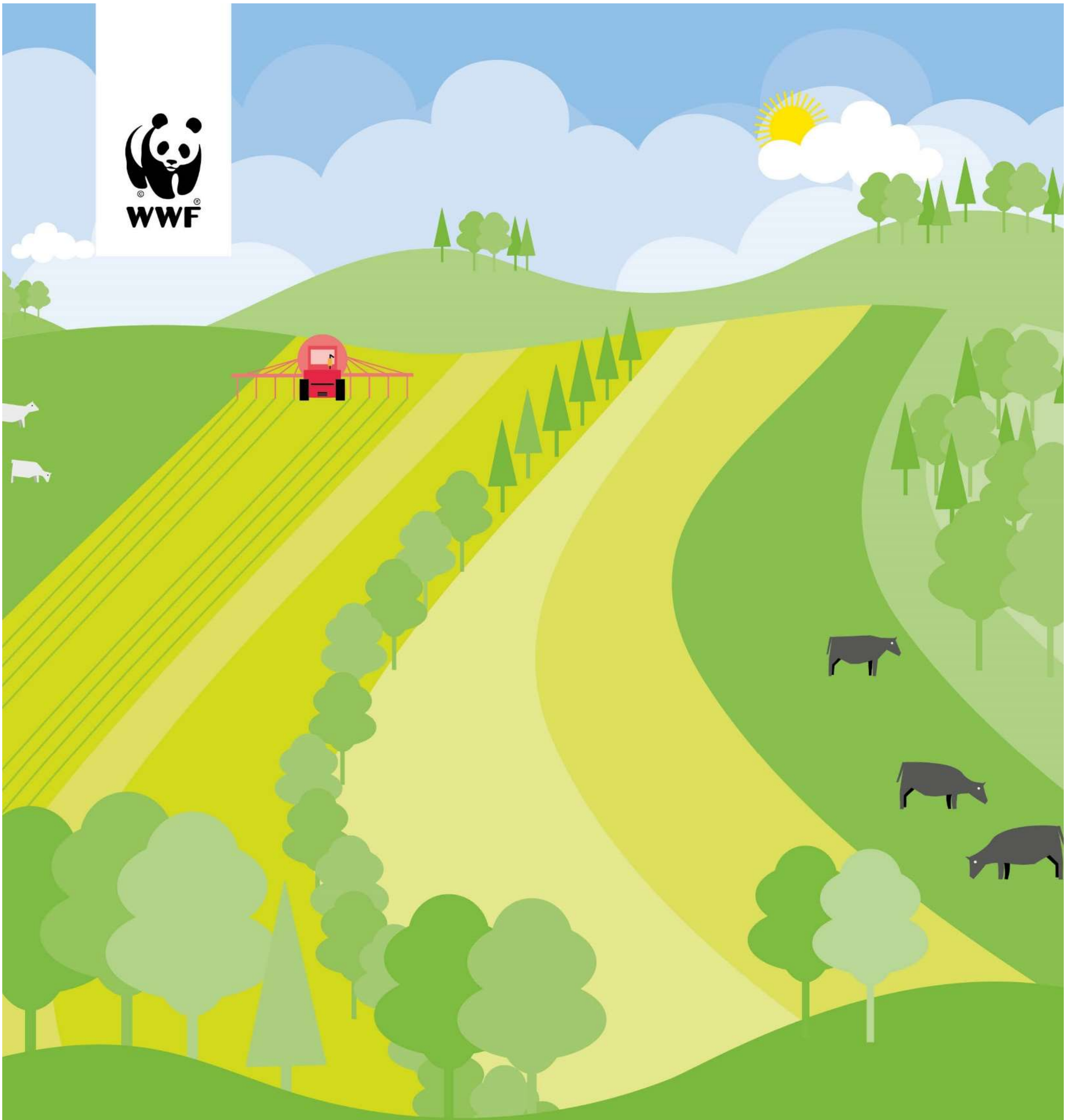

DELIVERING ON NET ZERO

Scottish Agriculture

Delivering on Net Zero: Scottish Agriculture

A report for WWF Scotland from the Organic Policy, Business and Research Consultancy

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NOVEMBER 2019

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Executive summary

The aim of this study was to identify whether, how and at what cost agricultural GHG emissions in Scotland could be reduced by 35% by 2045. In 2017, Scottish agricultural GHG emissions were estimated to be 7.6 Mt CO_2e making the 35% target 2.7 Mt CO_2e.

Building on previous work by SRUC and others, 37 different measures to reduce GHG emissions were evaluated, focusing on improvements in nitrogen fertiliser use, organic manure/slurry storage and use, mechanisation, soil management, cropping systems and management, livestock nutrition, health and breeding, as well as improved farming systems integrating multiple measures, represented by conservation agriculture, organic farming, pasture-fed livestock production and agroforestry.

Land use changes, such as from agriculture to peatland or forestry, as well as non-agricultural activities (including input manufacturing, food processing, retailing and consumption) were outside the scope of the study, although consideration was given to food losses on farms arising from decisions in other sectors. Embodied GHG emissions in inputs and impacts of output changes on other countries were also not assessed.

In theory, if taken up 100% and accounting for no interactions, the measures could reduce Scottish agricultural emissions by almost 100%. In practice, there are many reasons why measures might not be implemented in combination, or adopted, by all farmers. We estimated that the most promising measures could potentially deliver 2.9 Mt CO_2e annually, or 38% of 2017 GHG emissions, and concluded that the 35% target is achievable by 2045.

75% of Scottish agricultural GHG emissions are related to livestock production. This is not surprising given the importance of grassland and rough grazing in Scottish agriculture, which together account for almost 80% of agricultural land. Given this context, measures focused on tillage crops are relatively unimportant with respect to their potential for GHG reduction. The measures with most potential (all specified on annual basis) that we identified were:

a) Reduction in nitrogen fertiliser use. Measures to use nitrogen more efficiently, including better use of organic manures, could potentially generate reductions of nearly 350 kt CO_2e, or 13% of the target, within the next 10 years, if adopted on most farms.
b) More radical reductions in nitrogen fertiliser use, by encouraging the use of legumes in grassland to eliminate or substantially reduce the need for N fertiliser, could reduce emissions by nearly 300 kt CO_2e, or 11% of the target, within the next 15 years, if adopted on 40% of grassland.
c) The use of legumes combined with rotational grazing techniques in diverse-species grassland, which help build soil organic matter and sequester carbon, could increase the total benefit to 540 kt or 20% of the target. This could potentially be linked with a pasture-fed livestock approach.
d) Reducing methane emissions associated with ruminants by using feed additives including 3NOP, nitrates, probiotics, high dietary fat sources and seaweed derivatives could make a significant contribution. In the case of 3NOP, emissions could be reduced by 265 kt or 10% of the target within 10 years, if adopted on most dairy and some other cattle farms. This would require approval of 3NOP as a feed additive so that it can be marketed, and that at an affordable price.
e) Improved animal health and breeding, with increased fertility, growth rates and yields, and reduced morbidity/mortality could reduce total livestock numbers needed to deliver the same output, and deliver 366 kt emission reductions (14% of the target) with 40-50% uptake.
f) Organic farming, with 40% uptake, could potentially deliver 730 kt CO_2e reductions or 27% of the target. This is a result of combining no synthetic nitrogen fertiliser use with an overall 10% reduction in livestock numbers and the conversion of 20% of tillage land to rotational grassland. The financial impacts of these changes are reduced due to the premium markets for organic food.
g) Agroforestry also offers potential for substantial reductions: 570 kt (21% of the target) with 30% uptake. This is assuming 10% of farmland is used for trees, with consequent output reductions for crops and livestock, although with some scope to mitigate this.

Despite their emission reduction potential, organic farming and agroforestry both have the disadvantages of higher initial investment costs, greater complexity acting as a disincentive to adoption and longer lead-in times, as well as output reductions that, if demand remains unchanged, could lead to an increased requirement for imports and increased emissions elsewhere. However, the widespread adoption of these approaches would need to be considered in the context of changing human and animal diets, and the potential for reducing food losses and waste also highlighted in the report.

The financial assessment of these measures indicates that many are likely to be associated with increased costs and, in the absence of other financial benefits, reduced incomes, which would need to be addressed by policy support in some form. In several cases, reductions in nitrate leaching, ammonia emissions and other impacts leading to improvements in water and air quality could provide further justifications for support. In some cases, the improved productivity, for example associated with improved animal health and breeding, could create a win-win situation, with emissions reduction combined with financial benefits.

As most of the measures are unlikely to be driven by market forces, policy interventions are likely to be needed, including:

- Farming system payments for innovative approaches (whole or part farm)
- Input reduction and improved soil management, including support for advice and investments
- Regulatory and fiscal options including input taxes and quotas or tradeable carbon quotas linked to input use and sequestration opportunties
- Carbon, nitrogen and sustainability auditing
- Training, advice and skills
- Improved greenhouse gas monitoring and statistics
- Targeted research, and
- Dietary change and food waste reduction

In almost all cases, the practices and systems that could be adopted are well developed and understood, but actions are needed to ensure that financial and knowledge barriers are addressed in order to facilitate their adoption so that the desired GHG mitigation targets can be achieved.

1 Introduction

2019 marks the 10-year anniversary of the Climate Change (Scotland) Act 2009, which introduced a target to reduce greenhouse gas emissions in Scotland to 80% lower than the 1990 baseline by 2050. As a new climate change bill moved through parliament, we had the opportunity to build upon that progress and ambition to steer Scotland towards net zero emissions before 2045.

A recent report by the Intergovernmental Panel on Climate Change (IPCC) warns that reaching net zero carbon globally by 2050 is the only way to limit global warming to 1.5°C and avoid the worst predicted impacts of warming, implying Scotland would have to deliver net zero carbon significantly sooner and reach net zero GHG emissions before 2050[1]. In May 2019, the UK Committee on Climate Change (CCC) recommended that Scotland could reach net zero by 2045. In response, the Scottish Government has declared climate emergency and has committed to a net zero emissions target for 2045.

Scottish farmers are at the front line of climate change. The extreme weather of 2017-18 alone is estimated to have cost Scottish farmers £161 million due to livestock losses and lower crop yields[2]. However, agriculture also contributes to climate change. The sector contributed 26% of Scottish GHG emissions in 2016, including 68% of methane and 79% nitrous oxide emissions. Although some emissions will always be inherent in food production, there is room for improvement. However, emissions from agriculture and related land use have not changed significantly over the last 10 years and have fallen by an average of only 0.3% per year for the last 5 years.

As emissions from other sectors are drastically reduced, agricultural emissions will dominate by 2050[3]. The IPCC warned that 'transitions in global and regional land use are found in all pathways limiting global warming to 1.5°C with no or limited overshoot'. The report also highlights the importance of non-CO_2 emissions reductions, including methane and nitrous oxide. Therefore, agriculture has an important role to play in the fight against climate change and must be supported to do so, while meeting the food needs of a growing global population through a combination of waste reduction, dietary change and productivity increases if required[4].

A recent report by Vivid Economics, commissioned by WWF Scotland, concluded that net zero could be reached in Scotland well before 2050, but the agriculture sector would need to reduce emissions by 35%, and the land use sector as whole would have a critical role to play in scaling up GHG removal to more than offset Scotland's remaining emissions. It would be possible to do this and maintain current agricultural productivity if farmers employ virtually all available mitigation measures alongside GHG removal[3].

The key aim of this research is to present the Scottish Government and other relevant decision makers with an independent assessment of a pathway to secure 35% GHG emissions reductions from agriculture, contributing to a net zero emissions target by 2045. This will consider how current agricultural production can be maintained, implications for different farming systems, the lead in times for deployment and the framework of regulation, support and incentives required to secure it.

This work will contribute to a larger, multi-year portfolio of work, exploring the opportunities to transition towards climate-neutral land use in Scotland, which will include a module exploring the scope and policy framework for greenhouse gas removal activities by farmers.

