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Review of options for reducing greenhouse gas emissions via cattle slurry management in Scotland

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Summary

The Scottish Government commissioned ClimateXChange to assess the greenhouse gas abatement potential from a range of measures to manage slurry in Scotland, to inform policy thinking on the forthcoming Climate Change Plan. This report presents findings on the potential effectiveness of five types of measures.

Most cattle in Scotland are housed from the late autumn to early spring, which necessitates the storage of manures during this period. Greenhouse gases (methane and to a lesser extent nitrous oxide) are emitted during storage, and these currently account for 7% of total agricultural emissions in Scotland. Further emissions (mainly nitrous oxide) occur post-storage when manures are applied to land. This report compares mitigation measures available for the delivery of effective reduction in GHG emissions from the management and use of cattle slurry on Scottish farms.

Key findings are:

1. In 2015 the amount of volatile solids (VS – undigested organic matter) excreted and managed (i.e. not deposited directly by grazing animals) by Scottish cattle was estimated to be just over 700kt, comprised of 253kt from the dairy herd and 448kt from the beef herd.
2. 471kt of VS were managed as solids and 230kt were managed as liquids.
3. There is reasonable confidence that three of the measures (slurry covers, anaerobic digestion and slurry acidification) could lead to reductions in GHG emissions.
4. However, the extent to which GHG emissions can be mitigated appears to be modest, i.e. in the order of 20ktCO_2e in Scotland. Anaerobic digestion and slurry acidification seem most likely to be able to mitigate emissions at a cost that is lower than benefits (i.e. at less than the cost of carbon assuming a cost of £50/tCO_2e). However, acidification may pose an unacceptable health and safety risk. It may be possible to identify additional mitigation with further analysis, for example the abatement that could be achieved from manure exchange is not included in this total.
5. Recent evidence suggests that band spreading/injection may not lead to a net reduction in emissions due to increased rates of direct nitrous oxide production. At present there is insufficient evidence to estimate the AP of optimising the use of manures.
6. Some slurry mitigation measures, particularly those that also reduce ammonia (NH_3) (i.e. slurry covers, slurry acidification and band spreading/injection), can provide significant wider benefits such as improved human health, reduced eutrophication of water bodies and reduced soil acidification.

7. Policy to support slurry management measures should encourage, where possible, adoption of combinations of measures that have positive synergies.

The following table summarises findings on GHG abatement potential and cost effectiveness.

Table S1. Summary of the mitigation measure appraisal.
Disadvantage or barrier denoted by "-" Advantage denoted by "+".

Measure	**Main mode of mitigation**	**Abatement potential**	**Mitigation cost**	**Benefits, disadvantages and barriers to uptake**
Covering slurry stores	Reduced indirect nitrous oxide from ammonia emitted during slurry storage	5-7ktCO_2e	High unless co-benefits are included.	+Significant non-GHG benefits from ammonia reduction (i.e. human health and eutrophication) +Reduced slurry volumes +Increased N retention +Reduced odour -Some practical barriers to uptake
Anaerobic digestion	Reduced methane from slurry storage Provision of low emissions heat and power	~11ktCO_2e	Variable, depending on a wide range of factors	+Reduces non-renewable resource depletion -Technically complex -Securing feedstock can be challenging -Changing energy policy complicates the financial appraisal of AD projects -Potential food/feedstock trade-off
Slurry acidification	Reduced indirect nitrous oxide from ammonia during slurry storage and land application	~7ktCO_2e	High but potentially cost-effective	+Relatively simple to implement on farm +Reduced non-GHG impacts from ammonia +Increased nutrient value of slurry -Risk to human health and safety, particularly acid handling and increased hydrogen sulphide emissions -Increased corrosion of equipment -Risk of pollution swapping
Band spreading and injection	Reduced indirect nitrous oxide from ammonia during slurry land application	Negligible	High	+Reduced non-GHG impacts from ammonia +Increased retention of applied N in soil -Expensive. -Risk of increased direct nitrous oxide -Injection not suitable for stony soils
Optimising use of manures via manure exchange and animal movement	Improved targeting or organic fertiliser and reduced synthetic fertiliser demand.	Not known	Variable, depending on distance, manure properties, fertiliser cost etc.	+Non-GHG benefits of improved nutrient use efficiency, e.g. improved water quality +Could increase cropping diversity +Increased soil organic content -Manures more challenging to use than synthetic fertiliser -Animal health and welfare -Lack of infrastructure and knowledge required to manage livestock on some arable farms

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Abbreviations

AD	Anaerobic digestion
AF	Adult female cattle
AP	Abatement potential
AR	Abatement rate
AWMS	Animal waste management system
BtG	Biomethane to grid
CCL	Climate Change Levy
CE	Cost-effectiveness
CH_4	Methane
CHP	Combined heat and power
CO_2	Carbon dioxide
CO_2e	CO_2 equivalent
DECC	UK Department for Energy and Climate Change
DM	Dry matter
EI	Emissions intensity
ETS	EU Emissions Trading System
FIT	Feed-in tariff
FYM	Farm yard manure
GBR	General Binding Rule
H_2S	Hydrogen sulphide
IPCC	Inter-governmental panel on climate change
kWe	kilo watt electrical
kWh	kilo watt hour
MACC	Marginal abatement cost curve
MSW	Municipal solid waste
MWe	Mega watt electrical
N_2O	Nitrous oxide
NH_3	Ammonia
RHI	Renewable heat incentive
ROCs	Renewable obligation certificates
RTFO	Renewable Transport Fuel Obligation
VS	Volatile solids
VSx	Volatile solid excretion

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Introduction

Key terms

Manure is the general term for collected excreta (dung and urine). Excreta can be combined with bedding materials, such as straw, to produce a solid material that can be stacked without slumping (i.e. farm yard manure, FYM) or combined with rain water, wash water and bedding to produce a liquid material that can be pumped (i.e. slurry).

Slurries can vary a great deal in terms of their chemical composition, i.e. the amount of moisture, organic and inorganic matter they contain (Houlbrooke et al. 2011, p12). Because of this, mass of fresh slurry is sometimes an inappropriate unit of measure. In this report, amounts of slurry are sometimes expressed in terms of mass of volatile solids (VS), i.e. undigested organic matter, as it is the mass of volatile solids that determines the slurry's methane production potential. Organic materials (such as crops or manures) are partly comprised of moisture. As moisture contents can vary, masses are often expressed in terms of dry matter (DM, i.e. the mass without moisture) rather than fresh yield (the mass including the moisture content).

Rationale for the study

Most cattle in Scotland are housed from the late autumn to early spring, which necessitates the storage of manures during this period. Greenhouse gases are emitted during the storage of manures and their subsequent application to land. This report compares mitigation measures available for the delivery of effective reduction in GHG emissions from the management and use of cattle slurry on Scottish farms.

Five groups of mitigation measures were reviewed: (1) covering slurry stores (including slurry bags); (2) anaerobic digestion; (3) slurry acidification; (4) slurry application methods, i.e. band spreading and injection; (5) optimising use of manures via manure exchange (moving manures between farms) and animal movement.

Emissions from manure

Manure accounts for 0.74MtCO_2e, or 7% of total agricultural emissions, mainly arising in the form of methane and, to a lesser extent, nitrous oxide from cattle systems (Figure 1 and E1). In addition, a significant proportion of soil nitrous oxide arises from the application of cattle manures to land.

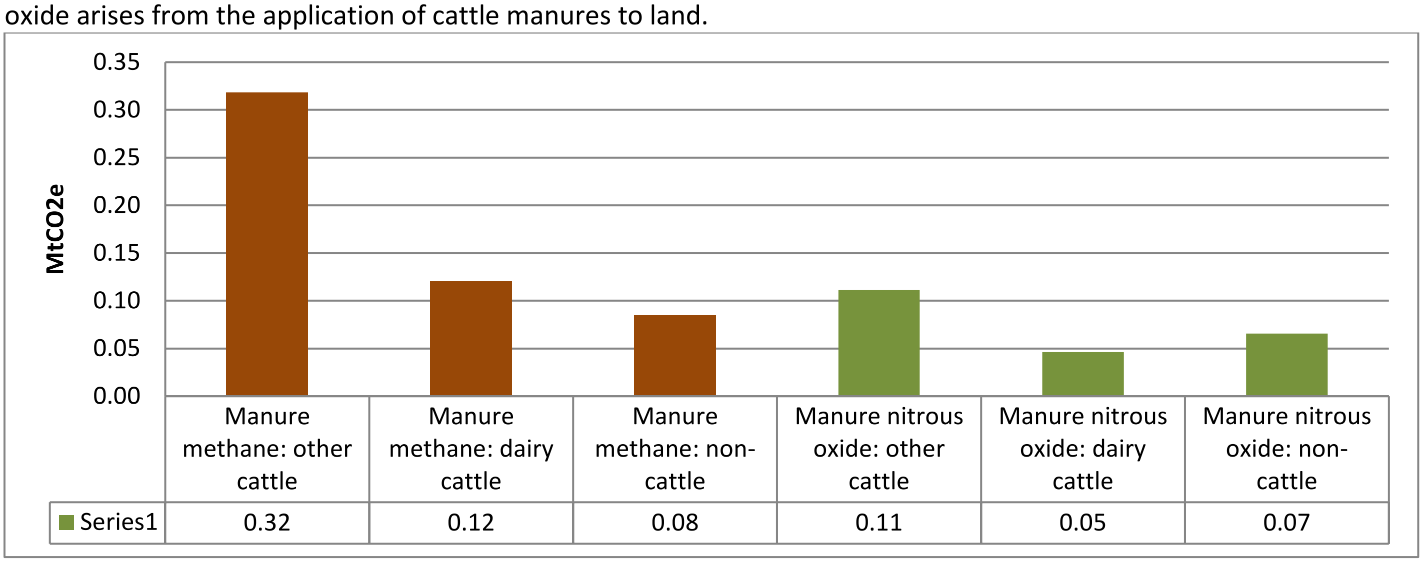

Figure 1. Scottish greenhouse gas emissions 2014, manure management (Scottish Government 2016a)

Patterns of cattle manure production and management in Scotland

The total manure production for Scotland in 2010 was estimated in Smith and Williams (2016) (see Appendix F). For the present study, the total volatile solids excreted, collected and managed as liquid were calculated and mapped (see Figure 2). Details of how the calculations were undertaken and the breakdown for dairy and beef cattle are provided in Appendix F.

