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A scenario-based approach to emissions reduction targets in Scottish agriculture

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1 Executive summary

The Climate Change (Emissions Reduction Targets) (Scotland) Act 2019 sets the ambitious net zero greenhouse gas (GHG) emissions reduction targets by 2045.

Agriculture contributes to 18% of GHG emissions in Scotland. Reductions can be achieved through mitigation and carbon sequestration measures implemented on farms. Taken together with options identified in the wider food chain and land use, such as dietary change, land use change and food waste reduction, there is clear potential to move food production closer to net zero.

The Update to the Climate Change Plan (Scottish Government 2020b) set out policies to provide further GHG mitigation in Scotland's non-emission-trading sectors. Agriculture is required to reduce its emissions by 31% from 2019 levels by 2032.

1.1 This research

This report provides an updated assessment of the emission reduction potential of the most effective mitigation measures in Scotland. The research team assessed 25 distinct farm technologies (in total 39, when considered for different livestock types) and practices which can reduce GHG emissions in Scotland by 2050. The measures were derived via a systematic process taking forward the most suitable options for Scotland for quantitative modelling. We drew extensively from recent UK and Scottish agricultural abatement reports, including the farmer-led reports published in the winter of 2020-21, which together proposed around 190 measures.

- The agricultural activity scenarios are the same as those used in the agricultural report for the 6th Carbon Budget. They represent future pathways of agricultural technology, human dietary and food waste change. The Business as Usual scenario assumes

current trends continuing, while, at the other end, the Widespread Innovation and Tailwinds scenarios assume large changes in the above areas.

- The uptake scenarios were defined as: Low Feasible Potential, Central Feasible Potential, High Feasible Potential representing low, medium and high uptake of the measures by farmers with Maximum Technical Potential at the theoretical upper limit.
- Although the net zero target in Scotland is 2045, modelling constraints necessitated using 2050 as the target year. However, the mitigation difference between 2045 and 2050 would be small, and only due to agricultural activity differences, as all the mitigation measures are fully implemented in the model by the early 2040s.

NOTE: These scenarios were established by the Climate Change Committee and do not fully correspond to intended policy in Scotland. As such, the results offer useful insights but may not be suitable in terms of considering the potential impacts of future policy.

1.2 Key findings

- Assuming mitigation measures are implemented at the Central Feasible Potential uptake scenario (45% of farmers) wherever applicable, the total mitigation potential in 2050 varies between 0.9 and 4.3 metric tons of carbon dioxide equivalent (Mt CO_2e), depending on the agricultural activity scenario.
- The mitigation attributable to changing practices and technologies on farms is between 0.4 and 0.9 Mt CO_2e in 2050, while the remaining mitigation is due to reduced agricultural activity. These on-farm mitigation estimates are in line with previous, similar studies.
- The Tailwinds and Widespread Engagement activity scenario offer the highest total GHG reduction, most of it arising from reduced agricultural activity.
- The Business as Usual activity scenario has the highest abatement potential on farms, consistent with this scenario having the largest dairy herd, grassland area and arable production, but offers the lowest overall GHG mitigation. However, reducing the land areas and livestock numbers (via increasing yield and reducing demand for livestock products) generates higher total abatement (Central Feasible Potential). These results (despite them not including the mitigation effect from land use change) are in line with the numerous studies pointing to the high GHG savings potential in reducing livestock consumption
- Five mitigation measures stand out as providing high emission reduction potential at negative or low abatement cost in most scenarios:
    - Growing clover-grass mix instead of pure grass is the most cost-effective mitigation option and also one of those measures which offer the largest abatement.
    - Using genomics in dairy breeding could also provide net savings to the farmers and offers high emissions reduction potential in most scenarios.
    - Increase the beef output from dairy herds using sexed semen could offer considerable mitigation at zero net cost
    - Finishing beef animals faster is also cost effective and offers high mitigation
    - Nitrate as a feed additive for beef can be implemented at a cost which is lower than the carbon price.

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2 Abbreviations and glossary

AD	Anaerobic digestion
CH_4	Methane
C	Carbon
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
GHG	Greenhouse gas
MACC	Marginal abatement cost curve; a visual representation of the cost of reducing emissions
N	Nitrogen
N_2O	Nitrous oxide
SOC	Soil organic carbon
TIMES	The Integrated MARKAL-EFOM System; a modelling tool
VRNT	Variable rate nitrogen technology

3 Background

The Climate Change (Emissions Reduction Targets) (Scotland) Act 2019, amending the Climate Change (Scotland) Act 2009, set the ambitious net-zero greenhouse gas (GHG) emissions reduction targets by 2045.

Agriculture contributes 18% of GHG emissions in Scotland (Scottish Government 2020a), and with the very slow decline in these emissions its share is increasing in the total carbon budget. However, in addition to the already identified key mitigation pathways through dietary and land use change and food waste reduction (Committee on Climate Change 2019), agriculture can offer opportunities in GHG mitigation and carbon sequestration which need to be utilised to move food production closer to net-zero (Eory *et al.* 2015).

The Update to the Climate Change Plan set out policies aiming to provide further GHG mitigation in Scotland's non-emission-trading sectors, including agriculture, and draws an emission envelope in 2032 for agricultural emissions at 5.3 Mt CO_2e y^{-1}; 2.3 Mt CO_2e y^{-1} less than emissions in 2020 (Scottish Government 2020b). This emission reduction requirement is substantially larger than the cost-effective GHG mitigation potential simulated to support the Climate Change Committee's work on the 5th carbon budget. This suggested that by 2030 an annual 0.88 Mt CO_2e GHG can be saved in Scotland when considering the interactions between the mitigation measures (Eory *et al.* 2015). It is also larger than earlier estimates (MacLeod *et al.* 2010; Moran *et al.* 2008).

Since the 5th carbon budget report further UK level studies were carried out on mitigation scenarios (Eory *et al.* 2019a; Eory *et al.* 2020a) and the Clean Growth for Sustainable Development project[1], commissioned by Defra, has examined a larger set of mitigation measures. In Scotland, work has been carried out to inform the Update to the Climate Change Plan 2018-2032 (Scottish Government 2020b), estimating the abatement potential and costs of fifteen mitigation measures as requested by Scottish Government (Eory *et al.* 2020b). This work informed modelling in TIMES and did not provide a cumulative abatement.

Further work has examined the extent to which GHG mitigation in Scottish agriculture is reflected in the UK GHG Inventory (Eory *et al.* 2019b). It highlighted the additional problem that, though the UK GHG Inventory's methodology is increasingly capturing environmental and management effects on GHG emissions, data collection bottlenecks mean that Scottish emissions are not reflected well in the Inventory. Lastly, following the publication of the Update to the Climate Change Plan, farmer-led groups were established to report on how they envisage GHG mitigation in their respective sectors (arable, dairy, suckler beef, hill farming/crofting and pig). These reports summarise stakeholder views on GHG emission mitigation and accounting and thus provide valuable information for mitigation assessment (see the full list of reports reviewed in Appendix A).

To better understand the most effective mitigation measures in Scotland, this project has examined if specific measures could provide significant further mitigation in Scotland. We revisited the earlier mitigation estimates, and explored the mitigation potential using agricultural activity scenarios described in the sectoral report for the 6th carbon budget

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[1] http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&ProjectID=20123&FromSearch=Y&Publisher=1&SearchText=Clean%20Growth%20&SortString=ProjectCode&SortOrder=Asc&Paging=10#Description

(Eory *et al.* 2020a). The results were produced in the format suitable for use in the Scottish TIMES model.

4 Methodology

The aim was to assess a set of mitigation options applicable in Scotland, against the background of various agricultural activity and uptake scenarios, adjusting – as needed – mitigation reports published earlier. Accordingly, the methodology and the report relies significantly on earlier work, mainly Eory *et al.* (2020a), Eory *et al.* (2020b) and the Defra-funded Clean Growth for Sustainable Development project[2].

4.1 MACC modelling tool

The Scotland-wide mitigation potential and cost-effectiveness of the measures were modelled in the MACC tool, which has been used in Scotland and the UK for over ten years (Eory *et al.* 2015; Eory *et al.* 2020a; Eory *et al.* 2020b; MacLeod *et al.* 2010; Moran *et al.* 2008). The methodology is described in Eory *et al.* (2015).

The key assumptions of the tool are summarised below:

The modelled year is 2050. Though the Net Zero target in Scotland is 2045, modelling constraints necessitated using 2050 as the target year. However, the mitigation differences between 2045 and 2050 would be small, and only due to agricultural activity differences, as all the mitigation measures are fully implemented in the model by the early 2040s.

Only the GHG and on-farm financial effects are considered, other environmental impacts (e.g. changes in ammonia emissions or water pollution) and social and wider economic impacts are not included in the analysis.

The mitigation is estimated on an annual basis.

The boundary of the model is the agriculture sector, i.e. mitigation potential achievable within the farm gate in Scotland, not including upstream (e.g. emissions embedded in fertiliser production) and downstream (e.g. emissions from food processing and consumption).

The mitigation potential is a combination of two elements. First, the difference between the emissions arising from agricultural activities given a certain activity (i.e. crop/grass area and livestock numbers) scenario and the emissions arising if mitigation measures are implemented. Second, the GHG savings from the reduced agricultural activity. It does not consider potential carbon sequestration from using former agricultural land differently (e.g. afforestation, peatland restoration).

The total Scottish production is capped at current productivity level: when measures which increase yield are modelled, the number of animals or cultivation area is proportionally reduced. Such mitigation would only manifest in real life if production did not increase.

The mitigation effects and costs are estimated as an average for each measure (with some disaggregation between different cropping and livestock activities within the

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[2] http://sciencesearch.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&ProjectID=20123&FromSearch=Y&Publisher=1&SearchText=SCF0120&SortString=ProjectCode&SortOrder=Asc&Paging=10#Description

model, but presented in an aggregated way in the results), not considering the wide variation between farms.

The mitigation calculations follow the UK agricultural inventory calculations (Brown *et al.* 2021), 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.

To convert methane (CH_4) and nitrous oxide (N_2O) emissions to carbon dioxide equivalent (CO_2e), the GWP100 values without climate change feedback were used, i.e. 28 and 265, respectively (Brown *et al.* 2021).

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%.

The carbon price was set to £241 t CO_2e^{-1}, based on Climate Change Committee estimates.

The MACCs consider interactions in mitigation between the mitigation measures (i.e. reducing double counting of mitigation potential if the measures are implemented on the same farms). Unless otherwise stated, the results presented include these interactions.

The data underpinning the national level mitigation and abatement cost estimates are based on available sources, which vary in robustness, depending on the scientific information available on them.

4.2 Mitigation measures

Over a hundred distinct mitigation measures were collected from sixteen Scotland and UK specific reports (Appendix A). They were screened to remove those which are not clearly defined and from the remaining measures those which are likely to offer the highest mitigation potential across Scotland were selected for analysis (Appendix C).

A short description of the mitigation measures and the detailed assumptions about them can be found in Appendix C, along with some useful observations for practitioners.

Please note - Agroforestry was included in the MACC modelling (i.e. interactions between agroforestry and other measures are accounted for), but its abatement is excluded from the total abatement results as it is not yet clarified if the mitigation it could generate would belong to the agricultural or the land use part of the inventory.

4.2.1 Agricultural activity in Scotland, 2016

Agricultural activity in 2016 was used as the starting year for the scenarios (between 2016 and 2021 changes in grass area, cropland area and livestock numbers were below 5% each; Scottish Government, 2021). Tables 1 and 2 show the agricultural activities in Scotland for 2016.

Table 1 : Crop activity data for Scotland in 2016

Crops	**(ha)**	**Crops**	**(ha)**
Field beans harvested dry	3,002	Spring oilseed rape	531
Field peas harvested dry	776	Sugar beet	0
Leafy forage crops	4,089	Top fruit	98
Linseed	58	Vegetables brassicas	3,008
Maize	763	Vegetables legumes	9,329
Minor cereals	4,357	Vegetables not differentiated	0
Other field crops	7,325	Vegetables other non-legumes	5,830
Other fodder crops	7,073	Wheat milling	56,989
Other horticultural crops	1,123	Wheat non milling	50,413
Potatoes maincrop	14,766	Willow short rotation coppice	0
Potatoes seed or earlies	12,760	Winter barley malting	17,291
Root crops for stockfeed	4,536	Winter barley non malting	30,740
Soft fruit	604	Winter oats	8,091
Spring barley malting	146,570	Winter oilseed rape	30,141
Spring barley non malting	92,329	Improved permanent grass	1,117,854
Spring oats	23,119	Improved temporary grass	210,080

Table 2 : Livestock activity data for Scotland in 2016

Livestock	(head)	Livestock	(head)
Dairy calves female	59,180	Beef steers	387,473
Dairy replacements female	31,123	Beef cows	426,490
Dairy in calf heifers	70,044	Lamb	3,454,132
Dairy cows	176,126	Mature ram	89,507
Beef heifers for breeding	153,622	Mature ewe	3,316,676
Beef females for slaughter	324,293	Sows	26,851
Beef bulls for breeding	31,608	Other pigs	182,969
Beef cereal fed bull	85,217		

4.3 Scenarios for agricultural activity and measure uptake

4.3.1 Agricultural activity scenarios

Agricultural activity is described in six different scenarios. Five scenarios are as developed by the Committee on Climate Change and described in Eory *et al.* (2020a) (Appendix B), representing various assumptions on food production and consumption. The behavioural and technological changes in these scenarios result in considerable change in agricultural area and livestock numbers over the coming decades. An additional *Business as Usual* (BAU) scenario describes agricultural activities without these behavioural and technological changes.

Scenario
Business as Usual
Balanced Net Zero
Headwinds
Widespread Engagement
Widespread Innovation
Tailwinds

In the *Business as Usual* (BAU) scenario all mitigation measures were included, however, as the other scenarios assumed a high yield increase in crops and milk production and an increase in stocking rates, those mitigation measures which would be increasing these yields were removed to avoid double counting.

Measures removed from all scenarios but BAU
Loosening compacted soils and preventing soil compaction (MM01)
Keeping pH at an optimum for plant growth (MM02)
Variable rate nitrogen application (MM07)
Improving ruminant nutrition for beef and sheep (MM18 and MM19)
Increased uptake of dairy genetic improvement, current breeding goal (MM35)
Increased uptake of dairy genetic improvement, current breeding goal with genomic tools (MM36) and Shift to lower emissions intensity breeding goal in dairy breeding, using genomic tools (MM38): smaller milk yield improvement

4.3.3 Uptake scenarios

The uptake scenarios were defined as in Moran *et al.* (Moran *et al.* 2008) (Table 3). Uptake is assumed to start to increase after 2 years of the implementation year (2022), allowing time for policy scheme development (apart from lower emission breeding goal measures, where research and development is still needed, therefore this lead-in time is 10 years). Uptake reaches the maximum under the uptake scenario within 10 years after the lead-in period.

Table 3 Uptake scenarios

Maximum technical potential (MTP)	Assuming the measure is implemented everywhere where it is applicable
High feasible potential (HFP)	Assuming 92% uptake for those measures which are easier to enforce and 85% for those which are not easy to enforce
Central feasible potential (CFP)	45% uptake overall
Low feasible potential (LFP)	Assuming 7% uptake for measures with positive net costs and 18% for those with zero or negative costs

NOTE: These scenarios were established by the Climate Change Committee and do not fully correspond to intended policy in Scotland. As such, the results offer useful insights but may not be suitable in terms of considering the potential impacts of future policy.

5 Results and discussion

5.1 Marginal abatement cost curves in farming

The results for two activity and uptake scenario combinations are presented in Table 29, Table 30 in Appendix D, the full set of results have been provided for Scottish Government.

When all the mitigation measures are implemented at Central Feasible Potential (45% of farmers) in the *Business as Usual* scenario, the mitigation potential is 0.9 Mt CO2e y^{-1} in 2050. With the reduced agricultural activity in the other activity scenarios the mitigation potential decreases too, to 0.6 and 0.4 Mt CO_2e y^{-1}, in the *Balanced* and *Tailwinds* activity scenarios, respectively.

As individual measures, not considering the interactions, four out of the five measures with highest abatement potential are beef mitigation measures (Table 31). The abatement potential of some of the measures are much higher as individual mitigation measure than in the MACC, since the interactions can reduce the abatement potential of those measures which have higher abatement cost (this is a result of how interactions are considered in the model).

Fourteen measures have negative abatement cost, meaning that they could provide financial savings to farmers and another six have zero abatement cost, likely to result neither in savings nor costs. Only five measures – considering interactions – have too high abatement costs to be considered for mitigation (urease inhibitor (MM08), nitrification inhibitor (MM09) and high fat diet for ruminants (MM23-MM25).

The mitigation measure ‘grass-legume mixtures’ (MM4) consistently, across scenarios, has a very favourable abatement cost and one of the highest abatements. Other high-abatement measures with negative or zero abatement cost are genomics breeding for dairy (MM36), faster finishing beef (MM29) and using sexed semen in cattle production (MM42). Nitrate feed additive for beef (MM21) and 3NOP for beef (MM27) have considerable mitigation potential and a positive, but not very high abatement cost.

5.2 Mitigation estimates for the TIMES model

The stand-alone mitigation results for the *Business as Usual* activity scenario (Maximum Technical Potential, High Feasible Potential, Central Feasible Potential, Low Feasible Potential uptake scenarios) were converted to metrics for TIMES modelling, as these are not standard outputs of the MACC model. The CFP results are presented in Table 32 in Appendix D.

5.3 Mitigation on farms and from reduced agricultural activity

The above estimates only consider the mitigation happening on the agricultural area in each activity scenario, not including the emission change due to the changes in agricultural activities and land use. Table 33 in Appendix D presents the estimated mitigation from the reduction in agricultural activities (mostly livestock production) in each activity scenario compared to *Business as Usual* in 2050, looking at the theoretical upper bound (Maximum Technical Potential). The potential carbon sequestration from changing the land use from arable and grasslands to other types is not included in these estimates.

The largest abatement (0.9 Mt CO_2e in 2050 with Central Feasible Potential) within agriculture can be achieved in *Business as Usual* activity scenario, due to the largest agricultural activity (livestock production, grass and crop production activities). Furthermore, the *Business as Usual* activity scenario has eight more mitigation measures included, as those measures which improve yield were excluded (or got their yield effect reduced) from the other activity scenarios to the extent of the implicit yield increase assumptions in these scenarios.

The three activity scenarios with the lowest agricultural area and livestock numbers (resulting from yield increase, efficiency gains and lower livestock consumption) – *Widespread Innovation, Widespread Engagement, and Tailwinds*– have the lowest mitigation from agricultural areas and the highest mitigation from the reduced agricultural activity. Overall, *Widespread Innovation, Widespread Engagement and Tailwinds* offer the highest reductions in GHG emissions, 4.2, 4.3 and 4.3 5.1 Mt CO_2e in 2050, respectively, at Central Feasible Potential.

6 Conclusions

The modelling, as expected, shows that the highest mitigation from agricultural activities can be achieved when the cropping area and livestock numbers are the largest (*Business as Usual* activity scenario; in Central Feasible Potential 0.9 Mt CO_2e y^{-1} in 2050).