[1] http://report.ipcc.ch/sr15/pdf/sr15_spm_final.pdf p. 23. See also Chapter 3 of the full report: http://report.ipcc.ch/sr15/pdf/sr15_chapter3.pdf

[2] Ecosulis (2019) The economic impact of extreme weather on Scottish Agriculture. WWF Scotland, Edinburgh

[3] Vivid Economics (2018) A Climate of Possibility: Harnessing Scotland's natural resources to end our contribution to climate change. https://www.wwf.org.uk/sites/default/files/2019-01/WWF_Report_VIVID_Jan_2019.pdf

[4] Berners-Lee M, Kennelly C, Watson R, Hewitt CN (2018) Current global food production is sufficient to meet human nutritional needs in 2050 provided there is radical societal adaptation. *Elem Sci Anth* 6(1).

This report addresses the following research questions:

1. What is the portfolio of known mitigation measures required to secure agricultural GHG emissions reductions of 35% by 2045, whilst maintaining current agricultural production? (Chapter 2)
2. Can these mitigation measures be sequenced in terms of priority and feasibility of deployment and what are the relative contributions of each of these measures to the 35% target over time? (Chapter 3)
3. What are the implications of each of these mitigation measures for agricultural production across different farming systems over the next three decades? (Chapter 4)
4. What policy mechanisms are required from Scottish Government to help the agriculture sector transition to a 35% reduction in emissions by 2045, including the framework of regulation, advice and incentives and how can they be appropriately sequenced? (Chapter 6)

2 Portfolio of mitigation measures

2.1 Introduction

The aim of this part of the report is to address the question: What is the portfolio of known mitigation measures required to secure agricultural GHG emissions reductions of 35% by 2045, whilst maintaining current agricultural production? In 2017, the Scottish Government estimated agricultural GHG emissions to be 7.6 Mt CO_2e. 35% of this is 2.7 Mt, the target for this study.

The portfolio outlined here is specifically focused on measures to reduce greenhouse gas emissions from agriculture, which can include a wide range of measures aimed at reductions in and improving efficiency of input use, as well measures to reduce waste or losses of food produced. While individual practices can be looked at in isolation, there can be synergies or other advantages associated with combinations of practices in farming systems, such as conservation agriculture, pasture-fed livestock production, agroforestry or organic farming. Where appropriate, we identify potential upstream and downstream supply chain impacts (e.g. from the production of agrochemicals and animal feed inputs and from the grading and processing of agricultural outputs) although it is recognised that these are often not included in official estimates of agricultural emissions.

There are a number of other measures, including peatbog restoration, rewilding, and afforestation, which involve changes from agricultural land use and which will be the subject of future study, so they are not analysed here.

2.2 Measuring greenhouse gas emissions and global warming potential

Agriculture is associated with a range of greenhouse gas emissions that contribute to climate change, including carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Ammonia (NH_3), although not directly a greenhouse gas, is considered in the calculations as a result of the indirect N_2O emissions resulting from deposition on land.

CO_2 is associated with the use of fossil energy for transport, farm mechanisation and agrochemical manufacture, as well as the breakdown of organic matter. Conversely as a biological, plant-based industry, agriculture also has the potential to fix CO_2 through photosynthesis and in certain circumstances to sequester carbon in wood and soils, although in the latter case a new steady-state soil C content will be reached a few decades after a change in management.

N_2O emissions are particularly associated with the use of nitrogen fertilisers (synthetic and organic) and N excreted by grazing livestock, while CH_4 and NH_3 are more usually associated with livestock production and the storage and spreading of manures and slurries.

There are a number of other gases including the fluorocarbons that are much more potent, but are not directly associated with agriculture and not included in the calculations for this industry.

Global Warming Potential (GWP) is measured in terms of carbon dioxide equivalents (kg CO_2e), which takes account of the relative impact of the different gases involved. Because gases break down to their component elements over time, the time horizon also matters – the 2006 IPCC guidelines[5] have been set for time horizons of 20, 100 and 500 years, with Scottish and UK GWP reporting using 100 years, and GWP (radiative forcing) values of 25 and 298 times that of CO_2 for methane and nitrous oxide respectively.

While it may be relevant to focus on a specific gas such as methane in specific circumstances, doing so may not tell the full story if emissions of other gases, such as N_2O emissions associated with fertiliser use, are reduced, potentially outweighing the initial concern.

Methane is also more complex to assess as it breaks down relatively quickly (12.4 years lifetime) and its contribution may therefore be overstated. In the context of the 100 year horizon for the 'standard' GWP calculation, it can be considered a 'flow' gas – i.e at a constant rate of emission, methane does not considerably increase global warming, unlike the other long-lived gases such as CO_2 and N_2O, which are

[5] IPCC (2006) Guidelines for National Greenhouse Gas Inventories. https://www.ipcc-nggip.iges.or.jp/public/2006gl/

effectively cumulative in their warming effect over 100 years. An increase or decrease in CH_4 emissions would however have an impact albeit at a fixed point.

A newly developed GWP* calculation accounts for the short-lived effect of methane on global temperatures by considering increases or decreases in the rate of emissions when defining agriculture's contribution over a 100-year timeframe (Allen et al., 2018)[6]. Given that the work on GWP* for methane is still under refinement, we have applied the IPCC 2006 guidelines currently used in the UK GHG inventory in defining GWPs used within this study. It should also be noted that more recent IPCC guidelines[7] have been published, but as these have not been used for previously published UK inventories, we have not adopted these.

We have also based the reduction on current UK GHG inventory data which excludes some relevant factors, such as emissions generated in the manufacture of agricultural inputs, emissions from retail, catering and food-use at home and offsets from soil carbon sequestration. This focus is therefore on Scope 1 (direct) and 2 (indirect) emissions from farm businesses, and not on Scope 3 (other parts of the food value chain). In doing so we potentially exclude approximately 60% of food related GHGs and the potential to offset 20-35% of anthropogenic greenhouse gas emissions (Allen et al., 2018[2], Garnett et al., 2016[8], Minsany et al., 2017[9]). However, our focus here is on GHG emissions within the agriculture and land use sectors as this forms the basis for the 35% reduction target mentioned in Section 2.1.

Scotland and UK GHG emissions estimates also do not take account of emissions incurred in other countries, but which may be relevant to domestic food production. For example, imported animal feeds may contain 'embodied' emissions that are not considered as part of the emissions associated with livestock production. Ceasing to undertake activities that generate emissions may benefit domestic GHG inventories, but may have no benefits on a global level if the activities are displaced to other countries and the products imported back. GHG consumption reports focusing on global supply chains, for example as developed by the Stockholm Environment Institute[10] attempt to address this, but we have not attempted a similar exercise in this study.

In considering options for Scotland to reduce its own agricultural GHG emissions, there is also a need for Scotland to play a lead role in helping to reduce global emissions. This is recognised in the Scottish Government's Climate Change Plan, which also includes reference to carbon sequestration options for agriculture that would not be reflected in the agricultural GHG inventory. Where relevant, we have highlighted these issues in the discussion of individual measures.

The consideration of relative performance of different measures to reduced GHG emissions will also depend on the denominators used. For agricultural emissions, the units are usually land based (per ha) or livestock based (per head) or holding based (per farm). For national inventories, these are relevant as land areas and holding numbers are relatively constant. On a global basis, however, GHG emissions per unit (e.g. kg) food produced may be more relevant. However, McAuliffe et al. (2018)[11] have argued that such comparisons are misleading, because the human nutritional value per kg of different foods is not comparable, and that nutrient intake should be used instead as a basis for making comparisons between different food types, and in particular for comparisons between different meat types (beef, poultry etc.). While acknowledging this, we have focused in this report on national or land-based data and impacts, reflecting the practice in the agricultural GHG inventory.

[6] Allen MR, Shine KP, Fuglestvedt JS, Millar RJ, Cain M, Frame DJ, Macey AH (2018) A solution to the misrepresentations of CO_2-equivalent emissions of short-lived climate pollutants under ambitious mitigation. *NPJ Climate and Atmospheric Science*, 1:16.

[7] IPCC (2019) Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html

[8] Garnett T, Smith P, Nicholson W, Finch J (2016) *Food Systems and Greenhouse Gas Emissions.* University of Oxford.

[9] Minasny B, Malone BP, McBratney AB et al. (2017) Soil carbon 4 per mille. *Geoderma* 292:59-86.

[10] https://www.sei.org/topic/supply-chains/

[11] McAuliffe GA, Takahashi T, Lee MRF (2018) Framework for life cycle assessment of livestock production systems to account for the nutritional quality of final products. *Food and Energy Security,* 7(3).

2.3 *Emission reduction measures to be analysed*

In this section we have focused on describing the mitigation measures, how they work, and the key assumptions made. The results in terms of mitigation potential if they are fully adopted are summarised in the next section in Table B.

We have relied primarily on Eory *et al*. (2015)[12] for the description and assessment of measures, except where indicated otherwise. A number of earlier/alternative inventories of emission reduction measures exist, including Moran *et al*. (2008)[13], MacLeod et al. (2010)[14], Newell Price et al. (2011)[15], and Frelih-Larsen et al. (2014)[16]. It is acknowledged that there are many more potential mitigation measures that might be considered. We have focused mainly on those that have achieved a degree of recognition in earlier studies and ignored some that were also not taken forward in those studies. However, we have also introduced some, such as the systems-based approaches, that have not previously been considered in great detail.

To facilitate cross-referencing of the mitigation measures analysed by these different authors, the following coding is used:

- M1 etc. – this study
- E1 etc. – Eory et al. (2015)
- FL1 etc. – Frelih-Larsen et al. (2014)
- NP1 etc. – Newell Price et al. (2011)
- MMAA etc. – Moran et al. (2008) and MacLeod et al. (2010)

In addition, we indicate with 'FBC' which of the measures we have assessed are covered by the Farming for a Better Climate Programme[17], which is run by SRUC on behalf of the Scottish Government.

A. Improved nitrogen fertiliser use

2.3.1 M1 (E1, FBC): Improving synthetic N utilisation

Synthetic nitrogen use in agriculture has implications for greenhouse gas emissions due to:

- Use of fossil energy releasing CO_2 in manufacture and distribution
- Release of NO_x as part of the manufacturing process
- Release of N_2O as part of the soil nitrogen cycle

For fertilisers, manufacturing emissions account for about 30% of the total emissions of ca. 10kg CO_2e per kg fertiliser N used[18], but these manufacturing emissions are not attributed to the

[12] Eory V, MacLeod M, Topp C, Rees R, Webb J, McVittie A, Wall E, Borthwick F, Watson C, Waterhouse A (2015) Review and update the UK Agriculture Marginal Abatement Cost Curve to assess the greenhouse gas abatement potential for the 5th carbon budget period and to 2050. Final Report to Defra. SRUC.

[13] Moran D, MacLeod M, Wall E, Eory V, Pajot G, Matthews R, McVittie A, Barnes A, Rees R, Moxey A, Williams A, Smith P (2008) UK marginal abatement cost curves for the agriculture and land use, land-use change and forestry sectors out to 2022, with qualitative analysis of options to 2050, Report No RMP4950, Committee on Climate Change, SAC.

[14] MacLeod M, Moran D, McVittie A, Rees R, Jones G, Harris D, Antony S, Wall E, Eory V, Barnes A, Topp CFE, Ball B, Hoad S, Eory L. (2010) Review and update of UK marginal abatement cost curves for agriculture. Report to Committee on Climate Change, SAC.

[15] Newell Price JP, Harris D, Taylor M, Williams JR, Anthony SG, Duethmann D, Gooday RD, Lord EI, Chambers BJ, Chadwick DR, Misselbrook TH (2011) *An Inventory of Mitigation Methods and Guide to their Effects on Diffuse Water Pollution, Greenhouse Gas Emissions and Ammonia Emissions from Agriculture.* User Guide. Prepared as part of Defra Project WQ0106. ADAS and North Wyke Research.

[16] Frelih-Larsen A, MacLeod M, Osterburg B, Eory V, Dooley E, Katsch S, Naumann S, Rees RM, Tarsitano D, Topp CFE, Wolff A, Metayer N, Molnar A, Povellato A, Bochu JL, Lasorella MV, Lonhitano D (2014) Mainstreaming climate change into rural development policy post 2013. Ecologic Institute, Berlin.

[17] https://www.farmingforabetterclimate.org/

[18] Fertilizers Europe (2011) Mineral fertilizer carbon footprint reference values. Fertilizers Europe, Brussels. www.fertilizerseurope.com

agricultural sector as part of the UK agricultural GHG inventory. A recent study[19] has suggested that methane emissions in particular may be up to 100 times higher than previously estimated where natural gas is used as the fuel source, due to supply leakages. As this study is focused on reducing the official agricultural emissions total, we have also not included an allowance for these.