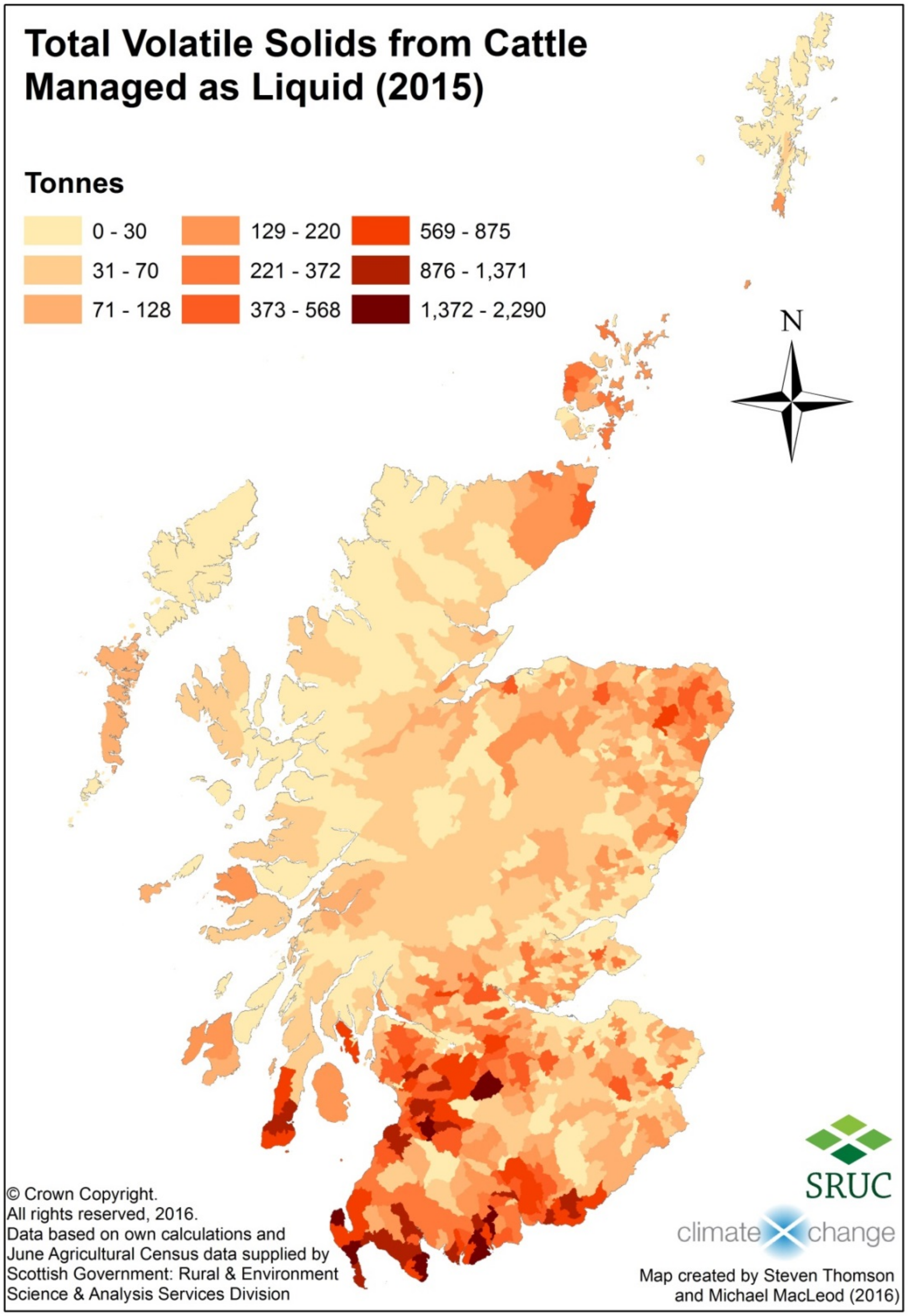

Figure 2. Total VS excreted by dairy and beef cattle and managed as liquid each year, by parish.

Seasonality of cattle manure production

Manure production is highly seasonal with only a small number of animals housed during the summer months (Figure 3). This raises logistical problems for AD plants which require a stable supply of feedstock (in terms of feedstock volume and composition). In order to manage this, AD plants can store manures for use during the summer months and gradually change the mix of feedstocks, partially substituting manures for crops (or other feedstocks). However, this brings significant financial, regulatory and management implications.

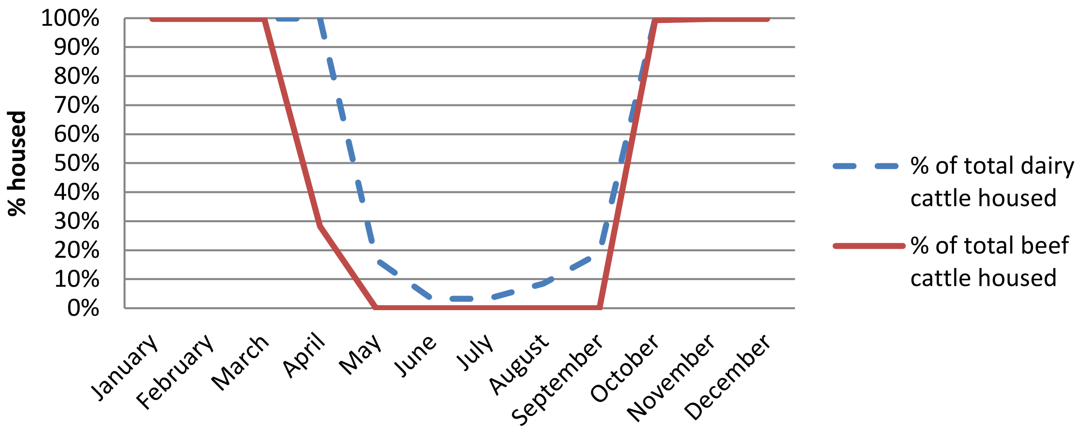

Figure 3. Estimated % of total beef and dairy herds housed during the year (based on Bell 2016)

Slurry management and application in Scotland

In order to make recommendations about how slurry management might be changed, it is necessary to know how it is currently managed. Tables 1 and 2 outline recent estimates of how slurry is stored and subsequently applied in Scotland. Further information on manure management is given in Appendix G.

Table 1 % of VS excreted managed by animal waste management system (AWMS), Scotland 2014. These are the assumptions used in the 2014 UK National GHG Inventory (2016 issue). Source Misselbrook (2016). PRP: pasture, range and paddock, i.e. dung/urine deposited by grazing animals. AD: anaerobic digestion.

	Slurry tanks		Slurry lagoons	Daily spread	Deep litter	PRP	AD	Other	Total
	Above ground	Below ground							
Dairy cows	9%	13%	3%	1%	26%	48%	0%	0%	100%
Dairy followers	5%	7%	1%	1%	15%	71%	0%	0%	100%
Beef cattle	6%	9%	2%	1%	17%	65%	0%	0%	100%
Calves	0%	0%	0%	0%	46%	54%	0%	0%	100%

Table 2. Mode of application of slurry in Scotland, same for beef and dairy. Source Misselbrook (2016)

Mode of application	Arable	Grassland
% of slurry broadcast and not incorporated within 4 hours	67%	78%
% of slurry broadcast and incorporated within 4 hours	11%	NA
% of slurry applied by trailing hose	9%	9%
% of slurry applied by trailing shoe	0%	0%
% of slurry applied by shallow injection	10%	10%
% of slurry applied by irrigation	3%	3%

Summary of the mitigation measures

This section provides a brief summary of each measure (details are provided in Appendix A), its abatement potential and advantages/disadvantages. Detailed quantification of abatement potential is a complex task and is beyond the scope of this project. The estimates made in this report are preliminary and should therefore be treated with caution.

Covering slurry stores

As liquid and solid manures decompose they produce ammonia, a proportion of which is subsequently converted to nitrous oxide. Covering slurry stores (including the use of slurry bags) reduces the area exposed to air and surface area air velocity, thereby reducing the rate of ammonia production.

If an additional 50% of slurry stores were covered, the reduction in nitrous oxide arising from ammonia volatilisation during slurry storage is estimated to be 5-7ktCO2e (Table 3). Further mitigation may arise from reduced synthetic N purchase, as the reduced volatilisation rates mean that more nitrogen is retained in the slurry. The cost of mitigation is likely to be high unless co-benefits are included.

Table 3. Estimated abatement potential (AP) from covering slurry stores

Parameter	Units	Value	Notes
Nitrous oxide via ammonia, all cattle on slurry	$ktCO_2e$	18	Calculated
Permeable (e.g. hexacover) uptake		50%	Assumption
Permeable cover reduction in ammonia		60%	Van der Zaag *et al.* (2015)
Permeable cover AP	$ktCO_2e$	*5.5*	*Calculated*
Impermeable cover (e.g. tent) uptake		50%	Assumption
Impermeable cover reduction in ammonia		80%	Van der Zaag *et al.* (2015)
Impermeable cover AP	$ktCO_2e$	*7.3*	*Calculated*

There are some practical barriers to uptake (such as the difficulty of retrofitting certain types of impermeable covers), but this measure does have other benefits, such as:

- Significant non-GHG benefits from ammonia reduction (i.e. human health and eutrophication);
- Reduced slurry volumes;
- Increased slurry N retention;
- Reduced odour.

Anaerobic digestion

Anaerobic digesters (AD) control the decomposition process and allow methane to be captured and used as a fuel. They can reduce the amount of methane that is emitted from slurry storage and provide heat and electricity to displace fossil fuel combustion. However, they require significant capital investment, and expertise for day-to-day management.

It is estimated than a 1MWe plant (which would be large compared to existing farm-fed plants – see Appendix B) would reduce emissions by about 2.8$ktCO_2e$ per year (see Appendix A2). Increasing Scotland's installed AD capacity by 4MWe (i.e. four 1MWe plants) would therefore reduce emissions by approximately 11$ktCO_2e$ each year. AD can be a cost-effective mitigation measure, but this is dependent on a wide range of factors (such as capital and operating costs, and the price electricity is sold for). While AD reduces non-renewable resource depletion (e.g. fossil fuels) it is technically complex and can be an uncertain investment in face of changing energy policy. Securing a stable supply of quality feedstock is challenging and can lead to food/feedstock trade-offs.

Slurry acidification

Slurry stored in tanks can be acidified by adding strong mineral acids. The acidification reduces the ammonia volatilisation from the tank (and the consequent indirect nitrous oxide emissions), but more importantly also reduces volatilisation from the slurry when applied in the field. Alternatively, slurry can be acidified after storage during field application.

It is estimated that acidification could reduce nitrous oxide emissions from slurry storage by 6ktCO_2e (Table 4). Slurry acidification will also lead to a reduction in emissions during the application of slurry to land, although this reduction is expected to be small (around 1ktCO_2e) due to the small amount of nitrous oxide arising from the volatilisation of N during slurry application. As a result of the 2016 revisions to the National Inventory method, indirect nitrous oxide from ammonia arising during slurry application accounts for only about 2% of the total nitrous oxide arising from application of slurry and FYM to land. Further mitigation may arise from reduced synthetic N purchase.

Acidification is potentially cost-effective and, in theory, relatively simple to implement on farm. It increases retention of N in the slurry and provides the non-GHG benefits from ammonia reduction (i.e. human health and eutrophication). However, the measure may pose an unacceptable risk to human health and safety (particularly via acid handling and increased hydrogen sulphide emissions) and may increase equipment corrosion.

Table 4. Estimated reduction in nitrous oxide from slurry storage via slurry acidification

Parameter	**Units**	**Value**	**Notes**
nitrous oxide via ammonia, all cattle on slurry	ktCO_2e	18	Calculated
Acidification - uptake		50%	Assumption
Acidification - reduction in ammonia		70%	Assumption
Acidification - AP	ktCO_2e	6.4	Calculated

Band spreading/injection of slurry

Livestock slurry can be applied to the soil using a range of techniques. By far the most common approach in Scotland is to use a low trajectory splash plate, which accounts for over 90% of applications. Alternative systems are (a) band spreading in which a series of parallel pipes connected to a slurry tank applies the slurry in discreet bands on the grass surface and (b) injection of slurry below the soil surface.

The use of band spreading and injection can dramatically reduce ammonia emissions (and odour) and thus reduces indirect nitrous oxide emissions. However, the AP is likely to be negligible, given that (a) the assumed rates of ammonia loss from slurry application is low (see slurry acidification, above) and (b) these measures may lead to an increase in direct nitrous oxide. Furthermore they are expensive and injection is unsuitable for stony soils.