However, reducing the land areas and livestock numbers (via increasing yield and reducing demand for livestock products) generates higher total abatement, providing an overall annual mitigation of 4.3 Mt CO_2e in 2050 (Central Feasible Potential). These results (despite them not including the mitigation effect from land use change) are in line with the numerous studies pointing to the high GHG savings potential in reducing livestock consumption (Aleksandrowicz *et al.* 2016; Lamb *et al.* 2016).

The mitigation estimates in this study are in line with previous, similar studies, despite a number of differences in the underlying assumptions about the measures. The study underpinning the Climate Change Committee's 5th carbon budget estimated the annual mitigation potential in Scotland at 0.88 Mt CO_2e y^{-1} at Central Feasible Potential (Eory *et al.* 2015). The work informing the Climate Change Committee's 6th carbon budget found that 1.1 Mt CO_2e y^{-1} could be mitigated in Scotland with an uptake between 50-80% in the *Business as Usual* activity scenario (Eory *et al.* 2020a).

Five mitigation measures stand out as consistently providing high abatement at negative or low abatement cost. These are grass-legume mixture on swards (MM04), genomics breeding for dairy (MM36), faster finishing beef (MM29), using sexed semen in cattle production (MM42) and nitrate feed additive for beef (MM21). Promoting these measures could provide the quickest and largest GHG savings, though the implementation of a very wide variety of technologies and practices (along with the above-mentioned changes in the wider supply chain and land use) would be needed to achieve large reductions in GHG emissions from agriculture.

7 Acknowledgements

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9 Appendix A: Reports used for selecting the mitigation measures

Table 4 Reports used for selecting the mitigation measures

(2020) Farming for 1.5°: A transformation pathway. Independent inquiry on farming and climate change in Scotland.

Dairy Sector Climate Change Group. (2021) The Dairy Sector Climate Change Group report.

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Suckler Beef Climate Group. (2020) Suckler beef climate scheme.

The Scottish Pig Industry Leadership Group (2021) Bringing home the bacon: Reducing greenhouse gas emissions from the Scottish pig sector.

10 Appendix B: Agricultural activity scenarios

Table 5 : Agricultural activity scenarios (Eory et al. 2020a)

	Balanced Net Zero	Headwinds	Widespread Engagement	Widespread Innovation	Tailwinds
Diet change[1]: livestock product replacement with plant-based food	35% all meat; 20% all dairy to plant-based	20% all meat; 20% all dairy to plant-based	50% all meat; 50% all dairy to plant-based	50% meat (30% switch to lab-grown meat, 20% to plant-based), 50% dairy products.	As in Widespread Innovation
Food waste reduction across the food chain	As in Widespread Innovation	50% by 2030 and constant to 2050	50% by 2030 70% by 2050	50% by 2030 60% by 2050	As in Widespread Engagement
Average wheat yield[3] (t DM ha $^{-1}$)	As in Headwinds	11.0	As in Headwinds	13.0	As in Widespread Innovation
Indoor horticulture	As in Headwinds	10% of production indoors	10% of production indoors	50% of production indoors	As in Widespread Innovation

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[1] The underlying scenarios assume that diet change translates into production change nationally

[3] Yield improvements are given for wheat and equivalent increases are assumed for other crops.

	Balanced Net Zero	Headwinds	Widespread Engagement	Widespread Innovation	Tailwinds
Grazing intensity	As in Headwinds	Decrease livestock in upland grazing areas by redistributing to other grassland, with an overall 10% increase in the stocking rate on the remaining grassland (medium ambition)	Decrease livestock in upland grazing areas by redistributing to other grassland, with an overall 5% increase in the stocking rate on the remaining grassland (low ambition)	10% increase in the stocking density of the reduced area of upland grassland, 10% increase in stocking density on improved grassland (high ambition)	As in Widespread Innovation
Dairy productivity increase	As in Headwinds	0.6% y^{-1} 2020-2050	0.6% y^{-1} 2020-2050	2.9% y^{-1} 2020-2030, 0.6% y^{-1} 2030-2050	As in Widespread Innovation
Other livestock productivity	No change	No change	No change	No change	No change

11 Appendix C: Mitigation measure descriptions

Table 6: Initial mitigation measure selection and measures assessed

ID	Mitigation measure	Included in the MACC?
MM01	Loosening compacted soils and preventing soil compaction	Yes
MM02	Keeping pH at an optimum for plant growth (e.g. liming)	Yes
MM03	Use of catch and cover crops	Yes
MM04	Legumes-grass mixtures	Yes
MM05	Grain legumes in crop rotations	Yes
MM06	Intercropping with legumes	No (provides yield benefit only compared to very low fertilisation rates, otherwise the total yield is less than in conventional systems, therefore it would cause emission displacement)
MM07	Variable rate nitrogen application (precision farming)	Yes
MM08	Urease inhibitor	Yes
MM09	Nitrification inhibitor	Yes
MM10	Low emission manure and slurry spreading	No (uncertain and low GHG abatement potential; inconclusive data on direct N_2O effect)
MM11	Slurry acidification	Separated by animal categories (MM43-MM45)
MM12	Covering slurry with impermeable (plastic) cover (dairy, beef, pig)	Separated by animal categories (MM46-MM48)
MM13	Anaerobic digestion, cattle	Yes
MM14	Anaerobic digestion, pig/poultry	Yes

ID	Mitigation measure	Included in the MACC?
MM15	Agroforestry	Yes, included in the MACC for interactions, but its abatement is excluded from the total abatement results
MM16	Better grazing systems (increasing utilisation rate), beef	No (too much overlap with MM18)
MM17	Better grazing systems (increasing utilisation rate), sheep	No (too much overlap with MM19)
MM18	Improving ruminant nutrition, beef	Yes
MM19	Improving ruminant nutrition, sheep	Yes
MM20	Nitrate feed additive, dairy	Yes
MM21	Nitrate feed additive, beef	Yes
MM22	Nitrate feed additive, sheep	Yes
MM23	High fat diet, dairy	Yes
MM24	High fat diet, sheep	Yes
MM25	High fat diet, beef	Yes
MM26	3NOP feed additive, dairy	Yes
MM27	3NOP feed additive, beef	Yes
MM28	3NOP feed additive, sheep	No (no experimental data on mitigation)
MM29	Faster finishing of beef cattle	Yes
MM30	Increasing beef calving rate	Yes
MM31	Reducing age of first calving in beef	Yes
MM32	Improving health, dairy	Yes
MM33	Improving health, beef	Yes

ID	Mitigation measure	Included in the MACC?
MM34	Improving health, sheep	Yes
MM35	Increased uptake of dairy genetic improvement, current breeding goal	Yes
MM36	Increased uptake of dairy genetic improvement, current breeding goal with genomic tools	Yes
MM37	Increased uptake of beef genetic improvement, current breeding goal with genomic tools	Yes
MM38	Shift to lower emissions intensity breeding goal in dairy breeding, using genomic tools	Yes
MM39	Shift to lower emissions intensity breeding goal in beef breeding, using genomic tools	Yes
MM40	Increased uptake of sheep genetic improvement practices using the current breeding goal	No (the few available scientific papers show increased GHG emissions)
MM41	Dual purpose cattle breeds	No (cannot represent the effect well in the MACC due to lack of cattle herd model)
MM42	Using sexed semen in dairy cattle production	Yes
MM43	Slurry acidification, dairy	Yes
MM44	Slurry acidification, beef	Yes
MM45	Slurry acidification, pigs	Yes
MM46	Impermeable slurry cover, dairy	Yes
MM47	Impermeable slurry cover, beef	Yes
MM48	Impermeable slurry cover, pigs	Yes

MM01: Loosening compacted soils and preventing soil compaction

11.1.1 Overview

Soil compaction has been reported to increase N_2O emissions (Ball *et al.* 1999; Cranfield University *et al.* 2007) and strongly reduce the soil's ability to be a CH_4 net sink (Ruser *et al.* 1998). Reduced root penetration and primary productivity (Chamen *et al.*, 2015) is also likely to reduce soil C inputs, which may reduce CO_2 sequestration in soil. Therefore, reducing soil compaction and preventing its re-occurrence can contribute to GHG mitigation, amongst providing other benefits, e.g. improved soil function and increased yield.

Prevention of soil compaction requires better planning of field operations to avoid traffic on wet soil, avoiding or strongly reducing tillage of wet soil and reducing stocking density, particularly during wetter periods (Frelih-Larsen *et al.* 2014). At the same time, for the best long-term results, there should be a regular assessment of drainage and improvements carried out when needed. Where soils become compacted, loosening of the soil is required: in case of moderate compaction cultivation is appropriate, otherwise sub-soiling of tillage land and ploughing and re-seeding grassland might be required (Cranfield University *et al.* 2007).

11.1.2 Evidence base

The modelled mitigation is based on the N_2O reduction and yield increase. The literature reports a varying magnitude of reduction in the soil N_2O emission factor EF_1; estimates (as reported by Eory *et al.*, 2015) vary from around 6% (Moran *et al.*, 2008) up to 65% (Ball *et al.*, 2000). The Farmscoper tool (Gooday *et al.*, 2014, 2015) assumes a reduction of 0-10% (typically 2%) for direct N_2O emissions, and 10-50% (typically 25%) reductions in leached N resulting in indirect N_2O emissions where soil compaction is alleviated, and 2-25% (typically 10%) reductions in all N_2O emissions resulting from use of correctly inflated (low ground pressure) tyres.

Yield losses resulting from soil compaction stem from a) increased penetration difficulty for roots, b) reduced soil water, and c) decreased aeration (Chamen *et al.* 2015). Losses to arable crops measured by Håkansson & Reeder (1994) averaged 3.7% over a 12-year recovery period; at the end of this period, in the absence of further compaction, yields had recovered to c. 99% of non-compacted controls. Graves *et al.* (2011) estimated overall yield losses on UK farmland of 3-6%, 3-5% and 1-3% on compacted horticultural, arable and grassland respectively. For compacted land, this translates to crop yield impacts of 17% in clay soils, 25% in sandy soils, and 4% in medium, shallow and peaty soils. We assumed, conservatively, 2% and 1% increase, respectively, for tillage crops and grass (and related increase in crop residue).

Sporadic data sources exist about compaction and land liable to compaction. In England in 2012 51%, 43% and 20% of farms had problems with compaction, respectively of topsoil, plough depth and whole soil profile (Defra 2013). A grassland survey in England showed that 10% of the soils were in poor and another 60% in moderate condition (Newell-Price *et al.* 2013). Another survey in England and Wales estimated that 42% of arable land and 39% of grassland is liable to compaction (Graves *et al.* 2011). Based on the information summarised above we assumed that, for both tillage land and grasslands, 20% of the land area was compacted in the UK, and another 20% was susceptible to compaction.

Chamen *et al.* (2015) identify subsoiling, targeted subsoiling and ploughing as remediation strategies for soil compaction, and low tyre pressures, tracked tractors and controlled traffic systems for avoidance of compaction. Posthumus *et al.* (2015) estimate costs of £15-25 ha^{-1} $year^{-1}$ to prevent soil compaction in field cultivation tramlines (i.e. vehicle wheelings through the planted area of the field). Post-harvest cultivation of compacted soils with discs or tines is estimated to cost £4 ha^{-1} $year^{-1}$ (Cuttle *et al.*, 2006). Eory *et al.* (2015) report costs of £60 ha^{-1} $year^{-1}$ for alleviating deep compaction on tilled land, £4-25 ha^{-1} $year^{-1}$ for alleviating topsoil compaction on tilled land, and £11-40 ha^{-1} $year^{-1}$ for alleviating compacted grassland. Chamen *et al.* (2015) estimate costs of £20-56 ha^{-1} $year^{-1}$ for compaction remediation strategies, and £0-21 ha^{-1} $year^{-1}$ for avoidance strategies; variation in this estimate stems from technology type and soil type.

11.1.3 Assumptions in the model

Table 7 Assumptions for MM01

Variable	Animal/crop type	Value type	Unit	Value
Crop yield	Arable	Relative	change from original value	0.02
Crop yield	Temporary grassland	Relative	change from original value	0.01
Crop residue N	Arable	Relative	change from original value	0.02
Crop residue N	Temporary grassland	Relative	change from original value	0.01
EF_1		Relative	change from original value	-0.06
Current uptake		Absolute	-	0
Applicability	Arable	Absolute	-	0.2
Applicability	Temporary grassland	Absolute	-	0.2
Applicability	Permanent grassland	Absolute	-	0
Cultivation cost		Absolute	£ ha^{-1}	30
Lifetime of cultivation		Absolute	Year	10

11.1.4 Description for practitioners and monitoring

Preventing soil compaction

- Tyre pressure. Tyre pressure needs to be tailored to the activity. Seedbed preparation will require a lower tyre pressure to spread the weight of the machine over a wider area. Road haulage work will require a higher pressure for vehicle control and reduce tyre wear. Weighing machines will help to safely adjust pressures aligned with manufacture guidance.
- Machine choice. Using lighter/smaller machines can help to reduce compaction, carrying wheel weights and weight blocks when they are operational not required can increase the compaction risk.
- Tyre design. Tyre design can make a huge difference to compaction as different designs may reduce the forces into the soil. Trailer tyres such as super singles which have very ridged sidewalls give excellent stability and performance on the road but are very poor in field as they concentrate the carried weight into a very small contract area. Wider more flexible floatation tyres are far for forgiving to soil structure.
- Soil moisture. A dry soil has greater bearing capacity for loads, while a wet soil is compressed under a similar pressure. Avoiding cultivations, travelling on, or grazing livestock on wet soils can help to prevent compaction.
- Limiting machine wheelings. Control traffic farming (CFT) principle is that all machines run in designated wheeling’s only meaning as little of the field is run on. Full CFT farming can be very restrictive but the principle of driving on tramlines as much as possible can easily be implemented.
- Stocking densities. Lower animal stocking numbers reduces the concentrated weight of a flock or herd of animals grazing on soils.
- Crop rotation. Deep rooting crops such as oil seed rape, beans and vetch within a rotation can help to keep soils free as their longer roots can break up soil layers.
- Establishment method. Direct drilling or no inversion farming can reduce compaction as very little soil is moved in the establishment process. The soil structure can improve year on year as it is not turned over (ploughing) which can create hard pans at depth.
- Increasing organic matter. Soils with higher organic matter levels are harder to compact as the organic material prevents the soil particles pressing together and locking as tightly.

Loosening compaction

- Identification. Locating the level of compaction and at what depth in the soil it is at is the first step. Carrying out a VESS test can give vital information that will be needed decide what steps are taken to remove compaction within the soil.
- Cultivation. Depending on the depth of compaction within the soil profile different machine can be used. For surface compaction an aerator can be used or light cultivation. Deeper compaction then a sward lifter or subsoil may be required to break up compacted layers.
- Depth of cultivations. Cultivating at different depths can break up compaction pans only if soil moisture is suitable
- Deep rooting crops. Crops such as oil seed rape, beans and vetch within a rotation can help to keep soils free as their longer roots can break up soil layers

11.1.5 References

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MM02: Keeping pH at an optimum for plant growth

11.1.6 Overview

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 in N-fertilisers becomes less efficient (Goulding 2016). Soil pH is highly important in the spatial distribution of soil organic carbon (Tu *et al.* 2018), with alkaline soils capable of supporting greater concentrations. Lime application therefore may increase organic matter inputs (Fornara *et al.*, 2011; Jokubauskaite *et al.* 2016) with the effect of increasing soil carbon stocks (Fornara *et al.* 2011). Evidence shows that more acid conditions are likely to lead to a higher N_2O emission rate (Goulding 2016; Simek *et al.* 1999; Zhu *et al.* 2019) – an increase of pH (e.g. by liming) in soils will thus also reduce N_2O emissions.

11.1.7 Evidence base

The mitigation effect is modelled through an increase in yield (and related crop residue), carbon sequestration and reduced N_2O emissions.

The response of soil organic content to pH is complex and context specific (Li *et al.* 2018). In grassland, Fornara *et al.* (2011) report substantial increases in grassland soil C for limed treatments, both in fertilised and unfertilised swards. For cropland, Tu *et al.* (2018) report a positive correlation between pH and SOC ($r^2 = 0.43$); the model reported in this assessment suggests a non-linear relationship between pH and SOC, with an increase of 1 pH unit in the range pH 4-7 corresponding 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 (Goulding 2016) this roughly equates to an increase of 1.8-4.3 tonnes 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_2-eq ha^{-1} $year^{-1}$. Note that this is a broad extrapolation based on site-specific data and should be taken as an indication only, though as might be expected, forms a lower bound to the estimates provided by Fornara *et al.* (2011). Data reported by Kemmitt *et al.* (2006) also suggests a non-linear interaction between pH and SOC stocks in cropland, with maximum stocks occurring around pH 5.5-6 and reducing at both higher and lower pH values.

Lime extraction and application increases CO_2 emissions. The relevant IPCC Guidelines for National GHG 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 effects of soil pH on N_2O emissions are context-specific, with variable relationships between pH and the proportion of applied N emitted as N_2O (Skiba *et al.* 1998; Russenes *et al.* 2016). However, since liming increases soil nutrient availability (ALA 2011; Goulding 2016), requirement for N application may decrease, which would result in a net reduction in N_2O. A recent study from France showed an estimated reduction potential of N_2O emissions by liming of 15.7% (Hénault *et al.* 2019), while a reduction of 37% was estimated in an Irish study by Žurovec *et al.* (2021), showing a decrease in EFs of up to 0.8% with increasing amount of lime applied.

Where pH is suboptimal, liming increases crop yield. Based on UK data, Holland *et al.* (2017) show that yield response to liming is roughly linear below 90% maximum yield.

Field trials in the United Kingdom (ALA, 2011) reported yield increases of 3.6-9.2 tonnes ha^{-1} for sugar beet and 0.2-0.7 t ha^{-1} for barley. A Swedish study showed that increasing the pH from 6 to 7 almost doubled yields of winter wheat and spring barley and even at pH values above 6.5, yields of cereals still increased amounting to 640−1125 kg per 0.5 pH unit (Kirchmann *et al.* 2020).

Although vital for soil quality and agricultural production, liming tends to be strongly influenced by the economics of farming. Consequently, much less lime is being applied in the UK than required. Based on estimated application rates of lime products for cropland and arable land in the UK (Defra 2018), in comparison of requirements lime is underapplied even for land receiving lime. A recent survey of over 1000 fields from grassland (Ayrshire, Water of Coyle) and arable land (Perth, East Pow), showed that 34% of arable soils and 57% of grassland 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 costs of lime application include purchase of lime, spreading and soil analysis. It is recommended that farms apply lime at 3-6 year intervals depending on results of soil analyses (SRUC 2014). We assumed that on average 3.7 t ha^{-1} lime is needed in every 4 years, at a cost of £35 t^{-1} lime.

