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Scotland's Rural College

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Marginal abatement cost curve for Scottish agriculture

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1 Executive summary

Scotland is committed to meeting a net-zero target for greenhouse gas (GHG) emissions by 2045 (Climate Change (Emissions Reduction Targets) (Scotland) Act 2019[1]). Agriculture and the land use sector can help in two ways: by changing practices to reduce GHG emissions and by storing carbon in the soil and plants. In 2018 agriculture and related land use was responsible for 23% of total Scottish emissions. Emissions from agriculture have fallen by 30% since 1990, compared with a reduction of 45% across total emissions (Scottish Government 2020a).

The Climate Change Plan[2] (CCP) is a key policy tool which has been recently revised to help Scotland meet the new net-zero target. Policy development is informed by the Scottish 'TIMES model'[3]. This model pulls together emission, mitigation and mitigation cost data from all sectors to help understand the strategic choices required to decarbonise an economy. It identifies the effectiveness of carbon reduction measures to enable a consistent comparison of the costs of action across all sectors.

To ensure the model uses the most recent data for agriculture, our research updated estimates of the mitigation potential and the cost-effectiveness of a selection of agricultural mitigation options. It took into account the significant recent improvements in UK agricultural GHG inventory reporting (Smart Inventory)[4].

[1] http://www.legislation.gov.uk/asp/2019/15/contents/enacted
[2] https://www.gov.scot/publications/securing-green-recovery-path-net-zero-update-climate-change-plan-20182032/
[3] https://www2.gov.scot/Resource/0050/00508928.pdf
[4] https://www.theccc.org.uk/publication/reducing-uk-emissions-2018-progress-report-to-parliament/

We assessed 14 farm technologies and practices which can reduce GHG emissions in Scotland by 2050. Some of these measures can be applied to multiple types of livestock, raising the number of mitigation options to 21.

The aim was to estimate the different measures' average mitigation potential, capital and recurring costs per unit (e.g. hectare or animal), and total maximum applicability on-farm. This research considers average estimates. On an individual farm basis, both the mitigation and the net costs can be very different.

1.1 Key findings

- The mitigation measures applicable to agricultural land can save between 7 and 553 kg CO_2e every year on each hectare where they are applied. The single most effective measure is **increased cultivation of grain legumes** (i.e. peas and beans) which provides 553 kg CO_2e per hectare savings annually (see Table 1). The second and third most effective measures (on an area basis) are **variable rate nitrogen and lime application** (precision farming) and **soil pH management** (i.e. liming when necessary), providing 151 and 112 kg CO_2e mitigation per hectare annually, respectively.
- **Intercropping** can provide the highest cost savings to farmers per hectare per year (£45); **variable rate nitrogen and lime application**, **crop varieties with higher nitrogen use efficiency** and **soil pH management** can also provide savings. Grain legume cultivation is the most expensive option (£406 per hectare per year).
- The cattle mitigation measures assessed can save between 57 and 854 kg CO_2e every year for each animal they are applied to; **3NOP feed additive**, **breeding for low methane emissions** and **slurry store cover with impermeable cover** are the most effective.
- Cattle measures' net costs range from a saving of £359 to a cost of £31 per animal per year. The **dairy breeding measure** could save £359 per animal per year, and **improved health of dairy animals**, **dairy precision feeding**, **beef breeding for low methane emissions** and **covering beef slurry stores** can also save farmers money. The most expensive cattle measure is administering **3NOP feed additive to beef** animals (£31 per animal per year).
- The sheep measure investigated can provide 15 kg CO_2e mitigation per animal annually and a cost saving of £0.36 per head.
- The two measures applicable to pigs could reduce emissions by 25 and 86 kg CO_2e per head per year, for a £0.87 saving or cost of £0.52 per animal per year, respectively.
- It is important to note that these are average estimates. On an individual farm basis, both the mitigation and the net costs can be very different. For example, the livestock health measures cover a wide range of possible actions (which would be demanding to assess individually). Therefore, depending on the health status of the animals and the implemented change, the GHG benefits achieved and costs could vary widely.

Table 1: Unitary mitigation potential and cost of the measures, 2050 (without interactions between the measures)

Mitigation measures	Annual total mitigation (t CO2e ha^{-1} y^{-1} for crop and t CO2e $head^{-1}$ y^{-1} for livestock measures)	Annualised total cost (£ ha^{-1} y^{-1} for crop and £ $head^{-1}$ y^{-1} for livestock measures)*
Measures applicable for tillage and grassland		
Growing more grain legumes in rotation	0.553	406.00
Variable rate nitrogen and lime application	0.151	-16.83
Soil pH management	0.112	-7.86
Intercropping	0.079	-45.18
Nitrification and urease inhibitors	0.071	20.67
Crop varieties with higher nitrogen use efficiency	0.013	-10.17
Slurry injection	0.026	21.35
Trailing hose/shoe slurry application	0.007	8.16
Measures applicable for dairy production		
3NOP feed additive	0.855	17.78
Breeding for low methane emissions	0.627	-358.74
Covering slurry stores with impermeable cover	0.527	2.56
High starch diet	0.162	0.00
Precision feeding	0.104	-18.22
Improved livestock health	0.057	-26.89
Measures applicable for beef production		
3NOP feed additive	0.423	31.38
Covering slurry stores with impermeable cover	0.225	-0.25
Breeding for low methane emissions	0.116	-15.96
Improved livestock health	0.027	20.26
Measures applicable for sheep production		
Improved health of ruminants	0.015	-0.36
Measures applicable for pig production		
Covering slurry stores with impermeable cover	0.087	0.52
Precision feeding	0.025	-0.87

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Abbreviations

CH_4	Methane
C	Carbon
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent (using 100-year global warming potential)
EF_1	Emission factor representing the proportion of nitrogen applied to soils being emitted as nitrous oxide
GHG	Greenhouse gas
N	Nitrogen
N_2O	Nitrous oxide
PATs	Precision agriculture technologies
SOC	Soil organic carbon
VRNT	Variable rate nitrogen technology

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2 Background

The Scottish Government is committed to the net-zero reduction of greenhouse gas (GHG) emissions across all sectors of the economy by 2045, as legislated in the Climate Change (Emissions Reduction Targets) (Scotland) Act 2019[5]. The periodic plans on achieving these targets are described in the reports on policies and proposals, of which the latest, the Update to the Climate Change Plan 2018-2032[6], was published in December 2020.

To synthesise the potential mitigation options in Scotland regarding their likely outcomes and costs, the Scottish Government is using a high-level strategic model, covering the entire Scottish energy system and some additional sectors, such as agriculture. The Scottish TIMES model[7] combines two different, and complementary, approaches to modelling: a technical engineering approach (to quantify the mitigation potential) and an economic approach (to quantify the costs and economic effects). The model estimates GHG mitigation effectiveness to find the lowest cost mix of actions across all sectors to achieve the GHG target.

A recent large research programme[8] has resulted in a major refinement of the UK agricultural GHG inventory reporting, reflecting the relationship between agricultural management and GHG emissions better than before. The Smart Inventory was first used in the 2018 reporting year[9]. The key changes include a more detailed representation of nitrous oxide emissions from synthetic fertiliser types and methane emissions from enteric fermentation disaggregated by the animal's age, diet, breed and the production system used[10].

As the UK and Devolved Administration emission estimates have been updated, the UK agricultural mitigation estimates are being updated under two, related projects, funded by the Committee on Climate Change[11] and by the Department for Environment, Food and Rural Affairs ('Delivering clean growth through sustainable intensification'). These projects have informed the current work.

The objective of our research was to update the estimates for agricultural mitigation (of selected mitigation measures) in Scotland using a methodology aligned with the Smart Inventory and to produce the results in a format suitable for use in the Scottish TIMES model.

3 Methodology

The scope of the project was to assess a list of mitigation options requested by the Scottish Government and estimate the unitary mitigation potential, unitary costs (per hectare or animal) and maximum applicability - values required in the TIMES model. Further technologies and practices exist which could provide additional mitigation potential; and the total possible mitigation calculations have to consider interactions between the measures (i.e. the mitigation potential of a

[5] http://www.legislation.gov.uk/asp/2019/15/contents/enacted
[6] https://www.gov.scot/publications/securing-green-recovery-path-net-zero-update-climate-change-plan-20182032/
[7] https://www2.gov.scot/Resource/0050/00508928.pdf
[8] https://www.theccc.org.uk/wp-content/uploads/2018/08/PR18-Chapter-6-Annex-The-Smart-Agriculture-Inventory.pdf
[9] https://naei.beis.gov.uk/reports/reports?report_id=954
[10] https://www.theccc.org.uk/publication/reducing-uk-emissions-2018-progress-report-to-parliament/
[11] https://www.theccc.org.uk/publication/non-co2-abatement-in-the-uk-agricultural-sector-by-2050-scotlands-rural-college-adas-and-edinburgh-university/

measure might decrease if another measure, targeting the same emission source, is also implemented on the same farm). The results of this report need to be considered with these limitations in mind. This methodology section details the modelling tool used. It describes briefly the mitigation measures and explains how the MACC modelling had to be aligned to provide results which are in the required TIMES format and which are as consistent as possible with the TIMES model's assumptions.

3.1 MACC modelling tool

The mitigation potential and net costs of the measures were modelled in the MACC tool which has been used to estimate the agricultural mitigation potential in the United Kingdom and its four nations since 2008 (Eory *et al.* 2015; Eory *et al.* 2016; MacLeod *et al.* 2010; Moran *et al.* 2008).

The methodology is described in detail in Eory *et al.* (2015), with some changes described in Eory *et al.* (2019). These changes made it possible to align calculations closer to the UK agricultural inventory calculations (Brown *et al.* 2018) and accommodated agricultural land use and productivity projections for 2050 sourced from the report by Thomson *et al.* (2018).

The key assumptions of the tool are summarised below:

- The modelled year for the mitigation is 2050.
- The boundary of the model is the farming sector, i.e. mitigation potential achievable within the farm gate in Scotland.
- The total Scottish production is capped at current productivity level; measures which increase yield modelled as resulting in proportionally lower number of animals or smaller cultivated land area.
- The mitigation calculations follow the UK agricultural inventory calculations, reflecting the mitigation potential of the measures by modifying the activity data, emission factors and other parameters. The carbon sequestration potential is estimated from literature sources as a single value. Fuel and electricity emission changes are approximated as a proportion of current emissions.
- The mitigation is estimated on an annual basis.
- The mitigation effects and costs are estimated as an average for each measure (with some disaggregation between different cropping and livestock activities within the model, but presented in aggregated way in the results), not considering the heterogeneity between farms.
- The costs consist of technology costs on the farm, for example, investment in new machinery and savings in resource use, excluding changes in cost of labour. Other costs (transaction costs, policy implementation costs) are not included, nor are non-financial barriers. The capital costs were annualised using a discount rate of 3.5%.

3.2 Mitigation measures and data used

3.2.1 Activity data used

Table 2 details the data used for the agricultural activities in Scotland in 2016.

Table 2 : Activity data for Scotland in 2016

Crops	(ha)	Livestock	(head)
Field beans harvested dry	3,002	Dairy calves female	59,180
Field peas harvested dry	776	Dairy replacements female	31,123
Leafy forage crops	4,089	Dairy in calf heifers	70,044
Linseed	58	Dairy cows	176,126
Maize	763	Beef heifers for breeding	153,622
Minor cereals	4,357	Beef females for slaughter	324,293
Other field crops	7,325	Beef bulls for breeding	31,608
Other fodder crops	7,073	Beef cereal fed bull	85,217
Other horticultural crops	1,123	Beef steers	387,473
Potatoes maincrop	14,766	Beef cows	426,490
Potatoes seed or earlies	12,760	Lamb	3,454,132
Root crops for stockfeed	4,536	Mature ram	89,507
Soft fruit	604	Mature ewe	3,316,676
Spring barley malting	146,570	Sows	26,851
Spring barley non malting	92,329	Other pigs	182,969
Spring oats	23,119		
Spring oilseed rape	531		
Sugar beet	0		
Top fruit	98		
Vegetables brassicas	3,008		
Vegetables legumes	9,329		
Vegetables not differentiated	0		
Vegetables other non-legumes	5,830		
Wheat milling	56,989		
Wheat non milling	50,413		
Willow short rotation coppice	0		
Winter barley malting	17,291		
Winter barley non malting	30,740		
Winter oats	8,091		
Winter oilseed rape	30,141		
Improved permanent grass	1,117,854		
Improved temporary grass	210,080		

3.2.2 Selection of the mitigation measures

The Scottish Government requested the measures in

Table 3 be assessed. Two measures could not be analysed as the required data could not be obtained. The livestock measures were separated into animal categories. The description of the measures and the data used to estimate the cost-effectiveness mainly relies on the work done within the Defra funded project Delivering Clean Growth through Sustainable Intensification, with adjustments to better reflect circumstances in Scotland.

Table 3 : Mitigation measures assessed

Mitigation measures specified by Scottish Government	Mitigation measures assessed in this report	Mitigation measure ID
The uptake of soil testing on improved land, lime application to raise and maintain soil pH and reductions in fertiliser application	Soil pH management	MM3
Trailing shoe slurry application	Trailing hose/shoe slurry application (bandspreading)	MM50
Direct injection slurry application	Slurry injection	MM14
GPS lime application to raise and maintain soil pH	Variable rate nitrogen and lime application	MM51
GPS fertiliser application	Variable rate lime and nitrogen application	MM51
Fertiliser application with nitrogen inhibitors/urease	Nitrification and urease inhibitors	MM12
Grass lays or legumes to be added to rotation	Growing more grain legumes in rotation	MM60
	[Grass lays not assessed as baseline data could not be obtained]	
Crops be grown with a biological N-fixing companion crop	Intercropping	MM52
Low nitrogen varieties of barley and wheat	Crop varieties with higher nitrogen use efficiency	MM1
Better livestock health planning	Improved health of ruminants	MM30: dairy MM57: beef MM48: sheep
High starch diet for ruminants	High starch diet for dairy cattle	MM31
Precision feeding of livestock	Precision feeding of livestock	MM32: dairy MM56: pig
Rumen methane inhibitors (e.g. 3NOP, Rumitech)	3NOP feed additive for cattle	MM35: dairy MM54: beef
Methane capture from livestock houses	[Not assessed as mitigation and cost data could not be obtained]	
Covering slurry stores	Covering slurry stores with impermeable cover	MM47: dairy MM58: beef MM59: pig
Low methane cattle breeds	Cattle breeding for low methane emissions	MM27: dairy MM55: beef

3.2.3 Brief overview of the mitigation measures

- **Soil pH management**

One of the important properties of agricultural soils is their pH, in other words their acidity level. The optimal soil pH is between pH 5.6 and pH 6.2, depending on the soil type. Soil surveys in Scotland show that many areas have soils that are too acidic. The acidity of these soils compromises crop growth, reducing the yield, and increases the proportion of nitrogen fertiliser which is converted to nitrous oxide and emitted from the soil. Soil pH control is, therefore, a practice which can increase the yield and reduce nitrous oxide emissions at the same time. It involves applying lime to the soil, when and where needed, and usually testing the soils every four to five years.