Optimising use of manures via manure exchange and animal movement

These measures seek to improve the efficiency of nutrient use by better matching the rates at which organic manures are applied to crop requirements. This could be achieved by the reintegration of crops and livestock, either via the increased exchange of manure between livestock and arable farms or even the movement of livestock to arable farms for part of the year. This could reduce emissions by reducing the amount of N applied per kg of crop yield and reduce the demand for synthetic fertiliser. These measures could provide non-GHG benefits associated with improved nutrient use efficiency (e.g. improved water quality) and could increase cropping diversity and soil organic content.

However manures are more challenging to use than synthetic fertilisers, and some arable farms may lack the infrastructure and knowledge required to manage livestock. Livestock movement also raises issues of animal health and welfare. In summary, these are complex measures that require further investigation before preliminary estimates of AP can be provided.

Summary of the measures

The assessment of AP and mitigation cost are summarised in Table 5. There is reasonable confidence that three of the measures (slurry covers, AD and slurry acidification) could lead to reductions in GHG emissions. Recent evidence suggests that band spreading/injection may not lead to a net reduction in emissions due to increased rates of direct nitrous oxide production. At present there is insufficient evidence to estimate the AP of optimising the use of manures.

AD and slurry acidification seem most likely to be able to mitigate emissions at a cost that is lower than benefits (i.e. at less than the cost of carbon, assuming a cost of £50/tCO_2e). However, acidification may pose an unacceptable health and safety risk. It should be noted that some measures may provide significant ancillary costs and benefits, and these are not included in the assessment of mitigation cost. For example, measures that reduce ammonia emissions (i.e. slurry covers and acidification) will provide further benefits in terms of improved human health, reduced eutrophication of water bodies and reduced soil acidification. It may therefore be advisable to undertake social cost-benefit analysis of such measures during policy development.

Table 5. Summary of the mitigation measure appraisal.

Measure	Main mode of mitigation	Abatement potential	Mitigation cost
Covering slurry stores	Reduced indirect nitrous oxide from ammonia emitted during slurry storage	5-7ktCO_2e	High unless co-benefits are included.
Anaerobic digestion	Reduced methane from slurry storage Provision of low emissions heat and power	~11ktCO_2e	Variable, depending on a wide range of factors
Slurry acidification	Reduced indirect nitrous oxide from ammonia during slurry storage and land application	~7ktCO_2e	High but potentially cost-effective
Band spreading and injection	Reduced indirect nitrous oxide from ammonia during slurry land application	Negligible	High
Optimising use of manures via manure exchange and animal movement	Improved targeting of organic fertiliser and reduced synthetic fertiliser demand.	Not known	Variable, depending on distance, manure properties, fertiliser cost etc.

Interactions between the measures

The measures can be implemented on their own ("stand alone"), or in conjunction with other measures. When two or more measures are implemented simultaneously, they can interact producing positive or negative synergies, i.e. one measure may increase or reduce the efficacy of another. In some cases, measures may be mutually exclusive. Table 6 provides a summary of the potential interactions between measures. Further explanation of these interactions is given in Appendix C.

Table 6. Summary of the potential interactions between measures when implemented together.

If the measure below is implemented, what effect will it have on the AP of measures to the right?	Covering slurry stores	Anaerobic digestion	Slurry acid.	Band spreading/ injection	Manure exchange	Animal movement
Covering slurry stores		Positive	Uncertain	Positive?	Positive	Uncertain
Anaerobic digestion	Negative		Uncertain	Positive	Positive	Uncertain
Slurry acidification	Negative	Uncertain		Negative	Uncertain	Uncertain
Band spreading/injection	No effect	No effect	No effect		No effect	No effect
Manure exchange	Negative?	Negative?	Negative?	Negative?		Negative?
Animal movement	Negative	Negative	Negative	Negative	Negative	

Where possible, policy should seek to avoid combinations of measures with negative synergies and encourage adoption of combinations of measure with positive synergies, such as: (a) slurry covers or AD and manure exchange, (b) slurry covers or AD and adding acid to slurry tanks at the point of field application. It should be remembered that the measures in Table 6 may interact with other mitigation measures not considered in this project. For example, precision feeding can reduce rates of N excretion, reducing the nitrous oxide arising during manure storage and application, and the abatement potentials of the measures in this study.

Conclusions

In 2015 the amount of volatile solids (VS) excreted and managed (i.e. not deposited directly by grazing animals) by Scottish cattle was estimated to be just over 700kt, comprised of 253kt from the dairy herd and 448kt from the beef herd. 471kt of VS were managed as solids and 230kt were managed as liquids. The management of these VS is estimated to have led to the emission of 0.44MtCO_2e of methane and 0.16MtCO_2e of nitrous oxide in 2014. Further emissions of nitrous oxide arise during the application of the VS to land.

The extent to which GHG emissions can be mitigated via slurry management and application appears to be modest, i.e. in the order of 20ktCO_2e, with most of the mitigation being achieved by a substantial increase in the use of slurry as a feedstock in AD plants. Some slurry mitigation measures, particularly those that also reduce ammonia, can provide significant wider benefits, which could make certain measures (such as covering slurry stores and slurry acidification), cost-effective. Finally, measures can interact so it is recommended that policy should encourage, where possible, adoption of combinations of measures that have positive synergies.

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Appendix A. Slurry mitigation measures

A1. Covering slurry stores

How does it the measure work?
Decomposition of urea and other organic compounds in liquid and solid manures produces NH_3, a proportion of which is subsequently converted to N_2O. There are several ways in which the rate of NH_3 production can be reduced (Van der Zaag *et al*. 2015, p77):

1. Reducing the emitting surface area to volume ratio;
2. Reducing the surface air velocity;
3. Reducing the manure temperature;
4. Reducing the pH;
5. Collecting contaminated air and treating it.

Covering slurry stores (including the use of slurry bags) reduces the area exposed to air and surface area air velocity, thereby the rate of NH_3 production. Other potential GHG effects are summarised in Table A1.

Table A1. GHG effects of covering slurry

Emission source	**Effect**
Manure N_2O from NH_3	All covers should reduce NH_3 (Van der Zaag *et al*. 2015, p79)
Manure direct N_2O	Can be increased by crusts, straws and permeable plastic (ibid)
Manure CH_4	Reduced with impermeable covers which enable capture and combustion, less certain effect for other cover types (Eory *et al* 2015b, p181)
Soil N_2O	"could also increase direct N_2O emission after having been spread on the soil, unless low NH_3-emission spreading techniques are implemented" Eory *et al* (2015b, p178)
Other GHG effects	Increased N retention in slurry – reduced need for synthetic N

Potential measures
Van der Zaag *et al* (2015, p101) classified measures as being (1) practical with demonstrated efficacy, (2) promising but lacking in evidence on efficacy, (3) ineffective or impractical (positive air pressure covers, vegetable oil, waste petroleum oil, solid-liquid separation, separating faeces from urine, anaerobic digestion, and compaction.) The CE of selected measures classified as 1 and 2 are given in Table A2, along with the estimated value of the N_2O reduction arising from the measures. The N_2O reduction represents a small but significant benefit when compared to the measures' ammonia mitigation CE.

The human health effects of NH_3 result in a damage cost per kg 30 to 40 times that of CO_2. Defra *et al*. (2011) estimated the human health costs to be range from 1407 to 2050 £/ t of NH_3, which is equivalent to 2.01 to 2.90 €/kgNH_3-N. The NH_3 mitigation CE in Table A2 suggest that some measures may have a benefit: cost ratio > 1 once the full benefits of NH_3 mitigation (including the avoided N_2O emissions) are taken into account.

Table A2. The ammonia reduction from different slurry cover measures and estimated benefit of avoided N_2O emissions from ammonia (assuming a carbon price of £50/tCO_2e, and 0.01kgN_2O-N/kgNH_3-N (IPCC 2006)). For definition of classes, see text.

		Van der Zaag *et al*. (2015, p97, 101)			Calculated GHG benefit	
Type	Measure	Class	NH_3 reduction (%)	CE €/kgNH_3-N	N_2O mitigation (kgCO_2e/ kgNH_3-N)	Benefit of N_2O mitigation (€/kgNH_3-N)
Tight lid	Tent	1	80%	8.30	4.68	0.23
Tight lid	Wood lid	1	80%	5.63	4.68	0.23
Tight lid	Concrete lid	1	80%	9.69	4.68	0.23
Tight lid	Storage bag	2	80%	9.79	4.68	0.23
Floating	Hexacover	1	60%	3.58	4.68	0.23
Floating	Clay balls	1	65%	4.27	4.68	0.23
Floating	Impermeable plastic	2	80%	4.81	4.68	0.23
Floating	Permeable synthetic	2	60%	2.21	4.68	0.23

Abatement potential and cost-effectiveness

Eory *et al*. (2015, p183) estimated that covering slurry stores in Scotland could (by 2035) provide an annual reduction of 4ktCO_2e at a cost of 51£/tCO_2e. In the present study, the reduction in N_2O arising from NH_3 volatilisation during slurry storage is estimated to be 5-7ktCO_2e with an additional 50% of slurry stores covered (see Table 3). Further mitigation may arise from reduced synthetic N purchase. The cost of mitigation is likely to be high unless co-benefits are included.

Advantages disadvantages and barriers

- Non-GHG benefits of NH_3 mitigation, e.g. improved human health, reduced eutrophication of water bodies and reduced acidification.
- Impermeable covers exclude precipitation, thereby reducing the costs of manure storage and handling.
- Increased N retention in slurry, which could enable a reduction in the amount of synthetic N purchased.
- Reduced odour.

The main barrier to uptake of covers is likely to be costs and farmer attitudes. Defra (2013, p37) noted that:
"there are competing demands on available capital and that building slurry stores with adequate capacity, or extending existing stores, is not given a high priority in the context of those demands. There is also evidence to show that farmers sometimes do not understand the need for or benefits of effective slurry management. The continuing pressure on profitability has led some farmers to look at ways to boost income. In some circumstances, for example, increasing the size of a dairy herd has exacerbated the problems associated with a lack of slurry storage."

Finally, different types of covers present different practical challenges. Structural covers may require modification of the store, and some (e.g. concrete covers) can't be retrofitted. Floating covers require minimal modification, but make manure agitation/handling more difficult: "Generally, floating covers are not suitable for dairy slurry with high solids content because vigorous agitation is required to break apart matted solids and this is extremely difficult to do beneath a floating cover. Straw is an exception to this generality as it can enhance crust development." (Van der Zaag 2015, p78)

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A2. Anaerobic digestion

How the measure works

In aerobic decomposition (such as in composting) organic matter is broken down in the presence of oxygen to produce carbon dioxide and water (Eq1). Where the oxygen supply is insufficient, anaerobic decomposition can take place leading to the production of methane (Eq2). Anaerobic digestion also produces a solid residue (digestate) which is composed of undigested materials (such as lignin) and bacterial remains and retains most of the nutrients.

Eq1 $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$

Eq2 $C_6H_{12}O_6 \rightarrow 3CO_2 + 3CH_4$

Anaerobic digesters (AD) enable the process of decomposition to be controlled and the CH_4 to be captured and used as a fuel. They can mitigate GHG emissions in several ways:

1. Reducing the amount of CH_4 that is emitted from slurry storage.
2. Reducing the amount of NH_3 that is emitted from slurry storage.
3. Providing heat and electricity that can displace fossil fuel combustion.