There is a case that much of the nitrogen applied as synthetic or organic fertiliser is wasted as a result of leaching, denitrification and volatilisation. RSPB Scotland (2018)[20] estimated using Defra Soil Nutrient Balance data for 2017 that, in Scotland, 364 kt N were applied with 188 kt N taken up by crops and grass, and 176 kt or 92kg/ha N lost to the environment. Some of this is unavoidable as part of the normal functioning of soil ecosystems, and the crop yield to N use ratio has been improving over time, but there is clearly still potential for improvement.

By better targeting the utilisation of N for specific crops, including taking account of variability of soil nitrogen, the requirements for synthetic nitrogen use and consequent emissions can be reduced. Specific actions include soil analysis for pH control, calculation of N balances, decreasing N error margins on application and not applying N in wet/waterlogged conditions.

Eory et al. assumed that these actions could reduce nitrogen use by 10kg/ha. Given that grassland receives on average much less fertiliser N per ha, we have opted to modify this assumption to be a 10% reduction, which generates a similar result overall. We have used the published results for Scotland from the 2017 British Survey of Fertiliser Practice[21] to estimate the results for different land uses. As an indicator of the variability, 118kg N/ha was applied to tillage crops on average in Scotland in 2017, compared with 68 kg N/ha on grassland and an average of 86 kg N/ha across all crops and grass.

Moran et al. included two additional but related measures: reducing N fertiliser (by a third) and avoiding N excess use. We assume that these are (largely) covered within the context of M1.

2.3.2 M2 (E6): Controlled release fertilisers (CRF)

These are products intended to match nutrient release with crop demand by providing readily available N more slowly (over 2-6 months), reducing the potential for microbial nitrification and denitrification and hence N_2O emissions, which Eory et al. estimate to be reduced by 35%. In principle, this might also enable a reduction in fertiliser use, but this has not been assumed by Eory et al. or in this case.

In principle, CRFs could be applied to all situations where synthetic nitrogen is used, but Eory et al. excluded permanent grass (due to low fertilisation rates) and assumed 70% applicability on tillage land including rotational grass due to agronomic constraints. CRFs are not as effective on all soil types, in particular well-drained soils where reducing fertiliser water solubility will have less impact. We have assumed that controlled release fertiliser can be used on 70% of all tillage and grassland (but not rough grazing).

2.3.3 M3 (E10): Precision applications to crops

Precision farming covers a range of management practices relying on IT and remote sensing to better utilise machinery, in this case to more precisely distribute N fertiliser to crops. Although there is potential to use these techniques on grassland, we have assumed because of the lower rates of fertiliser use on grassland that they are only used on tillage land excluding fallows and rotational grass. Eory et al. assume a 20% reduction in nitrogen use on this land, which we have also assumed here.

[19] Zhou X, Passow FH, Rudek J, von Fisher HC, Hamburg SP, Albertson JD (2019) Estimation of methane emissions from the US ammonia fertilizer industry using a mobile sensing approach. *Elementa Science of the Anthropocene*, 7:19.

[20] RSPB Scotland (2018) Balancing Act: How farming can support a net-zero emission target in Scotland. http://www.scotlink.org/wp/files/documents/RSPB-Scotland-Balancing-Act-report.pdf

[21] Defra (2018) The British Survey of Fertiliser Practice: Fertiliser use in farm crops for the crop year 2017. National Statistics. https://www.gov.uk/government/collections/fertiliser-usage

There are potential interactions between M1, M2 and M3 which we have evaluated in the following chapters.

2.3.4 M4 (NP29, NP30): Urea replacement and urease inhibitor

Urea and urea-based (UAN: urea-ammonium nitrate) fertilisers are associated with higher NH_3 emissions (typically around 20% of total N applied as urea or 10% as UAN) and higher direct and indirect N_2O emissions than ammonium nitrate or calcium ammonium nitrate (CAN) fertilisers[18]. The NH_3 emissions can be reduced by substituting ammonium nitrate or other fertilisers, but with potentially increased nitrate leaching. Urease inhibitors used with urea fertilisers delay the conversion of urea to ammonium carbonate, allowing the fertiliser to be solubilised and local soil pH increases to be avoided, reducing the potential for NH_3 emissions. As NH_3 emissions are not directly included in the agricultural GHG inventory, we have not considered these options further here, although there would be some reductions in indirect N_2O emissions following reduced ammonia depositions from the atmosphere.

2.3.5 M5 (NP32): Phosphorus fertilisers

Emissions arising from the use of phosphorus fertilisers are primarily associated with processing, and not their use as such. For this reason, they are not considered to be an agricultural GHG mitigation option and we have not evaluated them further here. However, on a global level, issues of mining and transport, along with eutrophication arising from soil erosion (where phosphates are attached to soil particles) and leaching (which may become an issue when soil P index is high) may be significant. There is scope to deliver other environmental benefits by reducing P use and closing P cycles through the return of nutrients from urban to rural areas, for example through the use of sewage sludge and sewage treatment by-products such as struvite. Currently, the use of sewage sludge is discouraged for various uses, including malting barley, potatoes and organic production. Struvite, depending on the processing method, is less problematic than sludge, but yet to be recognised at EU level. Policies to address phosphorus use in Scottish agriculture may still be relevant to address the global and non-agricultural sector impacts, as well as these other environmental issues.

B. Improved use and integration of organic manures and slurries

The following three measures are closely related as improved organic N use permits reductions in synthetic N applications. Interactions between these measures are evaluated in subsequent chapters.

2.3.6 M6 (E2, FBC): Improving organic N planning

As with synthetic nitrogen (M1) there is scope for significant improvements in the utilisation of organic N sources. This includes manure/slurry analysis, the use of an N planning tool[22] to take account of manure nutrients, a decreased margin of error in manure applications, and not applying manure in very wet/waterlogged conditions. In Scotland, only 7% of farmers test the nutrient content of manure and the use of manure management plans is also limited[18]. It should however be recognised that at present analysis is not reliable for indicating the total nutrient value of manures and slurries due to the heterogenous nature of the materials.

Eory et al. assumed a reduction of 10 kg synthetic N per ha would be possible as the benefit of this approach. In order to relate the benefits to actual quantities of manure used, we have assumed the benefit to be about 0.5 kg synthetic N saved per tonne of manure/slurry applied. At typical average application rates of 20 t manure/slurry per ha, this is equivalent to Eory et al.'s 10 kg N saved/ha.

Eory et al. also assumed that 80% of tillage land and 60% of grassland was already subject to this measure, so that the potential future uptake would be restricted to a maximum of 20% tillage land and 40% grassland. We are sceptical about these assumptions, particularly with respect to nutrient analysis, and have assumed instead that almost all manure management would be capable of improvement.

[22] Such as PLANET/MANNER www.planet4farmers.co.uk

Not all land receives manure or slurry, and the use of slurry is more prevalent on dairy and pig farms than on other holdings. Although the published version of the British Survey of Fertiliser Practice only contains GB data on the use of organic manures, we were able to obtain unpublished 2017 data for Scotland from Defra Statistics, which we have used in part to better reflect the actual practices on different land types in Scotland. However, for the manure and slurry types other than for cattle, the sample sizes were too small to permit disclosure. Application rates for grassland were similar to the GB values, so GB values have been used in these situations. The major difference identified related to cattle manure and slurry use on crops, which was higher in Scotland, so we have used the Scottish data to reflect this. The higher use in Scotland is probably related to the balance of land use, with 52% of farmland cropped in England compared with 42% in Scotland, with proportionately more livestock and manures to be allocated.

There may be some interactions if M6, M1 and M2 are applied in combination, but we have not evaluated this.

2.3.7 M7 (E3): Low emission manure and slurry spreading

This involves switching to low emission spreading technologies (bandspreading, injection of slurry, incorporation of FYM within 24 hours) and other methods primarily to reduce ammonia emissions. Because the manure/slurry is incorporated in the soil, there may be some increase in N_2O emissions.

According to data from the Scottish Survey of Farm Structure and Methods, 2016[23] just over half (9.3Mt) of the total 17.2 Mt manure and slurry applied was not ploughed in or injected, representing significant scope for improvement.

Although the published version of the British Survey of Fertiliser Practice only contains GB data on the use of organic manures, we were able to obtain unpublished 2017 data for Scotland from Defra Statistics, which we have used to better reflect the actual practices with respect to cattle manure/slurry utilisation on crop land.

Based on RB209, the benefit of improved application techniques is about 0.5 kg N reduction/t manure/slurry applied. This is consistent with Eory et al.'s assumption of a 10kgN/ha fertiliser reduction benefit, using typical average manure/slurry application rates. Eory et al. assumed a 50% reduction in the ammonia volatilisation factor from 0.2 to 0.1, which we have also done.

2.3.8 M8 (E4): Shifting autumn manure applications to spring

As autumn/winter is the peak time for nitrate leaching, due to higher rainfall, low transpiration, and soils at field capacity, autumn manure applications are susceptible to leaching. Switching to spring applications means that more of the available nitrogen can be utilised by the growing crop. In nitrate vulnerable zones, restrictions on timing of applications exist to address this problem. In part as a consequence, Eory et al. assume that this measure is potentially applicable only to 2% of cattle slurry, 3% of cattle FYM, 10% of pig slurry and 23% of pig FYM.

Eory et al. assume abatement could be measured by avoided synthetic N fertiliser (estimated 10kg N/ha), although this does not account directly for nitrate leaching or the fraction of organic N volatilising. Following consultation with experts, the estimated synthetic N fertiliser reduction potential from this measure was increased by them to 50kg N/ha.

On the basis of our investigations, we believe this to be too high, although there are inconsistencies in the various data sources. Using the PLANET/MANNER models[20], one analysis[24] suggests that NO_3^- leaching losses could be reduced by the equivalent of 40 kg N/ha for 50t/ha cattle slurry applied

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[23] https://www.gov.scot/publications/scottish-survey-farm-structure-methods-2016/pages/21/.
Earlier data is available at: https://www.gov.scot/publications/results-scottish-survey-agricultural-production-methods-2010/pages/4/

[24] Think manures: a guide to manure management (page 20). Tried & Tested. NFU & partners. www.nutrientmanagement.org

(depending on timing and soil type), but the RB209 guide[25] gives a lower increase in available N for spring applied manures and slurries, equivalent to about 0.3kgN/t cattle slurry/manure and 0.6 kg N/t pig slurry/manure. A 50t application of slurry manure would only yield 15kg N benefit on this basis. To be conservative, we have used these RB209 derived values as the basis for our estimates.

Clearly the reduction in nitrate leaching provides the additional N from manures available to crops. We have not attempted to quantify the indirect N_2O emissions that might result from this leaching reduction.

C. Improved soil management

2.3.9 M9 (NP6): Cultivate land for crops in spring rather than autumn

Autumn cultivation of land, particularly when ploughing out grassland, stimulates the mineralisation of N from organic matter when there is little N uptake by the subsequent crop, resulting in increased NO_3 leaching. Delaying cultivations to the spring can reduce leaching and increase availability of the N to the following crop reducing the need for synthetic N fertiliser. Where late summer/autumn cultivations cannot be avoided, sowing a fast-growing catch crop such as mustard in the autumn to capture available N and hold it over the winter may also be relevant (see M14). The method is mainly applicable on light/medium soils prior to drilling of spring crops. According to Newell Price et al., nitrate leaching may be reduced by 20-50% (the interaction with manures (see M8) would be included at the higher end of this range).

We have assumed that the potential area for this would be equivalent to 20% of the rotational grass area, making some allowance for grass breaks of less than five years as well as some land that would already be ploughed in the spring. Various studies suggest nitrate leaching ranges from 150 to 250 kg N/ha following autumn ploughing of grass leys. We have assumed a central value of 200 kg N/ha, reduced by 25%, which would result in 50 kg less N/ha leached and 25 kg N/ha realised as fertiliser nitrogen reductions.