11.1.8 Assumptions in the model

Table 8 Assumptions for MM02

Variable	Animal/crop type	Value type	Unit	Value
Current uptake		Absolute	-	0
Applicability	Arable	Absolute	-	0.09
Applicability	Improved grassland	Absolute	-	0.22
Crop yield		Relative	change from original value	0.0622
Crop residue N	Arable	Relative	change from original value	0.0622
EF_1		Relative	change from original value	-0.03
C sequestration		Absolute	t CO2e ha^{-1} y^{-1}	0.3
CO_2 emissions from lime extraction and application		Absolute	t CO2e ha^{-1} y^{-1}	0.2
Lime cost		Absolute	£ ha^{-1}	129.5

Variable	Animal/crop type	Value type	Unit	Value
Spreading cost		Absolute	£ ha^{-1}	8.41
Cost lifetime		Absolute	year	4
Soil analysis		Absolute	£ ha^{-1}	20
Soil analysis cost lifetime		Absolute	year	4

11.1.9 Description for practitioners and monitoring

- Apply lime. The main method for optimising soil pH in Scotland, where soil is typically acidic (low pH), is by applying lime.
- Determine the liming requirement. Various factors including existing soil pH, soil type and types of crops in the rotation will affect the amount of lime needed. Regular soil sampling (every 3-5 years) will help to gain a regular picture of soil pH and nutrients and how often the soil will need to be limed. Some crops will be more sensitive to pH (e.g. vegetables) and others more tolerant to higher pH (e.g. potatoes), and pH affect nutrient availability and optimisation; understanding the optimum pH for crops in the rotation will help to determine how much lime to apply, and when is optimum in the rotation.
- Assess optimum timing of application. Lime will take 12 months to have full effect which should be factored into the timing of crops in the rotation. No particular time of year is recommended for liming (unlike nutrient application), but good ground conditions are advised to reduce negative effects of traffic on fields and soil.
- Choose the type of liming product. A consultant can advise on whether calcium or magnesium lime is needed, and what type of product as there are many different types for different conditions e.g. ground, prilled, hen manures etc. Factors will include the ratio of calcium and magnesium, neutralising value, reactivity etc. will affect how effective and quick acting the product is.
- Application method. Around 95% of farms in Scotland will use a contractor with specialist lime spreading equipment. However, some products such as granular lime can be applied in standard farm machinery such as a fertiliser spreader. If the equipment has GPS and soil nutrient and pH maps, lime can be applied variably across fields according to liming requirements.

11.1.10 References

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MM03: Cover crops

11.1.11 Overview

Cover crops are non-cash crops integrated into the main crop rotation. They are typically grown either to maintain soil cover during fallow periods (Ruis & Blanco-Canqui, 2017), or are planted alongside main crops to reduce bare soil area and reduce erosion. The former is either ploughed under as green manure or killed with herbicides under no-till regimes. Cover crops can be divided into catch crops, grown to prevent N leaching (Cicek *et al.*, 2015), and green manure, grown to improve soil physical conditions (Alliaume *et al.*, 2014) and main crop nutrition (Dabney *et al.*, 2010). Cover cropping serves to maintain SOC input to soil (Rutledge *et al.*, 2017), prevent erosion (De Baets *et al.*, 2011), decrease N leaching (Blombäck *et al.*, 2003), and increase main crop productivity (Lal, 2004).

11.1.12 Evidence base

Pellerin *et al.* (2013) and Pellerin *et al.* (2017) estimated soil carbon sequestration potential of 240 kg C ha^{-1} $year^{-1}$ (0.88 t CO_2e ha^{-1} $year^{-1}$) for arable cover cropping (both companion-type cover cropping, and fallow cover. The authors also estimated potentials of 490 kg C ha^{-1} $year^{-1}$ (1.80 t CO_2e ha^{-1} $year^{-1}$) and 320 kg C ha^{-1} $year^{-1}$ (1.17 t CO_2e ha^{-1} $year^{-1}$) for cover cropping in orchards and vineyards respectively. Aertsens *et al.* (2013) estimated sequestration of 160 kg C ha^{-1} $year^{-1}$ (0.59 t CO_2e ha^{-1} $year^{-1}$ based on rates reported in French systems. Poeplau & Don (2015), based on a global meta-analysis of the primary literature, estimated an annual sequestration potential of 320 ± 80 kg C ha^{-1} $year^{-1}$ (1.17 ± 0.29 t CO_2e ha^{-1} $year^{-1}$) for arable cover crops. The authors also estimated a saturation point of 16.7 t C ha^{-1} (61.2 t CO_2e ha^{-1}) for land under cover crops. This annual sequestration potential was adopted by Martineau *et al.* (2017) in the form of an upper and lower bound of 0.88 – 1.47 t CO_2e ha^{-1} $year^{-1}$. Posthumus *et al.* (2015) estimated a carbon sequestration potential of 479 kg C ha^{-1} $year^{-1}$ (1.76 t CO_2e ha^{-1} $year^{-1}$) for arable cover cropping in the United Kingdom. This is comparable with the recent review that has quantified the increase in soil carbon as ranging from 270-430 kg C ha^{-1} $year^{-1}$ (0.9-1.58 t CO_2e ha^{-1} $year^{-1}$) (Bolinder *et al.*, 2020). Although the evidence would suggest that cover crops increase soil carbon, it is worth noting that in a cropping sequence experiment in the UK where overwinter crops were included 4 years out of 10 the change in soil was -5.50 ± 1.06 t C (-2.02 ± 0.389 t CO_2e ha^{-1} $year^{-1}$) (Poulton *et al.* 2018). For this modelling we adopted the value estimated in the Defra Clean Growth for Sustainable Development project, which is 1,280 CO_2e kg ha^{-1} $year^{-1}$.

Cover crops reduce the N leaching by between 25% and 75% (Abdalla *et al.* 2019); however, the scale of the effect is dependent on precipitation events as well as the time of planting and the choice of species sown (Gaimaro *et al.* 2022). For an assessment in the UK, Eory *et al.* (2015) accounted for reduced N_2O emissions by assuming a 45% reduction in the leached N fraction (FracLeach) in the IPCC guidelines (de Klein *et al.*, 2006). Basche *et al.* (2014) found that cover crops increased direct N_2O emissions in 60% of cases, though in the long term, the net N_2O impact may be closer to zero. Cover crops may also reduce N_2O emissions by extracting unused N from the soil following the main crop harvest (Aertsens *et al.* 2013). Here we assumed no effect on direct N_2O emissions.

In 2015, the area of arable land that was under cover crops was 3.6%[4]. This is comparable to the estimate of between 1 and 10% of cropland globally is already under cover crops (Poeplau & Don, 2015). However, farmers in the UK are showing increasing interest in including cover crops in their rotations (Storr *et al.* 2019).

Around 50% of European cropland is covered each winter, which forms a baseline for the implementation of fallow cover cropping in Europe; around half of the remaining land (25% total area) is ‘conservatively’ assumed to be suitable for cover cropping (Poeplau & Don, 2015). Annual maintenance costs are expected to stem from seed purchase, and cover crop planting and destruction, with savings resulting from reduced crop N requirements. Posthumus *et al.* (2015) estimated per-hectare annual costs of £50 – 55, £25 – 60 and £25 for seed purchase, cultivation, and residue incorporation respectively. The scenarios considered were companion-type cover cropping (grass under sown maize) and barley sown as a winter cover. The authors also noted that a switch from winter to spring production (necessary, depending on baseline practice, to implement winter fallow cover cropping) could incur a substantial yield penalty equivalent to £175 ha^{-1}. The FarmScoper tool, developed by ADAS (Gooday *et al.* 2014), estimated costs of £63 ha^{-1} for implementation of autumn (fallow) cover cropping. The tool also estimated costs of £263 ha^{-1} if winter crop production was switched to spring to allow implementation of cover cropping. The analysis of the literature in the Defra Clean Growth for Sustainable Development project estimated the implementation costs as £139 ± 56 ha^{-1}.

11.1.13 Assumptions in the model

Table 9 Assumptions for MM03

Variable	Animal/crop type	Value type	Unit	Value
C sequestration		Absolute	t CO2e ha^{-1} y^{-1}	1.28
$Frac_{leach}$		Relative	change from original value	-0.45
Current uptake	Spring crops	Absolute	-	3.60%
Current uptake	Other cereals and oilseed rape	Absolute	-	1.66%
Applicability	Spring crops	Absolute	-	25%
Applicability	Other cereals and oilseed rape	Absolute	-	12%
Combined costs		Absolute	£ ha^{-1} y^{-1}	139

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[4] https://www.gov.scot/publications/scottish-survey-farm-structure-methods-2016/pages/18/

11.1.14 Description for practitioners and monitoring

- In advance: Catch and cover crops are mostly sown after the harvesting of an arable crop; the catch crops between cereal harvest in mid-late summer and autumn sowing of winter cereal crops and a cover crop between the harvest of a cereal or forage crop e.g. maize and the spring when next year’s crops are sown. The most critical issue is ensuring the crop can be sown as early as possible to maximise its growth potential particularly for catch crops.
- Prepare the seed bed: To prepare the seed bed the previous crop must be harvested, residues (straw) removed and soil cultivated. It is possible to broadcast seed (stubble turnips) into a standing cereal crop several weeks before harvest to enable the seedlings to establish earlier. The choice of herbicide may be restricted by the nature of the following crop – especially catch crop followed by winter cereals as this would preclude/ restrict the use of gramicides.
- Sow the cover or break crops: Direct drill into cultivated ground or stubble or broadcast into the harvested or standing cereal crop.
- Selection of the correct species and: for effective establishment – generally in Scotland small seeded species (stubble turnips, clover) should be drilled before the middle of August while large seeded crops (cereals) can be sown later into the autumn.
- Equipment required: You can use any suitable equipment you have for over sowing e.g. fertiliser spreader, grass seed broadcaster or seed drill.
- After sowing: If the soil is dry enough, roll immediately after you sow to improve seed-to-soil contact, keep in moisture and reduce risk of slug damage.

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MM04: Legumes-grass mixtures

11.1.16 Overview

N_2O emissions arising from the use of synthetic N fertilisers can be reduced by relying more on biologically fixed nitrogen in crop production. Besides the fixed N supporting the growth of the legume crop (e.g. clover), part of these N compounds also become available to the grass plants, reducing their need for synthetic N. This effect becomes substantial above a clover content of around 20%-30% in the sward. The effect is robust and persistent across legume species and climatic regions, as shown by a series of experiments in Europe over three years, where savings of 300 kg N ha^{-1} were achieved without compromising the yield (see a review in Lüscher *et al.* 2014). However, although fixation rates in Scotland can be as high as 180 kg N ha^{-1} [5], typical fixation rates are 70-120 kg N ha^{-1}. Applying high levels of nitrogen to the sward will result in the fixation mechanism being effectively switched off. Evidence suggests that the biological fixation itself does not lead to significant emissions – the IPCC 2006 recommendations (IPCC 2006) removed legumes as a source of direct N_2O emissions (Lüscher *et al.* 2014). Another effect of clover in the swards on GHG emissions is that the proportion of N leached into the ground (and eventually to ground and surface water) can increase if the clover content is too high (Lüscher *et al.* 2014).

11.1.17 Evidence base

Typical nitrogen synthetic fertiliser applications on are in the region of 150 kg N ha^{-1} (D. Lawson, *personal comms*), and assuming that farmers will continue to apply 50 kg N ha^{-1} to grass-clover swards, the reduction in synthetic fertiliser will be 100 kg N ha^{-1}. As leaching losses can increase if the clover content is too high (Lüscher *et al.* 2014), it is assumed that the indirect losses are not affected by the change in fertiliser applications.

The costs of establishing and maintaining a grass-clover mix include the cost difference between grass-only and grass-clover seed mix (once in every 2 and 5 years for temporary and permanent grass, respectively), the savings from the reduced use of synthetic N fertiliser, one less fertiliser spreading event per year, and, in the case of permanent grasslands, the additional cost of seeding (assuming direct drilling; once in every five years).

The measure is applicable on all improved grasslands (i.e. grassland which is fertilised). According to the latest Farm Practices Survey (Defra 2018) 46% of grassland is seeded with clover mix in England. From the Countryside Survey[6] Anthony concluded that the proportion of improved or semi-improved grassland with white clover in 2007 was 44% Scotland, respectively (*pers. comm.* Anthony in Eory *et al.* 2015). Based on these data we assumed that 44% in Scotland have clover mixes. However, anecdotally many of these swards received standard fertiliser inputs. Future additional uptake relates to grass swards that currently have no legumes or have legume content below 30%. Unfortunately, there is no available information on what proportion of the fields has sufficient clover to fix a significant proportion of the N requirements apart from information on Scottish dairy farmers. In a survey by Glenk *et al.* (2014) 35% of farmers indicated that they have high clover content swards (above 20% DM). Furthermore, this GHG mitigation measure is one of the most favoured measures amongst those who have not

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[5] https://www.farmingforabetterclimate.org/wp-content/uploads/2018/02/nitrogen_fixation.pdf

[6] https://countrysidesurvey.org.uk/

adopted it. We assumed that currently 75% the grass-clover swards have sufficient legume content, consequently the current uptake is 33% in Scotland.

11.1.18 Assumptions in the model

Table 20 Assumptions for MM04

Variable	Animal/crop type	Value type	Unit	Value
N fertilisation rate		Absolute	kg N ha^{-1} y^{-1}	-100%
Fuel use CO_2 effect	Temporary improved grass	Absolute	kg CO2e ha^{-1} y^{-1}	-4
Fuel use CO_2 effect	Permanent improved grass	Absolute	kg CO2e ha^{-1} y^{-1}	6
Current uptake	Improved grassland	Absolute	-	0.33
Applicability	Improved grassland	Absolute	-	1
Applicability	Other land	Absolute	-	0
Seed price difference	Improved grassland	Absolute	£ ha^{-1} y^{-1}	5
Seed lifetime	Temporary improved grass	Absolute	year	2
Seed lifetime	Permanent improved grass	Absolute	year	5
Fertiliser spreading	Improved grassland	Absolute	£ ha^{-1} y^{-1}	-10.66
Direct drilling	Permanent improved grass	Absolute	£ ha^{-1}	-52.42
Direct drilling cost lifetime	Permanent improved grass	Absolute	year	5

11.1.19 Description for practitioners and monitoring

- In advance: You can sow legumes on permanent grassland, or temporary grassland, including leys in arable rotation. Before you start you will need to identify and fix any causes of poor grass production.
- Prepare the grassland: To prepare the grassland, mow or graze the grass to reduce competition from existing plants or apply a low rate of a broad-spectrum herbicide to suppress the existing sward. Alternatively you can apply the seeds after a silage cut.
- Choose legume type: In cut grass, include red clover, alsike clover, sainfoin and lucerne in your seed mix. In grazed grassland, it is best to use white clover and bird's-foot trefoil. Choice of legume type may depend on soil type and suitability, if particular root depth and soil benefits are desired, the suitability for grazing livestock, as well as length of grassland or period between reseedings.
- Use the right proportion: If you are not sure you have the right proportion of legume seeds your seed supplier will advise. There are many seed mixtures on the market, with pros and cons for different mixes, including for livestock diet and soil health.
- Equipment required: You can use any suitable equipment you have for over sowing e.g. fertiliser spreader, grass seed broadcaster or seed drill.
- After sowing: If the soil is dry enough, roll immediately after you sow to improve seed-to-soil contact, keep in moisture and reduce risk of slug damage.
- Consider the dietary requirement of livestock: Some species will be more suited to certain livestock. A consultant or livestock nutritionist will be able to advise on more suited species for the diet of livestock, as well as the optimal mix. Special livestock diet software can help in incorporating legumes into and designing optimal feed rations. Sheep are known to selectively graze legumes, and preferred species will be eaten much sooner than less preferred ones; this may have impacts on choices of species, and/or length of grazing duration.
- Further information: https://www.gov.uk/guidance/grow-legumes-in-grassland-to-replace-nutrient-inputs

11.1.20 References

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MM05: Grain legumes in crop rotations

11.1.21 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. They 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 (Watson *et al.* 2017). 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 that 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 (Preissel *et al.* 2015). Although the nitrogen content of the residue return is higher than cereals, the evidence suggests that the emissions arising from the residue management are similar to those of wheat and oilseed rape (Sylvester-Bradley *et al.* 2015). A key challenge in growing legumes is the variability in yield.

11.1.22 Evidence base

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). It is assumed that the legumes are replacing a spring sown crop receiving 130 kg N ha^{-1} (SAC, 2021) (direct emissions of 2.04 kg N_2O ha^{-1} yr^{-1}, 0.61 t CO_2e ha^{-1} yr^{-1}). It is also assumed that there is a reduction in N fertiliser use of 28 kg ha^{-1} (23-31 kg ha^{-1}) on the subsequent crop (Preissel *et al.* 2015). The reduction in fertiliser use results in a reduction of 0.19 kg N_2O ha^{-1} yr^{-1}, 0.06 t CO_2 e ha^{-1} yr^{-1} in indirect emissions. Following Sylvester-Bradley *et al.* (2015) the emissions from the residue returns are assumed to be unaffected.

The costs incurred by the farm is the difference between the gross margin for legumes and the crop replaced in the rotation, which is approximated by an average value of £155 ha^{-1} y^{-1} (SAC 2021). The savings on N fertiliser are also included in the calculations.

The applicability of the measure covers all tillage land other than legumes (excluding land currently under legumes ensures that the only additionally planted legumes are included in the mitigation potential).

In 2015, the land area devoted to growing peas or beans in the UK, either for the vegetable market, processing, canning or feed is 2.3% of the arable land area (Scottish Government 2021). There are several factors that limit the area of grain legumes in the UK. The frequency of legumes in the rotation depends on different factors according to the nature of the legume. For example, disease pressures mean that peas and beans are grown only one year in five or six (https://www.pgro.org/crop-husbandry1/). Field beans are also harvested late and will delay sowing of winter sown crops, and hence yield, of any subsequent cereal crop. Due to the late harvest, there will be no opportunity to sow cover crops. 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 1/7 of the total arable crop area in any given year. This rotational constraint is dealt within the uptake.