The captured methane (also called biomethane) can be injected into the gas distribution network or used locally, usually in combined heat and power (CHP) plants. Injection into the network requires access to the network and upgrading technology which means that "this model has only been viable for larger schemes which generally rely on energy crop production from a number of local producers" (SRUC 2016, p14). However, ADBA (2016, p4) noted that biomethane to grid was finally taking off.

Current AD capacity in Scotland

The current installed AD capacity and associated feedstock usage is summarised in Table B1. AD (2016) reported twelve "farm-fed" AD plants in Scotland, accounting for 4.1MWe, out of a total AD capacity in Scotland (excluding sewage plants) of 34.4MWe (see Table A1 and B1). Most recent evidence (summer 2016), indicates that the farm-fed AD capacity in Scotland had increased to 17 plants with an installed capacity of 4.8MWe

GEOGRAPHICAL BREAKDOWN						
	Number of plants	MWe	m³/ hr biomethane	Agricultural tonnes per annum (capacity)	Industrial tonnes per annum (capacity)	Municipal/ commercial tonnes per annum (capacity)
England excluding sewage plants	253	210	32,792	3,590,470	4,274,621	2,878,796
Scotland excluding sewage plants	32	35	4,930	238,253	3,238,500	235,500
Wales excluding sewage plants	12	6	-	65,905	18,000	96,500
Northern Ireland excluding sewage plants	30	16	-	442,205	15,000	77,500
Total	**327**	**267**	**37,722**	**4,336,832**	**7,546,121**	**3,288,296**

Figure A1. Current (2016) installed AD capacity by devolved administration (ADBA 2016, p41)

Most of the growth in capacity in recent years has been in agricultural plants, and this trend is set to continue with most (73%) of approved planning applications for plants with agricultural feedstocks (ADBA 2016, p16). However, it should be noted that "since 2014 the UK has seen a downward trend of applications submitted per month, showing the impact of ever falling tariffs in both the FIT and RHI schemes and political uncertainty." (ADBA 2016, p16).

Manures as feedstock

Figures 2, F1 and F2 show the estimated amount of cattle slurry produced by parish in Scotland. In order to put these slurry production rates in context, the amount of VS required per kWe of installed capacity is given in Table B2. Slurries, which have already had much of the digestible organic matter removed by the cattle, have a relatively low biogas production rate per kg of VS compared to crops and household food waste. Depending on the mixture of slurry and other feedstocks, a feedstock requirement in the range of 2 to 8 tVS per kWe installed capacity could be expected, e.g. a 200kWe digester would required something in the order of 1000tVS per year, or 500tVS from slurry if 50% of the feedstock is derived from other sources.

Table A3 provides an estimate of the rates of VS excretion by dairy and beef cattle in Scotland. These are used to estimate the total mass of VS excreted and managed as liquid and solid (Table F2) and to estimate the size of herd required to supply AD plants with feedstock (Table A4). Note that the results are expressed in terms of the manure production from the entire herd, not just from cows, on a per cow basis. These estimates exclude VS excreted by grazing animals. The herds are divided into three categories: D1-Cows; D2-Bulls, replacement males and replacement females; D3-calves not required for replacement, reared for meat.

Scottish dairy and beef cattle produce approximately 700,000t of managed VS per year (see Table F2). Assuming a manure feedstock requirement of 5tVS/kWe (see Table B2), this implies that if 10% of all managed manure was used in AD plants, the installed capacity would be in the order of 14MWe. This is relatively modest compared to the 7234MWe installed renewable capacity in Scotland in 2014 (Scottish Government 2016c, p61) but represents a significant increase on the present farm-fed capacity in Scotland of 4.1MWe (AD 2016).

Table A3. Volatile solid (VS) production rates from dairy and beef herds, calculated by the authors using GLEAM. AF: adult female

	D1 (kgVSx/AF/yr)	D2 (kgVSx/AF/yr)	D3 (kgVSx/AF/yr)	Herd total (kgVSx/AF/yr)
Dairy				
VS excreted per AF	1629	450	291	2370
VS managed per AF	843	169	123	1135
VS deposited on pasture per AF	785	281	168	1235
Beef				
VS excreted per AF	1050	377	815	2242
VS managed per AF	367	152	344	863
VS deposited on pasture per AF	683	225	471	1379

Table A4. Estimated number of animals required to supply CHP AD units of 200kWe, 1000kWe and 5000kWe capacity.

		AD unit capacity			
Parameter	Units	A	B	C	Notes
Capacity	kWe	200	1000	5000	
Feedstock requirement	tVS/kWe	5	5	5	Estimate based on Mistry *et al*. (2011) and AD (2016)
Feedstock from manure	%	50%	50%	50%	Assumption
Manure required	tVS	500	2500	12500	
Dairy herd manure production*	tVS/year/cow	1.13	1.13	1.13	Calculated by authors using GLEAM
Beef herd manure production*	tVS/year/cow	0.86	0.86	0.86	Calculated by authors using GLEAM
Dairy herd to provide manure	# cows	441	2203	11014	
Beef herd to provide manure	# cows	579	2897	14486	

Abatement potential and cost-effectiveness

The abatement potential of two 1MW agricultural AD plants were calculated (Table A5). In Plant B, half of the crop feedstock is replaced with household food waste. It is assumed that the additional costs of using food waste (additional capital equipment to process the food waste, and procurement of a waste management license to spread the digestate) are offset by the gate fees received, and that food waste has a net cost of £0/t.

The APs of the two plants are similar, but Plant B is likely to have a better (i.e. lower) CE. This is primarily due to the lower net cost of food waste compared to maize silage. Mistry *et al*. (2010, p52) concluded that "The inclusion of food waste enhances the energy, economic and environmental credits that can be gained from AD plants." However, there are practical barriers to using food waste, such as:

- The cost of acquiring the additional equipment needed to pasteurize food waste in order to render the digestate suitable for application to land (BSI 2014, p20).
- Additional waste management licensing requirements.
- Increased risk of digestate contamination, e.g. with plastics.

Furthermore, forecasting the amount of food waste feedstock that will be available over the lifetime of a plant is not straightforward. It has been suggested (Bell 2016) that the actual amounts of food waste have turned out to be less than predicted. This may be due to segregated household waste collections increasing awareness of food waste and changing consumer behaviour.

Table A5. Abatement potential and cost-effectiveness of two agricultural AD plants in Scotland.

	Plant A	**Plant B**
Capacity (MWe)	1	1
Feedstock (%)		
Cattle slurry	50	50
Maize silage	50	25
Household food waste	-	25
Emissions (tCO_2e/year)		
Pre-digester storage	432	939
CH_4 leakage from digester	984	1,005
Silage production	1,076	538
Avoided electricity production	- 1,995	- 2,039
Avoided heat production	- 1,141	- 1,166
Avoided manure storage	- 2,158	- 2,158
Net emissions	**- 2,802**	**- 2,880**

Caveats

There can be wide variation in the financial and emissions performance of AD plants, and detailed investigation of these is beyond the scope of this report. The results in Table A5 are provided to illustrate the relative importance of emissions sources for two specific situations. Some emissions are not included, i.e.:

- The reduction in synthetic fertiliser purchase (and associated emissions and costs) resulting from the (additional) nutrient value of the digestate.
- Emissions from the construction of the AD plant.
- Emissions from feedstock (and digestate) transportation. Assuming an average return journey of 20km, emissions from feedstock transport would increase the total GHG arising from the plants by approximately 3%.
- NH_3 emissions from pre-digester feedstock storage and digestate storage.
- Indirect land use change induced by the use of crops as feedstock.

Some assumptions require verification, e.g. the net emissions from food waste disposal in the counterfactual are assumed to be zero – emissions arising from landfill disposal are assumed to be offset by reduced synthetic fertiliser consumptions arising from the production of compost from some of the food waste.

Abatement potential for Scotland

An installed capacity of 4MWe (i.e. 4 x 1MWe plants) would use 6% of the managed cattle slurry in Scotland as feedstock and reduce emissions by approximately 11ktCO_2e each year.

The AP and CE of AD plants is likely to decline over time as the electricity supply is decarbonised and the avoided GHGs reduced. DECC (2015b, p9) give Domestic Marginal emissions factors for electricity (in kgCO_2e/kWh) of 0.324 in 2016 and 0.081 in 2035. The CE is also sensitive to the cost of generation, which is a function of a range of parameters (Table A6).

Table A6. Financial costs and benefits accruing to an AD plant owner. Transfers such as capitals grants and FITs are not included.

	Costs	**Benefits**
One-off	Buildings, equipment, infrastructure Planning and consultancy Learning costs: fees and time	
Recurring	Maintenance Depreciation Labour Feedstock purchase Transport Foregone crop sales Professional fees and insurance	Sales of electricity, heat and gas. Avoided energy purchases Gate fees for wastes Nutrients in imported feedstock

Policy context and outlook for AD

UK wholesale gas and electricity prices are set to increase in real terms over the next 10 to 15 years (Figure A2). The policy context for AD is complex and provides further incentives via measures such as:

- Feed-in Tariff (FIT)
- Renewable Heat Incentive (RHI)
- Renewables Obligation (RO)
- Renewable Transport Fuel Obligation (RTFO)
- Climate Change Levy (CCL) Exemption for Renewables
- Gate fees for food waste lower – gate fees set by market, but DECC has to make assumptions about them when calculating RHI tariffs – ADBA (2016, p24) argue that DECC overestimate gate fees (and consequently pitch tariffs too low).
- EU Emissions Trading System (ETS) and carbon floor price. The UK is below our ETS emissions cap, so unlikely to provide any incentive to reduce emissions. Carbon floor price has been capped at £18/tCO_2 so "it will not deter investment in fossil fuel generation" ADBA (2016, p35).

It has been argued that there has been a reduction in the policy incentives for AD recently:

"*proposed changes to the renewable heat incentive (RHI) will severely limit, if not ban the use of energy crops in systems where RHI is claimed… These changes will make it difficult for crop-based AD plants to achieve financial viability unless the value of the energy produced increases" SRUC (2016, p14).*

"The current government's approach on renewable electricity support in particular has been hugely frustrating, drastically cutting incentives when they should be capitalising on the foundations that the AD sector has built over the past six years." ADBA (2016, p4).

"there is clearly very little 'push' from the government towards using manure for AD. And given that the 'pull' of tariffs for use of manure for small scale AD has been eroded, there is now little incentive for improving manure management" ADBA (2016, p7)

At present (October 2016) the UK Government is reviewing the results of its consultation on support for anaerobic digestion (UK Government 2016).

ADBA (2016) recommend the following actions to improve cost competitiveness:

1. Committed government action on bringing more food waste into AD (though this may be less of an issue in Scotland which has more separate food waste collection, as a result of the Waste (Scotland) Regulations 2012, which will ban biodegradable municipal waste being sent to landfill from 2020).
2. Increased public and business awareness of AD (to encourage uncontaminated separate collections).
3. Investment in research and innovation (e.g. advances in microbiology to improve digestion processes, and expanded grid capacities).
4. Recognition of benefits and use of digestate - creating markets for digestate (which often has no or negative value).
5. Policy certainty and predictability in future tariff rates.