2.3.10 M10 (NP7, FL6, MMAN): Reduced or minimum tillage

Reduced tillage, using discs or tines to cultivate the soil surface rather than ploughing, or no-till using direct drilling or broadcasting of seed (no-till), usually in combination with herbicides, can retain soil surface organic matter and preserve good soil structure, with up to 20% reduced NO_3^- leaching as a result of reduced organic matter disturbance. While indirect N_2O emissions would be reduced, there is some evidence of increased N_2O emissions from reduced/no-till land due to increased soil moisture levels. Although organic matter is conserved compared with traditional tillage, evidence of increases has only been found in upper soil layers (top 20cm) and it is considered that any carbon sequestration benefits are short-term due to the potential for breakdown of organic matter by soil biota. In the absence of a clear basis for assumptions about abatement potential with respect to N_2O emissions, we have not considered this option further. However, there are also benefits to be realised in terms of reductions in fuel use for cultivations compared with ploughing.

We have assumed 25% reductions in diesel use, or 6 L/ha based on typical values for ploughing of 25 L/ha[26]. According to the 2016 Scottish Survey of Farm Structure and Methods[21], 669 kha or 90% of the total of 742 kha cultivated, were cultivated using inversion tillage (ploughing). Only 48 kha were cultivated using conservation tillage and 26 kha using zero tillage, representing a reduction of 37% compared with 2013.

While there are potential interactions with this measure and M18 used in combination, we have not analysed them due to the limited relevance of this measure (see Table B).

[25] Nutrient management guide (RB209) Section 2: Organic materials. AHDB Stoneleigh.

[26] Williams AG, Audsley E, Sandars DL (2006) Determining the environmental burdens and resource use in the production of agricultural and horticultural commodities. Report for Defra. Cranfield University. http://randd.defra.gov.uk/Default.aspx?Module=More&Location=None&ProjectID=11442

2.3.11 M11 (E11, NP8, NP15): Loosening compacted soils and preventing soil compaction

Compaction increases N_2O emissions and reduces the soil's ability to be a methane sink. The focus here is on cultivations, not on improving drainage to reduce waterlogging (see M12). Eory et al. assume 20% of tillage and grassland (excluding rough grazing) is compacted and 20% more is susceptible. The main abatement potential relates to soil N_2O emissions, for which Eory et al. assume a 40% reduction. We have adopted Eory et al.'s assumptions in this case for the 20% of compacted land.

2.3.12 M12: Improved drainage for reducing frequency of waterlogging

Drainage can impact emissions in different ways. By closing drains (NP15) and creating ponds and artificial wetlands for flood management and climate change adaptation, soils become waterlogged and this can be used to slow or halt the breakdown of soil organic matter, keeping carbon fixed in soils. This is one of the primary strategies for peatland restoration, but as this effectively involves taking land out of agriculture, this is outside the scope of this study. However, water-logged soils also create the conditions for denitrification and N_2O release, as well as leaching which will occur once soils have reached field capacity. With low nitrogen inputs in moorlands, this is less of an issue.

For soils remaining in agricultural production, with higher nitrogen inputs, avoiding waterlogging is desirable. M1 (above) includes avoiding applying fertilisers to wet or waterlogged soils. The focus of this measure is on the potential for improving drainage to prevent waterlogging in the first place. It needs to be recognised that some waterlogged sites will be important as biodiversity-rich, wildlife habitats where it would be undesirable to encourage new drainage, so that any drainage improvement is assumed to be addressing issues on already improved/cultivated land.

In a review[27] of agricultural drainage and potential climate change impacts in Scotland, it was found that two thirds of cultivated land with wet soils (620 kha) had been drained at some point, with wet soils on more marginal land less likely to have been drained. However, there is a lack of good quality, direct experimental evidence to be able to adequately quantify the magnitude of the potential for mitigation that could be achieved by improving farm drainage systems. (In particular this would require more direct linkage of drainage status to land use and N fertiliser inputs than is available currently.) Given the lack of direct evidence, we have not attempted to quantify this measure.

2.3.13 M13 (NP28): Nitrification inhibitors

Nitrification inhibitors are chemical compounds that temporarily reduce populations of the *Nitrosomonas* and *Nitrobacter* bacteria in the soil that are responsible for converting ammonium to nitrite and nitrite to nitrate, potentially leading to the release of N_2O and leaching. By keeping N in the ammonium form (NH_4^+), a positively charged ion, it can be held in the soil by negatively charged clay particles and organic matter. The components of synthetic N that are already in the nitrate form (NO_3^-) are not affected by this process and will still be liable to denitrification and leaching. If weather and soil conditions are not conducive to N loss by the action of these bacteria, then there will be no benefit from the use of nitrification inhibitors. There is also evidence that NH_3 and associated indirect N_2O emissions may be increased, potentially outweighing the benefits[28]. Given the uncertainties concerning their effectiveness, we have not evaluated this option further.

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[27] Lilly A, Baggaley N, Rees R, Topp K, Dickson I, Elrick G (2012) *Report on Agricultural Drainage and Greenhouse Gas Abatement in Scotland*. Prepared for ClimateXChange. James Hutton Institute and SRUC.

[28] Lam SK, Suter H, Mosier AR, Chen D (2016) Using nitrification inhibitors to mitigate agricultural N2O emission: a double-edged sword? *Global Change Biology*, 23:485-489.

D. Improved crop selection and management

2.3.14 M14 (E5): Use of catch and cover crops

Normally sown after arable crops in late summer, catch-crops reduce the risk of nitrate leaching over winter, reduce soil erosion risk, improve soil structure, provide an N source to the following crop (due to N retention or fixation in the case of legumes) and may increase soil carbon sequestration (although on a more limited basis than for example 2+ year leys).

Eory et al. assume that catch crops will precede spring-sown crops, with the maximum area limited to 34% of the spring sown crops area. We have adopted this assumption, applied to the area of spring combinable crops, potatoes, fodder crops and vegetables.

Eory et al. have assumed the main effect will be reduced nitrate leaching, with a 45% reduction in leaching fraction (from 0.3 to 0.165). We have adopted this assumption.

2.3.15 M15 (E7): Plant varieties with improved N-use efficiency

New varieties that either require less N fertiliser for the same yield, or give greater yields for same fertiliser quantity, demonstrate greater nitrogen use efficiency (NUE). This is long-term option as there are not currently any substantive breeding programmes with this focus.

Eory et al. assumed a potential 20% N fertiliser reduction benefit, although in practice the benefits may be a combination of both increased yield and a lower level of N fertiliser reduction. We have adopted the 20% N fertiliser reduction assumption, and calculated the abatement potential with respect to wheat, barley, oilseed rape, potatoes, vegetables and rotational grass.

2.3.16 M16 (E8, FBC): Grain legumes in crop rotations

(This is interpreted as equivalent to NP31, MMAA and FL5, which focus on the use of biological nitrogen fixation in rotations.)

Legumes fix nitrogen biologically and may be included as break crops in arable rotations, as in this case, or in grass mixtures (M17), including as undersown crops, or cereals overseeded into a clover base. Grain legumes (peas/beans) can be grown as main crops or intercropped with cereals (e.g. peas/barley or beans/wheat). The nitrogen fixing potential of different legumes varies widely, ranging from 50 kgN/ha for peas, 100 for beans, 150 for white clover to 250+ for red clover. Eory cites 300 kg N/ha plus, which we consider is on the high side. We assume here 150kg N fixed per ha as a central value.

Consistent with the focus of Eory et al. on grain legumes as a break crop in an arable rotation, we have assumed that no fertiliser is applied to grain legumes and that this measure can be applied on a maximum of 1/6th of the total tillage area excluding temporary grass. However, we have assumed a lower level of 20 kg/ha[29] reduction in N required for the subsequent crop (also 1/6th of tillage area excluding temp grass).

It is acknowledged that 100% uptake of grain legumes on this scale is unlikely, due to market demand and economic factors – this is considered further in subsequent chapters.

2.3.17 M17 (E9, FBC): Legume-grass mixtures (reducing requirement for synthetic N)

For an explanation of the principal mechanisms, see M16. The main legume in this case would be white clover, but could also be red clover, lucerne, sainfoin and others. White clover would be the main legume in permanent grass, most of the others would only be found in shorter-term, rotational grass mixtures.

We assume fixation rates ca. 150 kg N/ha, with no N applied to rotational or permanent grassland. Eory et al. assume a continuing 50kg N/ha requirement, but this seems high compared with the current BSFP average use figures for grassland, so we have assumed zero continuing nitrogen fertiliser use, on the 69% of permanent grassland not currently receiving fertiliser.

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[29] SRUC (2013) Nitrogen recommendations for cereals, oilseed rape and potatoes. Technical Note TN651.

There would also be some reduction in N use on first crop following rotational grass in rotation. We have assumed that the area of first crop after grass will be equivalent to 25% of the rotational grass area. The use of N on this area of tillage crops (excluding fallow and rotational grass) is reduced by 50 kg/ha. This area is reduced by 13% to reflect the proportion of rotational grazing in Scotland not currently receiving fertiliser.

There is the potential for interaction between the measures in this section, as well as with reduced tillage. We have not considered these directly at this stage, but they are considered in the conservation agriculture and organic farming measures (M34 and M35).

E. Improved mechanisation

2.3.18 M18 (E24): Fuel efficiency of mobile machinery

Given their reliance on fossil fuels, and in particular diesel, mobile farm machinery is associated with both CO_2, N_2O and NO_x emissions on farm, as well as in the manufacturing process, although the latter is not included in the calculation of agricultural greenhouse gas emissions. The fuel efficiency of farm machinery based on existing technology can be increased by:

- Changing the behaviour by farm operatives to actively manage energy (fuel use)
- Carrying out regular maintenance of all farm machinery, including inspections, repairs and maintenance to ensure that equipment operates at optimum efficiency as well as complying with recommended service schedules, appropriate tyre choice/optimum ballasting and matching of tractors and implements.
- Improving driving style using eco-driving techniques such as improved speed and gear control techniques and planning routes ahead.
- Using energy data and knowledge bases to monitor and control energy use, tracking energy consumption against influencing factors (e.g. production levels, weather conditions, workrates) to identify areas of inefficiency.

In principle this could apply to all farm machinery. We assume that the potential savings in fuel use and related GHG emissions will be 10%, based on Eory et al.'s assumptions. The Efficient 20 project[30] targeted 20% reductions, indicating that greater savings could be possible. Improvements in efficiency due to technological change over time, or switching to electric or other alternative fuel sources, are not included.

F. Improved livestock management and genetics

In addition to ensuring well-nourished, healthy animals that are not limited in their productivity, generating additional GHG emissions, there are a range of feed additives that may help to reduce methane emissions in ruminants, or ensure that better utilisation of the feed provided is achieved[31]. We have considered some but not all of the feed additives currently under discussion, with seaweed one option that we have not been able to evaluate (a red macroalgae *Asparagopsis taxiformis* is showing promising results[32]). For further information on these topics (in addition to the sources listed above) see also Gerber et al. (2013)[33].

Based on an SRUC analysis[34], the total feed demand for livestock in Scotland is about 8 Mt dry matter (DM), of which about 2 Mt DM is concentrates. The same analysis indicates that the proportion of dietary energy

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[30] Strategies for saving fuel with tractors. Efficient 20 project. https://www.swarmhub.co.uk/energy-efficiency-master/fuel-saving-stragies/

[31] Rooke JA, Miller G, Flockhart J, McDowell M, MacLeod M (2016) Nutritional strategies to reduce enteric methane emissions www.climatexchange.org.uk/media/2033/nutritional_strategies_to_reduce_enteric_methane_emissions.pdf

[32] Rogue BM et al. (2019) Effect of the macroalgae *Asparagopsis taxiformis* on methane production and rumen microbiome assemblage. *Animal Microbiome* 1(3).

[33] Gerber PJ, Steinfeld H, Henderson B, Mottet A, Opio C, Dijkman J, Falcucci A, Tempio G (2013) *Tackling climate change through livestock – A global assessment of emissions and mitigation opportunities.* Food and Agriculture Organization of the United Nations (FAO), Rome. http://www.fao.org/3/a-i3437e.pdf

[34] Crop, feed and by-product supply and use in Scotland https://www.zerowastescotland.org.uk/sites/default/files/11%20Julian%20Bell%20SAC.pdf

obtained from concentrates is 100% for pigs and poultry, 31% for dairy cattle, 21% for beef and 5% for sheep and that the shares of total energy consumption from all sources are: poultry 5%, pigs 2%, dairy 15%, beef 52% and sheep 26%. We estimate from this that the share of consumption of concentrates is: poultry 21%, pigs 8%, sheep 5%, dairy 19%, and beef 46%. Focusing on the concentrates used by ruminants specifically, 8% are used by sheep, 28% by dairy and 65% by beef. We have used these estimates in subsequent calculations.