- **Slurry injection and bandspreading of slurry**

Livestock slurry can be applied to the soil using a range of techniques. The most common approach in Scotland is to use a low trajectory splash plate (broadcast). Bandspreading and injection are practical alternative methods that can be used for spreading slurry to cropland and grassland. In bandspreading, a series of parallel pipes connected to a slurry tank apply the slurry in discreet bands directly on the surface (trailing shoe / trailing hose), while in injection the slurry is placed into slits cut by machinery. These techniques reduce odour and crop contamination. They also mitigate ammonia emissions and subsequent nitrous oxide emissions (from the transformation of ammonia into nitrous oxide). However, due to the increased pool of ammonium-nitrogen in the soil and the changes in the soil conditions, direct emissions of nitrous oxide can increase.

- **Variable rate nitrogen and lime application**

Crop-growing conditions are not uniform within a field; while some parts of the field give high yields, in other parts the crops do not perform well. Differences in soil structure, acidity (pH), nutrient content, among other things, can cause such variation. If the variation is considerable, tailored field operations can save resources and enhance the yield. High-resolution sensors, mapping, and decision-making computer systems and variable-rate spreading technologies applied together (in other words precision farming technologies) are capable of varying the rate of inputs applied to soils within one square metre.

Variable-rate nitrogen fertiliser application can reduce GHG emissions and GHG emission intensity as these types of fertiliser result in high or equal yield while using the same or less input. The five main ways they can affect GHG emissions are: increasing yield, reducing nitrogen fertiliser application, reducing tillage and thus increasing soil carbon sequestration, reducing fuel consumption, and reducing other inputs to field operations (impacting off-farm emissions).

Maintaining soil pH at an appropriate level is considered important for both maximising crop production and efficient use of fertiliser. Lower crop biomass and higher nitrous oxide emissions in acid conditions can lead to a large increase in emission intensity nitrous oxide (the quantity of nitrous oxide produced per amount of crop produced). Precision lime application takes account of the often large gradients in pH within fields, applying lime with variable rate applicators on a spatial basis according to the lime required to bring soil up to a target pH.

- **Nitrification and urease inhibitors**

Nitrous oxide emissions from soils are a result of bacteria transforming nitrogen compounds (such as those applied as fertilisers) and in the meantime releasing some of the nitrogen as nitrous oxide. One of these processes, nitrification, can be slowed down by certain chemical compounds (like dicyandiamide (DCD), 3,4-dimethyl pyrazole phosphate (DMPP) and nitrapyrin), which depress the activity of nitrifying bacteria. This, in turn, improves the availability of the nitrogen fertiliser for the plants and reduces both nitrous oxide emissions and nitrate leaching (however, in some cases it can increase ammonia and hence indirect nitrous oxide emissions).

Furthermore, a large proportion of the nitrogen in urea-based fertilisers gets transformed into ammonia and, due to the urease enzyme, released by soil bacteria. This leads not only to ammonia (and indirect nitrous oxide) emissions but reduces the nitrogen plants can utilise. Urease inhibitors delay urea hydrolysis to ammonia, reducing ammonia emissions.

Using urea in combination with urease inhibitors and nitrification inhibitors can further reduce nitrous oxide emissions. Nitrification and urease inhibitors can be injected into the soil together with liquid fertilisers; applied as a coating on granular fertilisers; and mixed into slurry before application. They can also be spread after grazing to reduce emissions from urine.

- **Growing more grain legumes in rotations**

Legumes (e.g. peas, beans, clover) have the special ability to source nitrogen straight from the dinitrogen gas found in the atmosphere, requiring very low (or no) additional nitrogen fertilisers. This is possible due to their symbiotic relationships with bacteria in the soil. They also provide some of this nitrogen to crops which are cultivated with them and also to those which follow them in a rotation (as the above ground residues and roots of the leguminous crops increase the nitrogen content of the soil), reducing the fertiliser requirement for those crops. This measure is about increasing the area of grain legumes in rotations in Scotland.

- **Intercropping**

Intercropping is the spatially and temporally coexistence of two or more arable crops. Typically, one of the crops is a grain legume, and therefore biologically fixes nitrogen. Hence, there will be a reduction in the quantity of fertiliser applied per hectare. In addition, there is the potential for some of the fixed nitrogen to be transferred to the other crop, further reducing the requirement for inorganic nitrogen. However, the nitrogen concentration of legumes is higher than non-legume crops, thus the emissions from the residues will be increased. In the UK, the grain legume is typically pea or faba bean and the cereal is spring oats, spring barley or spring wheat. Although the technology is being developed to separate the cereal from the grain legume, intercrops are usually used as feed for ruminants or monogastrics. However, there will be the need to adjust the ration depending on the protein content of the actual harvested crop. It is assumed that the yield of the intercrop is similar to that of the sole cereal crop.

- **Crop varieties with higher nitrogen-use efficiency**

Nitrogen fertilisation is essential to achieve current yields of most crops. However, only 49% of the nitrogen applied to and biologically fixed by crops (including grass) is recovered as food and feed in Europe (Westhoek *et al.* 2015), most of the remaining being lost to the environment as ammonia, nitrate and nitrous oxide, causing multiple environmental problems.

Crops need nitrogen for their growth, but due to the nature of biophysical processes they can utilise only part of the nitrogen which is in the soil. Improving the efficiency of crops to utilise the nitrogen fertiliser is therefore key in mitigating emissions as well as reducing the economic loss as unrecovered nitrogen. Plant breeding can contribute to improving the nitrogen-use efficiency. Nitrogen-use efficiency varies between individual plants of the same species, and some of this variation is heritable. Therefore, plants with increased nitrogen-use efficiency can be selected for further breeding.

Additionally, radically new cultivars can improve nitrogen-use efficiency and thus reduce GHG emissions or at least the emission intensity of production. For example, perennial wheat can help retain more carbon in the soil as well as reduce fertiliser, pesticide, and fuel use. Nitrogen-fixing cereals, for which three main research streams are ongoing, could, when realised, bring substantial reduction in the nitrogen-fertilisation needs of plants. However, due to data limitations, these mitigation measures only look at possible improvements in existing cultivars.

- **Improved health of ruminants**

Endemic, production-limiting diseases are a major constraint on efficient livestock production, both nationally and internationally, and have an impact on the carbon footprint of livestock farming. UK systems are particularly vulnerable to endemic disease impacts because they are largely pasture-based. The emissions intensity of ruminant meat and milk production is sensitive to changes in key production aspects, such as maternal fertility rates, mortality rates, milk yield, growth rates and feed conversion ratios - all of which are influenced by the health status of the animal. Therefore, improving health status is expected to lead to reductions in emission intensity. Animal health is a complex topic, influenced by a plethora of diseases. It can be improved through preventative controls (such as changing housing and management to reduce stress and exposure to pathogens; vaccination; improved screening and biosecurity; disease vector control) and curative treatments such as antiparasitics and antibiotics. In this work a simplistic approach was chosen; rather than estimating the GHG effects of the prevention and control of individual diseases, a general improvement in the health status was assumed, without reference to specific management options.

- **High-starch diet for dairy cattle**

The amount of enteric methane emission depends on the composition of the animal feed, amongst other things. The more starch the diet contains, as opposed to fibre, the lower the methane emissions. This is the result of the different chemical pathways in ruminal fermentation; fibre digestion generates more dihydrogen and subsequently more methane. Thus. higher inclusion of high-starch feed components, for example grain or whole-crop cereal or maize silage, lowers enteric methane emissions. However, the partial replacement of grass (as a fibre source) with starch necessitates a change in plant production and therefore land use from grass to cereal areas. This is likely to induce the release of carbon from the soil, depending on the details of previous and new cultivation practices and the soil type. In this report, we assumed maize would be grown on temporary grass areas.

- **Precision feeding of livestock**

How well animals can utilise their feed depends on the individual animal and also on diet. Precision feeding allows for feed to be tailored to suit most of the needs of individual animals, increasing the efficiency with which nutrients in the feed are utilised. As less feed is used to achieve the same production, greenhouse gas emissions from feed production is reduced. This practice can also reduce the rate of nitrogen and volatile solid excretion and therefore the nitrous oxide and methane emissions arising from manure management. It is applicable primarily to housed animals that can be monitored at regular intervals, as such information is needed to adjust rations. For pigs, this may involve regular weighing of animals and adjustment of the ration protein content based on weight and growth rate, and supplementation of diets with synthetic amino acids. For ruminants, emissions could be reduced through improved characterisation of forages to enable appropriate supplementation.

- **3NOP feed additive for cattle**

3-Nitrooxypropanol (3NOP) is a chemical substance that reduces the emission of enteric methane by ruminants when added to their rations. It does so by reducing the rates at which rumen microbes convert the hydrogen in ingested feed into methane. Specifically, 3NOP inhibits the final step of methane synthesis by microbes. For housed animals, the 3NOP could be mixed in with the ration, while in grazing situations it may be possible to deliver the 3NOP via a bolus.

- **Covering slurry stores with impermeable cover**

Animal excreta stored in liquid systems is a source of substantial ammonia and methane emissions, as during the storage N and the volatile solids excreted turn into these gaseous compounds. Though nitrous oxide is not generated in large quantities in slurry stores, a small portion of the ammonia turns into nitrous oxide subsequently in the environment (the process is called indirect nitrous oxide emission). Several factors affect the rate of ammonia, methane and nitrous oxide emissions, including the airflow over the manure; by covering the stores these emissions can be reduced. The presence of a slurry cover increases the ammonia concentration of the slurry and hence its nitrogen content and fertiliser value, but also the potential subsequent ammonia and nitrous oxide losses when the slurry is applied to the soil, unless low ammonia-emission spreading techniques are implemented.

Cover technologies include floating covers, rigid covers, natural crust and suspended, tent-like structures, and their effects on the pollutant gases are very different. A review of experimental results showed that impermeable plastic covers have the potential to reduce ammonia and GHG emissions in parallel. However, there can be feasibility problems with floating covers if applied on slurry tanks or larger lagoons and their durability is not yet well tested. Impermeable covers do not inhibit methane formation, so the gas built up under the cover needs to be managed to avoid an explosion risk (in this measure the flaring or purification of the methane is not assumed). Furthermore, depending on the structure, rainwater can accumulate on impermeable floating covers and needs to be removed via e.g. pumping.

- **Cattle breeding for low-methane emissions**

The composition of the micro-organisms present in the gut of mammals is influenced by the genetics of the host animal. Studies indicate that it is possible to select dairy cattle for low-methane emission, as methane production is heritable to some extent. Inclusion of low enteric methane emission in the breeding goal could reduce methane emissions from cattle, though might limit the productivity and fitness improvements, as selection for low emission causes changes in the animal's nutritional physiology.

The measure assumes that enteric methane emission is introduced in the breeding goal and therefore animals are started to be selected considering their enteric methane emissions. The measure requires farmers buying (semen from) breeding animals with lower methane emissions. The improvements in emissions are cumulative over the years as the emissions from the individual animals get reduced by breeding. Genetic improvement in the national herd can be enhanced by using genomic tools, while farmers collect performance information on the individual animals and genetic testing, and feed this information back for breeding goal development. As well as the methane emission reductions, using genomics also means production traits can be improved.

3.2.4 Assumptions about the mitigation measures

Information on the potential abatement rate, net costs, applicability and current uptake of the measures were sourced from a mixture of peer-reviewed scientific literature, GHG mitigation cost-effectiveness reports and industry information available online or through personal communication (see the detailed assumptions in the Appendix). The measures' potential mitigation effects reported in the literature were transformed to fit in the IPCC calculations used by the UK agricultural greenhouse gas inventory, modifying the activity and/or the emission parameters.

The interactions between the measures were to be considered in the TIMES model. The following constraints were suggested to be applied in the TIMES model:

- The total uptake of trailing hose/shoe slurry application (bandspreading) (MM50) and slurry injection (MM14) together cannot be more than 17.5% of all agricultural land (slurry is applied on 25% of grassland which is 17.5 % of agricultural land and the two practices would not be applied together, on the same land).
- The total uptake of soil pH management (MM3) and variable rate nitrogen and lime application (MM51) together cannot be more than 32.5% of all agricultural land (this is where liming is required and the two practices would not be applied together, on the same land).
- The combined uptake of soil pH management (MM3), variable rate nitrogen and lime application (MM51), nitrification and urease inhibitors (MM12) and growing more grain legumes in rotation (MM60) cannot be more than 100% of agricultural land. Though these four nitrogen fertilisation management measures are not mutually exclusive (apart from MM3 with MM51), applying them together would reduce their mitigation effect. This rule is suggested as an approximation, in order to avoid overestimating the combined mitigation (it could slightly underestimate the total mitigation).
- No constraints were suggested regarding the other-crop related mitigation measures (though small interactions can happen between some, for example crop varieties with higher nitrogen use efficiency (MM1) and nitrification and urease inhibitors (MM12)).
- No constraints between the dairy measures were suggested to be included. Some interactions might occur in reality, but it was decided that as constraints can only be added in TIMES by constraining the combined uptake to a maximum value, such a method would restrict the mitigation potential far too much. These interactions could mainly happen between 3NOP feed additive for dairy (MM35) and dairy breeding for low methane emissions (MM27).
- No constraints between the beef measures were suggested to be included (though improved health of beef cattle (MM57) might slightly reduce the effectiveness of 3NOP feed additive for beef (MM54) as the amount of methane emissions is reduced).
- No constraints between the pig measures were suggested to be included (though precision feeding of pigs (MM56) could slightly reduce the effectiveness of covering pig slurry stores with impermeable cover (MM59) as the amount of excreted nitrogen is reduced).