11.1.23 Assumptions in the model

Table 31 Assumptions for MM05

Variable	Animal/crop type	Value type	Unit	Value
N fertilisation on following crop		Absolute	kg N ha^{-1} y^{-1}	-27
Area cultivated	Field beans and peas	Relative		14% of arable land
Area cultivated	Non-legume arable	Relative		Proportional reduction
Combined cost		Absolute	£ ha^{-1} y^{-1}	156
Applicability	Non-legume arable	Absolute		legume area divided by non-legume area (18% in 2050)
Current uptake		Absolute	-	2.36%

11.1.24 Description for practitioners and monitoring

- Options for application in Scotland: there have historically and continue to be concerns about the reliability of growing grain legumes in Scotland and the quality of the final product, as well as limitations on processing capacity for crops beyond the farmgate. However, there is scope for use as wholecrop silage, therefore for mixed farms who wish to reduce dependence on imported protein feeds. Some areas in Scotland will be more suitable than others; along the east coast will have the greatest potential for grain legumes.
- Soil pH. soil testing is advisable to determine pH as legumes do not like soil with pH of less than 5.5 or more than 6.5.
- Choosing varieties. In Scotland this refers only to spring varieties, given the climate. Peas and beans will be the main choice of crop. Using good seed is important for success, and early maturing varieties (the earliest maturing available) are highly recommended for Scotland. It is advised to go for early maturing over yield, and a crop that is suitable for the soil.
- Equipment. There are no major barriers for implementation with regards to equipment, as most arable farm equipment can be used or adapted – this is the case for legume seed from as small as clover up to the size of beans.
- Soil and nutrient benefits. Grain legumes will work well as a break crop in the arable rotation, benefiting soil health, providing a low input crop as well as a reducing the pest and disease bridge (so reducing reliance on pesticides in following crops). Think about where grain

legumes would best sit within the arable rotation so that subsequent crops can make best use of the residual nitrogen. Cover crops may help to retain this nitrogen in the soil if there is a gap between the legume and subsequent crop.
- Think about intended market. Processing capacity limited and grain legumes intended for food market may have to travel a long way (e.g. to England) for processing, which may affect the economic viability of the crop. Consider buyer and price options before growing.
- New knowledge required. Agronomists in Scotland will be less familiar with grain legumes and some reluctant to advise on it. This should be factored into risk management planning. Try to work with a specialist agronomist or consultant to understand what the farmer wants from the crop and how to go about producing that under the conditions of the farm. This continues to be a barrier for implementation in Scotland. There is lots of information available online from EU research projects on grain legumes, specifically through the EU Remix and OSCAR projects.
- Further information: https://www.remix-intercrops.eu/, https://cordis.europa.eu/project/id/289277/reporting

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MM07: Variable rate nitrogen application (precision farming)

11.1.26 Overview

Nitrous oxide (N_2O) emissions arising from the use of synthetic N fertilisers can be reduced by more targeted use of N fertilisers supported by a better understanding of spatial heterogeneity in field conditions, linked to technology capable of delivering variable rate fertiliser technology (VNRT). 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.* 2017). As the complexity of possible system specifications is large, and evidence on the environmental performance of the various systems is sparse, only one combination of technologies is selected for further evaluation: machine guidance (MG) with VRNT. Machine guidance technologies are systems that pilot machinery using GPS in order to reduce overlaps and avoid gaps of passes. VRNT systems can be useful both for crop and grass production (Berry *et al.* 2017).

11.1.27 Evidence base

VRNT applications in crop production can reduce GHG emissions and GHG emission intensity as they result in high or equal yield while using the same or less input (Rees *et al.* 2019). Besides, there are three other ways they can affect GHG emissions: reducing tillage and thus increasing soil C sequestration, reducing fuel consumption and reducing other inputs to field operations (impacting off-farm emissions) (Balafoutis *et al.* 2017). Studies from the UK have reported N savings up to 14%, cereal yields up by 3.5% (Yara, 2021), a 3% yield increase in oilseed rate while using the same N fertiliser rate (Pedersen *et al.* 2020), up to 0.46 t ha^{-1} y^{-1} yield increase in barley and wheat (Welsh *et al.* 2003a, 2003b) and -57% N use for maize (Mantovani *et al.* 2011). Wheat farmers reported of 5-10% yield increase and -5 – 5% N fertiliser rate change, while potato farmers perceived -5 – 5% change in both the yield and the N rate (Barnes *et al.* 2017). Based on these variable results we approximated the measure with an average 3% yield increase and 5% N reduction, accompanied by 3% reduction in fuel use.

The measure requires significant investment and has the related running cost of the equipment along with the subscription costs to data providers (e.g. satellite data) and software tools. Benefits arise from the reduction in in fertiliser and fuel use and improved yield quantity and quality. The cost calculations assume a farm size of 120 ha, and the capital costs do not depend on the farm size as VNRT can be carried out by contractors. The cost assumptions are sourced from the Clean Growth for Sustainable Intensification fiche.

The 2012 Farm Practices Survey on Current Farming Issues (Defra 2013) found that in England 2-22% of farms used precision farming technologies and 16% used variable rate application, though only 11% used yield mapping (25% cereal farms, 18% other crop farms, 5% pig/poultry and dairy farms, 2% grazing livestock farms, 11% mixed farms).

11.1.28 Assumptions in the model

Table 12 Assumptions for MM07

Variable	Animal/crop type	Value type	Unit	Value
N fertilisation rate		Relative	change from original value	-0.05
Crop yield		Relative	change from original value	0.03
Crop residue N		Relative	change from original value	0.03
Fuel use CO_2 effect		Relative	change from original value	-0.03
Current uptake	Cereals	Absolute	-	0.25
Current uptake	Improved grassland	Absolute	-	0.02

Variable	Animal/crop type	Value type	Unit	Value
Current uptake	Oilseed rape, potatoes	Absolute	-	0.18
Applicability	Cereals	Absolute	-	1
Applicability	Oilseed rape, potatoes	Absolute	-	1
Applicability	Improved grassland	Absolute	-	1
Applicability	All other crops	Absolute	-	0
Training costs		Absolute	£	500
Training cost lifetime		Absolute	Years	5
Auto-steer cost		Absolute	£	5,000
Auto-steer lifetime		Absolute	Years	5
Yield monitor		Absolute	£	5,000
Yield monitor lifetime		Absolute	Years	15
Maintenance		Relative	proportion of all capital costs	0.05
Signal cost		Absolute	£ y^{-1}	250
Fuel cost change		Relative	change from original value	-0.03

11.1.29 Description for practitioners and monitoring

- Benefits: Variable rate nitrogen application optimises the nutrients applied to crops or grassland according to differing nutrient requirements across as a field. This results in nitrogen being applied where it is needed, and potentially reduce waste of nitrogen overall if nitrogen application in other areas is reduced. If nutrient application is reduced, so are the associated emissions, in addition to improving variability of quality and consistency in crops or grassland.

- Types of nitrogen: Variable rate application has most commonly been used in the application of fertiliser, but there is increasing interest in variable rate slurry and digestate spreading. Variable application of farmyard manure is difficult due to nutrient measuring and difficulties in spreading.
- Soil mapping is needed to be able to identify the nutrient requirement of areas across the field. This is implemented with GPS mapping. To set up the nutrient maps each field must be mapped out using GPS and soil samples taken for nutrient analysis. Some manufacturers use drone or satellite imagery to assess crop canopy cover and then apply based on green area index. This helps to produce individual colour-coded field soil maps. The nutrient maps are then used to determine nutrient requirements of individual crops specific to the field, and adjust the amount of nutrient accordingly. This should factor in previous crops and operations in the field, cover crops, and any other organic or inorganic fertilisers applied.
- Equipment choices and compatibility: Variable rate controllers may not be compatible with older equipment. Some tractor functions need unlocking for some manufacturers to use at a cost. Variable rate controllers are mainly ordered as part of a new machine; modern tractors are increasingly built with integrated/built-in GPS. They can be implemented with autosteer and/or ISOBUS implement control (or equivalent), with the autosteer replacing manual steering from the driver, and the implement control replacing fully manual calibration and setup of the machine. Packages/set up can vary greatly according to level of sophistication, farm needs, capabilities of machinery and ability to retrofit existing equipment. Calibration of equipment and data subscription costs for GPS can come at extra cost, depending on the package and set up. With inorganic fertilisers, GPS soil mapping software works in conjunction with the fertiliser sprayer. Prescription maps are generated by soil analysis and other data which are then imported into the fertiliser spreader. With slurry, GPS works with a flow meter and trailing hose (dribble bar), trailing shoe, or injector.
- Further information: https://www.fas.scot/publication/real-time-manure-analysis-and-variable-rate-application-of-slurry/

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MM08: Urease inhibitor

11.1.31 Overview

Urea based fertilisers have a high rate of ammonia volatilisation when applied to soils, due to the urease enzyme in soil bacteria. This leads not only to ammonia (and indirect N_2O) emissions, but reduces the N plants can utilise. Urease inhibitors delay the urea hydrolysis to ammonia, reducing ammonia emissions (Harty *et al.* 2016). We considered the application of N-(n-butyl) thiophosphoric triamide (NBPT, e.g. in the commercial product Agrotain®), as this is the compound where most experimental results are available in the UK. Application rate is generally 0.5-1 g for each kg of urea applied (Harty *et al.* 2016).

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

11.1.32 Evidence base

Experiments at two permanent grassland sites in Ireland showed that urea applied with a combination of urease and nitrification inhibitor reduced N_2O emissions by 56% (Harty *et al.* 2016) while cumulative N2O emissions were reduced by 68% on agricultural plots (corn) in Canada with a combination of urease and nitrification inhibitor (Tosi *et al.* 2020). Urease inhibitors – as their primary aim – also reduce the NH_3 volatilisation from urea on average by 50% (Silva *et al.* 2017), thus reducing indirect N_2O emissions. The use of urea inhibitor alone showed a reduction of N_2O emission factors on arable land (winter wheat/ oil seed rape rotation) in Germany of 15-37% (Wang *et al.* 2021).

The cost of the measure consists of the additional cost of the inhibitor. On farmers' forum the reported cost was between \$3 and \$10 acre^{-1} (average: £13 ha^{-1}); assuming 150 kg N ha^{-1} average fertilisation of croplands with synthetic N gives the cost as 0.087 £ (kg N)$^{-1}$.

Current uptake is likely to be negligible in the UK for nitrification inhibitors (Gooday *et al.* 2014); Glenk *et al.* (2014) found 4.3% of dairy farmers reporting on the combined use of nitrification and urease inhibitors.

11.1.33 Assumptions in the model

Table 13 Assumptions for MM08

Variable	Animal/crop type	Value type	Unit	Value
EF_1 for urea		Relative	change from original value	-0.27
Current uptake		Absolute	-	0
Applicability, land receiving urea		Absolute	-	1

Variable	Animal/crop type	Value type	Unit	Value
Applicability, other land		Absolute	-	0
Fertiliser cost		Absolute	£ kg N^{-1}	0.1

11.1.34 Description for practitioners and monitoring

- Choose the product that suits the system and application. There are several protected urea products currently on the market, both for solid urea and UAN (Urea Ammonium Nitrate). The inhibitor is added to the fertiliser as a component part or a coating; these can take the form of coated urea (with a polymer) or urea treated with a urease and/or a nitrification inhibitor; or urease and/or nitrification additives/sprays available for UAN. Choice of inhibitor will therefore depend on usually choice factors for fertiliser including type appropriate for crop, soil, timing of application and equipment available to the farmer. Also, inhibitors added by the manufacturer during the granulation process have a better shelf life and efficacy than those that are simply sprayed on.
- Protected urea is cheaper – Protected urea is cheaper on a N rate basis than CAN or AN, though more expensive than straight urea. Due to reduced N losses, it can be used all year rather than the typical early spring urea application. Lower N losses result in lower required application rates, without a yield penalty, which can save costs to the farmer.
- Spreader Calibration – Urea is of lower density than AN based fertilisers so using the correct setting and bout width to ensure a more precise and even spread is vital. It is important to calibrate the spreader. Seek advice from a consultant if unsure.
- Storage and efficacy – Efficacy declines over time and solid urea is also hydroscopic (drawing in moisture from the air); without adequate storage it may be physically more difficult to spread evenly. All fertiliser has a date code of when it was manufactured and must be stored under the appropriate storage conditions to avoid degradation. For this reason, protected urea is not sold in bulk and has a recommended shelf life of 6 to 12 months after manufacture, with a minimum additive rate (g/tonne) for the urease inhibitor NBPT specified by EU legislation.
- Stability in mixes – Protected urea is most stable as a straight product, or S and K but when bagged with P it can cause the urease inhibitor to degrade quickly due to residual acidity.
- Further information: https://www.teagasc.ie/media/website/environment/climate-change/Andy-Boland--Patrick-Forrestal-Protected-Urea-April-2019-resized.pdf, https://www.fas.scot/crops-soils/soils/nutrient-planning/protected-urea-frequently-asked-questions/

11.1.35 References

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MM09: Nitrification inhibitor

11.1.36 Overview

When applied to soils, part of the nitrogen in ammonia-based fertilisers and in organic nitrogen sources is converted to nitrate by nitrifying bacteria. In this process other nitrogen compounds, including N_2O, are also released. Nitrification inhibitors alter these biochemical processes by depressing the activity of the nitrifiers, leaving the fertiliser in the soil in ammonium form longer, improving its plant availability (Akiyama *et al.* 2010, Macadam *et al.* 2003, Rodgers 1986). Consequently, nitrification inhibitors can reduce N_2O emissions and also nitrate leaching in high rainfall circumstances. As these compounds are degraded by soil bacteria, the temporary inhibition effect disappears (de Klein *et al.* 2011). Various compounds have been identified as nitrification inhibitor, probably the most widely studied ones are dicyandiamide (DCD), 3,4-dimethyl pyrazole phosphate (DMPP) and nitrapyrin. We considered the application of DCD as this is the compound where most experimental results are available in the UK. Application rate is generally 10-15 kg DCD ha^{-1} once or twice a year (Cardenas *et al.* 2019, de Klein *et al.* 2011, Misselbrook *et al.* 2014).

11.1.37 Evidence base

The effectiveness of nitrification inhibitors in reducing N_2O 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 N_2O 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), N_2O emissions from ammonium nitrate were significantly reduced at two sites (average effect -43%), while N_2O emissions from urea treatment were significantly reduced at four sites (average effect -54%). The mean N_2O 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 for one site, and yield was not significantly affected either in all but one case (where it was reduced by 20%).

The cost of the measure consists of the additional cost of the inhibitor. DCD costs £5 kg^{-1} (Eory *et al.* 2015*)*. With a rate of 15 kg DCD ha^{-1} once a year, assuming 150 kg N ha^{-1} average fertilisation of croplands, the DCD application cost if £0.5 $(kg\ N)^{-1}$.

Current uptake is likely to be negligible in the UK for nitrification inhibitors (Gooday *et al.* 2014); Glenk *et al.* (2014) found 4.3% of dairy farmers reporting on the combined use of nitrification and urease inhibitors.

11.1.38 Assumptions in the model

Table 14 Assumptions for MM09

Variable	Animal/crop type	Value type	Unit	Value
EF1 for urea		Relative	change from original value	-0.6

Variable	Animal/crop type	Value type	Unit	Value
EF1 for ammonium nitrate		Relative	change from original value	-0.3
Current uptake		Absolute	-	0
Applicability, land receiving urea		Absolute	-	1
Applicability, land receiving ammonium nitrate		Absolute	-	1
Applicability, other land		Absolute	-	0
Fertiliser cost		Absolute	£ kg N^{-1}	0.1

11.1.39 References

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MM13 and MM14: Anaerobic digestion, cattle and anaerobic digestion, pigs/poultry

11.1.40 Overview

During the storage of livestock excreta GHGs are formed and released, from liquid systems mainly CH_4, while from solid systems predominantly N_2O (Chadwick *et al.* 2011). Anaerobic digestion (AD) of excreta in a closed system utilises microbial processes, which convert much of the organic carbon into biogas (a mixture of CH_4 and CO_2). This biogas is captured and utilised as an electricity and/or heat source. The nitrogen and phosphorous and the remaining organic material form the digestate, which can be used as a fertiliser.

The environmental benefits of anaerobic digestion of livestock waste are manifold: in the closed system not only the GHG emissions can be reduced but also NH_3 and odour emissions. However, converting the organic carbon into CH_4 has its drawbacks, as the digestate will have a lower carbon content than the excreta (Nkoa 2014), reducing the soil improvement and C sequestration benefits of livestock waste. The N_2O and NH_3 emissions during the application of the digestate show no consistent pattern, they can be either higher or lower than those from undigested manure {Hou, 2015 1747 /id}. A further negative side effect is the increased land use (with related GHG emissions and water and air pollution) if the additional feedstock in the digester is not a material which could not be used at a higher level in the biomaterial value pyramid, e.g. as food or animal feed (Bacenetti *et al.* 2016). Furthermore, NH_3 emissions during landspreading could also be higher unless low emission spreading is employed as most of the N is in the form of ammoniacal N (Kupper *et al.* 2020), though acidification of digestate would prevent these NH_3 emissions (Finzi *et al.* 2019).

For our modelling we defined two systems: a 536 kW capacity plant (using 17 kt cattle manure and 5 kt (fresh weight) maize and a 984 kW capacity plant (19kt pig and poultry manure and 8 kt maize).

11.1.41 Evidence base and assumptions in the model

The abatement was estimated by comparing the net GHG emissions from the AD (including GHG replaced in energy exported) with the counterfactual emissions from manure storage (assuming slurry storage, with 17% CH_4 conversion factor (IPCC 2006)). The CH_4 producing capacity of the feedstock was calculated based on Mistry *et al.* (2011), with additional data obtained from various sources (IPCC 2006; Webb *et al.* 2014; Mistry *et al.*, 2011). We assumed 5% CH_4 and 5% CO_2 loss during storage before digestion (Møller *et al.* 2004; Bangor University & Thünen Institute 2015) and 0.5% CH_4 leakage from the plant (Bangor University & Thünen Institute 2015).

The net electricity generation was calculated by converting the volume of CH_4 to the energy (kWh) which can be generated by oxidising it (assuming 38% efficiency in electricity generation (Bangor University & Thünen Institute 2015)) and subtracting from it the electricity needed for the operation (0.78 MJ (m^3 biogas produced)$^{-1}$, assuming 53% CH_4 content of the biogas (Bangor University & Thünen Institute, 2015)). The net heat production was calculated by the same method, assuming 43% heat production efficiency and 1.64 MJ (m^3 biogas produced)$^{-1}$ heat needed for operation (Bangor University & Thünen Institute, 2015). We assumed that 100% of the electricity and 60% of the heat is used on the farm or exported (i.e. reduces costs or generates income). The GHG replacement value of the electricity and heat were 0.03 and 0.269 kg CO_2e kWh^{-1}, respectively, using the long-run marginal emission factor of electricity for the commercial sector and the average of oil and soil fuel based sectoral heat emission factors for agriculture (DECC, 2014).

The technology is highly capital intensive and requires technical skills as well as business skills. The subsidy structure, which has been changing over the years in the UK, has a considerable effect on the profitability of the plant. In general, operating the AD plant solely with livestock manure is usually not financially viable due to low CH_4 / volume ratio, therefore most AD plants co-digest other organic materials (e.g. food waste, maize silage, energy crops).

In our analysis the equation from Mistry *et al.* (2011) was used as it is the most up-to-date capacity – cost correlation for the UK we could find. Transportation costs are also considered. To calculate the income streams we assumed that both the electricity and the heat generated is utilised, using an electricity price proxy of projected European electricity price in final demand sectors (European Commission, 2016) which estimates electricity price to be €1.68 MWh^{-1} in 2050 and assuming that heat price is half of electricity price. No subsidy payments are included.

In 2019/2020 NNFCC estimated that 2.3 Mt manure/slurry was used in the UK (Defra 2021). For a comparison, 83 Mt livestock manure is available in the UK each year (Smith & Williams, 2016). We assumed that an additional 50% of the housed animals' manure will be utilised in AD in the future.