This does not, however, take account of the embodied emissions in livestock feeds which are estimated to range from 200 kg CO_2e/t wheat (own estimate based on N fertiliser use), to 2-5t CO_2e/t mported soya[35]. These embodied emissions are not currently included in the UK GHG inventory, and have therefore not been included in this study, but are clearly relevant from a global perspective.

2.3.19 M19 (E12, FBC): Improving ruminant nutrition

The aim with this measure is to improve the digestibility of livestock feeds so as to improve growth rates and yields and reduce enteric CH_4 emissions. The measure involves getting advice from an animal nutritionist to improve the composition of diets, complemented by forage analysis and improved grazing management. Eory et al. assume this is more relevant to beef and sheep as practices are currently more advanced in the dairy sector (currently 40% and 93% adoption respectively, we have assumed an additional 40% uptake for beef and sheep), and that a 2% improvement in nutrition results in a 2% reduction in enteric CH_4 emissions, which we have also assumed.

2.3.20 M20 (E13): Probiotic feed additive

Microbials, mainly yeasts (*Saccheromyces cerevisiae*), can be fed to increase productivity and/or reduce rumen acidosis. Eory et al. relied on a yield response model where the improvement reduces at higher yields, and calculated yield improvement levels ranging from 2.7-3.0%. We have assumed for this analysis a baseline 2.5% yield improvement, generating a similar reduction in CH_4 emissions. We have applied this initially to all ruminants except calves (0-1 year) and other sheep (i.e. focusing the measure on breeding females, replacements over 1 year, animals for finishing and lambs).

2.3.21 M21 (E14): Nitrate feed additive

This involves mixing 1.5% NO_3^- homogeneously into ruminant diets, e.g. in the form of $Ca(NO_3)_2$, partly replacing non protein-N sources (e.g. urea) or high protein components like soya and also partly replacing calcium sources, in order to reduce methane emissions. Concentrated nitrates can be toxic if fed unmixed, so thorough mixing is essential, ideally as part of a total mixed ration (including forage and concentrates). Eory et al. assume that this is possible on 85% of dairy farms and 20% of beef farms. The approach is assumed not applicable to sheep and calves. We have assumed that enteric CH_4 emissions are reduced by 17.5%.

2.3.22 M22 (E15. FBC): High fat diet for ruminants (dietary lipids)

Increasing the unsaturated fatty acids content of ruminant feed can reduce enteric CH_4 emissions by controlling some rumen microbes, acting as a hydrogen sink and partially replacing feed components which are digested in the rumen with ones which are digested in the intestine. This can be achieved using whole rapeseed or linseed. There is a need to restrict excess uptake, so 3% of dry matter supplementation is assumed (adding 10% rapeseed in diet), replacing other concentrates.

This approach is not practical to use in situations where animals are grazing and not receiving concentrates, which Eory et al. assumed to be 84% of sheep farms and 54% of beef/other cattle

[35] Opio C, Gerber P, Mottet A, Falcucci A, Tempio G, MacLeod M, Vellinga T, Henderson B, Steinfeld H (2013). *Greenhouse gas emissions from ruminant supply chains – A global life cycle assessment.* Food and Agriculture Organization of the United Nations (FAO), Rome.

farms and 2% of dairy farms. We have assumed 85%, 55% and 2% for sheep, beef and dairy respectively, and that the approach would not be used on calves under 1 year old or lambs.

Eory et al. assumed that the 3% additional fat would result in a reduction of enteric CH_4 emissions by 10.1, 5.9 and 20.8% for dairy, beef and sheep, respectively. The land use change effects were assumed to be negligible if using oilseeds grown in the UK, replacing forages and concentrates mostly comprised of UK-grown cereal products.

2.3.23 M23: 3-Nitrooxypropanol (3NOP)

3NOP is a relatively recent development showing significant potential for reducing enteric methane emissions from ruminants[31]. It inhibits the enzyme involved in CH_4 synthesis by rumen bacteria. The product is not yet available commercially nor finally accepted as a feed additive by the EU. Research trials indicate a potential reduction of methane emissions by dairy cows of 30%, but with high variability ranging from 0-85%, with fibre length, dose rate and cattle type all contributing factors[36]. For every 50g fibre per kg feed, impact is reduced by 8%, but this can be countered by increasing the dose. 3NOP was also found to be less effective in beef cattle, possibly due to lower feed intake than for dairy cattle. These results suggest that it may be less useful for mainly grass-fed cattle and better suited to those with high concentrate feed diets. We have assumed a 35% reduction for dairy cattle with 80% applicability and a 20% reduction for other cattle with 40% applicability in our analysis.

There may be interactions between M20, M21, M22 and M23 as they all involve dietary manipulations. We have not identified relevant evidence relating to this and have assumed that measures will not be implemented in combination. Each of these individually could be combined with M19, but the effects are anticipated to be additive, and no specific interaction calculations have been made.

2.3.24 M24 (E16, FBC): Improving cattle health

Improving productivity including feed conversion efficiency, increasing yields and growth rate, and improved reproductive performance/reduced mortality by improving animal health could lead to significant reductions in GHG emissions.

Eory et al. based their assessment of the abatement potential on a scenario analysis undertaken by ADAS (2014)[37], which quantified the effects of a 20% and 50% movement from a reference scenario to a healthy cattle population. Eory et al. concluded that 100% healthy cattle would deliver an 11% reduction in emissions. We have adopted this assumption.

2.3.25 M25 (E17. FBC): Improving sheep health

Similar to M24, although Eory et al. make their own estimates based on the method used in ADAS (2014)[37]. They conclude that 100% healthy sheep would lead to a 30% reduction in emissions for hill sheep, 6% for upland sheep and 13% for low-ground sheep. We have assumed 13% for non-LFA sheep, and an intermediate value between hill and upland of 20% for LFA sheep.

2.3.26 M26 (E18, FBC): Selection for balanced breeding goals

By improving livestock yields and productivity, and by reducing the amount of feed and land required to deliver a given level of output, breeding has the potential to reduce GHG emissions. A recent EU report[38] concluded that "*livestock breeding could reduce European livestock GHG emissions by up to 53.5MtCO₂e by 2029, representing an 8% reduction in emissions intensity*".

[36] Dijkstra J, Bannink A, France J, Kebreab E, van Gastelen S (2018) Antimethanogenic effects of 3-nitrooxypropanol depend on supplementation dose, dietary fiber content, and cattle type. Short communication. *Journal of Dairy Science*, 101:9041-9047.

[37] 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 to Defra AC0120.

[38] MacLeod M, Leinonen I, Wall E, Houdijk J, Eory V, Burns J, Vosough Ahmadi B, Gomez Barbero M (2019) Impact of animal breeding on GHG emissions and farm economics. JRC Technical Report. European Commission.

Eory et al.'s analysis extends the previous work by Moran et al. and Macleod et al. (MMCG/BF) to include beef cattle as well as dairy cattle. Sheep or other livestock have not been included. The abatement potentials were estimated building on detailed modelling of genetic improvement.[39] Eory et al. estimated that over a period of 20 years, the number of beef cows would fall by 10% as a result of productivity improvements. The earlier studies also estimated a 10% decline in dairy cow numbers with an average yield increase of 11% per cow. We have assumed a 10% decline in beef and dairy cattle (all types) numbers for this analysis.

This reduction in cattle numbers would also imply a reduction in use of grassland, manure quantities and related emissions. We have assumed the grassland area remains unchanged, so that stocking rates are effectively reduced by 10%, and we have reduced manure storage and application, and associated indirect emissions by 10% to reflect this. Other studies have assessed the afforestation of land spared, yielding potentially greater sequestration benefits, but this is outside the scope of our review.

2.3.27 M27: Improved grazing management of cattle and sheep

Given the prevalence of grassland in Scotland (and in many other parts of the world) the issue of grazing management to mitigate emissions and enhance carbon sequestration should be of greater interest than is indicated by the previous analyses of mitigation measures used here. A useful review of the issues and possibilities has been prepared by van den Pol-van Dasselaar (2017)[40] with the EIP Focus group Grazing for Carbon's final report published in 2018[41]. This work concludes that there is evidence of carbon sequestration within grassland systems in general, but in mixed grazing/ cutting systems there is less C sequestration than in pure grazing systems, and that rotational grazing has the potential to sequester more carbon than continuous grazing. The group also investigated the potential for diversifying pastures, concluding that "increasing plant diversity in low to moderate input/output grasslands can enhance yield, nutrient use efficiency and soil organic C storage, and decrease greenhouse gas emissions both from the soil and from livestock per unit of feed intake". This conclusion is supported by Yang et al. (2019)[42].

Another review of the potential for grazing management to enhance carbon sequestration, or at least whether the enhancements are sufficient to outweigh the emissions from livestock using the grassland, has been published by FCRN[43]. This report concludes that the sequestration benefits globally potentially offset 20-60% of the emissions from grazing systems, or 4-11% of total global livestock emissions.

While there is ongoing uncertainty about the best management practices to adopt to maximise C sequestration, we have made the assumption as a starting point for this analysis that 'improved grazing management' could sequester 0.1 t C per ha per year or 2.5 t C/ha total over 25 years, by which time a new equilibrium carbon status is likely to have been reached (IPCC, 2007)[44].

There may also be scope to improve grazing management and in particular to reduce over-grazing on rough grazing and peatland to reduce carbon losses, but we have not attempted to quantify this. Options could include limiting overall stocking rates (either for a specified time period, or on a

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[39] Bioscience Network Limited (2012) Developing options to deliver a substantial environmental and economic sustainability impact through breeding for feed efficiency of feed use in UK beef cattle, Report to Defra IF0207.

[40] Van den Pol-van Dasselaar A (2017) Starting Paper for EIP-Agri Focus Group: Grazing for Carbon. https://ec.europa.eu/eip/agriculture/sites/agri-eip/files/fg_grazing_for_carbon_starting_paper_final.pdf

[41] EIP-Agri (2018) Grazing for Carbon Focus Group Final report. https://ec.europa.eu/eip/agriculture/sites/agri-eip/files/eip-agri_fg_grazing_for_carbon_final_report_2018_en.pdf

[42] Yang Y, Tilman D, Furey G, Lehman C (2019) Soil carbon sequestration accelerated by restoration of grassland biodiversity. *Nature Communications* 10 (718) https://www.nature.com/articles/s41467-019-08636-w

[43] Garnett T, Godde C, Muller A, Roos E, Smith P, de Boer I, zu Ermgassen E, Herrero M, van Middelaar C, Schader C, van Zanten H (2017) *Grazed and Confused?* Food Climate Research Network, Oxford.

[44] IPCC (2007) Climate change 2007: the physical science basis *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge: Cambridge University Press)

spot (daily) basis, or by defining stock exclusion periods). Partial afforestation or agroforestry (M36) may also be relevant. This appears to be attracting interest given the low agricultural value of rough grazing land, but may also adversely impact on sensitive sites. The Macaulay Land Capability for Agriculture classification defines four categories of rough grazing (poor, low, moderate, high value grazing from semi-natural vegetation), covering 4Mha (>50% of Scottish land area, 59% of Scottish agricultural land) but these do not necessarily indicate suitability for alternative options such as peatland restoration and agroforestry. This would merit further study.

There may be interactions between this measure and M19 (improved ruminant nutrition), but the focus of the two measures is different, with this one primarily focused on carbon sequestration, so we have not attempted to evaluate this. This measure is potentially well-suited to combination with M17 – we have assumed the combined effects will be simple sums of the two measures.

