential and it is a practical measure. Slurry acidification is applied in Denmark, where there is a sales and maintenance network to support the technology. This technique for NH_3 abatement is, therefore, tried and tested, and has known mitigation potential for both NH_3 and GHGs (CH_4). However, In Scotland the sales and maintenance network is not in place, and farmers are unfamiliar with the technology.

Spreading timing (seasonal timing)

Spreading timing (appropriate seasonal timing)	
Strengths	Weaknesses
• Application when the crop can use the nutrients reduces the need for inorganic fertiliser. • Can be deployed on any farm. • Applicable to all farm systems.	• Requirement for sufficient equipment and staff to spread in a timely way (spreading may need to be compressed into a shorter time period). • Farms must have adequate storage; capital investment may be required. • Lack of understanding of the fertiliser value of spreading at the best time is a barrier.
Opportunities	Threats
• Application when the crop can use the nutrients reducing risk of non-compliance. • Application when the crop can use the nutrients reduces leaching of nutrients into ground water • GHG emissions reduction through better use of nutrients in slurry and reduced need for inorganic fertilisers	• No significant threats if good practice is followed

Spreading methods (e.g. trailing hose, trailing shoe, shallow injection)

Spreading methods (e.g. trailing hose, trailing shoe, shallow injection)	
Strengths	Weaknesses
• By applying slurry at ground level or in the soil saves NH_3 emission and therefore N loss, decreasing the need for inorganic fertiliser, estimated at between 1 and 2 kg N per m^3 of slurry applied. • Can be deployed on any farm, except for trailing shoe and injection on stony or steep ground. • Applicable to all farm systems.	• Costs greater than for alternatives; wear and tear of equipment is greater than for other spreaders; labour cost is greater than for other methods. • Farm loses flexibility when using contractors. • Capital investment may be required if contractors are not used. • More technically demanding field operation requiring greater operator expertise.
Opportunities	Threats
• GHG emissions reduction through better use of nutrients in slurry and reduced need for inorganic fertilisers.	• No significant threats if good practice is followed

Comparative analysis

Here we provide a comparative analysis of available technologies, in terms of GHG emissions and practical application in Scottish farm businesses. We have drawn together outputs from all the preceding tasks. The shortlisted management options (i.e. those using technologies that are already adopted at least to some extent, or are market-ready if not already adopted) are as follows:

- Store covers (e.g. floating, rigid)
- Store type (bags)
- Transfer to other farms/areas
- Anaerobic digestion of slurry
- Spreading timing (seasonal timing)
- Spreading methods (e.g. trailing hose, trailing shoe, shallow injection)

Store covers (e.g. floating, rigid)				
Description	Practical applicability	Current uptake	GHG emissions and mitigation potential	Barriers and opportunities
A floating cover is a floating cover on the surface of the slurry store or lagoon. This is often a plastic cover resting on the surface that rises and falls with the slurry volume. Rain water is usually collected and pumped away from these storage places to keep this separate from the slurry. Self-supporting covers are also used and form a tent-like structure over the store. Only applicable to tank structures.	• The store cover is applicable to most slurry-based livestock systems. It has additional benefits where storage capacity is limited (rainfall excluded). • The benefit of excluding rainfall, so less transport and spreading, leads to high receptiveness. • A store cover has a low requirement for technical knowledge on the farm.	The Scottish Survey of Farm Structure and Methods for 2016 states that, of the 3007 holdings with storage of slurry, 62.3% are covered. This does not detail where all stores on a holding were covered. It would not be prudent to assume that 62.3% of slurry in Scotland is covered as farms often have multiple storage facilities.	**Emissions:** Total from slurry management: 581 kt CO_2e Of this, the total from slurry storage is estimated to be 533 kt CO_2e (Percentage of NH_3 emissions from manure management in UK that are from storage: 11%) **Mitigation potential:** Studies give differing values depending on slurry type, cover type, store type, climate, etc. Values vary from 15% to 90%. Some mitigation already occurs. Based on a scenario because of poor data availability, we assume that 50% of slurry is already covered, and mitigation potential is 50%. We estimate a saving of 180 kt CO_2e per annum, approximately 2% of Scotland's agriculture GHG emissions. Some fertiliser is displaced by N saved through	**Barriers:** The main barrier for uptake will be capital cost. Justifying capital expenditure is difficult when there are limited benefits. The situations where store covers are more likely to be adopted is where there is investment required in new storage facilities or a herd expansion. These new investments put pressure on the slurry storage facilities. In this instance, diverting rain water will be less costly than installing new facilities for slurry storage. **Opportunities** • Compliance with NVZ rules for adequate storage is easier if rainwater is excluded, reducing capacity requirement • GHG and NH_3 emissions reduction – less methane emission [add values]