11.1.42 Description for practitioners and monitoring

- Map your organic feedstocks: All potential feedstocks from farm enterprises should be considered. In addition, local off-farm wastes such as food processing waste and distillery by-products should be identified. Cost effectiveness and sustainability of these feedstocks should be evaluated. For example, organic material should only be digested if it has minimal value as livestock feed and is not displacing land which could be used for food production. Combining food waste and slurry in the digester will boost biogas yield and improve farm income if gate fees are charged for waste. The reliability of feedstocks into the future is a critical consideration.
- Consider the moisture content of these feedstocks: Where dry matter of feedstocks is lower than 15%, the digester can be run continuously with feedstocks pumped in and out. If dry matter content is higher than 15%, the digester will need to be mechanically loaded and unloaded in batches. Wet systems are more common and easier to manage in the UK.
- Apply for planning permission: Multiple waste and planning regulations govern the implementation of new biomass plants depending on the feedstocks utilised.
- Invest in the right equipment: The scale of plant should be chosen to match feedstock supply. Larger plants are likely to have better financial returns. Biogas can be used in combined heat and power (CHP) plants or biogas boilers. Collaborative ventures across farms should be considered.
- Use all heat and power produced: Using all heat and electrical energy produced from an AD plant maximises its benefits by reducing purchased energy requirements.
- Ensure proper digester maintenance: Digesters need to be carefully managed to ensure stability of the internal bacterial community and avoid degradation of pumps and valves. Leakages should be identified quickly and resolved. Automated systems will be easier to manage but more costly to install.
- Ensure the complete recycling of nutrients in digestate: The liquid fraction of digestate can be spread as a liquid fertiliser and the solid fraction should be incorporated as a soil conditioner.
- Further information: https://www.fas.scot/publication/tn698-anaerobic-digestion-ad-farm-scale/, https://www.farmingforabetterclimate.org/downloads/practical-guide-anaerobic-digestion/?msclkid=97739dd3c15411eca07112f4a46e4dfe

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MM15: Agroforestry

11.1.44 Overview

Agroforestry is defined here as “the practice of deliberately integrating woody vegetation (trees or shrubs) with crop and/or livestock production systems to benefit from the resulting ecological and economic interactions” (AGFORWARD 2015). IAASTD (2009) identified agroforestry as a win-win multi-functional land use approach because of its ability to balance production with environment, culture and landscape services. Agroforestry systems usually combine plant species with different spatial and temporal growth characteristics and thus have the potential to utilise resources more efficiently than single species systems. The woody vegetation can be trees or shrubs and can be arranged in different ways – either systematically or randomly. Agroforestry is often classified as silvoarable or alley cropping systems with arable or horticultural crops grown between rows of trees or silvopastoral with trees at wide spacing in grazed pasture. However, agroforestry also includes the use of trees in buffer zones around water courses for the reduction of nutrient and sediment loss and the production of fruit in hedgerows. The woody vegetation can be used for timber, fuel or fruit. Trees can also provide browsing for animals in systems with mature trees. In young systems there is a requirement to protect trees from damage by grazing livestock. There is increasing interest in Europe in combining agriculture with short-rotation coppice.

11.1.45 Evidence base

Agroforestry systems can be as productive as or more productive than sole-cropped systems. Using the Land Equivalent Ratio (LER) concept (Mead and Willey 1980) designed for measuring productivity in intercrops Graves *et al.* (2007) predicted an LER of 1-1.4 for European agroforestry systems (LER > 1 indicates a productivity benefit). Nevertheless, the impact on the cereal yield is variable, ranging from -11% to + 16% (Kanzler *et al.* 2019; Staton *et al.* 2022). There will always however be a trade-off between increased productivity due to improved microclimate between trees and loss of productivity from shade and other forms of competition dependent on species and location.

The amount of carbon in soils generally decreases in the order of forest > pasture > arable (Watson *et al.* 2000). It is widely suggested in the literature that agroforestry stores more carbon than agricultural systems but there is relatively little evidence in temperate systems. Carbon sequestration in agroforestry depends on multiple factors including the initial carbon content of soil and existing biomass, the tree and understorey species and the environmental conditions. The fine root carbon in the soil under UK silvoarable agroforestry has been shown to be up to 79% greater than an arable control (Upson and Burgess 2013). Palma *et al.* (2007) predicted mean carbon sequestration through immobilization in trees in European agroforestry systems from 0.1 to 3.0 t C ha^{-1} y^{-1} (5-179 t C ha^{-1} over a 60-year period). Recent figures for silvopastoral agroforestry in NE Scotland suggest that after 24 years soil carbon stocks were slightly higher than a control pasture (Beckert *et al.* 2015). The same study estimated that a Scots Pine based silvopastoral systems had similar or even greater soil carbon stocks than woodland plots and that the proportions of protected carbon fractions were similar to pasture.

The smaller area of pasture or arable crop per unit land area reduces use of fossil fuels (machinery and agrochemicals including fertiliser) per unit land area. There is also the potential for reduced nitrate leaching as a result of luxury uptake of N by trees (Bergeron *et al.* 2011) and by increasing the volume and depth of soil explored by roots.

As described above, to estimate national impacts of agroforestry measures and land use change, the range of levels of uptake are used. For bio-physical components of the systems, a single standard figure of average carbon stocks within the tree component is proposed for simplicity.

Aertsens *et al.* (2013) in reviewing C sequestration in European agriculture supported the estimate of Hamon *et al.* (2009) of 2 t C ha^{-1} y^{-1} (7.34 t CO_2e ha^{-1} y^{-1}). This is approximately 2.5 t CO_2e ha^{-1} y^{-1} lower than the figures reported by Giannitsopoulos *et al.* (2020) but is between 15 and 25 fold higher than the carbon sequestered in a modelled fruit tree system (Staton *et al.* 2022).

For soil carbon, a zero change value is used for existing grassland systems that are adapted to silvoarable systems, but for current arable land changing to silvoarable systems an increment in soil carbon is included. These estimates ignore the large impacts of different tree species, soil types and environmental effects upon productivity and carbon fluxes. These all add extra variability and uncertainty to overarching estimates. The Soil Carbon Code (Forestry Commission 2014) provides look up tables to enable estimation of specific case study areas or to model a more stratified series of systems. Upson *et al.* (2013) measured soil carbon gains of 12.4 t C ha^{-1}. For silvoarable systems, converting to CO_2 and dividing by 30 years, this provides an estimate of 1.5 t CO_2 ha^{-1} yr^{-1}.

Establishment and maintenance costs are higher for silvopastoral systems than for silvoarable ones due to the need for protection against grazing animals (Eory *et al.* 2015).

den Herden *et al.* (2017) have reported the extent of a range of traditional agroforestry systems and of more novel newer systems and provided estimates of land cover under agroforestry as a proportion of UAA. The figure for UK is 2.2% cover, whilst the European average is 3.6%. We assumed that with policy support the agroforestry area could reach 5%.

11.1.46 Assumptions in the model

Table 15 Assumptions for MM15

Variable	Animal/crop type	Value type	Unit	Value
Tree carbon		Absolute	t CO2e ha^{-1} y^{-1}	7.34
Soil C	Grassland	Absolute	t CO2e ha^{-1} y^{-1}	0
Soil C	Arable	Absolute	t CO2e ha^{-1} y^{-1}	1.5
Establishment	Grassland	Absolute	£ ha^{-1}	150
Lifetime	Grassland	Absolute	years	50
Maintenance	Grassland	Absolute	£ ha^{-1} y^{-1}	70
Establishment	Arable	Absolute	£ ha^{-1}	83
Lifetime	Arable	Absolute	years	50
Maintenance	Arable	Absolute	£ ha^{-1} y^{-1}	50
Current uptake		Absolute		0.022
Applicability		Absolute	-	0.05

11.1.47 Abatement and cost-effectiveness results

Across the scenarios, with Central Feasible Potential uptake, the abatement potential of agroforestry varies between 5-8 kt CO_2e y^{-1} when not considering interactions, and 4-6 kt CO_2e y^{-1} with interactions. The corresponding abatement cost is 9 and 10-11 £ (t $CO_2e)^{-1}$.

11.1.48 Description for practitioners and monitoring

- In advance: If planning a silvopastoral system (trees and livestock), determine objectives of the planting and plan the species and layout of the trees to complement the livestock enterprises. If planning a silvoarable system (trees and crops), think about the spacing needed between alleys for farm equipment (e.g. harvesters, sprayers), as well as the type, height and thickness of tree alleys and the potential impact on crop establishment and ripening. Consider soil type and topography and note existing successful trees to aid tree species selection. You may wish to consider tree species based on secondary benefits, such as harvested tree crops or tree fodder (for livestock).
- Restrictions: Avoid planting on peat land or land designated for other conservation purposes.
- Spacing: Agroforestry spacing is typically between100-400 trees per hectare – lighter spacing favours better grass production but denser spacing might be more successful with thinning later on.
- Planting: In wet areas, spring planting is better, whereas in dry areas, late autumn planting is preferable. Invest in quality planting stock and consider tree protection if exposed to high winds.
- Protection from livestock: Unless trees are individually protected, cattle will need to be excluded for at least 10 years and sheep excluded for 5 years, their grazing will need to be carefully controlled thereafter. Individual protection is more expensive but allows access to the grazing between the trees from planting.
- Maintenance: Thinning may be required to maintain the grass growth and allow for preferred trees to grow. You will need to maintain the tree protection and prune during the winter months for the best quality timber trees – this will require training.
- Further information: https://www.soilassociation.org/media/19141/the-agroforestry-handbook.pdf?msclkid=a3153319beff11ecafa5ad8f0df916cd

11.1.49 References

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MM18 and MM19: Improving ruminant nutrition, beef and Improving ruminant nutrition, sheep

11.1.50 Overview

Improved forage quality, especially digestibility, has been found to improve productivity and therefore lower GHG emission intensity of livestock production (Hristov et al 2013). Already 20 years ago experiments with beef cattle in the UK showed that animals consuming a higher digestibility forage have increased dry matter intake and weight gain (Steen *et al.* 2002). Nevertheless, diet composition and nutrition are not always optimised for livestock, particularly on extensive ruminant farms.

11.1.51 Evidence base

Evidence on cattle and sheep diet is very scarce in the UK, this has already been identified as an area for improvement in the GHG Inventory (Eory *et al.* 2019). Due to this lack of baseline it is difficult to define a required improvement in diet and the related improvements in productivity metrics. Following Eory *et al.* (2015) we assumed a 2% relative increase in the digestibility of beef feed and 2% increase in final liveweight. Due to the different structure of the sheep modelling, the starting assumptions needed to be different: the measure was modelled as resulting in a reduction in CH_4 emissions and N excretion.

12%, 54% and 63% of dairy, lowland grazing and LFA grazing farms, respectively, rarely or never use nutritional advice when planning the feeding regime of the livestock in England (Defra 2019). For this Scottish modelling, we assumed that there is scope for improvement on 40% of beef and sheep farms. The cost of the measures (nutritional advice and forage analysis) were sourced from Eory *et al.* (2015): £200 farm^{-1} y^{-1} for advice and £60 farm^{-1} y^{-1} for analysis, converted to per animal costs assuming 48 beef cows and 208 ewes as average in Scotland (Scottish Government 2018).

11.1.52 Assumptions in the model

Table 16 Assumptions for MM18 and MM19

Variable	Animal/crop type	Value type	Unit	Value
Roughage digestible energy content	Beef	Relative	change from original value	0.02
Concentrate digestible energy content	Beef	Relative	change from original value	0.02
Liveweight	Beef	Relative	change from original value	0.02
Applicability	Beef	Absolute	-	1
Current uptake	Beef	Absolute	-	0.6
Nutritional advice, twice a year	Beef	Absolute	£ head^{-1} y^{-1}	1.25
Forage analysis, twice a year	Beef	Absolute	£ head^{-1} y^{-1}	0.38

Variable	Animal/crop type	Value type	Unit	Value
Y_m	Sheep	Relative	change from original value	-0.01
N_{ex}	Sheep	Relative	change from original value	-0.02
Applicability	Sheep	Absolute	-	1
Current uptake	Sheep	Absolute	-	0.6
Nutritional advice, twice a year	Sheep	Absolute	£ head^{-1} y^{-1}	0.46
Forage analysis, twice a year	Sheep	Absolute	£ head^{-1} y^{-1}	0.14

11.1.53 Description for practitioners and monitoring

- Establish the baseline: To accurately assess where in-efficiencies lie in the feeding system information must be gathered to assess current feeding strategies. The type of system will influence how improvements can be targeted, for example an extensive grass-based system vs. an intensive high in-put system will require different management strategies to achieve improved nutrition.
- Accurate animal information: The nutrient requirements of an animal are dependent on a number of factors including weight, breed, body condition score, target daily liveweight gain or milk yield. The more accurate this information can be the more precise you can be with rationing. Weighing animals using weigh cells is necessary as quite often estimations can be far off from reality.
- Metabolic profiling: Blood sampling a few animals in the group can be useful to identify any deficiencies in the current ration quickly and to make corrections.
- Forage analysis: The majority of UK winter rationing is based on fermented grass silage. The quality of which will vary from farm to farm depending on management at silage cutting. Silage, wholecrop and maize silage can be analysed by laboratories across the UK that are members of the forage analytical assurance group (FAA). This will allow for accurate rationing based on the nutrient supply provided by the silage.
- Feed quality: For livestock with high requirements such as high yielding dairy cows, growing/finishing animals and ewes in late pregnancy, feed of high metabolisable energy (ME) and protein are essential. Grass silage below 10 MJ of ME/kg DM is not appropriate for high performance livestock and in the short term will require careful balancing with bought- in concentrate feeding. Improving silage quality is a longer-term solution that will both reduce reliance on expensive concentrates and improve overall ruminant nutrition.
- Working with a nutritionist/feed adviser: A trusted nutritionist/feed adviser can improve nutrition by tailoring the ration to a group of livestock and their requirements by accurately assessing different feeds and their nutritive value to work out the feed rate needed to meet animal requirements.

- Feed out and presentation of feed: Ensuring the ration on paper is being fed in practice is vital. Ensuring good feed access, for example trough design and sufficient feed space to guarantee all animals have good access are able to achieve the desired dry matter intakes.

11.1.54 References

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MM20, MM21, MM22: Nitrate feed additive, dairy, Nitrate feed additive, beef and Nitrate feed additive, sheep

11.1.55 Overview

As part of the enteric fermentation process in the rumen, dihydrogen (H_2) is generated by the microbiota. This H_2 then reacts with the CO_2 present, creating CH_4. The chemical processes in the rumen can be modified to shift the balance between the compounds generated, for example by feeding the animals certain materials (Hristov et al. 2013; Cottle et al. 2011). One of these feed additives is nitrate, a naturally occurring chemical compound. In the presence of nitrate the H_2 is diverted and reacts with the nitrate (forming ammonia) rather than with the CO_2.

Nitrate occurs in animal feed; however, it needs to be fed in a higher dose to generate the desired mitigation. This nitrate would also be a useful non-protein nitrogen source for the animals (replacing urea) (Lee & Beauchemin 2014). Nitrate is toxic in too high a dose; therefore careful dosing is required.

11.1.56 Evidence base

There is a growing amount of experimental evidence on the effectiveness of nitrate. Though there is variation in the results, the effect is consistently shown, also in long-term studies (Lee & Beauchemin 2014). The modelling for dairy and beef cattle here uses the equation derived from a review by Veneman (2014), assuming a 1.5% nitrate concentration in the diet. With that dose the enteric CH_4 conversion factor is reduced by 17.5%. The mitigation effect in sheep is assumed to be -23% (Nolan et al. 2010).

The cost assumption is based on (Eory et al. 2015), including the cost of replacing urea and limestone in the feed, and using the Bolifor© product.

There is no evidence of farmers using this feed additive in Scotland currently.

11.1.57 Assumptions in the model

Table 17 Assumptions for MM20, MM21 and MM22

Variable	Animal/crop type	Value type	Unit	Value
Y_m	Dairy	Relative	change from original value	-0.175
Current uptake	Dairy	Absolute	-	0
Applicability - animals >1y, housed, not organic	Dairy	Absolute	-	1
Cost	Dairy	Absolute	£ $head^{-1}$ y^{-1}	26.96

Variable	Animal/crop type	Value type	Unit	Value
Y_m	Beef	Relative	change from original value	-0.175
Current uptake	Beef	Absolute	-	0
Applicability - animals >1y, housed, not organic	Beef	Absolute	-	1
Cost	Beef	Absolute	£ head^{-1} y^{-1}	14.5
Y_m	Sheep	Relative	change from original value	-0.23
Current uptake	Sheep	Absolute	-	0
Applicability - animals >6m, housed	Sheep	Absolute	-	1
Cost	Sheep	Absolute	£ head^{-1} y^{-1}	3

11.1.58 Description for practitioners and monitoring

- Research results: The reduction in methane has been reported at varying degrees in animal trials but the most recent analysis of the efficacy of nitrate cited by Duthie et al. 2018 found a mean inclusion of 21g nitrate per kg of dry matter intake (DMI) reduced mean CH_4 (g/kg DMI) by 21%. Although nitrate has been shown in many studies to reduce methane emissions from ruminants the potential for its use has been hindered due to the toxicity of the intermediate product (nitrite).
- Market availability: nitrate compounds such as calcium nitrate are currently not manufactured as a feed additive, therefore cannot be sold until registered as an additive with appropriate dossier of evidence. This would apply to pre-mixes, feed blocks and boluses.
- On farm actions: this is not yet registered as a product, or available for implementation on farm. As such it is difficult to assess practical steps for implementation of the measure. As mentioned, there is a high risk of adverse reaction (anoxia) if overfed or animals have not been appropriately adapted to build up tolerance to this method. Therefore, using nitrate would require strict guidelines and there would need to be clear warnings of the risks. It would be advised that farmers consult a specialist nutritionist or consultant to help the assess the feasibility and steps for implementation on farm, and optimise the level and method of application in the livestock diet.
- Factors influencing feasibility: Currently this would be a net cost measure to the farm, with little or no benefits to productivity or efficiency of livestock. This would suggest that financial

incentive would be required for farmers to even consider uptake. Also, existing studies on this measure have been applied to housed animals, and further studies would be needed to assess how additives can be incorporated into grazed livestock diets, e.g. through what products, how can amount be monitored to prevent toxicity etc. Current research highlights the lack of control or consistency in application of feed additives to grazed livestock through feed blocks given individual animal intakes from blocks can vary widely.

- Further information: https://pure.sruc.ac.uk/ws/portalfiles/portal/18494932/Rooke_et_al_Nutritional_Strategies.pdf

11.1.59 References

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MM23, MM24, MM25: High fat diet, dairy, High fat diet, beef and High fat diet, sheep

11.1.60 Overview

Like nitrate and other feed additives, fats can reduce CH_4 production in the rumen by partially changing the chemical pathways during fermentation. There are three main ways unsaturated fatty acids reduce CH_4 emissions: they control some of microbes, can react with the H_2 generated in the rumen and replacing feed components which are digested in the rumen with ones which are digested in the intestine and thus not going through enteric fermentation (Johnson and Johnson 1995, Martin et al. 2010). Like with nitrate, livestock diet contains fat already, but not in a high enough dose for CH_4 emission mitigation. However, too high fat ingestion can cause digestive problems.