2.3.28 M28 (FL11): Precision and multiple phase feeding

Precision feeding involves optimising the nutrient content of the diet, in particular protein, to closely match the animal's requirements. Multi-phase feeding involves grouping animals according to growth stage, sex, reproductive status, exercise level so that the feed conversion ratio and nitrogen utilisation is maximised for each group. Enteric methane emissions may be reduced by maintaining a healthy rumen and by maximising microbial protein synthesis. The main effects, however, are on direct and indirect N_2O as well as NH_3 emissions from manure storage and field applications due to reduced N excretions. Although the approach can be utilised for all livestock types, its use is more common for non-ruminants as it is less easy to apply to grazing livestock.

As a starting point for this analysis, we have assumed a reduction of 10% in the nitrogen excreted by pigs and poultry and the associated emissions. There may be some interaction with measures to improve manure use and reduce requirements for synthetic N fertiliser, but we have not evaluated this due to the limited quantities involved.

G. Improved manure management

Manures and slurries are a significant source of methane and ammonia emissions, both during storage and on application.

2.3.29 M29 (E19): Slurry acidification

Slurry acidification is achieved by adding strong acids to the slurry to achieve a pH of 4.5-6.8 depending on the slurry type and the acid used. This technique is applicable to slurry stored in tanks, regardless of the livestock type. It is a highly controversial approach raising environmental and health and safety concerns and not applied in the UK, although it has been used in Denmark.

The 2016 Scottish Farm Structure and Methods Survey found 2,739 holdings (8.5% of all holdings) with slurry tanks. A further 571 holdings (19% of holdings storing slurry) stored slurry in lagoons. The technique is therefore potentially applicable to 80% of slurry storage in Scotland, a substantially higher proportion than Eory et al. reported for the whole of GB. We have adopted Eory et al. assumptions that acidification could result in a 75% reduction in the methane conversion factor for stored slurry, with a 70% decrease in the fraction of the manure N which is volatilised as ammonia. Because more N is retained for spreading on land, N_2O emissions following manure spreading can increase by 23% - we have assumed 20% in this analysis, also for increased nitrate leaching.

This issue of reductions during storage being counter-balanced by additional losses on spreading (or vice versa) is important and affects most manure management approaches. There is also a need to consider the impacts on soil organisms, in particular earthworms, that may be adversely affected by the spreading of acidic or high ammonia containing materials.

2.3.30 M30 (MMFB): Slurry store covering

The covering of slurry stores is widely encouraged by grant schemes, and increasingly used by farmers, the primary aim being to control methane and ammonia emissions and exclude rainfall, reducing the quantity of material to be spread subsequently. The 2016 Scottish Farm Structure and Methods Survey indicates that 62 % of the 3007 holdings with slurry tanks and lagoons covered their stores (compared with 12% covering manure stores). A report by Ricardo (2018)[45] identified that a total of 6.3 Mt of slurry was produced annually in Scotland, with 3.0 Mt from dairy, 2.6 Mt from beef and 0.7 Mt from pigs. These results are lower than the total 9.5Mt value for slurry obtained from the 2017 British Survey of Fertiliser Practice[22], which we have used.

Slurry stores may be covered by a range of materials, including surface covers (natural crust, light expanded clay aggregates (LECA) or straw, or by impermeable floating or rigid (wood or concrete) covers. Surface covers reduced methane emissions by 38% (Ricardo, 2018)[34], but the methane needs to be captured otherwise it will be lost when the cover is removed. Misselbrook et al. (2016) [46] however found no CH_4 reduction from LECA covering, but did record a 77% reduction in NH_3 emissions. If the slurry stores become anaerobic as a result of covering, N_2O emissions will be increased – this is particularly the case for natural covers in dry weather. Increased microbial activity in covered stores may also impact on N_2O and CH_4 emissions.

Eory et al. assessed the potential of covering slurry stores as an additional, longer-term measure and reported rigid covers reducing methane emissions by 14-18%. Their analysis was based on floating impermeable covers, with NH_3 emissions reduced by 60% but no effect on CH_4 or N_2O assumed (but with some potential for increased N_2O losses from soils following spreading), whereas Moran et al. and MacLeod et al. assumed a 20% reduction in methane emissions.

For the purposed of our analysis, we have assumed a reduction of 20% in methane and 50% in ammonia emissions from the remaining 40% of holdings with uncovered slurry tanks/lagoons – assuming a proportional distribution of slurry quantities, this would apply to 3.8 Mt of slurry, but with an increase of 50% in the NH_3 emissions on spreading.

2.3.31 M31 (E20-E22): Anaerobic digestion

Anaerobic digestion is widely considered to provide the best option to capture methane from slurries and other organic matter and to use this as a renewable fuel source, although there are concerns that the production of maize as a feedstock may be at the expense of grassland with resultant losses of stored soil carbon and other environmental impacts. In addition, the availability of nitrogen, including as ammonia, is increased, leading to potential increases in emissions on application of digestate to land.

Eory et al. assessed three anaerobic digestion options from the perspective that anaerobic digesters are built and used to treat livestock excreta that would otherwise be stored in slurry tanks or lagoons. Manure and biomass would be transported to a nearby digester from surrounding farms. The three options investigated were 250kw, 500kW and 1000kW capacity digesters. The 250 kW capacity digester, for example, would be supplied with cattle manure and maize silage (annual supply of substrate from 1,800 dairy cattle, 360 beef cattle and 5,000 fresh t maize silage). Eory et al. assumed that farms above 100 dairy cows and 100 sows would export their manures to the plants, representing 78% of UK holdings in the case of this option. Scottish agricultural statistics indicate that, if holdings with 4 or few dairy cows are excluded, only 63% of the remaining holdings have dairy herd sizes of 100 cows or more, so the UK-based assumptions may overstate the potential.

The abatement potential includes the reduced emissions from storage and replaced emissions from energy production. However, while ammonia emissions from storage low, on spreading they are higher than from slurry and other sources. As the calculations undertaken for this option by Eory et

[45] Ricardo (2018) Slurry Storage on Scottish Farms – a Feasibility Study. Report for ClimateXChange. Ricardo Energy & Environment, Harwell

[46] Misselbrook TH, Hunt J, Perazzolo F, Provolo G (2016) Greenhouse Gas and Ammonia Emissions from Slurry Storage: Impacts of Temperature and Potential Mitigation through Covering (Pig Slurry) or Acidification (Cattle Slurry). Journal of Environmental Quality 45(5)

al. are more complex we have adopted their final Scottish abatement potential (AP) estimates of 18, 4 and 10 kt CO_2e per year for the 250kW, 500kW and 1000kW variants respectively.

2.3.32 M32: Slurry aeration

Low frequency aeration of slurries can reduce methane (CH_4) emissions without increasing nitrous oxide (N_2O) emissions[45]. Aeration encourages microbial activity in the slurry, fixing some of the nitrogen as microbial protein, which when spread is gradually broken down. Increased levels of ammonia may be lost during the aeration process, but this is usually associated with reduced ammonia losses on spreading, and reduced impacts on soil organisms including earthworms, also linked to the increased pH of the slurry following aeration. Aeration also reduces pathogen levels in slurry. One study[47] found NH_3 emissions increased by 20% while CH_4 emissions were reduced by 40% following aeration, with no relevant effects detected for CO_2 and N_2O. We have used these figures for our assumptions, as well as an increase of 20% in ammonia volatilisation on spreading.

We have been unable to find any reliable data on the extent of slurry aeration adoption in Scotland or the UK, but we believe it to be more widely adopted for pig than for cattle slurry storage. As a starting point, we have assumed that 5% of cattle slurry and 10 % of pig slurry is aerated, but this may be modified as the study progresses.

2.3.33 M33: Composting/covering of farmyard manures and other solid organic wastes

Composting is a process of aerobic treatment of solid organic materials, with turning by various means used to encourage aeration. During the process the bacteria involved will break down organic matter, releasing energy and increasing the temperature of the compost (up to 70°C). Available nitrogen will be utilised by the bacteria for growth and reproduction, becoming incorporated in microbial protein. The rate of breakdown and warming will be affected by frequency of turning, the carbon:nitrogen ratio of the starting material, the addition of water to replace water evaporated as a result of warming, and the protection by covering from excess water that might lead to leaching. While the focus here is on materials generated on farm, the potential benefits could be extended to include green-waste, mixed composts and other materials from urban areas.

Sanchez et al. (2015)[48] have undertaken a detailed review of GHG emissions associated with composting. They identified that, while there is potential to reduce CH_4 emissions, the act of turning in open composting systems, such as windrows common with farmyard manure management, can result in increased emissions of ammonia and N_2O. This could be reduced by avoiding turning early in the composting process, or by using closed systems where the gases can be captured. The capital investments required for closed systems are high and tend to be restricted to municipal waste composting systems.

Manure management and GHG emissions have also been reviewed by Petersen et al. (2013)[49], who identified significant potential from both covering and composting. Amon et al. (2001)[50] directly compared composted (aerobic) versus stacked (anaerobic) manure. Total ammonia emissions were higher for composted manure (25% in summer, 150% in winter, but most of this was during storage with only a small amount on turning and negligible amounts on spreading. Stacked manures had much lower ammonia emissions during storage, but more on spreading, in total still less than

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[47] Calvet S, Hunt J, Misselbrook TH (2017) Low frequency aeration of pig slurry affects slurry characteristics and emissions of greenhouse gases and ammonia. *Biosystems Engineering* 159:121-132

[48] Sánchez A, Artola A, Font X, Gea T, Barrena R, Gabriel D, Sanchez-Monedero MA, Roig A, Cayuela ML, Mondini C (2015) Greenhouse Gas from Organic Waste Composting: Emissions and Measurement. Chapter 2 in: E. Lichtfouse et al. (eds.), *CO2 Sequestration, Biofuels and Depollution, Environmental Chemistry for a Sustainable World*, Springer International Publishing, Switzerland.

[49] Petersen SO, Blanchard M, Chadwick D, Del Prado A, Edouard N, Mosquera J, Sommer SG (2013) Manure management for greenhouse gas mitigation. *Animal*, 7: 266-282.

[50] Amon B, Amon T, Boxberger J, Alt C (2001) Emissions of NH_3, N_2O and CH_4 from dairy cows housed in a farmyard manure tying stall (housing, manure storage, manure spreading). *Nutrient Cycling in Agroecosystems* 60**:**103-113.

composted. N_2O emissions were reduced by 35-40% with composting, Methane emissions were reduced by 90% with composting in summer, but increased by 30% in winter, presumably an effect of reduced microbial activity and higher moisture contents.

Moran et al. and MacLeod et al. considered the option (MMAO) of switching from slurry to composted manure, but raised concerns about high capital costs of housing modifications and where the straw would be sourced from. Their analysis focused on the reduction of N_2O emissions on soil application, again illustrating that higher losses during treatment might be compensated by lower losses on application. Newell Price et al. (NP59) also highlighted increased CO_2 emissions during composting but did not mention that fresh manures applied to soils would also release CO_2 as the organic matter is broken down.

In practice, few farmers actually compost solid farmyard manures (FYM), more frequently stockpiling it uncovered with restricted opportunities to capture run-off and avoid leaching. For the purposes of this study, we have assumed that the focus should be on improved management of existing FYM stocks by composting and covering or storing so run-off can be captured. As a starting point for the analysis, we have assumed that net storage and application emissions are reduced by 40% for CH_4, and by 20% for N_2O, but there is no net impact on CO_2 emissions. Ammonia emissions during are assumed to increase in total by 80%, but to be reduced by 80% on application. Only 11.7% of solid manures stores (on 720 of 6178 holdings) were reported as being covered in the 2016 Scottish Survey of Farm Structures and Methods, so there is significant potential for improvement. We have assumed that 90% of the 7.35 Mt of solid manures generated on Scottish farms (estimated from BFS data) could be processed in this way. These reduction estimates should be treated with considerable caution given the uncertainties involved.

H. Improved systems design

While all the practices outlined above can contribute to GHG mitigation, it is relevant also to consider what role defined systems-based approaches might contribute. These approaches have been developed with a wider range of environmental and social benefits in mind, in some cases associated with defined marketing standards to help ensure continuing financial viability. The potential of these approaches to contribute to GHG mitigation has been reviewed by the authors of this report in 2015[51], 2016[52] and 2018[53]. They have also been emphasised in the recent IPCC report[54], which concluded in its *Summary for Policy Makers* that "Sustainable land management … can prevent and reduce land degradation, maintain land productivity, and sometimes reverse the adverse impacts of climate change on land degradation (very high confidence). It can also contribute to mitigation and adaptation (high confidence)." We focus in this section on four of the options covered by these reports. The impacts of shift from intensive pig and poultry production to free

[51] Lampkin N, Pearce BD, Leake AR, Creissen H, Gerrard CL, Girling R, Lloyd S, Padel S, Smith J, Smith LG, Vieweger A, Wolfe MS (2015) *The role of agroecology in sustainable intensification.* Report for the Land Use Policy Group. Organic Research Centre, Elm Farm and Game & Wildlife Conservation Trust.