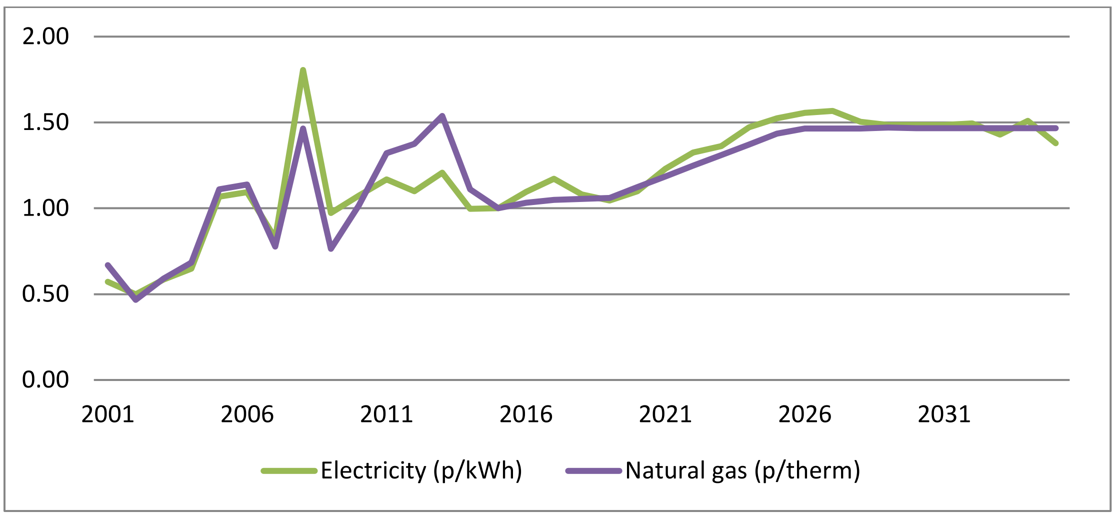

Figure A2. Index of historic and future projections of UK wholesale gas and electricity prices (based on DECC 2015a, Reference scenario, constant prices, 2015=1)

Wider impacts

While AD reduces ammonia emissions compared to uncovered storage, the effluent is high in NH_3/NH_4 (van der Zaag *et al*. 2015, p93). Expert opinion was that the total NH_3 emissions from uncovered storage and AD was likely to be similar: *"In Denmark, we concluded that there was probably not much difference between the proportion of nitrogen emitted as ammonia from digestate as from slurry. However, broadcast spreading is banned here, and both slurry and digestate are applied using low emission technologies (e.g. injection), so the ammonia emission is quite low anyway" Hutchings (2016)*

AD can lead to a reduction in pathogens and odours van der Zaag *et al*. (2015, p93).

Environmental impacts arise during the growing of crops for feedstock. As with other energy crops, there is also some loss of food production and indirect land use change. The sustainability requirements for using crops in AD plants are likely to make non-waste feedstock (such as crops) less attractive.

Conclusions

- Modest technical potential
- The extent to which the technical potential will be realised depends largely on the financial performance of AD, i.e. the returns it can provide compared to other investments.
- Financial outlook uncertain; government financial support is reducing, but energy prices are forecast to rise and gate fees may also increase as the result of domestic food waste policy (though using food waste can create issues with digestate spreading).
- In the absence of funding to incentivise AD, an alternative policy could be to identify niches where AD may be attractive, e.g.:
    - where there is an adequate and consistent enough supply of feedstock to achieve generation at a competitive cost;
    - where heating costs are high - "The high cost of heating oil relative to gas currently makes those farms or rural businesses using heating oil prime candidates for being able to make savings by installing AD plants." ADBA (2016, p39)

AD info sources

http://www.biogas.org.uk/
http://www.biogas-info.co.uk/
http://www.nnfcc.co.uk/
http://adbioresources.org/
http://www.agrocycle.eu/2016/08/22/utilising-agri-food-waste-barriers-opportunities/

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A3. Slurry acidification

Brief overview of how the measure works.

Ammonia (NH_3) is considered to be an indirect greenhouse gas, since deposited ammonia is rapidly converted to ammonium-N and nitrate, and during these processes nitrous oxide (a potent greenhouse gas) is released. Ammonia emissions from agriculture are regulated through UK commitments to the EU Directive on National Emissions Ceilings, which implements commitments agreed through the Gothenburg Protocol. Agriculture is the most significant source of NH_3 emissions to the atmosphere in the UK, and livestock slurries contain high concentrations of ammonium-N. Ammonia is a volatile gas which is easily lost from the surface of liquids by the process of volatilisation. This is a physical process, controlled by the difference in concentration between the liquid and the atmosphere, temperature, and the pH of the liquid environment. High rates of volatilisation are most likely when there are high concentrations of ammonia liquid, when there are higher temperatures, and when the pH of the liquid is above 6. The area of the liquid exposed to the atmosphere also influences the rate of volatilisation of ammonia. Because it is generally difficult to control ammonia concentration and temperature mitigation measures generally focus on creating a physical barrier between the liquid surface in the atmosphere, or controlling the liquid pH.

Slurry stored in slurry tanks can be acidified by adding strong mineral acids. Sulphuric acid would normally be used for this purpose on farms, and can effectively reduce the pH to levels (pH 6 and below) below which the rate of ammonia volatilisation is significantly reduced. This is currently practiced quite widely in Denmark. The acidification reduces the ammonia volatilisation from the tank, but more importantly also reduces volatilisation from the slurry when applied in the field. This reduction can range between 70-90% (Kai *et al.* 2008a).

Summary of advantages and disadvantages of the measure

The advantage of slurry acidification is that in addition to reducing for volatilisation rates, the acidified slurry would also retain more nitrogen and therefore provide benefits in terms of increased nutrient availability when subsequently applied to the soil. This would therefore imply that applications of synthetic N could be reduced when taking account of the increased nutrient value of the slurry contributing to a further reduction in indirect N_2O emissions.

The disadvantage of acidification concern health and safety and cost (Fangueiro *et al*, 2015). The concentrated sulphuric acid used for this purpose is an extremely powerful oxidising agent causing severe burns when in contact with the skin. Storage and application of the acid therefore needs to be carefully controlled and regulated. The purchase, storage and application of sulphuric acid are also associated with increased management costs, though these will be offset to some extent by the increased nutrient value of the slurry. Application of acidified slurry to soils will result in a small additional soil acidification affect; however, soils have very significant buffering capacity, which means that acidification effects are likely to be very minor, and can be overcome by appropriate liming strategies.

SEPA have expressed concerns about the use of soil acidification as a mitigation measure. Specifically they are concerned about safety issues related to the release of the toxic gas H_2S, and the handling on farm of concentrated sulphuric acid (Aitken 2016, pers comm.)

The Danish government has committed significant investments in slurry acidification to overcome some of these problems. Danish farmers receive subsidies from the EU pillar II rural development pool (N Hutchings pers comm). However, this only covers the housing for acidification not the tank or field acidification. Housing acidification is often used where a farmer wishes to increase the number of livestock but faces restrictions on ammonia emissions, or where air scrubbing is used to reduce odour. Another incentive is that legislation means the amounts of fertiliser and manure applied are limited, with the latter according to their mineral fertiliser equivalent. However, there is no special mineral fertiliser equivalent for acidified slurry, so by using acidification, farmers can increase the N applications.

Examples of the technologies currently used in Denmark are available for different sectors and activities:

Pig housing:	http://faurfarm.dk/film-forsuring-i-svinestalde
Cattle housing:	http://faurfarm.dk/film-forsuring-i-kvaegstalde
Tank acidification:	http://faurfarm.dk/gylleforsuring/film-om-forsuring-i-tank

Summary of the theoretical applicability within Scotland

Slurry acidification would be applicable across a wide range of farming enterprises in Scotland. Any farm which stores slurry overwinter would potentially be able to use mineral acids to reduce slurry pH thereby reducing ammonia losses. Two basic methods are available, one whereby acid is added to slurry storage tanks and a second where acid is added to slurry tanks at the point of application in the field (Fangueiro at al 2015). Operating costs of introducing slurry acidification are small and were estimated by a recent Danish study to be €60 per livestock unit (Kai *et al.* 2008b), although costs of capital investment noted above may be much larger. It is likely that widespread introduction of this measure would need to be associated with technical support emphasising health and safety requirements and providing guidance on net benefits.

Table A7. Advantages and disadvantages of slurry acidification.

Advantage	Disadvantage	Net affect
Relatively cheap and simple to implement. Contributes to significant reductions in ammonia volatilisation from stored and applied slurries. Increases nutrient retention in slurry	Some small cost implications. Acid storage and use require careful attention to H&S issues. Potential dangers from H_2S production. Uncertainties about pollution swapping	Significant reduction in NH_3 volatilisation and consequent indirect N_2O emissions. Increased nutrient value for slurries. However barriers are currently too great to consider wide scale application of this measure.

Estimate of abatement potential and the extent to which the abatement would be captured in the national GHG inventory.

Recent changes to the UK inventory have resulted in a reduction of the Emission Factor for NH_3 volatilisation, meaning that mitigation of emissions from this source is now less important than previously thought. Assuming a conservative estimate of a 70% reduction in ammonia volatilisation and assuming that ammonia volatilisation from typical slurry applications would range between 10-30 kg N/ha this would lead to a reduction of 7-21 kg NH_3-N /ha and a consequent reduction of 0.04-0.12 kg N_2O-N/ha (using new Tier 2 emission factors 0.006 for N_2O). The increased fertiliser value of the slurry would result in reduced synthetic N applications of a similar magnitude resulting in a net reduction of 0.08-0.24 kg N_2O-N/ha.

It is estimated that acidification could reduce N_2O emissions from slurry storage by 6ktCO_2e (Table 6). Slurry acidification will also lead to a reduction in emissions during the application of slurry to land, however this reduction is expected to be small due to the small amount of N_2O arising from the volatilisation of N during slurry application. Frac_gasm (the % of the applied manure N converted to NH_3 during application) was changed from 20% to 7% in the 2016 revision of the UK NIR (see National Inventory 2016 submission, common reporting format Table 3.D.). As a result of the 2016 revisions, indirect N_2O from NH_3 arising during slurry application accounts for only about 2% of the total N_2O arising from application of slurry and FYM to land. The AP is likely to be around 1ktCO_2e. Further mitigation may arise from reduced synthetic N purchase.

The AP from reduced NH_3 would not be recognised in the inventory unless a specific change in Emissions Factors was introduced to account for lower volatilisation of ammonia from acidified slurry. In theory reduced synthetic N applications should be captured in the inventory.

A4. Band spreading and injection of slurry

Brief overview of how the measures work.

Livestock slurry can be applied to the soil using a range of techniques. By far the most common approach in Scotland is to use a low trajectory splash plate (Fig A3a), which accounts for over 90% of applications to Scottish grasslands (UK National Inventory Data). The basic principle involves forcing a jet off slurry from the rear end of a tanker against a metal plate in order to distribute the slurry across a wide area of pasture. Various designs of splash plate are available which allow control over trajectory and volume of slurry spread. An alternative system known as the trailing shoe or band spreading uses a series of parallel pipes connected to a slurry tank which are dragged across a field in order to apply the slurry in discreet bands on the grass surface (Fig A3b). Again various designs of trailing shoe equipment are available to allow different widths and volumes of slurry to be spread. A third option is to inject slurry below the soil surface (Fig A3c). In this system parallel injector pipes attached to a slurry tank are drawn across the surface allowing slurry to be injected below the soil surface. Shallow and deep injection options are available.