11.1.61 Evidence base

Following Eory et al (2015), the equations derived by McBride et al. (2015) for dairy cattle, beef cattle and sheep, based in a meta-analysis for the UK are used. The reduction in the CH_4

emission factor with 3% additional fat is 10.1, 5.9 and 20.8% for dairy, beef and sheep, respectively.

A range of fat sources are available (various whole seeds and plant oils) and here we assumed that whole rapeseed or whole linseed is used, as suggested by Frelih-Larsen et al. (2014). Therefore, the cost is the difference between the high-fat feed component and the concentrates it replaces, estimated as £38, £21 and £4 head^{-1} y^{-1} for dairy, beef and sheep, respectively, by Eory et al. (2015).

Current uptake in dairy is estimated at 4% (Glenk et al. 2014), and assumed to be 0% for beef and sheep.

11.1.62 Assumptions in the model

Table 18 Assumptions for MM23, MM24 and MM25

Variable	Animal/crop type	Value type	Unit	Value
Y_m	Dairy	Relative	change from original value	-0.0338
Current uptake	Dairy	Absolute	-	0.04
Applicability - animals >1y	Dairy	Absolute	-	1 (half of those on LFA area)
Cost	Dairy	Absolute	£ head^{-1} y^{-1}	39.94
Y_m	Beef	Relative	change from original value	-0.0196
Current uptake	Beef	Absolute	-	0
Applicability - animals >1y	Beef	Absolute	-	1 (half of those on LFA area)
Cost	Beef	Absolute	£ head^{-1} y^{-1}	21.47
Y_m	Sheep	Relative	change from original value	-0.0692
Current uptake	Sheep	Absolute	-	0
Applicability - animals >6m	Sheep	Absolute	-	1 (half of those on LFA area)

Variable	Animal/crop type	Value type	Unit	Value
Cost	Sheep	Absolute	£ head^{-1} y^{-1}	4.2

11.1.63 Description for practitioners and monitoring

- Mode of action: Supplementation of feed with fat, especially polyunsaturated fatty acids (PUFA) and medium-chain fatty acids (MCFA) in cattle feed has been shown to significantly reduce methane emissions. These fatty acids have a toxic effect on fibre digesting bacteria, protozoa and methanogens and for this reason supplementation with a fat source rich in PUFA or MCFA, to a roughage-based diet, reduces the digestibility of cell wall carbohydrates, the production of hydrogen and finally methane levels. PUFA also has an inhibitory effect on methane production through direct use of hydrogen by saturation in the rumen. Lipid supplementation has also been found to reduce dry matter intake.
- Lipid supplements: Methods of providing lipid supplementation can be through a number of forms such as co-products of oil production (rapeseed, sunflower, linseed, palm) or of distillery cereal use (dark grains plus soluble of wheat, barley and maize). Or as a rumen-protected form of fat, for example calcium soap, or non-protected oil.
- Practical management: This measure is currently only applicable to dairy systems. Level of supplementation is related to both the lipid and protein content. Excess dietary lipid has adverse effects on rumen fibre digestion, feed intake and potentially livestock performance. Inclusion of lipid should not exceed 70g/kg dry matter of the diet. If applying in a housed environment, it would be advised that farmers consult a specialist nutritionist or consultant to help the assess the feasibility and steps for implementation on farm, and optimise the level and method of application in the livestock diet to minimise the risk of adverse effects. The daily intakes of lipid and nitrate required for effective mitigation are not compatible with the use of slow release intra-ruminal boluses. Equally, since the intake of nitrates and lipids must be controlled to avoid adverse effects, then the use of feed blocks is also not an option as individual animal intakes from blocks can vary widely.
- Potential risks: Fats including rumen-protected fats are expensive and there is a physical limit of how much can be fed. Higher levels of PUFA, when fed alongside rapidly fermentable carbohydrates can lead to reduced milk yields in dairy cattle.
- Cost of implementation: Cost is currently a major limiting factor as to implementation of high fat diet, as high fat feeds will come at a much higher cost than regular feeds. Currently this would be a net cost measure to the farm, with little or no benefits to productivity or efficiency of livestock. This would suggest that financial incentive would be required for farmers to even consider uptake.
- Further information: https://pure.sruc.ac.uk/ws/portalfiles/portal/18494932/Rooke_et_al_Nutritional_Strategies.pdf

11.1.64 References

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MM26, MM27: 3NOP feed additive, dairy and 3NOP feed additive, beef

11.1.65 Overview

Like other ruminant feed additives, 3-nitrooxypropanol (3-NOP) reduces CH_4 emissions from enteric fermentation. The mechanism is based on the inhibition of an enzyme – the methyl-coenzyme M reductase – which plays a key role in the CH_4 synthesis (Yu et al. 2021). 3-NOP is already in commercial production and approved as a methane reducing feed additive by the European Food Safety Authority.

11.1.66 Evidence base

A meta-analysis in 2018 by Jayanegara et al., based on 12 *in vivo* studies (dairy and beef cattle and sheep), found that 3-NOP reduced enteric CH_4 emissions both per dry matter intake and milk production while it had no significant negative influence on production parameters of dairy and beef cattle (Jayanegara et al. 2018). From analysing a similar set of studies Dijkstra et al. (2018) found that the CH_4 reduction effect for dairy and beef was -39% and -22%, respectively.

At the time of the modelling information on the cost of 3-NOP was not yet available, therefore, following the assumptions in the Clean Growth for Sustainable Intensification project we assumed that the cost will be approximately the same as the cost of Mootral (another CH_4 reducing feed additive)[7].

Currently 3-NOP is not used in Scotland.

11.1.67 Assumptions in the model

Table 19 Assumptions for MM26 and MM27

Variable	Animal/crop type	Value type	Unit	Value
Y_m	Dairy	Relative	change from original value	-0.3
Current uptake	Dairy	Absolute	-	0
Applicability - animals >1y, not organic	Dairy	Absolute	-	1 (half of those on LFA area)
Cost	Dairy	Absolute	£ $head^{-1}$ y^{-1}	38
Y_m	Beef	Relative	change from original value	-0.2

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[7] https://www.ecosystemmarketplace.com/articles/can-mootral-do-for-cows-what-tesla-is-doing-for-cars/

Variable	Animal/crop type	Value type	Unit	Value
Current uptake	Beef	Absolute	-	0
Applicability - animals >1y, not organic	Beef	Absolute	-	1 (half of those on LFA area)
Cost	Beef	Absolute	£ head^{-1} y^{-1}	38

11.1.68 Description for practitioners and monitoring

- Research results: 3-NOP has been evaluated in more than 50 peer- reviews studies, published in independent scientific journals and 45 on-farm trials in 13 countries across 4 continents. 3-NOP is effective with a mean reduction in methane of 30% depending on the animal type, size, diet and dose. Research studies on dairy and beef cattle has shown consistent decreases in methane with reductions as high as 82% in some cases. Efficacy is positively related to 3-NOP dose and negatively affected by neutral detergent fibre concentration of the diet, with greater responses in dairy compared to beef cattle when compared on the same dose.
- Market availability: In September 2021, Dutch State Mines (DSM) received its first full regulatory approval to commercialise Bovaer® (trade name for 3-NOP) from the Brazilian and Chilean authorities, for application in beef, dairy, sheep and goats. In February 2022, DSM received EU market approval for Bovaer® for dairy cows, following a positive European food safety agency (EFSA) opinion which confirmed that Bovaer® reduced enteric methane emissions from dairy cows and is safe for the animal and the consumer. It is the first time a feed additive authorised in the EU for environmental benefits can be marketed. DSM has partnered with dairy companies to prepare for wider use of the feed additive and is currently building a new production plant in Scotland at its existing site in Dalry Ayrshire.
- Practical implementation: Research and trials have tested the application and efficacy of 3NOP in a research environment, but has shown that implementation on grazed livestock is challenging. If implemented in a housed environment, it would be advised that farmers consult a specialist nutritionist or consultant to help the assess the feasibility and steps for implementation on farm, and optimise the level and method of application in the livestock diet.
- Limited use with grazed livestock: given the lack of control over diet and share of dietary inputs in a grazed environment, it would be difficult to ensure that all livestock are getting correct amounts of feed additives through supplements. For example, use of feed blocks is also not an option as individual animal intakes from blocks can vary widely.
- Cost of implementation: Currently this would be a net cost measure to the farm, with little or no benefits to productivity or efficiency of livestock. This would suggest that financial incentive would be required for farmers to even consider uptake.
- Further information: https://pure.sruc.ac.uk/ws/portalfiles/portal/18494932/Rooke_et_al_Nutritional_Strategies.pdf

11.1.69 References

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MM29, MM30, MM31: Faster finishing of beef cattle, Increasing beef calving rate and Reducing age of first calving in beef

11.1.70 Overview

The Suckler Beef Climate Scheme report, prepared by a farmer-led group, identified a large number of actions which could help reducing emissions or at least reducing emission intensity of beef production in Scotland (Suckler Beef Climate Group 2020). While many of these farm practices and technologies have already been included in previous MACC assessments, some general management improvements reducing inefficiencies have been missing from these studies. Three such actions have been identified in the current study as potentially providing substantial mitigation and specific enough to point to certain actions farmers can make.

11.1.71 Evidence base

The evidence to support the modelling assumptions for these three mitigation options is based on the calculations in one of the supplementing reports of the Suckler Beef Climate Scheme report (Moxey & Thomson 2020). The authors, estimating the emissions per age group and animal type and analysing herd parameters, highlighted potential improvements. As the MACC model does not have a herd module, these potential improvements were simplistically modelled by reducing the number of animals in the relevant categories.

Faster finishing was suggested as 3% of total beef emissions originate from slaughter animals which are older than 24 months (Moxey & Thomson 2020). The report also suggest that the maximum slaughter age could be reduced to even 21 months without impeding meat production, generating further reductions in GHG emissions. Though faster finishing will partially depend on improved beef genetics, health and nutrition (i.e. actions covered in other mitigation measures assessed in the current study), it also depends on the farmers' decisions on how long to keep the animals after they reached slaughter weight. Here we assume that animals kept longer than 24 months have already reached slaughter weight and could be finished. The modelling therefore reduces the number of animals reared for slaughter by the number of animals which are over 24 months (7.3%, 7.3% and 7.5% of steers, cereal fed bulls and females for slaughter are over 24 months, *pers. comm.* A. Moxey).

Increasing calving rate essentially is an increase in fertility of beef cows. The registered calving rate currently is only 80%, leaving one fifth of the cows unproductive (Moxey & Thomson 2020). Identifying and culling unproductive cows and/or improving fertility (and reducing calf mortality) would both improve the emission intensity of beef. In the current modelling we assumed the calving rate to increase from 0.8 to 0.9 and thus reduced the number of heifers and cows by 11%.

Reducing the age of first calving shortens the unproductive period of beef cows. There are a substantial number of heifers older than 24 months, contributing currently to 4% of beef emissions (Moxey & Thomson 2020). In this modelling we assumed that the number of heifers is reduced by 14.4% (this is the proportion of heifers over 30 months, *pers. comm.* A. Moxey).

The current uptake of these measures is assumed to be zero, as these are potential further improvements based on the current status of the national herd. As there were no specific actions identifiable which require capital investment or ongoing expenses, just a general improvement in managing the animals, a notional cost of zero was assigned to each of these mitigation measures.

11.1.72 Assumptions in the model

Table 20 Assumptions for MM29, MM30 and MM31

Variable	Animal/crop type	Value type	Unit	Value MM29	Value MM30	Value MM31
Number of animals	Beef females for slaughter, cereal fed bulls and steers	Relative	Change from original value	-0.075		
	Beef heifers for breeding and cows				-0.11	
	Beef heifers for breeding					-0.144
Current uptake	Beef	Absolute	-	0	0	0
Applicability	Beef	Absolute	-	0	0	0
Cost	Beef	Absolute	£ head^{-1} y^{-1}	0	0	0

11.1.73 Description for practitioners and monitoring: Faster finishing of beef cattle

- Maximise weaning weights (200days). Target 300kg+ (feed conversion rates are higher in younger cattle) – as younger cattle need the nutrients for bone development and muscular growth after puberty, they use the nutrients for fat lay down or repair of cells as well which lower the animal's efficiency to convert feed to weight.
- Maximise growth period and rates. Aim to ensure a growth period of at least 1kg/day to 400 days (with a target of 500kg), maximising growth rates of 1.5-1.6kg/day in the finishing period. This would be achieved by keeping the animal healthy and supplying it with all its nutritional needs to maximise its genetic potential
- Monitor growth rates and the performance of the ration using a set of weigh scales situated in your handling system or crush that make weighing easy and safe
- Minimise challenges and reduce stress on cattle (especially when entering the finishing stage) for example size of groups, moving groups, shed ventilation, allow for cattle to have adequate clean dry bedding and feed/ water
- Consistent diet. Ensure animals cannot select between ingredients, as sudden changes to diet may upset rumen and cause loss of performance. This might require varied diets across livestock groups if there are longer term changes to feeding strategy.
- Health planning. Have a plan to deal with issues such as fluke, worms and respiratory disease. Disease and poor health will slow growth rates, with energy being diverted towards maintaining livestock's health rather than increasing growth of the animal.
- Optimise housing. Housing not optimised for heat or comfort of livestock (e.g. draughts or damp bedding) can have an impact on body condition and growth rates, with extra energy being used to keep the animal warm or negative impacts on health slowing growth. Likewise, check that you are not overstocked.

- Access to feed and clean water. It is also important to ensure that all animals have access to feed. Access to clean water to ensure intakes are not reduced a 500kg animal will drink roughly 40 litres/day of water.
- Select breeding cattle on 200-day weights to ensure strong weaning weights. This gives an indication as to how heavy the animal's offspring are going to weight when you wean them to encourage maximum genetic growth.

11.1.74 Description for practitioners and monitoring: Increasing beef calving rate

- Proper nutrition. Ensure cows are not putting on weight in the last 4-6 weeks of pregnancy. Overprovision of food late in pregnancy can cause the calf to grow large, increasing risks of complications or loss in calving, or the body condition of the cow to reduce. Alongside this, ensure to supply all cows with adequate mineral requirements and energy and protein, as this will be important to enable a smoother calving process and minimise impact for the cow.
- Adequate body condition score. Look to have all cows at 2.5-3 score on the 1-5 scale when calving. This will reduce risks of cow and calf loss at calving.
- Healthy herd routine. Health vaccinations and monitoring of cattle health are important to keep on top of, to allow cows to be as healthy as possible. This will increase conception rate, as well as optimise health of the animal through gestation, and reduce risks to the cow and calf at and beyond calving.
- Crossbreeding. Introducing another breed into your breeding program can increase hybrid vigour (livestock strength & health), and also allow you to pick the best of traits from other breeds.
- Sound breeding practices. Keep bulls in good health and get them vet checked before the bulling period. This refers to both physical health and fertility checks. Bulls will use a lot of energy in the bulling period so must have good weight and body condition at the beginning, as well as strong and healthy back legs. Make sure cows are on a rising plain of nutrition and have plenty water and availability to minerals. Fertility checks ahead of bulling factor in time to find solutions or alternatives if any issues are found, to ensure maximum conception rate of cows.
- Annual culling and replacement. Picking out problem cows and older cows each year and replacing with heifers to regularly optimise current performance of the herd and potential future offspring.

11.1.75 Description for practitioners and monitoring: Reducing calving interval in beef

- Good nutrition – A cow's nutrient requirements are at their highest around breeding time. It is extremely important to make sure she is getting the required amounts of vitamins, minerals, energy and protein needed to support adequate performance and to help get ready to come into heat and breed back sooner.
- Monitor cow condition – Body Condition Score (BCS) cows regularly to ensure cows are in the right condition e.g. the ideal body condition score (BCS) at calving, for a spring calving suckler is 2.5. This has been shown to improve fertility, as cows tend to have a shorter interval to first heat, therefore get in calf sooner.
- Bull breeding examination – Make sure your bulls have had a breeding soundness exam (BSE) prior to turnout, at least 2 months before including a semen test. If bulls are not fertile or sub fertile calving interval extends when cows come into heat again for a second or third time depending on how quickly the issue is picked up on.
- Heat synchronisation – Advances in technology mean that getting cows to come into heat at the same time and more rapidly is easier than ever before. Technology like CIDR devices and timed A.I. can help tighten the calving window and get cows to come into heat sooner, resulting in a shorter calving window.

- Be disciplined – Be sure to note down when the bull went in with cows and make sure you take out the bull after nine weeks for cows and six weeks for heifers (industry-accepted targets). Pregnancy diagnose (PD) cows 30-45 days later and impose strict culling decisions.

11.1.76 References

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MM32, MM33, MM34: Improving health, dairy, Improving health, beef and Improving health, sheep

11.1.77 Overview

Animals not in good health tend to produce less useful outputs, grow slower, and usually have poorer reproduction outcomes; endemic diseases still pose a significant production constraint in Scotland (Skuce *et al.* 2015). Studies comparing animal performance and related GHG emissions of animals with and without certain diseases found that the emission intensity of the products from animals with disease can be as much as 33% higher – in the case of sheep infection with the nematode Teladorsagia (Fox *et al.* 2018) and even at the herd level a single parasite (liver fluke) is estimated to cause a 1% increase in emission intensity in beef meat in NE Scotland, as the analysis of abattoir data showed (Skuce *et al.* 2018).

However, assessing the current health status of the national herd regarding the key diseases and evaluating potential interventions is a complex exercise with high uncertainty in the existing data, cost and effectiveness of alternative treatments and therefore in the results.

11.1.78 Evidence base

The modelling in this work follows the assumptions described in Eory et al. (2015), where a scenario-based approach was used to derive the emission intensity improvements arising from an assumed 20% and 50% improvement from the baseline health status to all healthy animals. For quantifying the GHG emission changes for cattle the abatement potential and cost-effectiveness were based the results published by ADAS (2014). For sheep a similar approach was used, but given the lack of overall data on sheep health and GHG emissions, data obtained from researchers and agricultural consultants provided parameters for a life cycle analysis GHG modelling where in different health status scenarios. The details of these calculations are described in Eory et al. (2015).