3.3 Reconciliation between the two models

The outputs of the MACC model were needed to fit with the structure of the agricultural module of the Scottish TIMES model. To achieve this, the following decisions were made:

- The emission activity categories in the TIMES model follow the UK agricultural inventory (e.g. agricultural land, dairy cattle) and the baseline emission projections are expressed for these categories in TIMES. To be able to relate the mitigation to these baseline projections the mitigation effects needed to be expressed in these categories (e.g. dairy and beef cattle separately).
- The baseline activities (e.g. land area under different crops, number of sheep) between the two models needed to be as close as possible. In the MACC tool a 2016 baseline was used.
- The emissions are represented by gas and emission categories in the TIMES model (e.g. direct nitrous oxide emissions from soils), thus the mitigation effect in the MACC needed to be expressed in these categories.

- The uptake level in TIMES is estimated intrinsically; therefore, the mitigation and cost of the measures were provided for activity units (e.g. hectare, animal) rather than as a total value for Scotland. For livestock, the unit head livestock were chosen rather than livestock unit
- The TIMES model considers capital and annual costs separately; thus the relevant breakdown of costs is required. If a measure requires multiple capital investments which have different lifetimes, these were aggregated into a single value (by adding up the capital costs and calculating the weighted average lifetime of the multiple items).
- The maximum uptake level TIMES can assign to a mitigation measure needs to reflect the applicability and maximum further uptake of the measure; this was expressed as a proportion of the total activity in Scotland
- Interactions between the measures can occur (e.g. the mitigation potential of variable rate nitrogen application is lower if legumes are included in the rotation and thus the synthetic nitrogen applied is reduced).

4 Results: estimates of greenhouse gas mitigation and costs

The annual mitigation potential and annualised costs of the individual measures were calculated in the MACC tool for the year 2050, assuming maximum possible uptake (maximum technical potential, MTP). The results, in the format required for the TIMES model, are presented in Table *4* 4,Table *5* and 6. These results do not consider the potential reduction (or increase) in the cumulative abatement in case more than one mitigation measures is applied on any farm (these interactions are dealt with in the TIMES model).

The results are provided under the following headings:

- Mitigation measure abbreviation: abbreviated name of the measure
- ID: identification number of the measure, corresponding to the numbering in Table **1**
- Crop/livestock category: the type of activity the measure can be applied to
- Lifetime: average lifetime in years of the capital investment required (if any); if no capital investment needed the lifetime is one year
- Annualised total cost: the annualised net cost of the measure (considering the annual costs and benefits and the capital costs)
- Annual costs: the net annual cost of implementing the measure
- Capital costs: the capital cost required to implement the measure
- Start year: potential first year of rolling out implementation
- Capacity metric: the metric by which the measure's uptake is described
- Capacity unit: the unit in which the measure's uptake is described
- Full capacity: the total extent of the activity in Scotland
- Maximum capacity bound: the proportion of the total activity where the measure can be applied

- Unitary mitigation effect: the mitigation the measure can achieve in the various emission categories related to farming (negative values mean increased emissions)

Table 4: Cost of the measures, 2050 (without interactions)

Mitigation measure abbreviation	ID	Crop/livestock category	Lifetime (y)	Per unit costs: Annualised total cost (£ ha^{-1} y^{-1} for crop and £ head^{-1} y^{-1} for livestock measures)	Annual costs (£ ha^{-1} y^{-1} for crop and £ head^{-1} y^{-1} for livestock measures)	Capital costs (£ ha^{-1} for crop and £ head^{-1} for livestock measures)
ImpCropNUE	MM1	Agric. land	1	-10.17	-10.17	0.00
pHCrop	MM3	Agric. land	4	-7.86	-45.00	141.16
NitrifUreaseInhibitor	MM12	Agric. land	1	20.67	20.67	0.00
BreedingLowMethane-dairy	MM27	Dairy	18	-358.74	-359.15	4.40
HealthCattle-dairy	MM30	Dairy	1	-26.89	-26.89	0.00
HighStarchDiet	MM31	Dairy	1	0.00	0.00	0.00
PrecisionFeeding-dairy	MM32	Dairy	5	-18.22	-47.12	135.07
3NOP-dairy	MM35	Dairy	1	17.78	17.78	0.00
CoverSlurryImperm-dairy	MM47	Dairy	10	2.56	-0.40	25.55
HealthSheep	MM48	Sheep	1	-0.36	-0.36	0.00
3NOP-beef	MM54	Beef	1	31.38	31.38	0.00
PrecisionFeeding-pigs	MM56	Pigs	5	-0.87	-6.01	24.05
BreedingLowMethane-beef	MM55	Beef	6	-15.96	-16.20	2.59
HealthCattle-beef	MM57	Beef	1	20.26	20.26	0.00
VRTLime-VRTN	MM51	Agric. land	6	-16.83	-93.57	328.66
Intercropping	MM52	Agric. land	1	-45.18	-45.18	0.00
CoverSlurryImperm-beef	MM58	Beef	10	-0.25	-2.78	21.85
CoverSlurryImperm-pigs	MM59	Pigs	10	0.52	0.08	3.83
SlurryInjection	MM14	Agric. land	1	21.35	21.35	0.00
SlurryTrailingHose	MM50	Agric. land	1	8.16	8.16	0.00
GrainLegumes	MM60	Agric. land	1	406.00	406.00	0.00

Table 5: Applicability of the measures, 2050 (without interactions)

Mitigation measure abbreviation	ID	Start year	Capacity metric	Capacity unit	Full capacity ha for crop and head for livestock measures		Maximum capacity bound 2050 (proportion of full capacity)
					2016	2050	
ImpCropNUE	MM1	2020	Agricultural land	ha	1,863,646	1,784,193	0.238205
pHCrop	MM3	2020	Agricultural land	ha	1,863,646	1,784,193	0.325807
NitrifUreaseInhibitor	MM12	2020	Agricultural land	ha	1,863,646	1,784,193	0.808941
BreedingLowMethane-dairy	MM27	2020	Dairy cattle numbers	head	336,473	321,021	0.191117
HealthCattle-dairy	MM30	2020	Dairy cattle numbers	head	336,473	321,021	0.752021
HighStarchDiet	MM31	2020	Dairy cattle numbers	head	336,473	321,021	0.052345
PrecisionFeeding-dairy	MM32	2020	Dairy cattle numbers	head	336,473	321,021	0.261724
3NOP-dairy	MM35	2020	Dairy cattle numbers	head	336,473	321,021	0.529098
CoverSlurryImperm-dairy	MM47	2024	Dairy cattle numbers	head	336,473	321,021	0.30748
HealthSheep	MM48	2020	Sheep numbers	head	6,860,315	8,005,799	0.72431
3NOP-beef	MM54	2020	Beef cattle numbers	head	1,408,703	1,643,917	0.517495
PrecisionFeeding-pigs	MM56	2020	Pigs numbers	head	209,820	244,854	0.9
BreedingLowMethane-beef	MM55	2020	Beef cattle numbers	head	1,408,703	1,643,917	0.189979
HealthCattle-beef	MM57	2020	Beef cattle numbers	head	1,408,703	1,643,917	0.783723
VRTLime-VRTN	MM51	2020	Agricultural land	ha	1,863,646	1,784,193	0.172139
Intercropping	MM52	2020	Agricultural land	ha	1,863,646	1,784,193	0.059015
CoverSlurryImperm-beef	MM58	2020	Beef cattle numbers	head	1,408,703	1,643,917	0.247234
CoverSlurryImperm-pigs	MM59	2020	Pigs numbers	head	209,820	244,854	0.262597
SlurryInjection	MM14	2020	Agricultural land	ha	1,863,646	1,784,193	0.174936
SlurryTrailingHose	MM50	2020	Agricultural land	ha	1,863,646	1,784,193	0.174936
GrainLegumes	MM60	2020	Agricultural land	ha	1,863,646	1,784,193	0.045959

Table 6: Mitigation potential of the measures, 2050 (without interactions)

Mitigation measure abbreviation	ID	Unitary mitigation effect (t CO_2e ha^{-1} for crop and t CO_2e $head^{-1}$ for livestock measures)							
		Reduction in soil nitrous oxide from synthetic N use	Reduction in soil nitrous oxide from manure use	Carbon sequestration	Reduction in CO_2 from fuel use	Reduction in CO_2 from liming	Reduction in methane from enteric fermentation	Reduction in methane from manure storage	Reduction in nitrous oxide from manure storage
ImpCropNUE	MM1	0.01346	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
pHCrop	MM3	0.02738	0.00000	0.30000	0.00000	-0.21570	0.00000	0.00000	0.00000
NitrifUreaseInhibitor	MM12	0.07136	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
BreedingLowMethane-dairy	MM27	-0.00454	0.05801	0.00000	0.00000	0.00000	0.41283	0.06499	0.09612
HealthCattle-dairy	MM30	-0.00392	0.00335	0.00000	0.00000	0.00000	0.04448	0.00502	0.00784
HighStarchDiet	MM31	0.00000	0.00000	0.00000	0.00000	0.00000	0.16242	0.00000	0.00000
PrecisionFeeding-dairy	MM32	0.00284	0.00835	0.00000	0.00000	0.00000	0.06497	0.01429	0.01384
3NOP-dairy	MM35	-0.00063	0.00277	0.00000	0.00000	0.00000	0.84253	0.00446	0.00552
CoverSlurryImperm-dairy	MM47	-0.01959	-0.10195	0.00000	0.00000	0.00000	0.00000	0.45440	0.19413
HealthSheep	MM48	0.00000	0.00000	0.00000	0.00000	0.00000	0.01350	0.00037	0.00151
3NOP-beef	MM54	-0.00363	0.00114	0.00000	0.00000	0.00000	0.41947	0.00216	0.00347
PrecisionFeeding-pigs	MM56	0.00000	0.00174	0.00000	0.00000	0.00000	0.00000	0.00668	0.01665
BreedingLowMethane-beef	MM55	-0.00973	0.00263	0.00000	0.00000	0.00000	0.11002	0.00510	0.00834
HealthCattle-beef	MM57	-0.00408	0.00122	0.00000	0.00000	0.00000	0.02322	0.00249	0.00445
VRTLime-VRTN	MM51	0.06303	0.00000	0.30000	0.00381	-0.21570	0.00000	0.00000	0.00000
Intercropping	MM52	0.07444	0.00000	0.00000	0.00407	0.00000	0.00000	0.00000	0.00000
CoverSlurryImperm-beef	MM58	-0.08574	-0.07782	0.00000	0.00000	0.00000	0.00000	0.24356	0.14506
CoverSlurryImperm-pigs	MM59	0.00000	-0.00022	0.00000	0.00000	0.00000	0.00000	0.07045	0.01624
SlurryInjection	MM14	0.00000	0.02641	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
SlurryTrailingHose	MM50	0.00000	0.00660	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
GrainLegumes	MM60	0.553000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000

5 Results and conclusions

The unitary mitigation potential and net costs of the measures assessed are ranked within each category in Table 7. The mitigation measures related to crop and grass production assessed in this study can save between 7 and 553 kg CO_2e every year on each hectare where they are applied. Increased cultivation of grain legumes (i.e. peas and beans) could provide the highest mitigation per hectare, but it is also the most expensive. The second and third most effective measures, variable rate nitrogen and lime application (precision farming), and soil pH management (i.e. liming when necessary), could – on average – provide net savings to the farmers.

The cattle mitigation measures assessed can save between 57 and 854 kg CO_2e every year for each animal that they are applied to. In both the dairy and the beef sector the 3NOP feed additive is the most effective measure but it is also the most expensive. Breeding for low methane emissions and slurry store cover with impermeable cover are also very effective for cattle and they provide net savings (apart from dairy slurry cover, which, on average, is estimated to cost £2.56 per animal annually). The sheep measure investigated can provide 15 kg CO_2e mitigation per animal annually and a cost saving of £0.36 per head. The two measures applicable to pigs could reduce emissions by 25 and 86 kg CO_2e per head per year for a saving of £0.87 and a cost of £0.52, respectively.

These estimates assume that the mitigation measure is implemented on its own, with no other mitigation measures, i.e. potential interactions between the measures, which could reduce their mitigation potential, are not included.

Table 7: Unitary mitigation potential and cost of the measures, 2050 (without interactions)

Mitigation measure	Crop/livestock category	Annualised total cost (£ ha^{-1} y^{-1} for crop and £ $head^{-1}$ y^{-1} for livestock measures)	Annual total mitigation (t CO_2e ha^{-1} y^{-1} for crop and t CO_2e $head^{-1}$ y^{-1} for livestock measures)
Trailing hose/shoe slurry application	Agric land	8.16	0.007
Slurry injection	Agric land	21.35	0.026
Crop varieties with higher nitrogen use efficiency	Agric land	-10.17	0.013
Nitrification and urease inhibitors	Agric land	20.67	0.071
Intercropping	Agric land	-45.18	0.079
Soil pH management	Agric land	-7.86	0.112
Variable rate nitrogen and lime application	Agric land	-16.83	0.151
Growing more grain legumes in rotation	Agric land	406.00	0.553
Improved health of ruminants - dairy	Dairy	-26.89	0.057
Precision feeding of livestock - dairy	Dairy	-18.22	0.104
High starch diet for dairy cattle	Dairy	0.00	0.162
Covering slurry stores with impermeable cover – dairy	Dairy	2.56	0.527
Cattle breeding for low methane emissions – dairy	Dairy	-358.74	0.627
3NOP feed additive for cattle - dairy	Dairy	17.78	0.855
Improved health of ruminants - beef	Beef	20.26	0.027
Cattle breeding for low methane emissions – beef	Beef	-15.96	0.116
Covering slurry stores with impermeable cover – beef	Beef	-0.25	0.225
3NOP feed additive for cattle - beef	Beef	31.38	0.423
Improved health of ruminants - sheep	Sheep	-0.36	0.015
Precision feeding of livestock - pigs	Pigs	-0.87	0.025
Covering slurry stores with impermeable cover – pigs	Pigs	0.52	0.086

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7 Appendix: Mitigation measure descriptions

7.1 Soil pH management

7.1.1 Overview

The acidity of soils (soil pH) plays a major role in regulating the chemistry and fertility of soils and depends upon the net balance of a wide range of chemical and biological processes. Good management of soil acidity is essential to optimise crop productivity. Most crop plants are more productive in a range of pH between 5.5 to 7.0. Outside of this range productivity decreases and the utilisation of nutrients added – including nitrogen fertilisers – becomes less efficient. There is a range of indirect ways in which pH influences GHG emissions, making pH management an important tool in GHG mitigation.