			mitigation of NH_3 emission. We estimate that this will be less than 10 kt CO_2e, and less than 0.1% of Scotland's agriculture GHG emissions.	

Store type (bags)				
Description	Practical applicability	Current uptake	GHG emissions and mitigation potential	Barriers and opportunities
Large, strong bags, placed within a bundled area, are used to store slurry. Slurry is pumped into the bag. The slurry bags come in a range of sizes up to 7000m^3. This large capacity is used for a dairy herd or 220 at Harper Adams[31])	• Excluding rainfall helps to reduce level of transport and spreading required • With bunding, storage is more secure (less vulnerable to water contamination from leaks) than a covered lagoon. • Slurry bags will usually require new end-to-end slurry management system, adding to costs, which makes them less applicable. • Not suited to higher dry matter materials (over 8%% DM) • There is poor technical understanding of the capability of the system (e.g. concern about leaks) • May need larger land area than a lagoon, as slurry depth is less	Based on farm practices survey data, the current usage of slurry bags is less than 1% of holdings (handling slurry) • Slurry bags have a low deployment opportunity as they are only applied when new storage is required. In many cases slurry bags would not be selected as it is more expensive than alternative storing methods.	**Emissions:** Total from slurry management: 581 kt CO_2e Of this, the total from slurry storage is estimated to be 533 kt CO_2e (Percentage of NH_3 emissions from manure management in UK that are from storage: 11%) **Mitigation potential:** Based on a scenario because of poor data availability, we assume that 5% uptake of slurry bags and 90% mitigation of GHGs. We estimate a saving of 32 kt CO_2e per annum, approximately 0.4% of Scotland's agriculture GHG emissions. Some fertiliser is displaced by N saved through mitigation of NH_3 emission. We estimate that this to be trivial because of the low uptake.	**Barriers:** • From discussion with farm advisers, a perception of farmers is the risk of leaks and damage, with poor confidence in the membrane • Storage is one part of a slurry management system; changing to a slurry bag for storage requires changes to the whole system. • Concerns that high dry matter (DM) (over 7-8%) slurries will not be compatible with pumping slurries in and out of bags. • Capital cost is a barrier compared with other storage methods. • Slurry lagoons (especially on clay soils where no liner is required) are much cheaper to implement. **Opportunities** • Compliance with NVZ rules for adequate storage is easier if rainwater is excluded, reducing capacity requirement.

[31] http://www.harper-adams.ac.uk/sustainability/doc/Kirby_S_Slurry_Management.pdf

Transfer to other farms/areas				
Description	Practical applicability	Current uptake	GHG emissions and mitigation potential	Barriers and opportunities
The transfer of slurry and manures between farms to optimise the nutrient use efficiency	• This measure is not suitable for long distances between exporting and importing farms. • There are risks with transporting polluting materials via road networks due to spillages and accidents.	We were unable to obtain information on the quantity of manure or slurry transferred off farm. It is likely that the areas where slurry transfer takes place it will be due to NVZ restrictions on applications or if there are specific agreements between farmers about trading straw and manure returns. It is unlikely that the transfer/export of slurry happens beyond a 5km radius due to the costs associated with transportation. The transfer of animals between farms does occur. The most relevant example of this is the movement of store animals being bought for finishing on arable farms with crops to feed and straw for bedding. These animals provide a useful source of organic matter.	**Emissions:** Total from slurry management: 581 kt CO_2e **Mitigation potential:** No direct GHG mitigation. Mitigation potential relates to saving in NH_3 emission, more N applied to soil, and therefore decreased need for N fertiliser. We have not estimated the potential saving in N fertiliser application through more efficient use of slurry because the extent to which extra fertiliser is displaced, through transfer to another farm, is highly uncertain.	**Barriers:** • Cost of transport, machinery and staff time. • There is a perception of slurry as a waste rather than as a resource. • The costs of moving large volumes of slurry are high due to the bulk of the material and the low value. It is still viewed as a 'waste' so the recipient is unlikely to pay for haulage and the producer unlikely to export unless necessary. • This measure is not suitable for long distances between exporting and importing farms. • Application of organic materials such as cattle slurry have risks to soil and water resources if undertaken inappropriately **Opportunities** • Compliance with NVZ rules for N-max calculations is easier if N is exported from the farm. • Can maintain soil organic carbon on the importing farm, to aid compliance