[52] Lampkin N, Smith J and Smith L (2016) Agroecology and Organic Farming as Approaches to Reducing the Environmental Impacts of Agricultural Chemicals. In: Hester R (ed.) Agricultural Chemicals and the Environment. Royal Society of Chemistry; Cambridge. pp 94-113.

[53] Smith L, Lampkin N (2019) Greener farming: managing carbon and nitrogen cycles to reduce greenhouse gas emissions from agriculture. In: Letcher TM (ed.) *Managing Global Warming. An Interface of Technology and Human Issues.* Academic Press, London. pp 553-577.

[54] IPCC (2019) *Climate Change and Land.* Special report on climate change, desertification, land degradation, sustainable land management, food security and greenhouse gas fluxes in terrestrial ecosystems. https://www.ipcc.ch/report/srccl/. In this report, sustainable land management is defined as "the stewardship and use of land resources, including soils, water, animals and plants, to meet changing human needs, while simultaneously ensuring the long-term productive potential of these resources and the maintenance of their environmental functions. Examples of options include inter alia agroecology (including agroforestry), conservation agriculture and forestry practices, crop and forest species diversity, appropriate crop and forest rotations, organic farming, integrated pest management, the conservation of pollinators, rainwater harvesting, range and pasture management, and precision agriculture systems.

range production would also be relevant in this context, but we have not addressed this given the relatively low significance of pig and poultry production in Scotland.

2.3.34 M34: Conservation agriculture

Conservation agriculture is an approach to arable production that involves three key elements: extended, more diverse rotations, the use of catch-crops and reduced/zero tillage. For the purposes of this analysis, we have assumed that this can be represented by a combination of four of the measures: M1 (improved synthetic N utilisation), M10 (reduced tillage, M14 (catch crops) and M16 (grain legumes in crop rotations) – with the benefits associated with these measures. As the focus is on specialist arable systems, we have applied this to tillage land only, excluding rotational grass.

2.3.35 M35: Organic farming

Organic farming involves the replacement of synthetic nitrogen completely with nitrogen sourced from biological N fixation by legumes and from organic manures (mainly if not exclusively recycled). It also avoids the use of most pesticides/fungicides and all herbicides where reductions in manufacturing emissions would be relevant. Although associated with lower yields, the higher prices paid for certified organic products (certification is a legal requirement) and agri-environmental support payments, enable organic farmers to achieve similar incomes to their conventional counterparts. A recent review[55] has revisited the complex question of N_2O emissions and nitrate leaching from organic arable rotations.

We have represented organic farming in this analysis by a combination of the following: no synthetic nitrogen; livestock stocking rates reduced by 20% per grassland ha, and an increase in the proportion of grassland on different farm types. The overall effect is calculated to be 20% of the current tillage area converted to rotational grassland (at 7 tCO_2e/ha/year carbon stock change[56]), with individual tillage crops reduced proportionately. This mitigates the stocking rate reductions, so that cattle and sheep numbers fall by 10% and other livestock numbers are assumed to remain constant, with the additional grassland used to support free range production.

In principle, it would also be relevant to include M9 (cultivate in spring rather than autumn – for 50% of potential area), M14 (cover crops), M16 (grain legumes in crop rotations), M17 (legumes in grassland) and M33 (composting). However, as the benefits from most of these measures are linked to reduced N fertiliser use, this would be double counting, so we have not done this.

2.3.36 M36 Pasture-fed livestock production

The principle of pasture-fed livestock production is that ruminant livestock are fed entirely on grass and other forages, with no grain or other concentrated feeds fed. While N fertilisers can be used in such systems, there is greater interest in the use of clovers in grassland on these farms (M17). This avoids the importing of embodied emissions on to farms and has quality benefits for the meat and milk produced. A voluntary certification scheme is in place for pasture-fed livestock[57].

The GWP implications are complex to assess. The elimination of concentrate feeds and their replacement by forage will tend to increase methane emissions due to the lower digestibility of the forage and potentially also due to longer finishing periods. Hristov *et al.* (2013)[58] review a number of studies that have investigated the effect of concentrate feeds on greenhouse gas emissions.

[55] Hansen S, Frøseth RB, Stenberg M, Stalenga J, Olesen JE, Krauss M, Radzikowski P, Doltra J, Nadeem S, Torp T, Pappa V, Watson C (2019) Reviews and syntheses: Review of causes and sources of N_2O emissions and NO_3 leaching from organic arable crop rotations. *Biogeosciences*, 16:2795-2819.

[56] ECCP (undated) Working Group Sinks Related to Agricultural Soils. Final report. European Climate Change Programme. https://ec.europa.eu/clima/sites/clima/files/eccp/second/docs/finalreport_agricsoils_en.pdf

[57] https://www.pastureforlife.org/

[58] Hristov AN, Oh J, Lee C, Meinen R, Montes F, Ott T, Firkins J, Rotz A, Dell C, Adesogan C, Yang W, Tricarico J, Kebreab E, Waghorn G, Dijkstra J, Oosting SJ (2013) Mitigation of greenhouse gas emissions in livestock production: a review of technical options for non-CO_2 emissions. Animal Health and Production Paper, 177. FAO, Rome.

They conclude that the decrease in enteric CH_4 emissions is greatest when concentrates are included above 35-40% of dry matter intake. This depends on inclusion level, production response, effects on fibre digestibility, rumen function, milk fat content, plane of nutrition, type of grain and grain processing. They also found that supplementation with small amounts of concentrate feeds increased animal productivity and thus reduced emissions, although absolute CH_4 emissions may not be reduced. Despite these potential gains, they concluded that concentrate supplementation cannot be a feasible substitute for high-quality forage for ruminants. In addition, in many parts of the world, this may not be an economically feasible and socially acceptable mitigation option.

On the plus side, nitrogen fertiliser use is typically lower on grassland than on crops. The continued use of land as grassland in marginal areas, conversion from arable to grassland and improved grazing management (M26) that would be implied can all contribute to carbon sequestration and thus higher carbon stocks. There would also be a need to consider the embodied emissions associated with imported feeds (see section 2.3.19 above).

It is not yet clear whether there is a net benefit or cost to this approach and we have not attempted further evaluation for this study.

2.3.37 M37 (E6.3): Agroforestry

Agroforestry is a term that covers a wide range of combinations of crop and/or livestock production with trees and other woody perennials, that may be utilised for fruit, nuts, energy, tree fodder or timber. Combinations of trees, pasture and grazing livestock may be less structured in terms of tree placement, with options ranging from grazed woodlands to parklands and traditional orchards. On cropped land in the UK, alley cropping systems that permit mechanisation are more prevalent with trees grown in rows usually at 20-24 m spacings. At these spacings, and assuming the tree rows are ca. 3 m wide, about 10% of the land will be allocated to trees and the remainder of the field to agricultural production. Agroforestry systems are typically developed on a field-by-field rather than a whole farm basis.

The potential of agroforestry to contribute to climate change mitigation has been evaluated by a number of studies[50,52,59,] as well as the recent EU-funded Agforward research programme[60] and Eory et al. The main benefits of agroforestry are considered to be with respect to carbon sequestration, as well as climate adaptation (through the provision of shelter, soil protection and more hospitable micro-climates). In terms of productivity, while 10% of the land may be taken up by trees, agroforestry systems are typically more productive in terms of total biomass due to the better utilisation of water and soil resources and sunlight during the growing season. Trees can also capture ammonia emissions from livestock installations.

The literature on carbon sequestration potential contains wide estimates, from 0.1-3.0 t C/ha/yr over 60 years (Palma et al., 2007)[61]. Eory et al.'s analysis builds on an assumption of 2t C/ha/year or 7.34t CO_2e/ha/year, which we have adopted. There may also be mitigation impacts of not fertilising the 10% of fields in tree lines, or reducing fertiliser requirements through the use of leguminous trees like Alder, but the evidence on this is limited.

We have assumed that the adoption of agroforestry would exclude rough grazing on the basis of the reviews covered above. However, Perks et al. (2018)[58] have considered some specific options for rough grazing including upland wood pasture (single trees or clusters), native Scots pine woodland, low productivity native broadleaf and multi-purpose broadleaf and conifers on the

[59] Perks M, Khomik M, Bathgate S, Chapman S, Slee W, Yelurlpati J, Roberts D, Morison J (2018) Agroforestry in Scotland: potential benefits in a changing climate. https://www.climatexchange.org.uk/media/3312/agroforestry-in-scotland-potential-benefits-in-a-changing-climate.pdf

[60] https://www.agforward.eu/index.php/en/

[61] Palma JHN, Graves AR, Bunce RGH, Burgess PJ, De Filippi R, Keesman KJ, van Keulen H, Liagre F, Mayus M, Moreno G, Reisner Y, Herzog F (2007) Modelling environmental benefits of silvoarable agroforestry in Europe. *Agriculture, Ecosystems & Environment* 119:320-334.

better land. Given the interest in and potential benefits of trees in at least some rough grazing land (see also M26), this issue would benefit from further study.

I. Reducing food losses and food waste

Globally, it has been estimated that one-third of the food produced is lost or wasted[62]. If this waste could be avoided, we could produce one third less food and meet the 35% emissions reduction target set for this study without requiring any other actions. This would also open up opportunities for landuse changes (from agriculture to grassland, afforestation, rewilding, peat bog restoration) that would contribute to carbon sequestration.

Of course, the story is much more complex, because not all the sources of loss and wastage are within a farmer's control, and there are significant variations between countries, stages in the production/consumption process and individual commodities.

Food losses are usually defined as crops and livestock produced, but lost before a food product that can be consumed is created. Unharvested crops, storage losses due to pests and diseases, gradeouts on farms and in packhouses, and losses in abattoirs and processors are counted as losses rather than waste.

A new report by WRAP (2019)[63] includes the concept of food surplus alongside food losses from farms. Food surplus covers products that for various reasons are not marketed for human consumption but are mainly used as livestock feed. In some cases, this may include gradeouts from packing and processing by-products, but it is not clear whether some of the surplus defined was primarily intended for livestock use in the first place (e.g. milk to feed calves and cereals). 3.2% (1.6 Mt) of total food harvested in the UK is estimated to be wasted, of which 54% are horticultural crops and 30% cereals, and 4% of the total food harvested is surplus food fed to livestock. The UK % wastage losses are substantially lower than the estimates in other sources reviewed here.

Once food products have been created and enter the marketing chain, including wholesalers, retailers and the end consumer, then losses at this stage are defined as food waste. Dietary issues are also important in this context, as overnutrition and obesity can also be considered as food waste[64].

It is assumed that farmers have some potential at least to influence the level of food losses, but not food waste or over-consumption as this is primarily in the control of agents beyond the farm gate. However, on a global level food loss on farms is proportionally much greater than other sources of loss or waste[65].

In Europe, on average 280 kg per capita food is lost or wasted, of which 95 kg on average is at the consumer end, but there is higher consumer waste for certain commodities such as cereals (Table A)[47].

Table A: Food losses and waste (% of total losses) at different levels of the European food supply chain by commodity[50] and in the UK[51]

	All foods (kg/ha)	Cereals (%)	Roots/ tubers (%)	Oilseeds and pulses (%)	Fruit and veg. (%)	Meat (%)	Dairy (%)	UK all foods (%)
Consumer	85	22	10	3	13	10	6	60
Distribution		2	4	1	8	3	1	11
Processing		5	11	4	1	5	1	16
Post-harvest		3	7	1	4	1	-	-
Agriculture		2	20	10	20	3	4	13
Total losses	280	34	52	19	46	22	12	n/a

62 Gustavsson J, Cederberg C, Sonesson U, van Otterdijk R, Meybeck A (2011) Global food losses and food waste– Extent, causes and prevention. Food and Agriculture Organization of the United Nations (FAO), Rome

63 WRAP (2019) Food waste in primary production in the UK. http://www.wrap.org.uk/sites/files/wrap/Food_waste_in_primary_production_in_the_UK_0.pdf

64 Alexander P, Moran D (2017) Rethinking food waste for a healthier planet. *Lancet Planetary Health*, 1.

65 Alexander P, Brown C, Arneth A, Finnigan J, Moran D, Rounsevell MDA (2017) Losses, inefficiencies and waste in the global food system. *Agricultural Systems* 153:190–200.