(a) Splash plate	(b) Trailing shoe	(c) Injection

Figure A3. Common slurry application techniques

Different application methods are associated with different contributions to greenhouse gas emissions. Lowest emissions of nitrous oxide are generally associated with splash plate applications of slurry (Bourdin *et al.* 2014). However, such application techniques are also associated with highest emissions of ammonia. Although ammonia is not in itself greenhouse gas, the deposition of ammonia generally occurs in close proximity to source of emission. Deposited ammonia is then rapidly transformed in soil by the microbial processes of nitrification and denitrification resulting in nitrous oxide emissions. Ammonia volatilisation is therefore considered to represent an indirect source of greenhouse gas emissions. A recent review showed that ammonia emissions can range between 0.1-9.5% of the total N contained in the slurry, with this range being affected by slurry type, application method, soil conditions and climate (Chadwick *et al.* 2011).

The use of trailing shoe and injection technology can dramatically reduce ammonia emissions and odour and thus reduces indirect nitrous oxide emissions. However, studies have shown that such techniques increase direct nitrous oxide emissions (Bourdin *et al.* 2014; Thorman *et al.* 2007). A recent comparison between splash plate and band spreading techniques in Ireland concluded that there was no significant difference in net greenhouse gas emissions from the two techniques (Bourdin *et al.* 2014). However, the Bourdin paper did show that in some circumstances splash plate and band spread applications of slurry were not associated with significantly different N_2O emissions, a finding also reported by Chadwick et at (2011). They concluded that a shift in timing of slurry applications from spring to summer would provide greater mitigation potential and switching between application techniques. However, this conclusion may have been influenced by the particular years in which experiments were carried out. Recent studies of N_2O emissions from dung and urine sources applied to Scottish grassland at different times of the year indicated that summer emissions were higher than those in spring an autumn (Bell *et al.* 2016).

Summary of advantages and disadvantages of the measure

The splash plate application technique provides the advantage of allowing the application of large quantities of slurry over shorter time period at relatively low cost. However, concerns have been raised about high emissions of ammonia and problems with odour particularly near populated areas. The alternative trailing shoe and injection systems are effective at reducing ammonia emissions and odour but may be associated with higher direct nitrous oxide emissions. Band spreading does however provide better compliance with General Binding Rules (for further information on current GBRs, see SEPA 2016), and has become more common in Scotland over the past 5 years. The reduction of N volatilisation by band spreading also implies greater retention of N within the soil and opportunity for increased recovery of N by the vegetation. Band spreading methods also have capital costs and higher operating costs associated with increased fuel use particularly for injection systems when the machinery is moved more slowly across the field and more fuel is used in order to accomplish the injection process. It is generally the case that injection methods are less applicable in Scotland due to unsuitable soil conditions.

Summary of the theoretical applicability within Scotland

There are significant doubts about the opportunities for alternative slurry application techniques to reduce net greenhouse gas emissions. Although trailing shoe and band spreading may be introduced to reduce ammonia volatilisation and odour, they are unlikely to have a major impact on overall greenhouse gas emissions. Trailing shoe and injection technologies are currently used on a small number of farms in Scotland (<10%), with the main barrier to uptake being the capital costs of new equipment. Injection equipment can be less effective if the surface soil has a high stone content. This causes variable depths of injection and can cause damage to injection nozzles.

Table A8. Advantages and disadvantages of alternative slurry application methods.

	Advantage	**Disadvantage**	**Net affect on GHG**
Splash plate	Cheap and simple to apply large volumes	High ammonia and indirect N_2O emissions	Current baseline
Trailing shoe	Reduces ammonia volatilisation and odour. Better compliance with GBRs	Expensive and increases direct N_2O emissions	Little change
Injection	Reduces ammonia volatilisation and odour	Expensive and increases direct N_2O emissions	Little change
Altered timing (summer application)	Could provide more efficient recovery of N applied in slurry	Would require additional storage capacity (cost). Also uncertainty over applicability	Uncertain

Estimate of abatement potential and the extent to which the abatement would be captured in the national GHG inventory.

As noted above, alternate technologies for slurry application are not expected to make a significant impact on net greenhouse gas emissions. A move from splash plate to band spreading would potentially change the emission source from an indirect emission of N_2O to a direct source. The benefits associated with reduced odour and improved pasture quality for grazing livestock make this change worthwhile. There may also be some marginal benefits in terms of N_2O mitigation from bandspreading techniques under some soil and climatic conditions, although this needs to be explored with further research.

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A5. Optimising use of manures via manure exchange and animal movement

Historically in the UK, livestock production was part of an integrated system where a large proportion of the feed and bedding was homegrown and manure returned nutrients directly to crops on-farm. The reasons for increased specialisation in agriculture are complex, and a large scale return to traditional mixed farming is perhaps unlikely, but there are interesting questions around the appropriate geographical scale at which the reintegration of crops and livestock might be most useful from a resource perspective. Some argue that the farm is the appropriate scale e.g. Wilson (2009) but others that ecosystem services are produced at the landscape scale (Smith, 2010). There are a range of possibilities for reintegration including an “expanded” nutrient cycle where byproducts from crops harvested and processed for human consumption are returned to livestock farms as feed and manures are reapplied to arable land. In many parts of Europe there is interest in “Territorial Crop Livestock Systems” which is a structured way of reconnecting crop and livestock production in order to address both production issues and local environmental issues (Asai and Langer 2014). For example, Asai *et al*. (2014) found in 2009 that half of all Danish farms were involved in manure exchanges.

The movement of manures or livestock between farmers clearly poses logistical challenges and practical implementation may require a cost benefit analysis on a case by case basis. From the perspective of the livestock farmer transport of manure to an arable farm could be advantageous when more manure is produced than there is land available for spreading. Composting of solid manure prior to transport would not only reduce volume but also contamination risks (e.g. weed seeds). Various factors (e.g. manure properties, transport and synthetic fertiliser costs and emissions intensities) will determine the distances beyond which manure transport provides a net (private or social) cost. In general, it should be viable to transport manures with higher nutrient values per kg further, and there are treatment options, such as slurry separation, which can improve the efficiency of manure transport by allowing the liquid and solid segments to be used on different crops or farms. Available estimates suggest that while it may only be sensible to move raw manure 30-40 miles (Fealy and Schroder, 2008) concentrating nutrients in the manure through processes such as pelleting may increase the transport distances to around 200 miles (Penn *et al* 2011). For livestock movement, the determination of the point at which movement costs start to outweigh the benefits will need to include the effects of transportation on animal health and welfare.

If manure is exchanged for straw then this would be an incentive for an arable farm looking to dispose of straw. Using manure on arable farms could reduce their dependence on synthetic fertilisers which will in turn reduce GHG emissions associated with manufacture. One of the challenges of using manures on arable farms is that it is much more difficult to accurately predict the amount of nitrogen available to the crop compared to soluble fertiliser. This can have a knock on effect on both crop yield and quality. From a production perspective available P and K also needs to be accounted for. It may also reduce nutrient losses from livestock farms where manure is stored unused because it cannot be applied in amounts exceeding regulations.

The question of whether it is more efficient to move livestock or manure between systems will depend on circumstances. Livestock could be used in arable systems for grazing leys, stubbles and cover crops with the benefit of manure return to the system and its attendant benefits for soil organic matter and soil structure. The availability of manure may lead to changes in rotation such as the introduction of cover crops (e.g. Sulc and Tracy, 2007) and the resultant crop diversity could benefit soil carbon and soil structure as well as other ecosystem services. However, many arable farms will no longer have the buildings, fences and water trough distribution necessary for livestock production. Grant schemes could of course alleviate this particularly problem. If there are suitable unused buildings on arable farms then moving livestock temporarily to those systems would allow manure to be generated on site and this might be simpler and more cost effective than transport of manure. In addition to the financial cost it is important to recognise the need for possible training and knowledge exchange for participating farmers. Such exchanges of manure could be carried out directly between farmers or organised by a regional cooperative or other similar structure as described by Moraine *et al*. (2016). Where they are a result of direct farmer to farmer interaction then it is possible to plan very careful targeting of individual fields or soils types (Asai *et al* 2014). One concrete example of exchanges between livestock and crop producers in the UK is within the organic sector. Within the EU Regulation on organic production, poultry producers are requires to show that they have enough land for using the manure produced on farm. If the poultry is stockless or has limited land then the producer must enter into a written agreement with a farmer with land available for manure spreading.

Optimising manure use within a farm itself is often currently limited by logistics, and several studies show that fields close to animal housing tend to accumulate nutrients while fields at the edge of a holding become depleted. Precision agriculture approaches which are able to show spatial patterns in soil fertility/yield mapping will aid decision making on where to spread manures and slurries. Slurry separation and other manure treatments which make materials easier to handle may make it easier to spread materials over a wider land area. Similarly adequate storage facilities and low ground pressure vehicles can also ensure that manures and slurries are used in a timely manner over wide areas.

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Appendix B. Breakdown of AD plants in Scotland and feedstock assumptions

Table B1. Operational AD plants in Scotland, July 2016, not including sewage plants. Source: AD (2016)

Capacity (kWe)	CH_4 capacity (m3 /hr)	Output	Completion	Type	Feedstock	Using cattle manures	Feedstock demand (t fresh weight pa)
1000	0	CHP	2015	Farm-fed	Cattle manure, grass silage, wholecrop rye, energy beet, wheat straw & vegetable waste	y	20650
500	0	CHP	2015	Farm-fed	Cattle slurry & poultry manure	y	28000
500	350	BtG	2015	Farm-fed	Energy crops, cattle slurry & glycerol	y	24995
500	550	BtG & CHP	2015	Farm-fed	Rye, grass silage, energy beet, pot ale syrup, potato outgrades, vegetable cuttings & poultry manure		30450
500	605	BtG & CHP	2014	Farm-fed	Whole crop rye, maize, sugar beet off-cuts, raw silage & poultry litter		36000
460	0	CHP	2006	Farm-fed	Pig slurry & animal processing wastes		15000
250	0	CHP	2015	Farm-fed	Animal slurries & energy crops	y	9500
200	0	CHP	2014	Farm-fed	Cattle slurry & crop silage	y	11000
200	0	CHP	2015	Farm-fed	Cattle slurry, energy beet, maize silage & grass silage	y	5228
25	0	CHP	2012	Farm-fed	Cattle slurry & grass silage	y	2500
0	0	Heat only	2004	Farm-fed	Cattle manure	y	80
0	0	Heat only	2005	Farm-fed	Cattle slurry & manure	y	190
7200	2750	BtG & CHP	2009	Waste-fed	Brewery waste		300000
5500	0	CHP	2013	Waste-fed	Brewery waste		90000
3600	495	BtG & CHP	2011	Waste-fed	Organic fraction of MSW & C&I waste		100000
3500	0	CHP	2015	Waste-fed	Distillery wastes		80000
3400	0	CHP	2010	Waste-fed	Brewery waste		9855
2200	0	CHP	2011	Waste-fed	Energy crops & food waste		75000
1400	0	CHP	2014	Waste-fed	Food waste & green waste		45000
1000	0	CHP	2010	Waste-fed	Food waste		30000
700	0	CHP	2012	Waste-fed	Food waste & animal processing wastes		16000
500	0	CHP	2013	Waste-fed	Brewery waste		15000
500	0	CHP	2010	Waste-fed	Brewery waste		47450
500	0	CHP	2014	Waste-fed	Cattle slurry & brewery waste	y	30000
305	0	CHP	2007	Waste-fed	Food waste		7000
249	0	CHP	2014	Farm-fed	Maize silage and manure	?	
0	0	CHP	2015	Farm-fed	Maize grass silage and farmyard manure	y	11,200
0	0	CHP	2015	Farm-fed	Silage		22,000
0	0	Not stated	2015	Waste-fed	Distillery residues & co products and silage		
150			2014	Farm fed	Slurry, grass silage, rye	y	
200			2015	Farm fed	Chicken manure, rye, silage		
Total							
35039	4750						1,062,098

Y=using cattle manures. ?=not known.