11.1.79 Assumptions in the model

Table 41 Assumptions for MM32, MM33 and MM34

Variable	Animal/crop type	Value type	Unit	Value
Milk yield	Dairy	Relative	Change from original value	0.0638
Current uptake	Dairy	Absolute	-	0
Applicability	Dairy	Absolute	-	0.8
Cost	Dairy	Absolute	£ head^{-1} y^{-1}	27.8
Liveweight	Beef	Relative	Change from original value	0.0638
Current uptake	Beef	Absolute	-	0

Variable	Animal/crop type	Value type	Unit	Value
Applicability	Beef	Absolute	-	0.8
Cost	Beef	Absolute	£ $head^{-1}$ y^{-1}	27.8
Live weight	Sheep	Relative	Change from original value	0.1045
Current uptake	Sheep	Absolute	-	0
Applicability	Sheep	Absolute	-	0.8
Cost	Sheep	Absolute	£ $head^{-1}$ y^{-1}	7.69

11.1.80 Description for practitioners and monitoring: Improving cattle health

- Growth rate - this reduces the days to sale or slaughter, and the less cost and wastage in a system, growth rate in cattle is largely related to their mother's performance (and her health), the feed available in front of them and their health. Something as simple as a sore foot can knock this growth rate drastically. The growth rate also has an effect on how quickly the animal can be bred from with targets of reaching 60% of their mature growth by Bulling as a heifer or 80-90% of mature growth as a first calver.
- Longevity – a cow with longevity, is generally a healthy animal, this reduces replacement costs, increases genetics in the herd and the fertility.
- Monitor and diagnose – is essential to know the herd's health status, through veterinary testing.
- Biosecurity – Establish and follow good biosecurity practices. Practicing biosecurity will help to minimise the risk of disease on your farm and within your herd. Bringing new or sick animals onto a holding, can vastly aid health and welfare of a herd. Having a set area outwith any other contact with animals already on farm is essential till checks are complete.
- Buying stock. Buy from herds who have an established health status and ensure animals bought in are quarantined before being mixed with existing stock on the farm.
- Herd health planning – with a vet is an essential step, to look at a plan for the coming year, understand stats from the previous year and where inefficiencies lie. Consider joining a CHeCS approved health scheme to monitor and annually test for diseases such as Johne's and Leptospirosis.
- Develop a relationship with your vet. Work with your vet to develop a health plan specific to your herd which targets your needs and the need of your herd.
- Vaccines – use vaccines where possible to increase herd health, e.g. if IBR is a problem, then Bovillis or rispoval to cover animals thus reducing the spread in the herd, while reducing losses and increasing growth rates. Ensure routine vaccinations are kept up to date, administered at the correct dosing rate and time of year
- Diseases – there are numerous cattle diseases that have an impact on health, each works differently, but using the above biosecurity, monitor and diagnose, health planning and vaccines should substantially increase flock owners' awareness of underlying conditions in a herd, such diseases would include:
    - Pneumonia

  - Johnnies
  - TB
  - BVD
  - Blue tongue
  - IBR

11.1.81 Description for practitioners and monitoring: Improving sheep health

- The ideal sheep will grow fast, covert food to meat quickly and efficiently, require low inputs and have a low footprint on the environment. To achieve all of this, health, nutrition and genetics all play key roles and must be balanced. If one is not running effectively the overall performance of the animal will drop, as shown in the figure below.
- Heath is a constraint on efficiency – with numerous industry reports suggesting a 10% reducing in GHGs is possible by increasing the health of the national flock. As well as reducing GHGs, this would allow for further efficiencies, in less feed and inputs and genetic gains in the flock.
- Growth rate - this reduces the days to sale or slaughter, and the less cost and wastage in a system, growth rate in lambs is largely related to their mother's performance (and her health), the feed available in front of them and their health. Something as simple as a sore foot can knock this growth rate drastically. The growth rate also has an effect on how quickly the animal can be bred from with targets of reaching 60% of their mature growth by tupping as a ewe lamb or 80-90% of mature growth as a gimmer.
- Feed Conversion Efficiency – Lambs will convert more efficiently the younger they are converting at 4:1 up to weaning, and 12:1 by the time they are a year old. The better they convert food (grass/milk) to meat the less inputs are required and their growth rate is higher.
- Longevity – a sheep with longevity, is generally a healthy sheep, this reduces replacement costs, increases genetics in the flock and the fertility.
- Monitor and diagnose – is essential to know the flock health status, through veterinary testing.
- Biosecurity – on new or sick animals to a holding, can vastly aid health and welfare of a flock.
- Flock health planning – with a vet is an essential step, to look at a plan for the coming year, understand stats from the previous year and where inefficiencies lie.
- Vaccines – use vaccines where possible to increase flock health e.g. if foot rot is a flock problem, then footvac to increase health and efficiency of the flock, while reducing losses and increasing growth rates.
- Diseases – there are numerous sheep diseases that have an impact of sheep health, each works differently, but using the above biosecurity, monitor and diagnose, health planning and vaccines should substantially increase flock owners' awareness of underlying conditions in a flock, such diseases would include:
  - Iceberg diseases e.g. Maedi Visna (MV), Caseous LymphAdonitis (CLA), Johnes and Borders Disease
  - Sheep scab
  - Lameness
  - Jaagsiekte (OPA)

11.1.82 References

ADAS (2014) Study to model the impact of controlling endemic cattle diseases and conditions on national cattle productivity, agricultural performance and greenhouse gas emissions. Report No AC0120. Defra

Eory, V., MacLeod, M., Topp, C.F.E., Rees, R.M., Webb, J., McVittie, A., Wall, E., Brothwick, F., Watson, C., Waterhouse, A., Wiltshire, J., Bell, H., Moran, D., Dewhurst, R.J. (2015) Review and update of the

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MM35, MM36, MM37, MM38, MM39 - livestock breeding measures

MM35 : Increased uptake of dairy genetic improvement, current breeding goal

MM36 : Increased uptake of dairy genetic improvement, current breeding goal with genomic tools

MM37 : Increased uptake of beef genetic improvement, current breeding goal with genomic tools

MM38 : Shift to lower emissions intensity breeding goal in dairy breeding, using genomic tools

MM39 : Shift to lower emissions intensity breeding goal in beef breeding, using genomic tools

11.1.83 Overview

Many characteristics which are important for the quality or quantity of production and for the reproduction and health of livestock are partially determined by the genetics of the animal, therefore can be improved via genetic selection. Recent breeding programmes have already contributed to improvements in the overall efficiency of animals due to a combination of lower feed intake, higher yield and fewer non-productive animals in the herd (MacLeod *et al.* 2019). The trend in the past decades of increasing milk yield and decreasing enteric CH_4 emissions from dairy cattle (Brown *et al.* 2018) can be attributed to some extent to this genetic improvement (among improvements in feeding, reproductive and general animal management). Though it is expected that the efficiency is going to continue to increase (and thus the emission intensity of livestock production decrease) without further policy intervention, a more widespread and therefore larger increase in milk yield and growth rate can be expected from increased adoption of the best available genetic material. The uptake of using better genetic material is only around 20-25% in the dairy herd, and still lower in the beef herd (Defra 2018).

An increased uptake will lead to further improvements in efficiency, and, depending on the breeding tools used and the breeding goal chosen, can lead to different outcomes in terms of future production and GHG emissions. Farmers and breeders using genomic tools (collecting genetic records of the individual animals besides the phenotypic data and feeding this into the animal’s breeding index as well as into the breeding goal development) can substantially speed up the genetic gains achievable in each generation, leading to quicker improvements. Current breeding goals focus on productive and non-productive traits, but not on the environmental impact of the animals. As some of these environmental impacts, including enteric CH_4 emissions, also depend on the genetics of the animals and those of the micro-organisms present in the gut (Hegarty and McEwan 2010), is it possible to select for low emission animals – albeit this selection might limit the productivity and fitness improvements to some extent (de Haas et al. 2011, Roehe et al. 2016).

11.1.84 Evidence base

The mitigation measures model three different routes for genetic selection: a higher uptake of the current approach in the dairy herd (MM35), using the current breeding goals but enhancing the selection process by using genomic tools in both dairy and beef (MM36, MM37), and changing the breeding goal to include GHG emissions, still using genomic tools, in dairy and beef (MM38, MM39). The mitigation measures represent these different, hypothetical pathways for cattle breeding, with production and GHG impacts, and costs estimated based on past trends. The breeding measures as modelled in the MACC cannot be applied to the same animals, but they can still be applied at the same time within the national herd.

11.1.85 Assumptions in the model

Table 52 Assumptions for MM35, MM36 and MM38

Variable	Animal/crop type	Value type	Unit	Value MM35	Value MM36	Value MM38
Milk yield	Dairy	Relative annual	Annual change from original value	0.006	0.009	0.0075
Milk protein	Dairy	Relative annual	Annual change from original value	0.006	0.009	0.0075
Fertility	Dairy	Relative annual	Annual change from original value	0.0025	0.0038	0.003
Y_m	Dairy	Relative annual	Annual change from original value	0	0	-0.0015
Current uptake	Dairy	Absolute	-	0	0	0
Applicability	Dairy	Absolute	-	0.9	0.9	0.45
Total cost	Dairy	Absolute	£ $head^{-1}$ y^{-1}	0	NA	NA
Research investment	Dairy	Absolute	£ for the whole UK		500,000	2,500,000
Research investment lifetime	Dairy	Absolute	Year		20	20
Recurring research investment	Dairy	Absolute	£ for the whole UK		250,000	500,000
Recurring research investment lifetime	Dairy	Absolute	Year		5	5
Genomic testing for a bull	Dairy	Absolute	£ $(500 \text{ cows})^{-1}$ y^{-1}		20	20

Table 6 Assumptions for MM37 and MM39

Variable	Animal/crop type	Value type	Unit	Value MM37	Value MM39
Liveweight	Beef	Relative annual	Annual change from original value	0.0025	0.0025
Fertility	Beef	Relative annual	Annual change from original value	0.0025	0.0025
Y_m	Beef	Relative annual	Annual change from original value	0	-0.0015
Current uptake	Beef	Absolute	-	0	0
Applicability	Beef	Absolute	-	0.2	0.2
Research investment	Beef	Absolute	£ for the whole UK	1,500,000	2,500,000
Research investment lifetime	Beef	Absolute	Year	20	20
Recurring research investment	Beef	Absolute	£ for the whole UK	250,000	500,000
Recurring research investment lifetime	Beef	Absolute	Year	5	5
Genomic testing for bulls	Beef	Absolute	£ (100 cows)$^{-1}$ y^{-1}	20	20

11.1.86 Description for practitioners and monitoring: Increased uptake of dairy genetic improvement, current breeding goal AND Increased uptake of dairy genetic improvement, current breeding goal with genomic tools AND Increased uptake of beef genetic improvement, current breeding goal with genomic tools

- Look at EBVs (Estimated Breeding Value). When looking to add genetic traits look to at EBVs as a tool to help you make your decision. You very much must use your eye and know your own farm and business needs when making the decision also. For example, looking at birth weight figures will give a figure compared to the average of the breed and a percentage of how accurate it is based on the number of calves with similar breeding that have been recorded, this is the same for all traits. Be aware that any trait used to the extreme can lead to issues, if constantly selection bulls for milk, then it can lead to cows milking off their backs as they are producing so much and this may lead to struggling to get them back in calf, which is the key performance indicator to most beef herds.

- When looking at EBVs we should consider the traits in the breeding indices (Table 24 and Table 25).

Table 74 Terminal sire EBVs (ram/bull)

EBVS	**Interpretation**	**Notes**
Birthweight (kgs)	Negative Values equal lighter caves at birth	High birth weights are more likely to be associated with difficult calvings
Gestation Length (Days)	Negative values equal shorter gestations	Short gestation lengths result in easier calvings because birthweights tend to be lower, short gestation also increases the interval between calving and mating, thus giving the cow more time to recover body condition
Calving ease (direct) (%)	Positive values equal more unassisted calvings	Estimates the percentage of unassisted calvings that can be from a particular line
200/400 day growth (kgs)	Positive values equal faster growth rates	Selection for faster growth will result in animals that have heavier carcasses at the same fat class at the same age
Muscle Depth (MM)	Positive values equal deeper loin muscle	Selecting for these traits will increase the yield of meat from the carcass
Backfat depth (MM)	Negative values equal leaner carcasses	Indicates animal is capable of producing lean carcass or can be taken to a heavier weight without becoming over fat

Table 25 Maternal EBVs (cow/heifer/ewe)

EBV	**Interpretation**	**Notes**
Longevity (Days)	Positive Values equal longer breeding life	Predicts the length of an animals breeding life
Age at 1st Calving (Days)	Negative vales equal puberty reached at an earlier age	Herds looking to calf heifers at two years old should use bulls with a negative EBV, this will increase conception at first mating

EBV	Interpretation	Notes
Calving interval (Days)	Negative values equal more cows that get back in calf quickly	Can be used to breed cows with short calving intervals that get back in calf quickly
200 Day milk (kgs)	Positive values equal more productive female replacements	The maternal side of this EBV indicates how well a bull's heifer calf will perform when they become mothers and is influenced by milking ability
Maternal calving ease (%)	Positive values equal more unassisted calvings	Identifies females that will calf easier, do not confuse with calving ease direct, which predicts how easily born a bull's progeny will be.

11.1.87 Description for practitioners and monitoring: Shift to lower emissions intensity breeding goal in dairy breeding, using genomic tools AND Shift to lower emissions intensity breeding goal in beef breeding, using genomic tools

- Research and data required. There is not yet a lot of data yet on genetics that will lower emissions, but it is an area that is starting to grow with pedigree breeders using feed weigh boxes to monitor weight and feed usage to determine a figure or FCE (Feed conversion efficiency).
- Theoretical application. In theory cattle all use feed in different ratios. Therefore, always using bulls that have the lowest feed usage to weight gain should be genetically passable to offspring, thus lowering emissions of buying in feed or actual amounts used.
- Steps to implementation. To enable this to be implemented, there are a number of steps to establish:
    - Rigorous research and proof of links between feed ratios and cattle breeds.
    - Comprehensive recording of this evidence to current breed recording.
    - Monitoring and recording of cattle genetics on farm, across generations.
    - A system to integrate feed ratio data.
    - Potentially, systems to monitor and verify actual feed ratio versus evidence of feed ratio, and test/prove actual impact on emissions.

11.1.88 References

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MM42: Using sexed semen in dairy cattle production

11.1.89 Overview

In the dairy herd the focus is on milk production and the maintenance of the herd by generating heifers to be replacement cows or cows used to expand the herd. The remaining offspring – 50-70% of calves – are not needed as dairy animals; there is 'surplus' dairy calf production at the system level (Bolton & von Keyserlingk 2021). These calves can be reared and slaughtered for meat; however, they are not all equally profitable as beef animals. Depending on the production system and the county, they can be slaughtered at a very young age as veal (gaining little meat from them therefore having a high emission intensity), or even killed without utilising them (Bolton & von Keyserlingk 2021). Particularly dairy male calves are likely to be not utilised as beef animals due to their low feed conversion ratio and poor growth characteristics. According to Hyde *et al.* (2020) over 25% of dairy male calves are slaughtered by 3 months of age in the UK (2018 data), and male dairy calves have the highest on-farm mortality rate compared to female dairy and male and female beef calves. On the other hand, surplus female dairy calves and cross-bred calves (produced by using beef semen) born on dairy farms can be reared for maturity to generate meat profitably.

The use of sexed semen, i.e. using only female semen, in dairy cow insemination can almost eliminate the production of male calves, allowing for higher profitability and environmental efficiency at the herd and system level.

11.1.90 Evidence base

The system level GHG effect of using sexed semen in the dairy herd depends on the current utilisation of dairy calves and the complex links between the dairy and the beef herds. Previous studies have come to contrasting conclusions regarding the environmental benefits of sexed semen use. While in a modelling work Eory *et al.* (2014) found that meat production from dairy farms increased by 47% with sexed semen use, with a 9-12% improvement in meat emission intensity and an increase in profits for typical UK dairy farms, Holdern and Butler estimated a 2% improvement in meat emission intensity in Ireland and Audsley and Wilkinson found only a little effect in the availability of male and female dairy calves for beef production (2014).

In the current work we modelled the effect of sexed semen use via reducing the number of beef cows and heifers as a result of more dairy calves entering the beef supply chain. This indirect modelling was required as the MACC model is static and does not have an underlying dairy-beef herd module.

Though sexed semen is already used to some extent in Scotland, the current uptake was set at zero as the model is estimating the further possible change. The cost of the measure was assumed to be zero, considering that while sexed semen is more expensive, than unsexed semen and feeding and looking after the calves until they are sold costs money, the increased selling price is expected to compensate for these costs.

11.1.91 Assumptions in the model

Table 26 Assumptions for MM42

Variable	Animal/crop type	Value type	Unit	Value
Number of animals	Beef cows	Relative	Change from original value	-0.93 * (number of beef steers)
	Beef heifers			-0.03 * (number of beef steers)
Applicability		Absolute	-	1
Current uptake		Absolute	-	0
Cost		Absolute	£ head^{-1} y^{-1}	0

11.1.92 Description for practitioners and monitoring

- Why use sexed semen? Allows increased rate of genetic improvement in the dairy herd by targeting the best animals you want to breed herd replacements from. The remainder of the herd can be served to beef semen, greatly improving the value of calves for selling or finishing, as opposed to having dairy bull calves which are lower value, are in less demand and produce lower value carcases. Using sexed semen also reduces rearing costs by only rearing the number of heifers that are required to maintain herd size.
- Identifying appropriate bulls. Not all bulls are available as sexed. Identify the bulls with the highest breeding indexes (PLI, SCI or ACI) that are sexed and then select bulls that are most suited to the herd's breeding goals.
- How to target sexed semen use: Best used on heifers as they should be the most fertile, as well as the genetically superior animals in the herd. It is also commonly used on young cows, ideally those in 1st or 2nd lactation as again, they are likely to be the more fertile than older cows (but its use in cows will depend on the number of replacements required). The best animals to breed from can be identified through genomic testing or AHDB's Herd Genetic Report, available to farmers that milk record.
- How much sexed semen will be required? Work out how many replacements are required and add a safety margin to account for any losses. Also bear in mind that sexed semen is 90% accurate in producing a heifer calf, and so the odd dairy bull calf may result.
- Considerations: Conception rates to sexed semen may be slightly poorer (around 90% of conventional semen conception rates). If conception rates are not as expected, there are a number of important areas to review such as timing of insemination, thawing and handling of semen and artificial insemination technique. As sexed semen will have shorter viability in the reproductive tract compared to conventional semen, the timing of insemination is even more important for good conception rates. Aim to serve between 14-20 hours after the onset of heat.

- Cost: Sexed semen is more expensive than conventional (can be around double the cost) but will pay for itself through improvements in herd health, milk output and better calf returns from crossbreeding the rest of the herd to beef.

11.1.93 References

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MM43, MM44, MM45: Slurry acidification, dairy, Slurry acidification, beef and Slurry acidification, pigs

11.1.94 Overview

Stored manure is a significant source of GHG emissions, their profile depending on the content of the excreta, management decisions (such as liquid or dry storage), environmental factors (most notably temperature) (Chadwick et al. 2011). Liquid storage is associated with high level of CH_4 (and ammonia) emissions, which increase with temperature, surface area and pH. Reducing the pH to 4.5-6.8 by adding strong acids can reduce both CH_4 and ammonia emissions (Petersen et al. 2012, Fangueiro et al. 2015). The acid can be added to the slurry at different stages: in the animal house when the slurry is collected, to the storage tank, or only before field application. In the current study we assume that the slurry is acidified right from the time of collection.

11.1.95 Evidence base

The modelling follows the assumptions developed in (Eory et al. 2015), following the review results of Fangueiro et al. (2015) for sulphuric acid, who found that 67-87% and 50-88% reductions have been achieved for CH_4 and ammonia, respectively.