Soil pH plays an important role in regulating and modifying nitrous oxide emissions. In more acid soils, there is a higher ratio of N_2O:dinitrogen[12] emission because the N_2O reductase enzyme which converts N_2O to dinitrogen is inhibited (Liu *et al.* 2014). Thus, in soils that have a tendency to produce N_2O by denitrification, more acid conditions are likely to lead to a higher N_2O emission rates (Simek *et al.* 1999; Goulding 2016; Zhu *et al.* 2019). Because soil acidity can also reduce crop growth, maintaining soil pH at an appropriate level is considered important for both the optimisation of crop production and efficient use of fertiliser inputs (Goulding 2016). Lower crop biomass and higher nitrous oxide emissions in acid conditions can lead to a large increase in the quantity of Nitrous Oxide produced per unit of crop product) (nitrous oxide emission intensity).

Evidence suggests that lime application may modify soil microbial communities (Goulding 2016) and increase organic matter inputs (Fornara *et al.* 2011; Jokubauskaite *et al.* 2016) with the effect of increasing soil carbon stocks (SOC) (Li *et al.* 2018, Fornara *et al.* 2011).

Managing soil pH involves gathering information on the current status of the soil (e.g. via soil sampling and analysis) and the application of lime on land which is below the optimal pH for crop or grass growth. Optimal pH varies depending on the land use, type of crop grown, and soil type. Required lime application rates to optimise pH vary depending on soil type and on the difference between the existing soil pH and the target pH. Usually it is sufficient to repeat this process in every four years.

7.1.2 Greenhouse gas mitigation summary

Changes in nitrous oxide emissions following lime application result from changes to the nitrification and denitrification processes. These effects are context specific, with variable relationships between pH and the proportion of applied nitrogen emitted as nitrous oxide (Skiba *et al.* 1998; Russenes *et al.* 2016). However, since liming increases soil nutrient availability (ALA 2011; Goulding 2016), requirement for nitrogen application is likely to decrease, or the same nitrogen fertilisation rate would result in increased yield, i.e. a net reduction in nitrous oxide emission intensity.

SOC content is likely to increase where pH is raised – again, a complex and context specific response (Li *et al.* 2018). In grassland, Fornara *et al.* (2011) reported substantial increases in grassland SOC for limed treatments, both in fertilised and unfertilised

[12] Dinitrgoen (N_2) is the for of nitrgoen making up 78% of the Earth's atmosphere; it has a very low reactivity and is not a greenhouse gas or nitrogen pollutant

swards. For cropland, Tu *et al.* (2018) reported a positive correlation between pH and SOC. Based on the aforementioned papers and work in SRUC here we assume that an increase of 1 pH unit in the range pH 4-7 corresponds to an increase in SOC concentration of 0.82-1.97 g kg^{-1}. At a typical soil bulk density of 1.1 g cm^{-3}, and assuming pH impact to 20 cm depth (Goulding 2016) this roughly equates to an increase of 1.8-4.3 t C ha^{-1}. Assuming a 20-year stabilisation period (de Klein *et al.* 2006), this equates to a sequestration rate of 330-788 kg CO_2e ha^{-1} $year^{-1}$. Note that this is a broad extrapolation based on site-specific data and should be taken as an indication only. To provide a conservative estimate we assume 300 kg CO_2e ha^{-1} $year^{-1}$ C sequestration in this work.

Direct CO_2 emissions from lime application means that lime can be (though is not necessarily) a net source of CO_2 (Hamilton *et al.*, 2007). The relevant IPCC Guidelines for National greenhouse gas Reporting (de Klein *et al.*, 2006) assume lime to be a CO_2 source, with an estimate of 0.0625—0.125 kg CO_2 kg $lime^{-1}$. This emission factor is directly related to the mass fraction of C in lime ($CaCO_3$), with the maximum emission assuming release of all molecular C to the atmosphere as CO_2 (de Klein *et al.*, 2006; Fornara *et al.*, 2011). This contrasts with the findings of Hamilton *et al.* (2007), who show that whilst lime can be a source of CO_2, it is more often a net sink. Fornara *et al.* (2011) also show that lime can be a C sink; the authors identify two pathways by which this can be the case. Lime may either a) increase carbonic acid (HCO_3^-) concentrations in soil water, sequestering 25-50% of lime C, or b) contribute to the movement of existing soil C from labile to humified pools, increasing its net storage time in the soil.

Emissions associated with lime extraction (embedded emissions) have been estimated at 0.074 kg CO_2e kg $lime^{-1}$ (range 0.054—0.089 kg CO_2e kg $lime^{-1}$) (Kool *et al.* 2012).

7.1.3 Costs

The costs of lime application include purchase of lime, spreading and soil analysis. It is recommended that farms apply lime at three to six year intervals depending on results of soil analyses (SRUC 2014). The financial benefits of soil pH management consist of the additional income from yield increase.

7.1.4 Applicability and uptake

The Scottish Government (2018a) reports that 64% and 30% of farms carried out pH testing on arable and grazing land respectively in 2016. A recent survey of over 1,000 fields of grassland (Ayrshire, Water of Coyle) and arable land (Perth, East Pow), showed that 57% of grassland soils and 34% of arable soils had low or very low pH values (SRUC 2018). This is consistent with UK data indicating that between 31% and 49% of arable and grassland soils have suboptimal pH (PAAG 2016). The applicability of the measure is assumed to be 50% on fertilised grasslands and 30% on croplands.

7.1.5 Summary of assumptions used in the MACC

Table 8: Assumptions used in the modelling

Parameter	Change in value
Yield change	+6.22% (crops and grass)
EF_1 change	-3%
C sequestration	300 kg CO_2e ha^{-1} y^{-1}
Lime cost	£111 ha^{-1} (3.7 t ha^{-1} lime @ £30 t^{-1}) in every 4 years
Lime spreading cost	£10.16 ha^{-1} in every 4 years
Soil analysis cost	£20 ha^{-1} in every 4 years

7.2 Slurry injection and bandspreading of slurry

7.2.1 Overview

Livestock slurry can be applied to the soil using a range of techniques. The most common approach in Scotland is to use a low-trajectory splash plate (broadcast), which accounts for over 68% of applications (Scottish Government 2016). Bandspreading and injection are practical alternative methods that can be used for spreading slurry to cropland and grassland.

Compared to broadcast, these techniques spread the slurry more evenly, reducing odour and crop contamination (Thorman 2011). Bandspreading and injection have also been shown to reduce ammonia emissions (Hafner *et al.* 2019), and therefore the associated indirect GHG emissions. However, due to the increased pool of ammonium-nitrogen in the soil and the changes in the soil conditions, emissions of nitrous oxide can increase (Thorman 2011).

The measure entails switching from applying slurry via a splash plate (broadcast) to: (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 (trailing shoe / trailing hose) or (b) injection of slurry below the soil surface.

7.2.2 Greenhouse gas mitigation summary

Trailing shoe and injection technology can dramatically reduce ammonia emissions (Defra 2007, Hafner *et al.* 2019). The semi-empirical model of Hafner *et al.* (2019) using European data predicted a reduction relative to broadcast of 63% by injection; this compares with a reduction of 48% observed in a UK study (Defra 2007). The model predictions for trailing shoe were 33% lower than for broadcast (Hafner *et al.* 2019). However, in a UK study, trailing shoe / hose only had a significant impact on ammonia emissions in three of fourteen experiments with a mean reduction of 12% (Defra 2007). The lack of effect was explained by the fact that the slurry did not stay in the band and therefore did not rapidly infiltrate the soil. The results of the Defra Greenhouse Gas Platform Project[13] revealed that trailing hose resulted in a reduction in emissions in spring, but not in autumn. The leaching losses associated with autumn applications of slurry were higher for trailing shoes than for broadcast. In terms of direct nitrous oxide emissions, the effect of application method was variable with either no effect or increases in emissions being reported (Bourdin *et al.* 2014, Chadwick *et al.* 2011, Defra 2007). The results of the Defra study (2007) showed no consistent impact on N use

[13] http://www.ghgplatform.org.uk/

efficiency of the slurry, and thus there is no consistent effect on reducing the requirement for the associated inorganic fertiliser inputs.

Compared to broadcast, the energy cost of trailing hose and injection are higher. The Farmscoper tool (ADAS 2017) assumes that the significant reductions on ammonia volatilisation will be offset by increases in energy required to power the equipment for both band spreading and injection, along with mixed effects on nitrate leaching and direct nitrous oxide Table 9 *and*

Table *10*.

Table 9: Effect on pollutant flows of Farmscoper measure 70: Using slurry trailing hose / trailing shoe application techniques (ADAS 2017)

	Ammonia	**Energy use**	**Nitrate**	**Nitrous oxide**	
Pathway(s)	Gaseous	Gaseous		All flows	All flows
Effect	-50%	-25%	+50%	+10%	+10%

Table 10: Effect on pollutant flows of Farmscoper measure 71: Use slurry injection application techniques (ADAS 2017)

	Ammonia	**Energy use**	**Nitrate**	**Nitrate**	**Nitrous oxide**	**Nitrous oxide**
Pathway(s)	Gaseous		Runoff/ Preferential	Leaching	Runoff/ Preferential	Leaching
Effect	-80%	+100%	-50%	+25%	-50%	+25%

From the evidence detailed above, it is assumed in this work that the volatilisation (FRACgas) is reduced by 48% and 12% for injection and trailing hose, respectively. Thus, the revised FracGas values are 0.1 for injection and 0.18 for trailing hose. It is assumed that the increase in fuel use offsets the reduction in nitrous oxide emissions and thus neither is changed in the model.

Table 11: Data from literature on abatement

Abatement	Value	Country	Reference
FracGas	Injection: 0.1 Trailing shoe / hose: 0.18	UK	(Defra 2007)
Energy CO_2	No change (reduction in nitrous oxide is offset increase in CO_2)	UK	(ADAS 2017)

7.2.3 Costs

This measure involves the purchase of equipment for band spreading or injection and higher operating costs associated with increased fuel use, particularly for injection systems. Cost estimates are given in

Table *12*.

Table 12: Financial costs and benefits of the measure

Costs/savings	Value ('-' sign for savings)	Reference
Trailing shoe / trailing hose	£0.91/m^3 slurry	(ADAS 2017)
Slurry injection	£2.38/m^3 slurry	(ADAS 2017)

7.2.4 Applicability

In the UK, 43% of the organic manures applied is cattle or pig farm-yard manure (FYM), and 44% is cattle or pig slurry (Defra 2019). Therefore, it is assumed that the measure is applicable to 50% of organic manure applications. Slurry is applied to 2.2 % of the winter sown crops, 5.6% of the spring sown crops and 25.6% of grassland (Defra 2019). It has been assumed that the slurry applied to cropland is incorporated at the time of application. Therefore, this measure is regarded as only being applicable to grassland.

7.2.5 Current uptake and maximum additional future uptake

In Scotland in 2016, 17.2 million tonnes of FYM or slurry was applied (Scottish Government 2016). In 2016, 4.8 million tonnes (28%) was bandspread, and 0.6 million tonnes (3.5%) was injected. In addition, 0.4 million tonnes were broadcast and ploughed in within 4 hours (2.3%). These technologies reduce ammonia emissions; therefore, the reduction in indirect emissions will not apply to this (we assume that these technologies are used on cropland). Based on UK figures, we estimated that 50% of the 17.2 million tonnes is slurry and the remainder FYM (Defra 2019). Thus, as ammonia emission mitigation technologies are already applied to 5.8 million tonnes (bandspread, injected and ploughed in within 4 hours), the potential for uptake is 2.8 million tonnes.

7.2.6 Assumptions used in the MACC

Table 13: Assumptions used in the modelling

Parameter	Change in value
FracGas	Injection – 0.1 Trailing shoe / hose 0.18
Energy $_{CO2}$	Reduction in nitrous oxide is offset by increase in CO_2
Cost of trailing shoe / trailing hose application	£0.91 m^{-3} slurry
Cost slurry injection	£2.38 m^{-3} slurry

7.3 Variable rate nitrogen and lime application

7.3.1 Overview

Nitrous oxide emissions arising from the use of synthetic nitrogen fertilisers can be reduced by more targeted use, supported by a better understanding of spatial heterogeneity in field conditions, linked to technology capable of delivering variable rate fertiliser applications. Precision agriculture technologies (PATs) allow the farmers to consider the field as a heterogeneous entity and apply selective management, potentially increasing efficiency (Aubert et al. 2012). Schwartz *et al.* (2010) categorised PATs into guidance, recording and reacting technologies. Guidance technologies (e.g. controlled traffic farming, machine guidance) help to make machinery movement more precise within and between the fields. Recording technologies (e.g. soil mapping, canopy sensing) collect information from the field (including the soil and crops) before, during or after the growing period. Recorded data, in turn, can be integrated to support the use of variable rate nitrogen applications. This can take into account not only in-field variation, but the temporal aspect if in-season information is collected (Diacono *et al.* 2013). The technology is rapidly developing, and under the H2020 EU research funding scheme there have been more than a dozen projects in recent years working on technological and infrastructure development for precision solutions across farming systems[14].