Table B2. Energy content of selected feedstocks and the estimated mass of each feedstock (in terms of volatile solids (VS)) required per kWe of installed capacity

	Dairy cattle slurry	Beef cattle slurry	Sugar beet waste	Grass silage	Household food waste	Source
Biogas m3/tVS	300	300	560	600	500	Mistry *et al*. (2011, p26)
Biogas m3/t total solids	375	375	700	682	556	Mistry *et al*. (2011, p26)
Biogas m3/t fresh weight	22	22	81	111	104	Mistry *et al*. (2011, p26)
Biogas CH_4 content	0.65	0.65	0.65	0.65	0.65	Mistry *et al*. (2011, p26)
CH_4 (m3/tVS)	195	195	364	390	325	
CH_4 energy content (MJ/m3)	36.8	36.8	36.8	36.8	36.8	Mistry *et al*. (2011, p27)
Total energy content of CH_4 per t VS (MJ)	7176	7176	13395	14352	11960	
% converted to electricity	0.35	0.35	0.35	0.35	0.35	Mistry *et al*. (2011, p28)
% converted to heat	0.5	0.5	0.5	0.5	0.5	Mistry *et al*. (2011, p28)
Electricity produced (MJ/tVS)	2512	2512	4688	5023	4186	
Heat produced (MJ/tVS)	3588	3588	6698	7176	5980	
% of electricity used on plant	0.15	0.15	0.15	0.15	0.15	Mistry *et al*. (2011, p28)
% of heat exported	0.5	0.5	0.5	0.5	0.5	Mistry *et al*. (2011, p28)
Electricity exported (MJ)	2135	2135	3985	4270	3558	
Heat exported (MJ)	1794	1794	3348	3588	2990	
MJ/kWh	3.6	3.6	3.6	3.6	3.6	
Electricity exported (kWh/tVS)	593	593	1107	1186	988	
Heat exported (kWh/tVS)	498	498	930	997	831	
Hours per year	8760	8760	8760	8760	8760	
Load factor	0.69	0.69	0.69	0.69	0.69	(ADBA 2016, p26)
Implied capacity (kWe/tVS)	0.12	0.12	0.22	0.23	0.19	
Feedstock: capacity ratio (tVS/kWe)	8.66	8.66	4.64	4.33	5.20	

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Appendix C. Interactions between measures

Most of the effects in Table 6 arise from the following interactions:

- When two measures target the same emissions source the abatement rate of the second measure will be reduced. For example, acidification reduces the rate of ammonia volatilisation, thereby reducing the abatement achieved by other measures that reduce ammonia volatilisation, i.e. slurry covers and band spreading/injection.
- Measures that reduce N losses from slurry during storage (e.g. covers and AD) will increase the slurry N content, which may lead to increases in the nitrous oxide emissions during slurry application. If such increases in nitrous oxide occur, this will increase the abatement potential of measures that target these emissions, e.g. manure exchange.
- Manure exchange and animal movement are assumed to reduce the amount of slurry stored, thereby reducing the abatement achieved via other storage measures.

Further explanation of the interactions are provided below.

Covering slurry stores

Covering slurry could have a positive impact on AD (if covered stores are integrated into AD plants) as impermeable covers should reduce losses of CH_4 in pre-digester storage, and increase CH_4 yield in the digester.

Covers reduce NH_3 emissions during slurry storage, so the additional reduction in storage NH_3 mitigation arising from slurry acidification would be reduced. Covers lead to more N being retained in slurry, and potentially higher rates of NH_3 loss during slurry spreading. The mitigation of NH_3 achieved via acidification during application could therefore be increased by covers.

The effect of covers on the AP of band spreading and injection depends on the proportions of direct N_2O and indirect N_2O (via NH_3) produced during spreading. The increase in N retained in slurry could enhance the NH_3 mitigation effect of band spreading/injection, but there may also be an increase in direct N_2O.

The increased N content of slurry may improve the AP of manure exchange in the following ways: (a) increased N content>higher NH_3 emissions during spreading>increased mitigation via improved N application rates enabled by manure exchange; (b) by increasing the reduction in synthetic N use. Note there is a risk of increased NH_3 during land application of slurry on the receiving farm.

Anaerobic digestion

The AP of slurry covers would be reduced as the amount of slurry stored is reduced and (slurry and digestate) storage should be covered in AD plants. However, the effect should be small as the AP for AD is based on an additional 6% of total cattle slurry being used in AD plants.

The interactions between AD and acidification are uncertain: "more research is needed to understand the microbial dynamics in anaerobic digestion of H_2SO_4-acidified slurries and to suggest technology that can improve the synergism between acidification and anaerobic digestion of animal manure." Moset *et al*. (2016)

AD should have a positive impact on the AP of band spreading/injection as more N is retained in the digestate, and there is therefore more NH_3 (and indirect N_2O) to mitigate, but this may be offset by increased direct N_2O emissions.

AD could have a positive effect on the AP of manure exchange, for the same reasons as slurry covers.

Given the relatively small number of farms involved in AD and animal movement, there is likely to be limited interaction between these measures.

Slurry acidification

Slurry acidification and low emission spreading are combined in Demark, but this is not necessarily because of positive synergies for GHG mitigation (in fact acidification should reduce the need for low emission spreading) but because broadcasting manures is banned to reduce NH_3 emissions and odours (acidification leads to production of Hydrogen Sulphide (H_2S)).

The AP of slurry covers would be reduced as acidification reduces the NH_3 from storage.

The compatibility of acidification and AD is uncertain, see Moset *et al*. (2016) (quoted above).

Reduced pH and volatilisation rates should reduce the AP of band spreading/injection, and the increased slurry N content may increase direct N_2O emissions during spreading.

The increased N content of slurry may improve the AP of manure exchange (see slurry covers) but not all farms may be willing/able to handle acidified slurry.

Band spreading and injection

This should have no direct effect on the AP of measures reducing emissions from slurry storage. If band spreading/injection is assumed to have little net effect on GHG emissions during spreading, then the AP and CE of manure exchange should be unaffected.

Manure exchange

The effects will depend on how the manure exchange takes place. It could reduce the amount of manure stored, and/or the length of time manures are stored for. If so, then this should reduce the emissions arising during manure storage, and therefore the AP of slurry covers, and acidification (and to a lesser extent AD). It could also reduce the AP of band spreading/injection and of animal movements if is leads to better matching of nutrient application to crop requirement.

Animal movement

Animal movement is a different approach and would probably applied on different farms to the other measures. There would be an increase in the amount of nutrients recycled on farm, and an increase in direct deposition and a decrease in the amount of manure stored, thereby reducing the abatement potential of measures that reduce emissions during storage and application.

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Appendix D. Methodology

The project was comprised of two tasks: (a) clarifying the baseline and (b) appraisal of mitigation measures. The approach adopted for the tasks is summarised below.

a. Clarifying the baseline

1. Adjust manure management assumptions used in the UK National Inventory Report for Scotland (either based on published data or on expert opinion). Disaggregate (if possible) slurry into storage sub-categories: lagoon, open tank (no crust), open tank (with crust) covered tank, slurry bag, other.
2. Determine mode of slurry application (based on published data and expert opinion).
3. Calculate rates of VSx by cattle system and animal cohort.
4. Map the rate of slurry production at the highest resolution possible (either farm or parish level, depending on data availability).
5. Output: map of rate of slurry production and application by method.

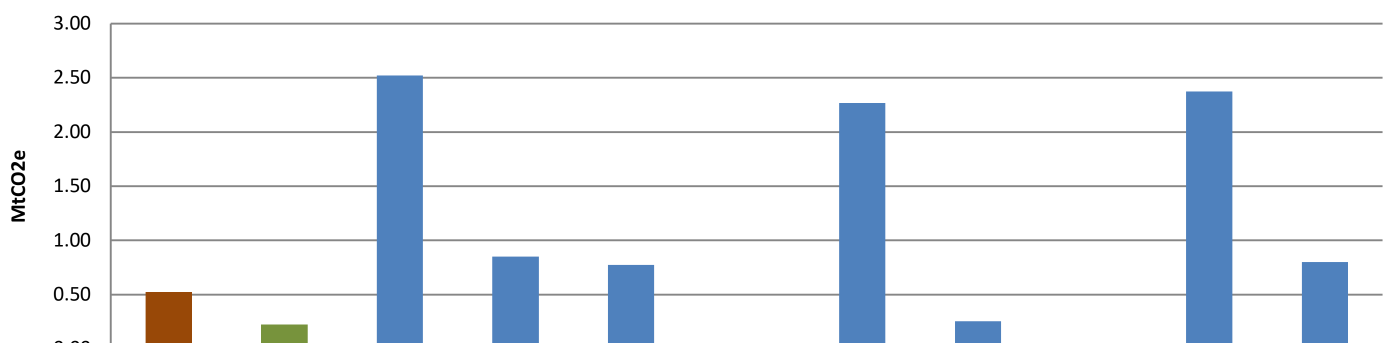
b. Appraisal of mitigation measures

The appraisal was based on a review of existing literature, augmented with feedback from experts on key points. For each measure, the report provides:

1. Brief overview of how the measures works.
2. Summary of advantages and disadvantages of the measure, including identification of potential barriers to uptake and a review, where appropriate, of the evidence on cost-effectiveness.
3. Summary of the theoretical applicability within Scotland and the likely feasible applicability taking into account barriers to uptake.
4. A preliminary assessment of the abatement potential and an explanation of how measures might interact.

Appendix E. Scottish agricultural greenhouse gas emissions 2014

Figure E1. Scottish greenhouse gas emissions 2014, agriculture and related land use (Scottish Government 2016a)



	Manure methane	Manure nitrous oxide	Enteric ferm: non-dairy cattle	Enteric ferm: sheep	Enteric ferm: dairy cattle	Enteric ferm: other	Soil nitrous oxide	Liming	Urea application	Agri LUC	Stationary and mobile comb.
Series1	0.52	0.22	2.52	0.85	0.77	0.05	2.27	0.25	0.03	2.37	0.80

Scottish Government (2016a) Scottish Greenhouse Gas Emissions 2014 (http://www.gov.scot/Publications/2016/06/2307/downloads, accessed 7/9/2016)

Appendix F. Additional information on patterns of manure production in Scotland

Table F1. Total manure production (Smith and Williams 2016) Mt undiluted slurry/FYM

	Undiluted slurry*	FYM or solids*	Undiluted slurry*	FYM or solids*
	Scotland	Scotland	UK	UK
Dairy cattle	1.98	0.76	17.73	10.58
Beef cattle	4.79	3.83	13.61	25.12
Pigs	0.44	0.13	2.62	3.42
Sheep + goats + deer	0	0.32	0	1.51
Horses	0	0.27	0	4.2
Poultry	0	0.41	0	4.58
Total	7.21	5.72	33.96	49.41

*includes litter usage but not rain or wash water

The total volatile solids excreted, collected and managed as liquid and solid were calculated and mapped in the following way:

1. An IPCC Tier 2 approach was used to determine the VS excretion rates for individual animals (e.g. by dividing the herds into different animal cohorts (cows, heifers, calves etc.) and calculating the net and gross energy requirement, feed dry matter intake and excretion rates).
2. The fate of the VS was determined using the most recent (2016) UK National Inventory assumptions for Scotland regarding the amount of time animals are housed and how manures are managed.
3. The results were scaled up using the livestock numbers and distributions from the 2015 June Agricultural Census.