The per animal cost is estimated from the volume cost of £2.40 (t slurry)$^{-1}$, reported by the Baltic Deal farmers' organisation (Baltic Deal 2015).

It is assumed that currently this method is not used in Scotland.

11.1.96 Assumptions in the model

Table 27 Assumptions for MM43, MM44 and MM45

Variable	Animal/crop type	Value type	Unit	Value
CH_4 conversion factor	Dairy, beef, pig	Relative	change from original value	-0.8
NH_3 volatilisation	Dairy, beef, pig	Relative	change from original value	-0.75
Current uptake	Dairy, beef, pig	Absolute	-	0
Applicability, slurry tanks	Dairy, beef, pig	Absolute	-	1
Applicability, other slurry storage	Dairy, beef, pig	Absolute	-	0
Combined annualised costs	Dairy	Absolute	£ head^{-1} y^{-1}	25

Variable	Animal/crop type	Value type	Unit	Value
Combined annualised costs	Beef	Absolute	£ head^{-1} y^{-1}	14
Combined annualised costs	Pig	Absolute	£ head^{-1} y^{-1}	2

11.1.97 Description for practitioners and monitoring

- Soil pH and soil testing. Obtaining a reliable estimate of your soil nutrient demand and pH, is generally good practice, but is especially key when applying acidified slurry to determine initial lime and soil requirements.
- Slurry testing. Testing slurry to determine nutrient content will also allow efficient and targeted application of slurry nutrient per individual field requirements and reduce reliance on inorganic fertiliser.
- Slurry timing and application method. It is generally good practice to apply slurry under cool and damp conditions and use Low Emission Spreading (LESS) techniques such as dribble bar, trailing hose, trailing shoe, or injection to further reduce emissions.
- Better slurry. Improvement in slurry fertiliser value due to increased nitrogen retention in a plant available form, leading to reduced need for inorganic fertiliser.
- Investment and operating costs. Capital outlay depends on the chosen slurry acidification technique, but initial capital investment may be expensive and the system difficult to retrofit. The acid itself can also be expensive. However, costs may be partly offset by reduction in inorganic fertiliser use and better slurry N efficiency.
- Health and safety. Strong acids are dangerous to handle and appropriate care and safety measures must be taken, e.g. avoiding exposure to slurry gases, monitoring gas levels, ventilating the area, keeping other people, especially children, clear of the area, not entering the tank without respiratory protective equipment etc..
- Increased need for liming. Extra lime will be needed to counteract the mild acidity of the slurry and associated decrease in soil pH over time, resulting in additional cost. This may well be balanced by other benefits of slurry acidification in terms of yield and performance.
- Choose where is most practical to acidify slurry. Acidification can be carried out in-house, during storage or at land spreading; the easiest way to acidify slurry is at the housing or storage stages. In-house acidification is best achieved by creating a new treatment system during construction of new housing facilities. Slurry is typically pumped from the underslat tank to a processing tank, where sulphuric or nitric acid is added, before being pumped into a storage tank and then back into the livestock housing. Slurry can also be acidified at land spreading using specialist equipment i.e. acidification equipment attached to tractor/tanker.

11.1.98 References

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MM46, MM47, MM48: Impermeable slurry cover, dairy, Impermeable slurry cover, beef and Impermeable slurry cover, pigs

11.1.99 Overview

Similarly to the previous measure, slurry acidification, this technology aims to reduce CH_4 and ammonia emissions from slurry. The mechanism is different, though, as it is based on reducing the airflow over the surface of the slurry, and thus limiting the gaseous emissions from it (Chadwick et al. 2011; Monteny et al. 2006; Sommer et al. 2004). A wide range of technologies can be used for covering slurry, and they considerably differ in effectiveness on the various emissions, costs, lifetime and suitability for different types of slurry storage (Kupper et al. 2020, VanderZaag et al. 2015). As the abatement cost of impermeable plastic covers were found to be lower in the Clean Growth for Sustainable Intensification project, that technology was selected for this work.

11.1.100 Evidence base

Following the assumptions in the Clean Growth for Sustainable Intensification, the CH_4 and N_2O reduction was assumed to be 47% and 100%, respectively (Rodhe et al. 2012), while the ammonia mitigation was set at 80% (VanderZaag et al. 2015).

The cost assumptions followed the review by VanderZaag et al. 2015 and the uptake values were sourced from the Smart Inventory.

11.1.101 Assumptions in the model

Table 28 Assumptions for MM45, MM47 and MM48

Variable	Animal/crop type	Value type	Unit	Value
CH_4 conversion factor	Dairy, beef, pig	Relative	change from original value	-0.47
NH_3 volatilisation	Dairy, beef, pig	Relative	change from original value	-0.8
EF_3	Dairy, beef, pig	Relative	change from original value	-1
Current uptake	Dairy	Absolute	-	0
Current uptake	Beef	Absolute	-	0
Current uptake	Pig	Absolute	-	0.24
Applicability, slurry tanks	Dairy, beef, pig	Absolute	-	1

Variable	Animal/crop type	Value type	Unit	Value
Applicability, slurry lagoons	Dairy, beef, pig	Absolute	-	1
Applicability, other slurry storage	Dairy, beef, pig	Absolute	-	0
Installation cost	Dairy, beef, pig	Absolute	£ (m^3 manure)$^{-1}$	3.79
Installation lifetime	Dairy, beef, pig	Absolute	years	10
Maintenance	Dairy, beef, pig	Relative	proportion of all capital costs	0.02

11.1.102 Description for practitioners and monitoring

- Decide what type of cover suits the system. Types of slurry covering options will largely depend on whether it is an existing store is being retrofit, or a new store is being purpose-built. The two main types of covers are floating and fixed. Lagoons tend to be covered with floating covers due to the size and structure, but tensioned covers are available. Floating covers can be fitted with an agitation hatch, and rainwater can be pumped off the top, but access for desludging is difficult. These are difficult to retrofit on existing lagoons as the lagoon requires to be totally empty to allow installation. These will most commonly be seen included as part of a new construction. Fixed covers enable rainwater to drain from the surface without pumping, but may not be compatible for retrofitting due to structural suitability and reinforcement needed.
- Assess pros and cons of cover type based on retrofitting feasibility. Retrofitting can pose various practical and engineering challenges, which will determine feasibility and options available, e.g. fixed or floating cover, is access needed, mixing, vents etc. Retrofitting slurry towers requires either reinforcement of the floor to support a central pole and strengthening of the top band, both of which come with significant additional cost on top of the cost of the cover itself. To retrofit the tank also needs to be empty which is very difficult, sometimes impossible, and limits the time of year when a cover can be fitted. Manholes are also needed so that someone can enter the tank to inspect it, which aren't very common.
- Planning permission for building new stores. If building a new store you must have planning permission which will include compliance with SEPA e.g. distance from water sources, impact on surrounding environment and other people. You will also need to assess capacity needed for the farm (including additional water/rainwater added), especially throughout winter, as well as the location of store on farm, accessibility, agitation options etc.
- Assess capacity of store needed. Capacity required for stores will affect the size of cover and therefore the price. Capacity is influenced by the amount of manures produced on farm, the amount of manures required for application to crops on farm (when and at what rate), the length of time stored, any additional water ingress or rainwater added to the store,

- Consider impact of reduced water content on equipment and method of application. Covering will reduce/prevent rainwater from adding volume to the slurry which comes at a cost to the farmer both to store and spread. Farmers will want to aim to reduce water ingress through surface and roof water into slurry systems, particularly where there is risk of contamination. However, reducing water content will have implications for the viscosity of slurry, practicalities of applying through tubes, and well as nutrient density. Farmers will need to consider if application equipment needs adapting for spreading thicker slurry.

11.1.103 References

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12 Appendix D: Results

Table 29 Business as Usual, Central Feasible Potential, 2050

Without interactions (ordered by abatement)			With interactions (ordered by abatement cost)		
Mitigation measure	Abatement kt CO_2e y^{-1}	Abatement cost £ $(t\ CO_2e)^{-1}$	Mitigation measure	Abatement kt CO_2e y^{-1}	Abatement cost £ $(t\ CO_2e)^{-1}$
3NOP beef	132	87	Grass-legume mix	52	-1,044
Nitrate feed additive beef	119	38	Variable rate nitrogen	19	-628
Sexed semen in dairy	93	0	Current breeding goal in dairy	39	-426
Faster finishing beef	90	0	Genomics breeding dairy	58	-446
Increasing beef calving rate	85	0	Genomics breeding beef	7	-432
3NOP dairy	70	36	Health dairy	11	-381
Genomics breeding dairy	61	-423	Lower emission breeding goal dairy	32	-339
Slurry acidification beef	60	20	AD pig poultry	10	-274
Grass-legume mix	52	-1,044	Soil compaction	2	-255

Without interactions (ordered by abatement)			With interactions (ordered by abatement cost)		
Mitigation measure	Abatement kt CO_2e y^{-1}	Abatement cost £ (t $CO_2e)^{-1}$	Mitigation measure	Abatement kt CO_2e y^{-1}	Abatement cost £ (t $CO_2e)^{-1}$
Nitrate feed additive dairy	45	41	Health sheep	39	-244
Health beef	40	-1	AD cattle	30	-184
Health sheep	40	-240	Lower emission breeding goal beef	8	-356
Current breeding goal in dairy	39	-426	Health beef	25	-2
Cover crops	36	103	Slurry acidification dairy	32	-1
Lower emission breeding goal dairy	32	-339	Faster finishing beef	66	0
Slurry acidification dairy	32	-1	Increasing beef calving rate	29	0
Nitrification inhibitor	31	182	Reducing beef calving interval	4	0
AD cattle	30	-181	Sexed semen in dairy	71	0
Reducing beef calving interval	27	0	Soil pH	17	17
Lower emission breeding goal beef	23	-124	Slurry acidification beef	42	28

Without interactions (ordered by abatement)			With interactions (ordered by abatement cost)		
Mitigation measure	Abatement kt CO$_2$e y^{-1}	Abatement cost £ (t CO$_2$e)$^{-1}$	Mitigation measure	Abatement kt CO$_2$e y^{-1}	Abatement cost £ (t CO$_2$e)$^{-1}$
Impermeable slurry cover beef	22	14	Impermeable slurry cover dairy	10	34
Variable rate nitrogen	21	-547	Impermeable slurry cover beef	9	36
Grain legumes	21	65	Nitrate feed additive beef	119	38
Soil pH	18	17	Grain legumes	18	76
High fat diet sheep	15	375	Slurry acidification pigs	2	84
Impermeable slurry cover dairy	14	25	Nitrate feed additive dairy	22	84
High fat diet beef	13	504	3NOP dairy	30	85
Health dairy	13	-327	Cover crops	33	110
Genomics breeding beef	10	-270	Impermeable slurry cover pigs	0	122
AD pig poultry	10	-274	Nitrate feed additive sheep	4	196
Nitrate feed additive sheep	9	81	3NOP beef	51	226
High fat diet dairy	7	339	Nitrification inhibitor	18	319

Without interactions (ordered by abatement)			With interactions (ordered by abatement cost)		
Mitigation measure	Abatement kt CO_2e y^{-1}	Abatement cost £ $(t\ CO_2e)^{-1}$	Mitigation measure	Abatement kt CO_2e y^{-1}	Abatement cost £ $(t\ CO_2e)^{-1}$
Urease inhibitor	5	220	High fat diet beef	13	504
Slurry acidification pigs	3	68	Urease inhibitor	2	518
Soil compaction	2	-255	High fat diet sheep	6	909
Impermeable slurry cover pigs	1	23	High fat diet dairy	1	3,395
			Total	931	

Table 30 Tailwinds, Central Feasible Potential, 2050

With interactions			Without interactions		
Mitigation measure	Abatement kt CO_2e y^{-1}	Abatement cost £ $(t\ CO_2e)^{-1}$	Mitigation measure	Abatement kt CO_2e y^{-1}	Abatement cost £ $(t\ CO_2e)^{-1}$
Grass-legume mix	35	-1,045	3NOP beef	66	87
Health dairy	5	-479	Nitrate feed additive beef	59	38
Genomics breeding beef	5	-274	Sexed semen in dairy	47	0
AD pig poultry	5	-274	Faster finishing beef	45	0
Health sheep	20	-242	Increasing beef calving rate	42	0
AD cattle	11	-181	Grass-legume mix	35	-1,045
Lower emission breeding goal beef	5	-283	3NOP dairy	31	31
Health beef	13	-2	Slurry acidification beef	30	20
Slurry acidification dairy	14	-1	Nitrate feed additive dairy	20	34
Faster finishing beef	34	0	Health beef	20	-1
Increasing beef calving rate	15	0	Health sheep	20	-240

With interactions			Without interactions		
Mitigation measure	Abatement kt CO_2e y^{-1}	Abatement cost £ (t CO_2e)$^{-1}$	Mitigation measure	Abatement kt CO_2e y^{-1}	Abatement cost £ (t CO_2e)$^{-1}$
Reducing beef calving interval	2	0	Cover crops	19	102
Sexed semen in dairy	38	0	Nitrification inhibitor	18	180
Impermeable slurry cover dairy	5	25	Slurry acidification dairy	14	-1
Slurry acidification beef	21	28	Reducing beef calving interval	14	0
Nitrate feed additive dairy	20	34	Grain legumes	12	59
Impermeable slurry cover beef	4	36	AD cattle	11	-181
Nitrate feed additive beef	54	41	Lower emission breeding goal beef	11	-120
Grain legumes	12	59	Impermeable slurry cover beef	11	14
3NOP dairy	13	74	High fat diet sheep	8	375
Slurry acidification pigs	1	84	High fat diet beef	7	504
Cover crops	19	102	Impermeable slurry cover dairy	6	20

With interactions			Without interactions		
Mitigation measure	Abatement kt CO_2e y^{-1}	Abatement cost £ (t CO_2e)$^{-1}$	Mitigation measure	Abatement kt CO_2e y^{-1}	Abatement cost £ (t CO_2e)$^{-1}$
Impermeable slurry cover pigs	0	122	Genomics breeding beef	5	-266
3NOP beef	34	172	Health dairy	5	-479
Nitrate feed additive sheep	2	188	AD pig poultry	5	-274
Nitrification inhibitor	12	266	Nitrate feed additive sheep	4	81
Urease inhibitor	1	402	High fat diet dairy	3	292
High fat diet beef	7	504	Urease inhibitor	3	220
High fat diet sheep	3	903	Slurry acidification pigs	1	68
High fat diet dairy	0	2,923	Impermeable slurry cover pigs	1	23
			Health dairy	5	-479
Total	412				

Table 31 Range of abatement and abatement cost of each measure across the six activity scenarios (all Central Feasible Potential). ('Without interaction' values represent abatement and cost assuming no other mitigation options are implemented.)

	Without interactions				With interactions			
	Abatement (kt CO_2e y^{-1})		Abatement cost £ (t $CO_2e)^{-1}$		Abatement (kt CO_2e y^{-1})		Abatement cost £ (t $CO_2e)^{-1}$	
Mitigation measure	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
3NOP beef	66	132	87	87	26	51	172	226
Nitrate feed additive beef	59	119	38	38	54	119	38	41
Sexed semen in dairy	47	93	0	0	35	71	0	0
Faster finishing beef	45	90	0	0	33	66	0	0
Increasing beef calving rate	42	85	0	0	14	29	0	0
Current breeding goal in dairy	39	39	-426	-426	39	39	-426	-426
Grass-legume mix	35	52	-1,045	-1,044	35	52	-1,045	-1,044
3NOP dairy	31	70	31	36	13	30	74	85
Genomics breeding dairy	30	61	-425	-423	30	58	-446	-424
Slurry acidification beef	30	60	20	20	21	42	28	29
Variable rate nitrogen	21	21	-547	-547	19	19	-628	-628
Nitrate feed additive dairy	20	45	34	41	11	22	34	84
Health beef	20	40	-1	-1	13	25	-2	-2

	Without interactions				With interactions			
	Abatement (kt CO_2e y^{-1})		Abatement cost £ (t $CO_2e)^{-1}$		Abatement (kt CO_2e y^{-1})		Abatement cost £ (t $CO_2e)^{-1}$	
Mitigation measure	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Health sheep	20	40	-240	-240	20	39	-244	-242
Cover crops	19	36	102	103	19	33	102	110
Nitrification inhibitor	18	31	180	182	12	18	266	319
Lower emission breeding goal dairy	16	32	-340	-339	16	32	-340	-339
Slurry acidification dairy	14	32	-1	-1	14	32	-1	-1
Soil pH	14	18	7	17	14	17	8	17
Reducing beef calving interval	14	27	0	0	2	4	0	0
Grain legumes	12	21	59	65	12	18	59	76
AD cattle	11	30	-181	-181	11	30	-185	-181
Lower emission breeding goal beef	11	23	-124	-120	4	8	-370	-283
Impermeable slurry cover beef	11	22	14	14	4	9	36	36
High fat diet sheep	8	15	375	375	3	6	903	915
High fat diet beef	7	13	504	504	7	13	504	504

	Without interactions				With interactions			
	Abatement (kt CO_2e y^{-1})		Abatement cost £ (t CO_2e)$^{-1}$		Abatement (kt CO_2e y^{-1})		Abatement cost £ (t CO_2e)$^{-1}$	
Mitigation measure	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Impermeable slurry cover dairy	6	14	20	25	5	10	25	34
Genomics breeding beef	5	10	-270	-266	3	7	-470	-274
Health dairy	5	13	-479	-327	5	11	-479	-363
AD pig poultry	5	10	-274	-274	5	10	-274	-274
Nitrate feed additive sheep	4	9	81	81	2	4	188	204
High fat diet dairy	3	7	292	339	0	1	2923	3395
Urease inhibitor	3	5	220	220	1	2	402	518
Soil compaction	2	2	-336	-255	2	2	-336	-255
Slurry acidification pigs	1	3	68	68	1	2	84	84
Impermeable slurry cover pigs	1	1	23	23	0	0	122	122
Improving nutrition beef	0	0	0	0	0	0	0	0
Improving nutrition sheep	0	0	0	0	0	0	0	0

Table 32 Input data for Scottish Government analysis (Business as Usual, Central Feasible Potential, 2050; unit mitigation expressed in t CO2e ha^{-1} y^{-1} or t CO2e head^{-1} y^{-1})

This table is published as a separate spreadsheet on the ClimateXChange publications library under the name A scenario-based approach to emissions reduction targets in Scottish agriculture – appendix tables.

Table 33 Mitigation from change in agricultural activity level and applying mitigation measures in 2050 at Central Feasible Potential (kt CO_2e)

Activity Scenario	Mitigation from reduced agricultural activity	Mitigation from measures on farms	Total mitigation from reduced activity and mitigation measures	Share of mitigation from measures
Business as Usual	0	931[8]	931	0%
Balanced Net Zero	2,424	624	3,048	20%
Headwinds	1,534	712	2,246	32%
Widespread Engagement	3,670	480	4,150	12%
Widespread Innovation	3,869	412	4,281	10%
Tailwinds	3,874	412	4,285	10%

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[8] Business as Usual activity scenario has the highest abatement on farms as it has the highest agricultural activity

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