Machine guidance technologies are systems that pilot machinery using GPS in order to reduce overlaps of and avoid gaps between passes. At the entry level a GPS receiver mounted on the machinery and a lightbar or an on-board display providing driving direction is needed; with such systems ±40 cm accuracy can be achieved. More advanced solutions, with accuracy up to ±2 cm, use auto-guidance systems (auto-steering) integrated in the tractor's hydraulics and directly control steering. Machine guidance is a prerequisite for VRNT, but could be used in itself (Barnes *et al.* 2017a).

Figure 1: Example of a VRNT system (Stamatiadis et al. 2018)

Variable rate nitrogen technology (VRNT) makes it possible to adjust the application rate to match fertiliser need better in that precise location within the field. Using a digital map or real-time sensors, a decision tool calculates the N needs of the plants and transfers that information to a controller, which adjusts the spreading rate (Barnes *et al.* 2017a). VRNT applications in crop and grass production can reduce GHG emissions and their intensity as they result in high or equal yield while using the same or less input. The five main ways they can affect GHG emissions are summarised by Balafoutis *et al.* (2017): increasing yield with while reducing N fertiliser application; reducing tillage and thus increasing soil C sequestration; reducing fuel consumption; and reducing other inputs to field operations (impacting off-farm emissions).

Current commercially available VRNTs adjust N rates on the basis of canopy reflectance measurements using software to model the link to crop N requirement. However, new research is being undertaken on the underlying causes of variable reflectance (and N

[14] https://cordis.europa.eu/article/id/400295-precision-farming-sowing-the-seeds-of-a-new-agricultural-revolution/en

recovery), which is likely to be soil related. The outcome of this research is likely to lead to new approaches to precision management within the next 5-10 years.

Nitrous oxide accounts for a significant share of the GHG emissions from arable and grassland systems. Soil pH plays an important role in regulating and modifying these nitrous oxide emissions. In more acid soils, there is a higher ratio of nitrous oxide:N_2 emission from denitrification because the nitrous oxide reductase enzyme which converts nitrous oxide to N_2 is inhibited (Liu *et al.* 2014; Zhu *et al.* 2019). Thus, in soils that have a tendency to produce nitrous oxide by denitrification, more acid conditions are likely to lead to higher nitrous oxide emission rates. Because soil acidity can also reduce crop growth, maintaining soil pH at an appropriate level is considered important for both the optimisation of crop production and efficient use of fertiliser inputs (Goulding 2016). Lower crop biomass and higher nitrous oxide emissions in acid conditions can lead to a large increase in emission intensity nitrous oxide (the quantity of nitrous oxide produced per unit of crop). New precision approaches to lime application take account of the often large gradients in pH within fields, applying lime with variable rate applicators on a spatial basis according to the lime required to bring soil up to a target pH. Although this management approach is specifically designed to optimise crop growth through pH management, it is likely that there will be co-benefits in terms of nitrous oxide emission given the sensitivity of emissions to pH. Preliminary measurements highlight the increased emissions of nitrous oxide in the more acidic areas of grassland (Figure *2*). Work is currently underway at SRUC in the UK in partnership with other European countries and AgResearch in NZ to test this hypothesis using conventional and variable rate lime applications on grassland soils, followed by subsequent measurements of nitrous oxide emission during the growing season (http://eragas.eu/research-projects/magge-ph).

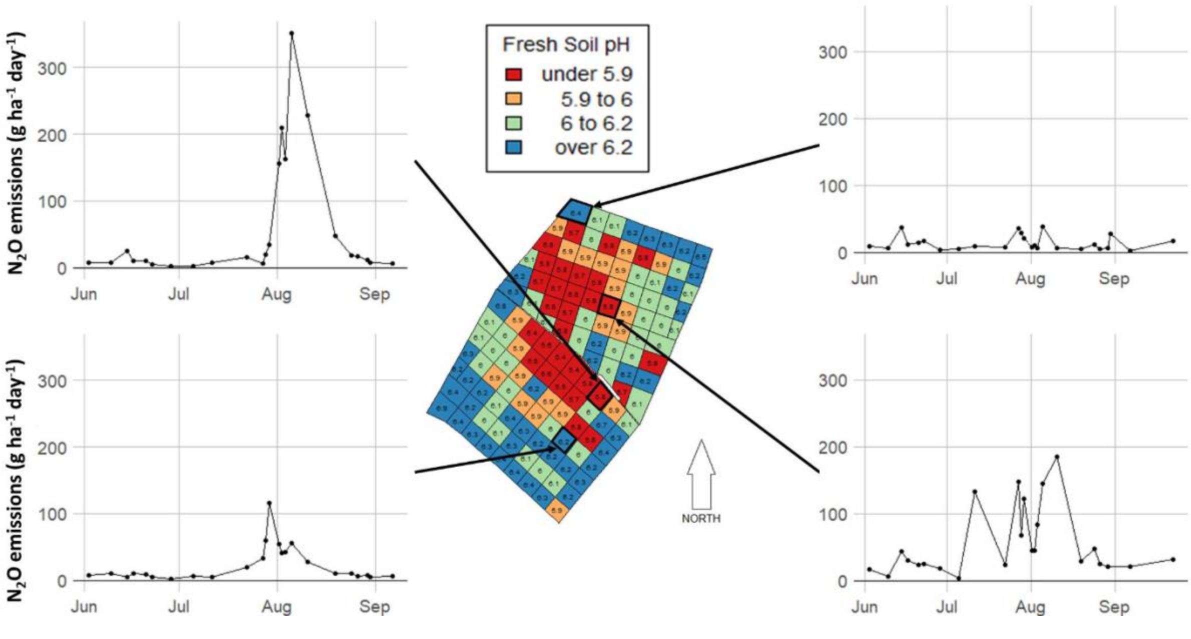

Figure 2: Spatial heterogeneity of pH and associated nitrous oxide emissions from a Scottish grassland soil to a depth of 20 cm measured on a 10 by 10 m grid (each square on this map) at the Easter Bush field site in SE Scotland. Measurements of pH provided by Soil Essentials.

Variable-rate lime applications may therefore provide an opportunity to optimise productivity while reducing GHG emissions. The technology is becoming widely available, and although uptake is currently low, it is likely there will be increased adoption of precision liming over the next 10 years.

The measure would require farmers to use machine guidance systems as well as VRNT and variable rate lime application for their arable and temporary grassland field operations, either buying the system, or using contractors for fieldwork who use these technologies. In line with our previous estimates (Eory *et al.* 2015), we assumed the implementation of a medium accuracy system, capable of 10 cm-accuracy auto-steering and including yield mapping and variable-rate nitrogen application.

7.3.2 Greenhouse gas mitigation summary

As the variety of possible VRNT system specifications is large, and measurements of environmental effects are relatively sparse, currently it is not possible to derive robust quantitative information on the GHG effects of this technology. Eory *et al.* (2015) derived a central estimate from international studies of 20% N reduction in application, assuming no effect on the yield. Experimental evidence on the N fertiliser use and yield effect shows a large variation, between -57% and +1% and -2% to 10%, respectively. However, from a commercial perspective, it is most likely that a grower would choose to use the same amount of fertiliser N and obtain a high yield when using this technology. Barnes *et al.* (2017b) found that most potato and wheat farmers in the UK reported a -5% - +5% effect of the technology on N fertiliser and fuel use, and a 5-10% increase in wheat yield. From this information, the abatement here is assumed to consist of a 5% decrease in N use and a 7.5% increase in yield.

Experimental evidence suggests modest yield responses and emission reductions in response to lime. The magnitude of the response depends on the baseline. Liming on acid soils is considered to be a part of good agricultural practice; However recent surveys in Scotland have indicated that 63% of soils have a pH of 6.25 or below and 13% of soils have a pH of 5.5 or below (Edwards *et al.* 2015). These values lie below the optimum for many crops and are likely to require lime addition to ensure improved crop production.

7.3.3 Costs

We derived the net costs for an average size (120 ha) farm, considering: capital investment in equipment (auto-steer: £5,000 every 5 years; yield monitor: £5,000 every 15 years); maintenance of the equipment (5% of capital cost); signal costs (annual £250); training (£500 every 5 years); and changes in fuel and fertiliser costs and income. We assumed that the costs, calculated at an area basis, would be the same on smaller farms as it is possible to hire contractors to apply VRNT.

The additional cost of the variable rate liming was estimated by adding the cost of soil mapping; £120 ha^{-1} (Soil Essentials *pers. comm.*).

7.3.4 Current uptake and maximum additional future uptake

The measure is applicable on all conventional (fertilised) arable and improved grasslands (i.e. grassland which is fertilised) which needs pH management. To reflect constraints we assumed that it is applicable on 30% of cropland and 20% of grassland. Current adoption of VRNT is around 8% across the UK (Barnes et al. 2017b). However, uptake is probably rather smaller in Scotland (~5%), given the smaller arable farm size. The current uptake of variable rate nitrogen and lime application is estimated to be negligible (0%).

7.3.5 Assumptions used in the MACC

Table 14: Assumptions used in the modelling

Parameter	Change in value
Yield	+7.5%
Synthetic N application rate	-5%
C sequestration	300 kg CO_2e ha^{-1} y^{-1}
Fuel CO_2	-3%
Emissions from the use of lime	215.70 kg CO_2e ha^{-1} y^{-1}
EF_1 change	-3%
Lime cost	£111 ha^{-1} (3.7 t ha^{-1} lime @ £30 t^{-1}) in every 4 years
Lime spreading cost	£10.16 ha^{-1} in every 4 years
Soil analysis and map cost	£120 ha^{1} in every 4 years
Training	£500 in every 5 years
Auto-steer	£5,000 in every 5 years
Yield monitor	£5,000 in every 15 years
Signal cost	£250 y^{-1}
Maintenance	5% of capital cost
Change in field operation costs from reduced overlaps	-3%

7.4 Nitrification and urease inhibitors

7.4.1 Overview

Nitrification inhibitors depress the activity of nitrifying bacteria, improving the nitrogen fertiliser's plant availability and reducing nitrous oxide emissions and also nitrate leaching in high rainfall circumstances (Akiyama et al. 2010), although in some cases they can increase ammonia (and hence indirect nitrous oxide) emissions (Lam et al. 2017). Various compounds have been identified as nitrification inhibitors; probably the most widely studied are dicyandiamide (DCD), 3,4-dimethyl pyrazole phosphate (DMPP) and nitrapyrin. Furthermore, urea-based fertilisers have a high rate of ammonia volatilisation when applied to soils, due to the urease enzyme released by soil bacteria. This leads not only to ammonia (and indirect nitrous oxide) emissions, but reduces the N plants can utilise. Urease inhibitors delay urea hydrolysis to ammonia, reducing ammonia emissions (Harty et al. 2016). Using urea in combination with urease inhibitors and nitrification inhibitors can therefore further reduce nitrous oxide emissions.

Nitrification and urease inhibitors can be injected into the soil together with liquid fertilisers, applied as a coating on granular fertilisers and mixed into slurry before application. They can also be spread after grazing to reduce emissions from urine.

In our analysis, we considered the application of nitrification inhibitors with ammonium nitrate fertiliser, and nitrification and urease inhibitors with urea applications. We expressed the effect as a change in the soil nitrous oxide emission factor.

7.4.2 Greenhouse gas mitigation summary

The effectiveness of nitrification inhibitors in reducing nitrous oxide emissions and nitrogen leaching depend on a variety of factors. In a meta-analysis of 113 datasets of field experiments Akiyama *et al.* (2010) found that the nitrous oxide reduction effect depended on the type of nitrification inhibitor and land use type. The effect also depends on the type of fertiliser used (Misselbrook *et al.* 2014) and on environmental conditions at the site (Cardenas *et al.* 2019).

UK experiments showed variable results. In fertiliser experiments by Misselbrook *et al.* (2014) across six sites (including arable and grassland fields), nitrous oxide emissions from ammonium nitrate were significantly reduced at two sites (average effect -43%), while nitrous oxide emissions from urea treatment were significantly reduced at four sites (average effect -54%). The mean nitrous oxide emission reduction across the six experiments was 38% and 64% for DCD applied with ammonium nitrate and urea, respectively. There was no significant effect of DCD on ammonia emissions, apart from at one site. Nor was yield significantly affected either in all but one case (where it was reduced by 20%).

Cattle urine experiments by the same authors showed significant reduction in three out of four cases, with a mean effect of -70%. Ammonia emissions and grass yields were not significantly affected. Slurry experiments did not reveal any significant effect, as variability amongst the replicates was very high (Misselbrook *et al.* 2014).

Grassland experiments in the UK with ammonium nitrate and urea fertiliser showed mixed results too. Cardenas *et al.* (2019) found that DCD increased the nitrous oxide emission factor at one site significantly (by 20%), decreased it at another site significantly (by 52%), and had no significant effect at a further three sites. When DCD was applied with urea the nitrous oxide emission factor changed significantly at only one site (-94%). However, applying urea instead of ammonium fertiliser reduced the nitrous oxide emission factor by 49%, and using urea combined with DCD resulted in a 85% reduction in the nitrous oxide emission factor compared to using ammonium nitrate only. Yield changes were not significant in any case.

Experiments at two permanent grassland sites in Ireland showed that urea applied with a combination of urease and nitrification inhibitor reduced nitrous oxide emissions by 56% (Harty *et al.* 2016).

Table 15: Data from literature on abatement

Abatement	Value	Country	Reference
Nitrous oxide emissions	Average: -38% (95% confidence interval: -44% to -31%) DCD: -30% (95% confidence interval: -36% to -26%) nitrapyrin: -50% (95% confidence interval: -55% to -30%) DMPP: -50% (95% confidence interval: -55% to -42%)	Across the world	(Akiyama *et al.* 2010) meta-analysis
Nitrous oxide emission factor	DCD with ammonium nitrate: -38% DCD with urea: -64% DCD with cattle urine: -70%	UK, grass and arable	(Misselbrook *et al.* 2014) - experiments
Nitrous oxide emission factor	DCD with ammonium nitrate: -19% DCD with urea: -66%	UK, grass	(Cardenas *et al.* 2019) - experiments
Nitrous oxide emission factor	DCD and NBPT with urea: -56%	Ireland, grass	(Harty *et al.* 2016) - experiments

7.4.3 Costs

Agrotain® Plus, which is a combined urease and nitrification inhibitor, costs around £0.1 (kg N)$^{-1}$, derived from information posted on agricultural forums (precise price information was not publicly available). This value was used for both the nitrification and urease inhibitor application.