The total VS production is given in Table F2 and amount of (liquid) VS managed by parish are shown in Figures 2, F1 and F2. These are preliminary estimates and should be treated with caution, as the estimates may change as certain assumptions are refined (e.g. regarding cattle dry matter intakes, excretion rates, time spent grazing, and prevalence of animal waste management systems).

Results

Table F2. Estimated total VS production from the dairy and beef herds in Scotland, 2015. Calculated by authors using GLEAM, based on 2015 livestock numbers in Scottish Government (2016b).

		D1* (tVS/year)	D2** (tVS/year)	D3*** (tVS/year)	Total (tVS/year)
Dairy	Total VS managed	187,814	37,628	27,333	252,775
Dairy	VS managed as liquid	89,211	6,987	3,590	99,788
Dairy	VS managed as solid	98,602	30,642	23,743	152,987
Beef	Total VS managed	190,716	79,050	178,491	448,257
Beef	VS managed as liquid	90,590	16,267	23,443	130,301
Beef	VS managed as solid	100,126	62,782	155,048	317,956

*D1-Cows; **D2-Bulls, replacement males and replacement females; ***D3-calves not required for replacement, reared for meat.

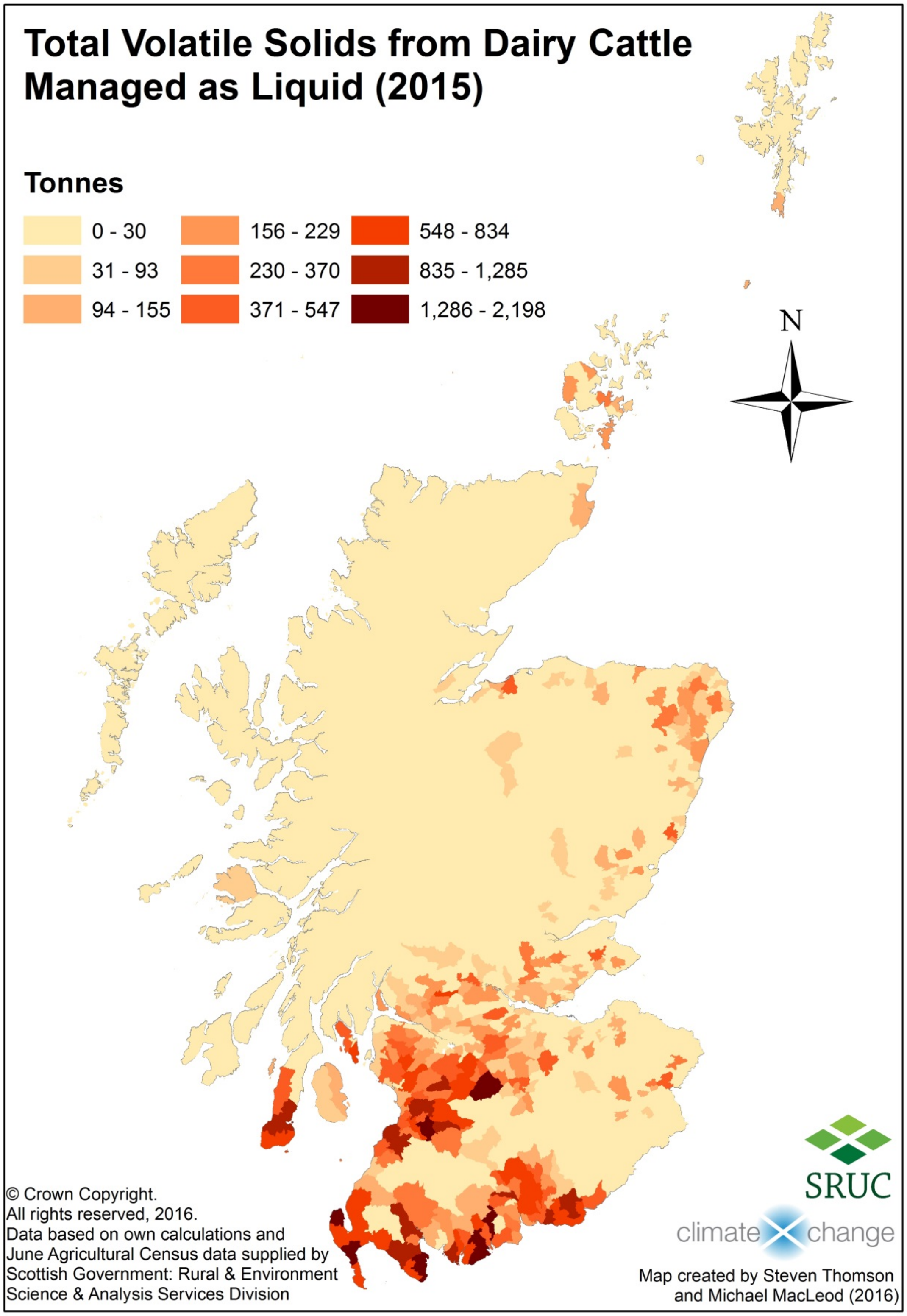


Figure F1. Total VS excreted by dairy cattle and managed as liquid each year, by parish.

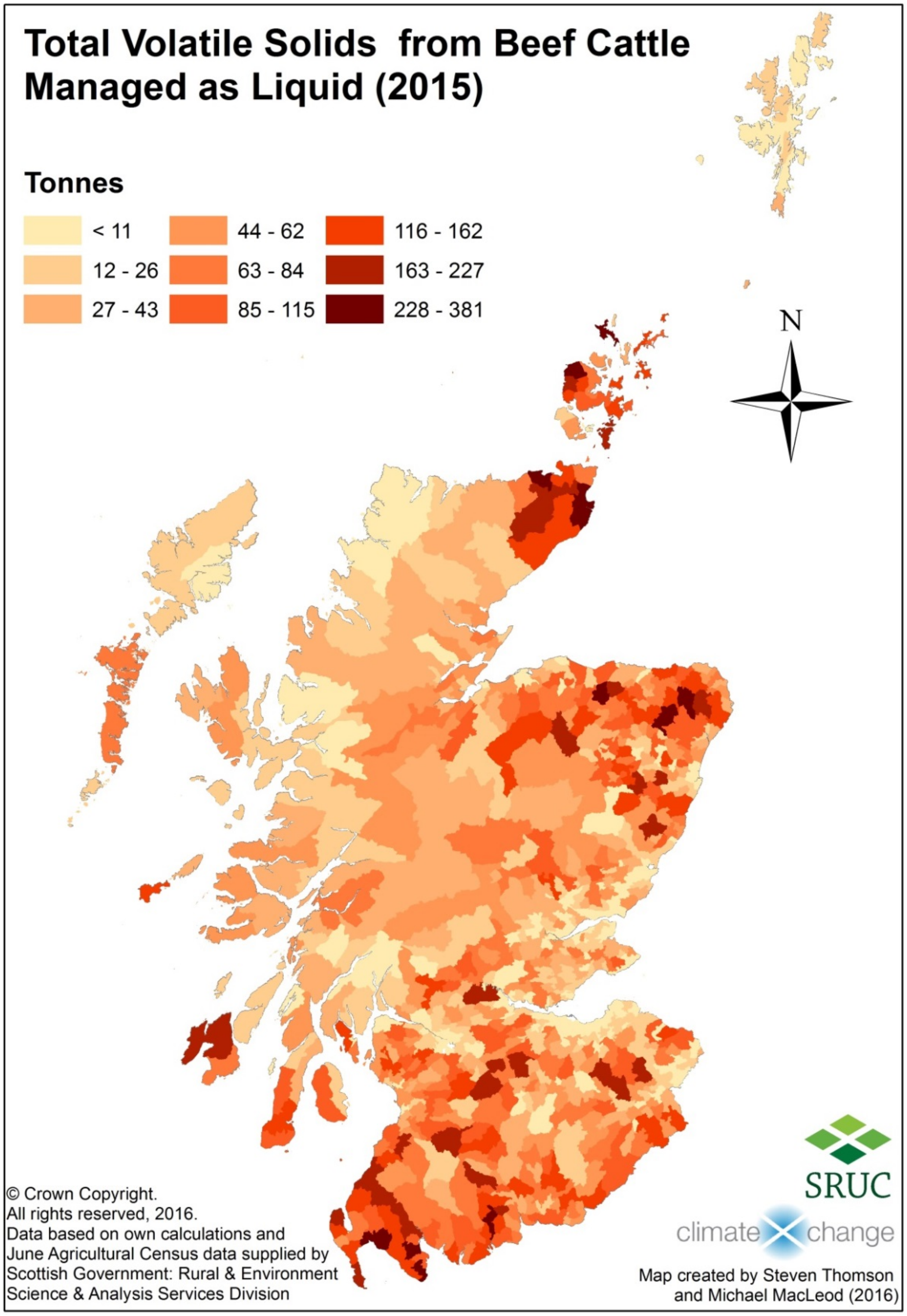


Figure F2. Total VS excreted by beef cattle and managed as liquid each year, by parish.

Scottish Government (2016b) Economic Report on Scottish Agriculture 2016
Smith, K.A. and Williams, A.G. (2016) Production and management of cattle manure in the UK and implications for land application practice. Soil Use and Management 32 pp73-82

Appendix G. Additional information on manure management and application

The results for beef cattle in Bell (2016) (Table G1) are similar to those in Misselbrook (2016), i.e. (a) about 60% of the total VS produced by the Scottish beef herd is deposited directly on pasture by grazing animals and (b) about 60% of the VS excreted during housing is managed as solid manures. However, the results for dairy cattle are quite different, with Bell (2016) indicating that most of the VS excreted during housing is managed in liquid systems, whereas Misselbrook (2016) assumes a more or less even split between liquid and solid manure management. Furthermore, based on the review of AD (see Appendix A), we estimate that 2-3% of the total managed cattle manure VS in Scotland (excluding VS deposited by grazing animals) is currently being used as feedstock in AD plants.

Misselbrook (2016) estimated that most slurry is stored in tanks (Table 3) without covers (Table G2). It should be noted that Scottish Government (2013) reported 61% of holdings with slurry having covered slurry stores, but did not specify the type of cover (presumably these are crusts).

Bell (2016) indicates marked regional differences in AWMS with a greater prevalence of slurry in the south and west of Scotland, for both dairy and beef cattle.

Finally, Misselbrook (2016) concludes that most slurry is currently broadcast, with a small mount being band spread or injected (Table 4).

Table G1 Estimated % of VSx managed by animal waste management system (AWMS) in Scotland. These are based on a survey undertaken in 2016 (Bell 2016). PRP: pasture, range and paddock, i.e. VS deposited by grazing animals.

	Slurry systems	FYM systems	PRP	Total
Female Dairy Cattle	58%	6%	37%	100%
Total Beef Cattle	18%	26%	56%	100%

Table G2 Percentage of slurry stores with covers. Source Misselbrook (2016)

Storage and cover type	Dairy slurry	Beef slurry
% tanks crusted	80%	80%
% tanks with rigid cover	0%	0%
% tanks with floating cover	0%	0%
% lagoons crusted	80%	80%
% lagoons with floating cover	0%	0%

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