				with GAEC 6 (maintain the level of organic matter in the soil). • GHG emissions reduction through more effective use of nutrients, partially displacing manufactured fertiliser. • Avoidance of nutrient leaching on the farm producing slurry, by reducing overall nutrient load. • Potential for greater implementation if cost barriers for longer-distance transport (e.g. from intensive livestock regions to mainly arable regions) can be overcome.
Anaerobic digestion of slurry				
Description	Practical applicability	Current uptake	GHG emissions and mitigation potential	Barriers and opportunities
Anaerobic digestion (AD) is the biological breakdown of organic matter into a gas (biogas), water and residual matter. The AD process can be undertaken on wet material capable of flowing and being pumped, or dry material that does not flow. Slurry is a more common feedstock in UK AD processes than FYM. AD facilities consist of tanks	• This measure is applicable to a wide range of farm systems. • Access to a reliable feedstock supply for co-digestion is required. • There are specific skill requirements for operation and maintenance.	Uptake is very low in terms of numbers of farms and volume of material. There are 5 facilities are recorded as *only* processing slurry/manure (two no longer in operation). There are a further 16 facilities that are reported to process animal slurries and manure alongside other wastes and crop feedstocks (14 facilities), with a combined	**Emissions:** Total from slurry management: 581 kt CO_2e Of this, the total from slurry storage is estimated to be 533 kt CO_2e **Mitigation potential:** Based on a scenario of 5% increase in slurry processed by AD, and and 90% mitigation of GHGs, we estimate a saving of 32 kt	**Barriers:** • A significant barrier is the capital cost and lack of payback for the farmer for Slurry only AD. The economics of co-digestion are better but require good gas grid connections which is a major limiting factor. • Securing finance for this type of investment can be difficult.

from which biogas is harvested. These tanks can act as storage facilities for farms.		processing capacity of 300,500 tonnes per annum	CO_2e per annum, approximately 0.4% of Scotland's agriculture GHG emissions. There will also be displacement of grid energy emissions, through substitution of grid energy by biogas. There will also be displacement of fertiliser emissions, but the change from current practice will be small.	• Often overlooked are the risks associated with the transportation and application of large quantities of digestate within a relatively small area. This is especially the case with larger plants. There are costs associated with transporting digestate. • Planning and feasibility costs are high. Tens of thousands of pounds may need to be spent before knowing if a project can go ahead. **Opportunities** • Harvested biogas reduces methane emissions and replaces other natural gas requirements • AD facilities also provide slurry storage capacity • Improved nutrient value of digestate • Reduced DM content for ease of pumping and applications • Reduced Chemical Oxygen Demand (COD) • AD plants are eligible for Feed-in-Tariff and Renewable Heat incentive