7.4.4 Current uptake and maximum additional future uptake

The current uptake is assumed to be 0%.

7.4.5 Assumptions used in the MACC

Table 16 Assumptions used in the modelling

Parameter	Change in value
Ammonium nitrate EF_1 change	-25%
Ammonium nitrate EF_1 change	-50%
Fertiliser cost change	£0.1 kg N^{-1}

7.5 Growing more grain legumes in rotations

The description, assumptions and results in the UK MACC report of 2015 (Eory *et al.* 2015) was used for this measure.

7.5.1 Overview

N fixing crops (legumes) form symbiotic relationships with bacteria in the soil that allows them to fix atmospheric N and use this in place of N provided by synthetic fertilisers. This measure is about increasing the area of grain legumes in arable rotations, thereby reducing N fertiliser use in two ways: by requiring no N fertiliser (so there will be a reduction per ha equivalent to the N fertiliser which would have been applied to the non-leguminous crop that would otherwise have been grown); and by having a residual N fertilising effect so that the crops grown after legumes require less N than when grown after non-legumes (Defra 2011).

7.5.2 Greenhouse gas mitigation summary

Grain legumes are able to fix in excess of 300 kg N ha-1 y-1; can supply N to subsequent crops; are valuable as a break crops in arable rotations; and can provide biodiversity benefits (Rees et al. 2014). The abatement achievable is due to the change in crop areas (i.e. replacement of other arable crops with grain legumes in the rotation and applying no fertiliser on them) and a reduction in N fertiliser use of 30 kg ha-1 on the subsequent crop (Defra 2011).

Table 17: Data from literature on abatement

Abatement	Value	Country	Reference
N use	-0.5 t CO_2e ha^{-1} of soil nitrous oxide emissions	UK	(Moran *et al.* 2008)
N use	-0.5 t CO_2e ha^{-1} of soil nitrous oxide emissions	UK	(MacLeod *et al.* 2010)
N use	No fertiliser on the legume, -33 kg N ha^{-1} on the following crop; i.e. -0.64 t CO_2e ha^{-1} where legumes introduced (not rotation average)	France	(Pellerin *et al.* 2013)

7.5.3 Costs

We estimated the cost of this measure from the difference of the gross margin in grain legumes (field beans and peas £380 ha^{-1}, (SAC 2013)) and other crops (weighted average: £809 ha^{-1}, (SAC 2013). The fertiliser savings from the reduced fertilisation of the following crop is accounted for as benefit (-£23.55 ha^{-1}). The net cost is in high contrast with the only data found in the literature, which estimates the net costs as £13.6 ha^{-1} for the area where legumes are introduced (Pellerin *et al.* 2013). This estimate consists of savings in fertilisers and their applications, elimination of tillage operation for the following crop, and changes in the gross margins of the rotations.

7.5.4 Current uptake and maximum additional future uptake

The frequency of legumes in the rotation depends on different factors according to the nature of the legume. For example, peas are grown only one year in five due to the need to reduce the risk of disease. This is less of a concern for field beans but these are harvested late and delay sowing, and hence yield, of any subsequent cereal crop. Therefore, in practice, beans are also only likely to be grown once in every 5 years. The inclusion of peas and beans in rotations including oilseed rape is limited to once in every six years, due to disease risk. Peas are unsuitable for 'heavy' soils (effectively clay loam and heavier), while beans are unsuited to light soils (sandy loam and equivalents). Therefore, we limited the applicability of the grain legumes to 1/6 of the total arable crop area in any given year.

In 2016, field beans and peas and peas and beans for human consumption were grown on 3,100 ha and 9,300 ha (0.7% and 1.7% of the arable crop area, respectively) in Scotland. Although we assumed the introduction of Greening measures in the Common Agricultural Policy increases the area where field beans and peas are cultivated to 5% of the arable area, this increase is not included in the future reference scenario, but included in the abatement of this measure.

7.5.5 Assumptions used in the MACC

Table 18: Assumptions used in the modelling

Parameter	Change in value
N fertiliser use on subsequent crop	-30 kg N ha^{-1}
Cost (difference in gross margin between field beans and peas and other crops)	£429 ha^{-1}

7.6 Intercropping

7.6.1 Overview

Intercropping is the spatially and temporally coexistence of two or more arable crops. Typically, one of the crops is a grain legume, and therefore biologically fixes nitrogen. Hence, there will be a reduction in the quantity of fertiliser applied per hectare. In addition, there is the potential for some of the fixed nitrogen to be transferred to the other crop, further reducing the requirement for inorganic nitrogen. However, the nitrogen concentration of legumes is higher than non-legume crops; thus the emissions from the residues will be increased. In the UK, the grain legume is typically pea or faba bean and the cereal is spring oats, spring barley or spring wheat. Although the technology is being developed to separate the cereal from the grain legume, intercrops are usually used as feed for ruminants or monogastrics. However, there will be the need to adjust the ration depending on the protein content of the actual harvested crop. It is assumed that the yield of the intercrop is similar to that of the sole cereal crop.

7.6.2 Greenhouse gas mitigation summary

The mitigation arises due to the reduction in inorganic fertiliser applications. In addition, there is the potential for a reduction in fuel use as there will be a reduction in the number of tractor passes due to a reduction in the number of fertiliser applications. There will be an increase in the nitrous oxide emissions from the residues due to the higher nitrogen concentration of the legume relative to the cereal.

As a result of the legume component of the intercrop, it is assumed that the inorganic fertiliser input is approximately halved (SAC 2018). It is assumed that this measure is only applicable to the spring barley and oat area that is used for feed. Based on spring barley and spring oat area, and IPCC (2006), it is assumed that the N contained in the residue will increase by 40%.

7.6.3 Costs

Pea seed is approximately 50% more expensive than barley seed (SAC 2018). Assuming a replacement rate seed mixture, the costs of the seeds will be three times higher than for a pure barley crop.

7.6.4 Current uptake and maximum additional future uptake

The measure is applicable to the area sown for feed production. The crop can be harvested as either whole crop silage or grain. Based on reported figures (Scottish Government 2018b), the tonnage used for feed is 50% of the barley crop, which equates to 43% of the spring barley area. In the case of oats, 30% was used for feed. Therefore, the applicability is 43% of winter and spring oat, and 100% of spring non-malting barley.

There is increasing interest in growing intercrops. However, there are no reported figures on current uptake. It has been assumed that this measure is applicable to intercrops that are grown for feed. As the technology improves, there is the potential for the grain to be separated and therefore used for human consumption. However, for this to be common practice, there is the need for the market to accept products that have been grown as intercrops as opposed to pure stands.

7.6.5 Assumptions used in the MACC

Table 19: Assumptions used in the modelling

Parameter	Change in value
N application rate	-50%
Residue returns (N)	+40%
Energy CO_2	Reduction in 1 tractor pass: -1.57 l ha^{-1} (@2.594 kg CO_2e l^{-1})
Seed costs	+200% (+£150 ha^{-1})

7.7 Crop varieties with higher nitrogen-use efficiency

7.7.1 Overview

Nitrogen fertilisation is essential to achieve current yields of most crops. However, only 49% of the nitrogen applied to and biologically fixed by crops (including grass) is recovered as food and feed in Europe (Westhoek *et al.* 2015), most of the remaining being lost to the environment as ammonia, nitrate and nitrous oxide, causing multiple environmental problems.

Improving the efficiency of crops to utilise the nitrogen fertiliser is therefore key in mitigating emissions as well as reducing the economic loss of unrecovered nitrogen. Nitrogen-use efficiency (NUE) is defined as yield per unit of nitrogen available to the crop (Moll *et al.* 1982). Barraclough *et al.* (2010) demonstrated that season and nitrogen input had a significant effect on NUE, but crop variety choice also contributed to NUE variation. It has been proposed that NUE can be improved both via adopting crop, soil and fertiliser management practices and through plant breeding (Barraclough *et al.* 2010; Hawkesford 2014; Hawkesford 2017; Sylvester-Bradley & Kindred 2009). The latter is possible as NUE varies between plants and some of this variation is linked to phenotypic traits and genotypic markers (Bingham *et al.* 2012). This variation can be as much as threefold (from 27 to 77 kg DM (kg N)$^{-1}$), as Barraclough *et al.* (Barraclough *et al.* 2010) found in wheat varieties from four different European countries.

Additionally, radically new cultivars can improve NUE and reduce GHG emissions. For example, perennial wheat can help retain more C in the soil as well as reduce fertiliser, pesticide and fuel use (Bell *et al.* 2008). Nitrogen-fixing cereals (for which three main research streams are ongoing, targeting nodule development, identification of nitrogen-fixing biofertilisers and the introduction of nitrogenase enzyme and pathway into the plant (Beatty & Good 2011)) could, when realised, bring substantial reduction in the nitrogen fertilisation needs of plants.

Breeding for improved NUE can target both the efficiency of nitrogen uptake and nitrogen utilisation in the plant; as these are different physiological processes they are genetically independent, raising the potential for parallel gains (Hawkesford 2014). However, such breeding needs to consider potential trade-offs with other desirable traits; for example, the root system can be modified to increase the uptake of subsoil nitrate, but this adversely affects the uptake of phosphate from the topsoil (Bingham *et al.* 2012; Ho *et al.* 2005).

Despite the yield plateau of the last two decades (Knight *et al.* 2012), most of the experimental studies which have looked at the improvements in NUE of different varieties of the same crop concluded that there has been a continuous improvement in NUE in the past decades. The economics of grain price and fertiliser costs are two potential causes of the yield plateau, resulting in stagnating nitrogen applications in the past two decades for newer varieties which require higher nitrogen rates to manifest their full yield improvement (Knight *et al.* 2012). This suggests that the improvement might continue as a baseline in the future, and there is scope to accelerate these gains. The assumption in this report is that these improvements can be achieved faster and adopted on larger growing areas, given increased incentives to breeding companies to research and develop and to farmers to adopt such cultivars.

This mitigation measure examines using traditional breeding to improve NUE and considers three major crops in Scotland: wheat, barley and oilseed rape. The measure means cultivating varieties of already common crops in Scotland that have higher NUE than the currently common varieties.

7.7.2 Greenhouse gas mitigation summary

The abatement rate is approximated from an estimate of the NUE or yield improvement, assuming that yields are kept constant and nitrogen application decreases to achieve the same yield. As the genetic gain in breeding is cumulative, the mitigation measure is assumed to have an annually increasing nitrogen-reduction effect (even though new cultivars with improved yields tend to require increasing nitrogen inputs (Foulkes *et al.* 1998; Knight *et al.* 2012)).

For wheat and oilseed rape, the gap between the improvements in new cultivars and the realisation of that on farms is 0.013 and 0.012 t ha^{-1} y^{-1}, respectively, equivalent to 0.2% and 0.4% yield increase annually. The assumed annual nitrogen reduction is therefore 0.2% and 0.4% for these two crops, respectively. The barley annual NUE gain is 1.2%. If we assume that 80% of this gain is realised on farms, there is an additional potential improvement of 0.24% in the NUE. Thus, we assume an annual nitrogen reduction of 0.24%.

Table 20: Data from literature on abatement

Abatement	Value	Country	Reference
Wheat			
Yield	+0.063 t ha^{-1} y^{-1} (cumulative) of new cultivars (~1%)	UK	(Knight *et al.* 2012)
Yield	+0.05 t ha^{-1} y^{-1} (cumulative) realised on farms	UK	(Knight *et al.* 2012)
Yield	+0.096 t ha^{-1} y^{-1} (cumulative) historically over 20 years (1969-1988)	UK	(Foulkes *et al.* 1998)
NUE (kg grain N (kg N) $^{-1}$)	+0.9% y^{-1} historically over 20 years (1969-1988)	UK	(Foulkes *et al.* 1998)
Barley			
Yield	+1% y^{-1} (cumulative) historically over 75 years (1931-2005)	W Europe	(Bingham *et al.* 2012)
NUE (kg yield DM (kg N) $^{-1}$)	+1.2% y^{-1} (cumulative) historically over 75 years (1931-2005)	W Europe	(Bingham *et al.* 2012)
Oilseed rape			
Yield	+0.06 t ha^{-1} y^{-1} (cumulative) of new cultivars (~2%)	UK	(Knight *et al.* 2012)
Yield	+0.048 t ha^{-1} (cumulative) realised on farms	UK	(Knight *et al.* 2012)

7.7.3 Costs

A price premium might have to be paid for varieties with improved NUE. We assume that other traits of the crops are not going to be adversely affected with the level of improvement set out above; therefore, no costs or benefits beyond the seed price premium and the nitrogen savings are included in the calculations. The seed price premium is estimated to be 10% of the price.

7.7.4 Current uptake and maximum additional future uptake

The measure is in theory applicable to all crops, although here we considered only three major crops: wheat, barley, and oilseed rape.

The current NUE of the common cultivars is regarded as the baseline, and thus the current uptake of this measure is assumed to be zero.

7.7.5 Summary of assumptions used in the MACC

Table 21: Assumptions used in the modelling

Parameter	Change in value
N application	-0.13% annually (cumulative)
Crop yield	No change
Seed cost	+10%

7.8 Improved health of ruminants

7.8.1 Overview

Endemic, production-limiting diseases are a major constraint on efficient livestock production, both nationally and internationally, and have an impact on the carbon footprint of livestock farming (Elliott *et al.* 2014). UK systems are particularly vulnerable to endemic disease impacts because they are largely pasture based. The emissions intensity of ruminant meat and milk production is sensitive to changes in key production aspects, such as maternal fertility rates, mortality rates, milk yield, growth rates and feed conversion ratios. All of these parameters are influenced by health status, so improving health status is expected to lead to reductions in emission intensity (Skuce *et al.* 2014). However, there have been few empirical studies investigating the impact of any of the production diseases on GHG emissions intensity.

Health can be improved through preventative controls (such as changing housing and management to reduce stress and exposure to pathogens, vaccination, improved screening and biosecurity, disease vector control) and curative treatments such as antiparasitics and antibiotics.

7.8.2 Greenhouse gas mitigation summary

The impact of endemic disease is difficult to quantify, often relying on old data from experimental challenge studies, which do not reflect the natural presentation of many of these diseases. ADAS (2014) attempted to quantify the impact of the top cattle health 'conditions' on the carbon footprint of a litre of milk, and the reductions that could be made via veterinary and/or farm management interventions. The study concluded that a 50% movement from current health status to a healthy cattle population (assumed to be the maximum improvement achievable) would reduce the UK emissions by 1436 kt CO_2e year^{-1}, or 6%. Eory *et al.* (2015) used a similar approach to quantify the effect of improving sheep health, and estimated that a 50% movement from current health status to a healthy sheep population would reduce the UK emissions by 484 kt CO_2e year^{-1} by 2035.

Several studies have been undertaken since the 2015 MACC (Eory *et al.* 2015), which are briefly summarised below.

- **UK cattle and sheep health**

Skuce *et al.* (2016) reviewed the evidence on prevalence and impact for 12 key ruminant diseases. They identified potential GHG emissions savings for all twelve diseases evaluated, while noting that some diseases are more tractable than others. They concluded that emissions intensity could be reduced through control measures relating to:

- milk yield and cow fertility rates (dairy systems)
- cow/ewe fertility and abortion rates
- calf/lamb mortality and growth rates (beef and sheep systems), and
- feed conversion ratios (all systems).

Three diseases, one from each of the major livestock sectors, were considered more cost-effective and feasible to control: neosporosis (beef cattle), infectious bovine rhinotracheitis, IBR (dairy cattle) and parasitic gastroenteritis (sheep).

- **Worms in sheep**

Houdijk *et al.* (2017) undertook experiments to determine the effect of parasitism on the emissions intensity (EI) of sheep and found that infection with Teladorsagia increased calculated global warming potential per kg of lamb weight gain by 16%. Fox *et al.* (2018) also undertook experiments infecting sheep with Teladorsagia and found that infection led to a 33% increase in methane yield and a significant decrease in lamb growth rates, which led the authors to conclude that "there is potential for parasitism to have an extensive impact on greenhouse gas emissions".

- **Worms in beef cattle**

Gut worms are the most important gastrointestinal nematode parasites of grazing cattle, responsible for considerable sub-clinical disease and production loss. Bellet *et al.* (2016) undertook an abattoir study of prevalence and production impacts in England and Wales of Ostertagia spp. (the study also recorded the effects of rumen fluke and liver fluke). Based on this data set, MacLeod and Skuce (2019) estimated that the growth rates of cattle with a high Ostertagia burden were about 10% lower than those with a low burden. This translates into a difference in EI of 3.9%, i.e. the high-burden herd produced 3.9% more GHG for every kg of liveweight output. Assuming the overall burden could be halved with appropriate treatment implies that the EI could be reduced by 2%.

- **Liver fluke in beef cattle**

Skuce *et al.* (2018) investigated the impact of liver fluke infection on cattle productivity and associated GHG emissions intensity (EI) using abattoir data from NE Scotland from 2014-2016. The study focused on a cohort of 22,349 Charolais males from a total dataset of ~250,000 cattle. Liver fluke infection resulted in a statistically significant reduction in liveweight gain of 0.023kg/day and an extra 21 days to slaughter. As a result, the EI of meat from a herd with no fluke is approximately 1% lower than the same herd with fluke. The study only focused on one impact of fasciolosis (reduced growth rates) - other effects include changes in feed conversion ratio, mortality and fertility, milk yields and quality of output (e.g. carcass conformation and rates of liver condemnation). These will have an additive effect on greenhouse gas EI, so removing fluke may have a much greater impact on EI in practice.

- **Lameness in dairy cattle**

Lameness can reduce dairy cow milk yield, thereby increasing the EI of the milk produced. Chen *et al.* (2016) calculated the effect of lameness on EI, using the impacts of lameness reported in a series of studies undertaken in Europe and North America. They estimated that lameness can lead to an increase in emissions intensity of 1-8% compared to a baseline scenario, depending on the prevalence of the disease. Mostert *et al.* (2018) investigated the effects of three types of foot lesions in Dutch dairy cattle: digital dermatitis (DD), white line disease (WLD), and sole ulcer (SU). They found that the impacts of these lesions on milk yield and calving interval led to an average increase in milk emissions intensity of 1.5%.

- **Conclusion**

The studies undertaken since 2015 indicate that the abatement potentials given for improved cattle and sheep health in Eory *et al.* (2015) are achievable (while bearing in mind that studies with negative findings are less likely to be submitted for publication). Furthermore, they provide specific examples of how the abatement potential might be achieved, i.e. by reducing the incidence of gastrointestinal parasites, liver fluke and lameness.

7.8.3 Costs

As improving livestock health is a very broad measure, encompassing a variety of livestock management, disease prevention and treatment options, this study, following previous studies, estimated the cost-effectiveness of the measures (based on earlier publications) and derived the costs from the cost-effectiveness.

Eory *et al.* (2015) estimated that improving cattle health could be achieved at an average of £-42 t CO_2e^{-1}, while the cost-effectiveness of improving sheep health would be £30 t CO_2e^{-1}. As there are many possible combinations of health challenges and treatments, the cost-effectiveness of achieving mitigation via improved health is likely to vary considerably; flocks and herds with below average health status are likely to provide scope for larger and more cost-effective reductions in greenhouse gas.

7.8.4 Current uptake and maximum additional future uptake

We assume that 80% of the herd could have improved animal health.

7.8.5 Assumptions used in the MACC

Table 22: Assumptions used in the modelling

Parameter	Change in value
Milk yield	+6.38%
Cost	£28 animal^{-1}

7.9 High starch diet for dairy cattle

7.9.1 Overview

A high starch diet increases the digestible energy (DE%) content of the diet by increasing the amount of starchy concentrates in the ration, while keeping the total crude protein content of the diet constant. This reduces the rate of enteric methane emissions. In practice, this can be achieved by replacing conserved grass with maize silage, to increase the digestibility of the ration. This will reduce enteric methane emissions and manure methane (as less volatile solids will be excreted). The starch content could also be increased by replacing grass silage with high starch concentrate. However, Moran et al (2008) found this to be a more expensive way of achieving mitigation.

7.9.2 Greenhouse gas mitigation summary

According to Hristov *et al.* (2013, p37) “it is generally believed that higher inclusion of grain (or feeding forages with higher starch content, such as whole-crop cereal silages) in ruminant diets lowers enteric methane production”. IBERS (2010, p3) concluded that “feeding more maize silage and less grass silage reduced methane production relative to feed intake and milk yield (13% and 6% reduction per unit of dry matter intake and per litre of milk output respectively when shifting from a 75:25 grass silage: maize silage ration to a 25:75 ration). Feeding less protein reduced nitrogen excretion in manure and increased the efficiency of dietary nitrogen utilization.” They assumed that this measure could be implemented year-round in 50% of the UK dairy sector and would lead to a 5% reduction in enteric methane emissions and a 20% reduction in N excretion. They assumed no impact on livestock performance. (IBERS 2010, p17). Doreau *et al.*, (2012) reported similar results, i.e. a reduction in methane yield and N excretion.

According to Dewhurst (2013), reducing N intake by inclusion of maize silage in mixtures with legume silages leads to a marked reduction in urine N without loss of production potential. It is predicted, on the basis of their chemical composition and rumen kinetics, that legume silages and maize silages would reduce methane production relative to grass silage, though in vivo measurements are lacking.

In contrary, Wilkinson and Garnsworthy (2017) found that a maize silage diet could lead to higher methane emissions than a grass silage diet (although the overall effect on the carbon footprint of milk was modest, when other emission sources were included).

It should be noted that changes in enteric methane conversion factor as a result of high starch diet are likely not to be additive with other methane mitigation methods, e.g. breeding and 3NOP.

7.9.3 Costs

We assume that as grass silage and maize silage have the same production costs, and as grass silage will be replaced with maize silage, the net costs are zero.

7.9.4 Current uptake and maximum additional future uptake

Because maize needs to be grown in warm areas on medium soils (Morgan and Frater 2015), it will not be readily cultivated on a significant proportion of the grassland on dairy farms in Scotland. This is reflected by the current cultivation area (Scottish Government 2018b) and average yield: the production in Scotland in 2018 was only 13,500 t DM; this covers about 0.8% of the Scottish dairy feed DM intake.

Assuming that the maize inclusion rate in diets ranges from 25% to 75%, this would mean that maize is fed to 1-3% of Scottish dairy cows. This figure is comparable to North East England (1%) and much lower than the current uptake rate in the whole of England (11%). Therefore, a maximum uptake rate of 10% is assumed here as a conservative estimate. No changes are suggested to other assumptions of the earlier MACC.

7.9.5 Assumptions used in the MACC

Table 23: Assumptions used in the modelling

Parameter	Change in value
Methane conversion factor (Y_M)	-5%
Cost	0

7.10 Precision feeding of livestock

7.10.1 Overview

Precision feeding provides opportunities for reducing the feed conversion ratio of animals, and, as less feed would be used, GHG emissions from feed production would fall. It can also reduce the rate of N (and volatile solid) excretion and therefore the nitrous oxide and methane emissions arising during manure management. It is applicable primarily to housed animals that can be monitored at regular intervals, and the information used to adjust rations, i.e. dairy cattle and pigs, and chicken.

The measure requires technology to match the diet more closely to the animal's nutritional requirements. For pigs, this may involve regular weighing of animals and adjustment of the ration protein content based on weight and growth rate, and supplementation of diets with synthetic amino acids. For ruminants, emissions could be reduced through improved characterisation of forages to enable appropriate supplementation.

Accurate analysis of feed composition is the first step in the precision-feeding process. Feed analysers based on near-infrared reflectance spectroscopy (NIRS) technology can measure the nutritional content and automatically adjust the ration composition (Hristov *et al.* 2013).

Eory *et al.* (2015) stated that for dairy cattle, precision-feeding opportunities lie in the capacity to offer individually tailored supplements to cows in out-of-parlour feeders (which have been available for over 30 years using neck-based transponders); or to individual cows in standard milking parlours; or through automated milking systems (milking robots). Combining milk recording and automated weighing systems with milking parlour visits provides good data on which to provide tailored supplement levels. Hills *et al.* (2015), in a comprehensive review of individual feeding of pasture-based dairy cows, however, highlight the complexity in determining responses to supplementary feeds and provided compelling evidence that both cow-level (e.g. genotype, parity, days in milk, cow body weight, condition score, feed intake) and system-level (e.g. pasture allowance and other grazing management strategies and climate) parameters can influence the marginal milk production response to supplementary feeding. Basically, the responses are likely to be system and farm specific.

7.10.2 Greenhouse gas mitigation summary

Pomar *et al.* (2011) found that growing pigs with daily tailored diets had nitrogen intake reduced by 25% and N excretion reduced by more than 38%. Cherubini *et al.* (2015) showed that pig diets low in protein had improved carbon footprints, principally through lower need for imported soya.

The 2015 UK MACC (Eory *et al.* 2015) had the measure "Improving beef and sheep nutrition", which involved improving animal performance and reducing methane yield via improvement of ration nutritional values (i.e. digestibility of the ration). This was achieved by getting advice from an animal nutritionist to improve the composition of the diet, complemented with forage analysis and improved grazing management. Eory *et al.* (2015) assumed that improved diet formulation and grazing management increases the digestibility of the roughage and concentrate by 2% from their original values (i.e. from 70% to 71.4%), and results in a 2% improvement in growth rates.

The Farmscoper tool has three measures which relate to precision feeding. Their effect on pollution is presented in Table *24*.

Table 24: Effect on pollutant flows of Farmscoper measures (ADAS 2017)

Farmscoper measure ID	Farmscoper measure	Methane	Direct nitrous oxide	Indirect nitrous oxide
332	Reduce dietary N and P intakes: Pigs	**-2%**	**-2%**	**-10%**
333	Reduce dietary N and P intakes: Poultry	**-2%**	**-2%**	**-10%**
34	Adopt phase feeding of livestock	**-2%**	**-2%**	**-2%**

The measure was modelled assuming a 2% reduction in the gross energy needs of dairy cows and a 5% reduction in both the volatile solid and N excretion of pigs.

7.10.3 Costs

Pomar *et al.* (2011) found that feed cost was 10.5% lower for pigs fed daily tailored diets. Andre *et al.* (2010) found that tailoring feeding to the individual dairy cow led to a 10% increase in profit margins by increasing concentrate supplementation and milk yields. The costs estimated in the Farmscoper tool are presented in Table *25*.

Table 25: Costs of Farmscoper measures (ADAS 2017)

Farmscoper measure ID	Farmscoper measure	Capital cost (£ animal^{-1})	Operational cost (£animal^{-1} y^{-1})	Cost (£ m^{-3} manure)
		0.00	**0.76**	**0.76**
332	Reduce dietary N and P intakes: Pigs	0.00	2.59	2.59
333	Reduce dietary N and P intakes: Poultry	0.00	6.39	6.39
34	Adopt phase feeding of livestock	0.94	-3.81	-2.87

Based on the information from the industry, a 5% reduction in feed cost is assumed. Without exact information on investment costs, based on anecdotal industry information a four-year payback time is assumed. Therefore, the capital cost is calculated as four times the annual feed cost savings. The lifetime of the investment is five years.

7.10.4 Current uptake and maximum additional future uptake

Pellerin *et al.* (2013) reported the maximum technical potential applicability: 52% of dairy cows, 20% additional uptake of biphase pig feeding and almost 100% pigs for multiphase feeding.

Martineau *et al.* (2016, p141) stated that "for pigs and poultry, phase feeding and the use of synthetic amino acids have been widely adopted by producers and future reductions in N excretion are likely to be at the lower end of the ranges cited (5 and 10% for pigs and poultry respectively)".