Spreading timing (seasonal timing)				
Description	Practical applicability	Current uptake	GHG emissions and mitigation potential	Barriers and opportunities
Applying slurry and manure at optimum times to ensure that the nutrient content can be utilised by the crop when it is in a growth and development stage. Optimum timings tend to be in the spring and early summer but timings do vary depending on the development stage of the plant.	• Requirement for sufficient equipment and staff to spread in a timely way (spreading may need to be compressed into a shorter time period). • Farms must have adequate storage; capital investment may be required. • Good understanding of the fertiliser value of spreading at the best time is necessary. • Can be deployed on any farm and applicable to all farm systems.	There is limited evidence indicating timings of applications. In NVZ areas the appropriate timing of applications is likely to more common due to the requirements for storage through the winter and closed periods for applications out-with the growing season.	**Emissions:** Total from slurry management: 581 kt CO_2e Of this, the total from slurry application is estimated to be 48 kt CO_2e (Percentage of NH_3 emissions from manure management in UK that are from application: 26%) **Mitigation potential:** No direct GHG mitigation. Mitigation potential relates to saving in N lost from the slurry through leaching because of poor application timing. We have not estimated this potential saving because the extent of current poor practice, and therefore the potential for improvement, is highly uncertain.	**Barriers:** • Limited risks. Perception of logistical difficulty. • Access to machinery for timely field cultivations. • Perceptions of benefits. **Opportunities** • Application when the crop can use the nutrients reduces risk of non-compliance. • Application when the crop can use the nutrients reduces leaching of nutrients into ground water • GHG emissions reduction through better use of nutrients in slurry and reduced need for inorganic fertilisers

<table>
<tr><th colspan="5">Spreading methods (e.g. trailing hose, trailing shoe, shallow injection)</th></tr>
<tr><th>Description</th><th>Practical applicability</th><th>Current uptake</th><th>GHG emissions and mitigation potential</th><th>Barriers and opportunities</th></tr>
<tr>
<td>There are several spreading alternative methods:

Shoe: Delivers slurry to soil surface below the crop canopy in narrow bands (20-30 cm apart) reducing the emitting surface area. This is mainly applicable to grassland and arable crops with widely spaced rows. The machine working width is typically limited to 6 – 8 m.

Hose: The trailing hose discharges slurry at or just above ground level through a series of hanging or trailing pipes or flexible hoses, which either hang a short distance (<150 mm) above the soil or are dragged along the soil surface. The working width is typically between 6 and 12 m, but units up to 24 m wide are commercially available.

Injection: (not shortlisted) The Slurry is injected below the soil surface into slots made by discs.</td>
<td>• Can be deployed on any farm, except for trailing shoe and injection on stony or steep ground.
• Applicable to all farm systems.
• Farm loses flexibility when using contractors that are necessary for some of these methods.
• Capital investment may be required if contractors are not used.
• More technically demanding filed operation requiring greater operator expertise.</td>
<td>Band spreading and injection less than 10% (SRUC CXC report)

4% injection and trailing shoe

24% band spreader with trailing hose

The current uptake of band spreading and injection is less than 10% (SRUC CXC report)

For injection and trailing shoe the current uptake is 4% and for band spreading with trailing hose current uptake is 24%.</td>
<td>**Emissions:**
Total from slurry management: 581 kt CO_2e. Of this, the total from slurry application is estimated to be 48 kt CO_2e. (Percentage of NH_3 emissions from manure management in UK that are from application: 26%)

Mitigation potential:
No direct GHG mitigation (see Appendix 2 for comment on N_2O emissions).

Mitigation potential relates to saving in NH_3 emission, more N applied to soil, and therefore decreased need for N fertiliser.

Some fertiliser is displaced by N saved. Assuming 50% uptake of improved spreading methods, we estimate that this will be less than 25 kt CO_2e, and less than 0.3% of Scotland's agriculture GHG emissions.</td>
<td>**Barriers:**
• The added cost is difficult to justify. Many farms own tankers and it is easier and cheaper to spread using their own labour and existing machinery.
• Advisers we have spoken to have all mentioned the difficulties in applying an inconsistent slurry through a shoe, hose or direct injection method and how they cannot handle dry matter content over 6-7%. Additional work taking a longer time for application is a barrier despite the potential additional N.
Opportunities
• More N available for uptake by the crop reducing N fertiliser applications. Indicatively, the benefit could be £5-£9 per ha benefit[32]; there is also a GHG saving.</td>
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</table>

[32] http://farmnw.co.uk/factsheets/cost_effective_slurry_spreading

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