Adoption of phase feeding is believed to be implemented widely in the pig and poultry industry. Similarly, the current uptake of phytase supplements that increase the availability of dietary phosphorus is estimated to be already close to the potential as including the enzyme in the diet is cost neutral. Industry sources indicate that phytase is incorporated into approximately 90% of pig diets, 90% of hen feeds and 40% of broiler rations manufactured in the UK (Gooday & Anthony 2015).

The implementation rates estimated in the Farmscoper tool are presented in Table *26*.

Table 26: Implementation rates of Farmscoper measures (ADAS 2017)

Farmscoper measure ID	Farmscoper measure	Prior	Maximum	Additional
332	Reduce dietary N and P intakes: Pigs	80%	100%	20%
333	Reduce dietary N and P intakes: Poultry	80%	100%	20%
34	Adopt phase feeding of livestock	80%	100%	20%

In pig production, nearly all farms in Scotland are expected to follow biphase or three-phase feeding already. This is because Scottish pig production is highly centralised and concentrated in large units. Therefore, the improvement in feeding is expected to be a shift to multiphase feeding. Technology for multiphase feeding already exists. However, the installation costs are high and, therefore, this is expected to applicable in large units only. Since Scottish pig production is concentrated in large units, a potential uptake rate of 90% is assumed, as a conservative estimate.

The applicability for dairy cows was assumed to be 50%, as an approximation of the time cows and heifer spend housed.

7.10.5 Assumptions used in the MACC

Table 27: Assumptions used in the modelling

Parameter	Change in value
Dairy	
Gross energy need	-2% (resulting in 2% methane and 3% nitrous oxide reduction)
Feed costs	-5%
Capital costs	Four times the savings in feed costs in every 5 years
Pig	
Volatile solid excretion rate	-5%

Parameter	Change in value
N excretion rate	-5%
Feed costs	-5%
Capital costs	Four times the savings in feed costs in every 5 years

7.11 3NOP feed additive for cattle

7.11.1 Overview

3NOP is a chemical that reduces the excretion of enteric methane by ruminants when added to their rations (or introduced via a bolus). It does so by reducing the rates at which rumen archaea convert the hydrogen in ingested feed into methane. Specifically, 3NOP inhibits methyl-coenzyme M reductase, the final step of methane synthesis by archaea (Duin *et al.* 2016).

The ingestion of a small amount of 3NOP each day is required, typically in the range of.0.05 to 0.2g NOP per kg of DMI (Javanegara *et al.* (2017), i.e. for cattle the effective dose is likely to be in the order of 2-3g of 3NOP/animal/day (Haisan *et al.* 2014, Martinez-Fernandez *et al.* 2018). For housed animals. the 3NOP could be mixed in with the ration. For grazing animals, it may be possible to deliver the 3NOP via a bolus (Rooke *et al.* 2016, p13).

7.11.2 Greenhouse gas mitigation summary

While 3NOP is a new mitigation measure (it was patented in 2012, Duval and Kindermann 2012) a range of experimental studies and meta-analyses have been undertaken. Most of the studies with 3NOP have focused on high quality concentrate-based diets. However Martinez-Fernandez et al (2018) found a reduction in enteric methane from beef cattle fed a roughage diet.

Table 28: Summary of studies of the mitigation effect of 3NOP

Livestock type	Parameter	Effect	Country	Year	Reference
Dairy cattle	Enteric methane yield Milk yield and fat Milk protein	-4 to -7% No effect Increase	UK	2014	Reynolds *et al.* (2014)
Beef cattle	Enteric methane yield Daily weight gain DMI	-33% No effect Small decrease	Canada	2014	Romero-Perez *et al.*, (2014)
Dairy cattle	Enteric methane yield DMI, milk yield Daily weight gain	-60% No effect Increased	Canada	2014	Haisan *et al.*, (2014)
Dairy cattle	Enteric methane yield DMI, milk yield Daily weight gain	-30% No effect Increased	USA	2015	Hristov *et al.*, (2015)
Beef cattle	Enteric methane yield Daily weight gain DMI	-7 to- 81% (varies with diet and dose) No effect High dose: reduced	Canada	2016	Vyas *et al.*, (2016)
Beef and dairy cattle	Enteric methane yield	-30%	Canada	2016	Duin *et al.* (2016)
Ruminants	Enteric methane yield	-19 to -33%	Various	Various	Jayanegara *et al.*, (2017)

Livestock type	Parameter	Effect	Country	Year	Reference
Beef cattle	Enteric methane yield Daily weight gain	-38% Increase	Australia	2018	Martinez-Fernandez et al (2018)
Beef cattle	Enteric methane yield FCR	-37 to -42% -5%	Canada	2018	Vyas *et al.* (2018)
Beef cattle **Dairy cattle**	Enteric methane yield Enteric methane yield	-17.1% ±4.2% -38.8% ±5.5%	Various	Various	Dijkstra *et al.* (2018)

*methane yield: the kg of methane per kg of dry matter intake (DMI)

Jayanegara *et al.* (2017) undertook a meta-analysis of 3NOP based on 12 *in vivo* studies from 10 articles. Their results showed that increasing level of 3NOP addition in diets of ruminants decreased enteric methane emissions per unit of DMI, while having no effect on DMI and limited effects on the production performance of both dairy cows and beef cattle. They concluded that "3NOP is an effective feed additive to mitigate enteric methane emissions without compromising productive performance of ruminants". Papers published since 2017 reinforce this conclusion.

Based on the above-mentioned results, we assumed that 3NOP reduces the enteric methane yield by 30% and 20%, respectively, in dairy and beef.

In theory, the feed energy otherwise lost as methane will be transferred for animal functions; this will improve the animal performance. Assuming that 10% of the feed energy is consumed in generating methane, and that the methane reduction as a result of the use of 3NOP ranges from 20% (beef) to 30% (dairy), then the reduction of feed consumption when 3NOP is used would range from 2% (beef) to 3% (dairy). As a conservative estimate, we applied a 2% yield increase for both dairy and beef.

It should be noted that changes in enteric methane conversion factor as a result of 3NOP are likely not to be additive with other methane mitigation methods, e.g. breeding and high-starch diet.

7.11.3 Costs

No one-off costs arising from the measure are predicted. The main recurring costs are likely to arise from the purchase and administering of 3NOP. It has been estimated that the cost of Mootral (an alternative to 3NOP) would be $50 per cow per year (Zwick 2017). i.e. £38.

7.11.4 Current uptake and maximum additional future uptake

In theory, 3NOP could be used with beef cattle, dairy cattle, and sheep. The current uptake of the measure is zero. The industry is seeking approval for commercial application of 3NOP by early 2021. If it is successful, the potential uptake rate from that date is 100% in Scotland - we assumed maximum uptake on all housed animals.

7.11.5 Assumptions used in the MACC

Table 29: Assumptions used in the modelling

Parameter	Change in value
Dairy	
Y_M	-30%
Milk yield	+2%
Cost	£38 animal^{-1}
Beef	

Parameter	Change in value
Y_M	-20%
Live weight	+2%
Cost	£38 animal^{-1}

7.12 Covering slurry stores with impermeable cover

7.12.1 Overview

Animal excreta stored in liquid systems is an important source of ammonia and methane emissions because, during the storage, N and the volatile solids excreted turn into these gaseous compounds. In these systems (unless the slurry is aerated), direct nitrous oxide formation is less important as the anaerobic environment blocks denitrification (Sommer *et al.* 2000). However, a small portion of ammonia emissions turns into nitrous oxide (indirect nitrous oxide emissions). Several factors affect the rate of ammonia, methane and nitrous oxide emissions, including the airflow over the manure. Thus, by covering the store, these emissions can be reduced (Hou *et al.* 2014; VanderZaag *et al.* 2015).

Cover technologies include floating covers, rigid covers, natural crust and suspended, tent-like structures (VanderZaag *et al.* 2015). Ammonia loss is a physiochemical process controlled by the ability of ammonia in the slurry to diffuse to the atmosphere; covers restrict diffusion by creating a physical barrier. With reduced ammonia emissions, indirect nitrous oxide emissions also reduce. The presence of a slurry cover increases the ammonia concentration of the slurry and hence its N content and fertiliser value, but also potential subsequent ammonia and nitrous oxide losses when the slurry is applied to the soil, unless low ammonia-emission spreading techniques are implemented.

The effects of cover solutions on direct GHG emissions are less explored however, with variable and inconclusive results (Hou *et al.* 2014; Montes *et al.* 2013; Sajeev *et al.* 2018; VanderZaag *et al.* 2008; VanderZaag *et al.* 2015). Crust formation, straw addition and the use of granules, in particular, tend to increase nitrous oxide emissions substantially, often overriding the emission savings in methane and indirect nitrous oxide emission reductions (Hou *et al.* 2014; Sajeev *et al.* 2018). The effects of these covers on methane emissions are variable, with high probability of increased emissions. A review of Hout *et al.* (2014) showed that impermeable plastic covers have the potential to reduce ammonia and GHG emissions in parallel.

However, there are feasibility problems with floating covers, in general, if applied on slurry tanks or larger lagoons (not on small earth-banked lagoons), and their durability is not yet well tested (Amon *et al.* 2014). When the slurry is covered by impermeable films, the formation of methane is not eliminated, and the gas builds up under the cover and in the liquid, creating an explosion risk and escaping when the cover is opened (Montes *et al.* 2013). With additional devices (gas pipes and pumping system) most of the methane can be captured and converted to CO_2 either by direct flaring, reducing the GWP substantially, or by purification and use in electricity or heat generation. Furthermore, depending on the structure, rainwater can accumulate on impermeable floating covers and needs to be removed via e.g. pumping.

7.12.2 Greenhouse gas mitigation summary

Table 30: Data from literature on abatement

Abatement	Value	Country	Reference
Methane emissions	-47% (g methane–C (kg VS)$^{-1}$)	Sweden	(Rodhe *et al.* 2012)

Abatement	Value	Country	Reference
Direct nitrous oxide emissions	-100% (g nitrous oxide–N m^{-2})	Sweden	(Rodhe *et al.* 2012)
Ammonia emissions	-80% (range: -59% - -95%)	Various	Review of four papers in (VanderZaag *et al.* 2015)

7.12.3 Costs

Cost information on slurry covers has been collated by VanderZaag *et al.* (2015) from North American and UK sources. They estimated the capital costs of floating impermeable covers to be in the range of €1.70 m^{-2} to €63 m^{-2} with a lifespan of 8-10 years and 2% annual maintenance costs for rainwater collection. The high cost solutions included negative pressure covers to keep the film tight on the slurry surface.

7.12.4 Current uptake and maximum additional future uptake

The slurry covers can be installed on all slurry tanks and lagoons.

7.12.5 Assumptions used in the MACC

Table 31: Assumptions used in the modelling

Parameter	Change in value
Methane conversion factor	-47%
Direct nitrous oxide emissions from storage	-100%
Ammonia emissions from storage	-80%

7.13 Cattle breeding for low methane emissions

7.13.1 Overview

The composition of the micro-organisms present in the gut of mammals is influenced by the genetics of the host animal (Hegarty and McEwan, 2010). It has been shown possible to select sheep for high or low methane emissions, as methane production is heritable to some extent (Pinares-Patiño *et al.* 2013). Studies indicate that dairy cattle have the potential for genetic selection for low methane emission too (de de Haas *et al.* 2011, Roehe *et al.* 2016). Inclusion of low enteric-methane emission in the breeding goal could reduce methane emissions from cattle, but might limit the productivity and fitness improvements to some extent, because selection for low emission causes changes in the animal's nutritional physiology.

The measure entails starting breeding for low enteric-methane emission in the national herd (via including the methane emissions in the breeding indices) and farmers buying the animals with lower methane emissions. The improvements in emissions are cumulative over the years as the emissions from the individual animals get reduced by breeding.

Genetic improvement in the national herd can be enhanced by using genomic tools. This entails farmers collecting performance information on the individual animals and genetic testing and feeding back this information to breeding goal development. By using these tools not only can the gains in methane emission reduction be achieved more quickly but production traits can also be improved.

7.13.2 Greenhouse gas mitigation summary

Dairy and beef production would increase (annual gain of 0.75% in milk yield, milk protein and fertility for dairy, and annual gain of 0.25% in live-weight, growth rate and fertility for beef cattle), reducing the emission intensity of products, and the enteric methane conversion factor would decrease by 0.15% of its value every year.

7.13.3 Costs

To realise the measure £2.5m in research investment would be needed in the UK for the dairy herd, of which 9% would be attributed to Scotland (based on dairy cow proportions between the four nations). The beef research would need another £2.5m in the UK, 21% of it falling to Scotland. Furthermore, in every five years £0.5m would be needed to fund both the dairy and the beef genomic tools in the UK.

The genomic testing required on farms costs £20 for each bull (either dairy or beef). It is assumed a dairy bull would serve 500 cows while a beef bull would serve 100 cows.

The productivity gains would translate into increased income from sales at the farm level.

7.13.4 Current uptake and maximum additional future uptake

The measure is assumed to be applicable to 45% of the dairy and 20% of the beef herd.

7.13.5 Assumptions used in the MACC

Table 32: Assumptions used in the modelling

Parameter	Change in value
Dairy	
Milk yield	0.75% $year^{-1}$
Milk protein content	0.75% $year^{-1}$
Cow fertility	0.75% $year^{-1}$
Methane conversion factor	-0.15% $year^{-1}$
R&D cost	£2.5M in every 5 years in the UK (9% of it in Scotland)
Genomic tool cost	£0.5M in every 5 years (9% of it in Scotland)
Genomic testing	£20 $bull^{-1}$ (serving 500 cows)
Beef	
Live-weight	0.25% $year^{-1}$
Growth rate	0.25% $year^{-1}$
Cow fertility	0.25% $year^{-1}$
Methane conversion factor	-0.15% $year^{-1}$
R&D cost	£2.5M in every 5 years in the UK (21% of it in Scotland)
Genomic tool cost	£0.5M in every 5 years (21% of it in Scotland)
Genomic testing	£20 $bull^{-1}$ (serving 100 cows)

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