The relatively low level of dairy output lost on farms has been confirmed in a more recent study[66], which estimate 1.8% of milk lost on farms, including 0.55% not retained (e.g. after antibiotic use), 0.66% linked to on-farm consumption, 0.5% lost during on-farm storage, and 0.09% at point of transfer from tanker to processor.

The Scottish Government's climate change plan[67] (February 2018) commits to reduce Scotland's food waste by 33% by 2025. This target includes both avoidable and unavoidable food waste, focusing on prevention ahead of food waste recycling, where the food has already been wasted. A food waste reduction action plan[68], developed in partnership with Zero Waste Scotland, was published in April 2019.

[66] March M, Toma L, Haskell M, Thompson B (2019) Milk loss in primary production on Scottish dairy farms. SRUC presentation to Agricultural Economics Society conference, Warwick University.

[67] https://www.gov.scot/publications/scottish-governments-climate-change-plan-third-report-proposals-policies-2018/

[68] https://www.gov.scot/publications/food-waste-reduction-action-plan/

2.4 Summary of 100% abatement potential of each measure

This section summarises our estimates of the potential impact of a maximum 100% adoption of each measure, given the assumptions outlined above. In the next section, we analyse the cross-impact on other private and public benefits. In Chapter 3, we assess the applicability, barriers to uptake and timescales for adoption of the different measure, so as to determine the actual potential contribution to the 35% reduction by 2045 target.

The measures analysed could, individually, contribute to mitigating almost 100% of 2017 agricultural GHG emissions in Scotland. However, the measures cannot necessarily all be used in combination and it is unlikely that the 100% uptake represented in this table can be achieved in practice.

Table B: Estimated GHG emission impacts of each measure (Part 1 of 2)

Values in kt CO_2e, calculated using IPCC Tier 1 methodology		Total (both tables)	1A4 Emissions from machinery	2D1 Emissions from lubricant use	3A1 Enteric fermentation from cattle	3A2 Enteric fermentation from sheep	3A3 Enteric fermentation from swine	3A4 Enteric fermentation from other livestock	3B11,12 CH_4 emissions from manure management (cattle)	3B13 CH_4 emissions from manure management (swine)	3B134 CH_4 emissions from manure management (other)	3B21,22 N_2O emissions from manure management (cattle)	3B23 N_2O emissions from manure management (swine)	3B24 N_2O emissions from manure management (other)	3B25 Indirect N_2O emissions from manure management
Reported values 2017 GHG Inventory Scotland		7,565	770	0	2,748	909	12	38	509	42	35	333	19	37	53
Potential savings with 100% uptake of all options and no interactions or exclusions		7,488	101	0	1,701	503	0	0	273	5	4	71	0	0	1
Potential savings as % of 2017 values		99%	13.1%	0.0%	61.9%	55.3%	0.0%	0.0%	53.6%	11.4%	11.7%	21.5%	0.0%	0.0%	2.1%
ID	***Description***														
M1	Improving synthetic N use	100													
M2	Controlled release fertilisers	252													
M3	Precision fertiliser applications	82													
M4	Urea replace/inhibitors	n/a													
M5	P fertiliser reduction	n/a													
M6	Better organic N planning	58													
M7	Low emission spreading	68													
M8	Spring manure application	1													

Values in kt CO_2e, calculated using IPCC Tier 1 methodology		Total (both tables)	1A4 Emissions from machinery	2D1 Emissions from lubricant use	3A1 Enteric fermentation from cattle	3A2 Enteric fermentation from sheep	3A3 Enteric fermentation from swine	3A4 Enteric fermentation from other livestock	3B11,12 CH_4 emissions from manure management (cattle)	3B13 CH_4 emissions from manure management (swine)	3B134 CH_4 emissions from manure management (other)	3B21,22 N_2O emissions from manure management (cattle)	3B23 N_2O emissions from manure management (swine)	3B24 N_2O emissions from manure management (other)	3B25 Indirect N_2O emissions from manure management
M9	Spring crop cultivations	14													
M10	Reduced/zero tillage	12	12												
M11	Reduced soil compaction	58													
M12	Improved drainage	n/a													
M13	Nitrification inhibitors	n/a													
M14	Catch and cover crops	9													
M15	Improved N-use varieties	100													
M16	Legumes in rotations	77													
M17	Legumes in grassland	540													
M18	Fuel use efficiency	77	77												
M19	Better ruminant nutrition	74			46	28									
M20	Probiotic feed additive	14			12	2									
M21	Nitrate feed additive	145			145										
M22	High fat (lipid) diet	118			95	22									
M23	3NOP feed additive	265			265										
M24	Improve cattle health	308			308										
M25	Improve sheep health	269				269									
M26	Breeding selection	330			280				42			1			1
M27	Improved grazing management	484[a]													
M28	Precision feeding	1											0	0	0
M29	Slurry acidification	67							65	2		2	0		

Values in kt CO_2e, calculated using IPCC Tier 1 methodology		Total (both tables)	1A4 Emissions from machinery	2D1 Emissions from lubricant use	3A1 Enteric fermentation from cattle	3A2 Enteric fermentation from sheep	3A3 Enteric fermentation from swine	3A4 Enteric fermentation from other livestock	3B11,12 CH_4 emissions from manure management (cattle)	3B13 CH_4 emissions from manure management (swine)	3B134 CH_4 emissions from manure management (other)	3B21,22 N_2O emissions from manure management (cattle)	3B23 N_2O emissions from manure management (swine)	3B24 N_2O emissions from manure management (other)	3B25 Indirect N_2O emissions from manure management
M30	Slurry store covering	9							9	0					1
M31a	Anaerobic digestion (250kW)	18													
M31b	Anaerobic digestion (500kW)	4													
M31c	Anaerobic digestion (1000kW)	10													
M32	Slurry aeration	42							41	1					-1
M33	Compost/cover solid manures	20							16	1	4	1	0	0	-6
M34	Conservation agriculture	143	12												
M35	Organic farming	1,827[b]			275	91			51			33			5
M36	Pasture-fed livestock	n/a													
M37	Agroforestry	1,897[a]			275	91			51			33			
I	Food loss reduction	n/a													

[a] M27 and M37: contribution estimated due to carbon stock change, will reach new equilibrium post 2040 with no further benefits expected.

[b] M35 includes 735 kt contribution from carbon stock change resulting from 20% of current tillage area converted to rotational grassland, new equilibrium expected after 20 years

Table B: Estimated GHG emission impacts of each measure (Part 2 of 2)

Values in kt CO_2e, calculated using IPCC Tier 1 methodology		Total (both tables)	3D11 Direct emissions from inorganic nitrogen fertilisers	3D12 Application of animal manures to soils (cattle)	3D12 Application of animal manures to soils (other)	3D12 Application of sewage sludge	3D13 Urine and dung deposited by grazing animals	3D21 Atmospheric deposition	3D22 Nitrogen leaching and run-off	3H Urea application	3G Liming	3D14 Crop residues	3D15 Mineralisation soil organic matter	3D16 Cultivation of organic soils
Reported values 2017 GHG Inventory Scotland		7,565	610	103	19	10	162	58	225	25	222	193	193	239
Potential savings with no interactions		7,488	1,750	22	0	0	35	124	210	17	0	19	735	0
Potential savings as % of 2017 values		99%	287.0%	20.9%	0.2%	1.1%	21.4%	212.3%	93.4%	68.4%	0.0%	10.0%	380.8%	0.0%
ID	***Description***													
M1	Improving synthetic N use	100	72					7	16	5				
M2	Controlled release fertilisers	252	252											
M3	Precision fertiliser applications	82	62					6	14					
M4	Urea replace/inhibitors	n/a												
M5	P fertiliser reduction	n/a												
M6	Better organic N planning	58	41					4	9	3				
M7	Low emission spreading	68	22					40	5	1				
M8	Spring manure application	1	1					0	0					
M9	Spring crop cultivations	14	5					0	8					
M10	Reduced/zero tillage	12												
M11	Reduced soil compaction	58	58											
M12	Improved drainage	n/a												
M13	Nitrification inhibitors	n/a												
M14	Catch and cover crops	9							9					
M15	Improved N-use varieties	100	76					8	17					
M16	Legumes in rotations	77	58					6	13					
M17	Legumes in grassland	540	404					40	91	4				

Values in kt CO_2e, calculated using IPCC Tier 1 methodology		Total (both tables)	3D11 Direct emissions from inorganic nitrogen fertilisers	3D12 Application of animal manures to soils (cattle)	3D12 Application of animal manures to soils (other)	3D12 Application of sewage sludge	3D13 Urine and dung deposited by grazing animals	3D21 Atmospheric deposition	3D22 Nitrogen leaching and run-off	3H Urea application	3G Liming	3D14 Crop residues	3D15 Mineralisation soil organic matter	3D16 Cultivation of organic soils
M18	Fuel use efficiency	77												
M19	Better ruminant nutrition	74												
M20	Probiotic feed additive	14												
M21	Nitrate feed additive	145												
M22	High fat (lipid) diet	118												
M23	3NOP feed additive	265												
M24	Improve cattle health	308												
M25	Improve sheep health	269												
M26	Breeding selection	330		3			2	1	1					
M27	Improved grazing management	484[a]												
M28	Precision feeding	1			0	0		0	0					
M29	Slurry acidification	67		-2	0			0	0					
M30	Slurry store covering	9						0						
M31a	Anaerobic digestion (250kW)	18												
M31b	Anaerobic digestion (500kW)	4												
M31c	Anaerobic digestion (1000kW)	10												
M32	Slurry aeration	42						0						
M33	Compost/cover solid manures	20						3						
M34	Conservation agriculture	143	91					9	27	4				
M35	Organic farming	1,827	610	10			16						735	
M36	Pasture-fed livestock	n/a												
M37	Agroforestry	1,897[a]		10			16					19		
I	Food loss reduction	n/a												

2.5 *Impacts on other private and public benefits*

The measures proposed potentially have impacts on other issues that are of importance to farmers and policy-makers. We have relied here on a process of expert judgement to indicate the potential impacts that could be relevant, without undertaking an in-depth quantitative assessment, except in the case of farm profitability which is the focus of Chapter 4. Where there are significant synergies or conflicts between GHG reduction and other objectives, this is taken account of in the prioritisation of measures in Chapter 3.

Table C: Farm-level and wider impacts

ID	*Impact* / *Description*	*Yields*	*Animal welfare*	*Bio-diversity*	*Air (NH_3, NO_x)*	*Soil health*	*Water quality*	*Conserve resource*	*Social*
M1	Improve synthetic N use	↔[a]	↔	↔↑[m]	↔	↑[m]	↑[y]	↑[α]	↔
M2	Controlled release ferts	↔[a]	↔	↔↑[m]	↔	↑[m]	↑[y]	↑[α]	↔
M3	Precision fert application	↔[a]	↔	↔↑[m]	↔	↑[m]	↑[y]	↑[α]	↔
M4	Urea replace/inhibitors	↔[a]	↔	↔↑[m]	↔	↑[m]	↑[y]	↑[α]	↔
M5	P fertiliser reduction	↔[a]	↔	↔↑[m]	↔	↑[m]	↑[y]	↑[αβ]	↔
M6	Better organic N plan	↔[a]	↔	↔↑[m]	↔	↑[m]	↑[y]	↑[α]	↔
M7	Low emission spreading	↔[a]	↔	↓[n]	↑[u]	↓[n]	↑[y]	↑[α]	↔
M8	Spring manure applics	↔[a]	↔	↔↑[m]	↔	↑[m]	↑[y]	↑[α]	↔
M9	Spring crop cultivations	↔[a]	↔	↑[o]	↔	↑[m]	↑[y]	↑[α]	↔
M10	Reduced/zero tillage	↔[a]	↔	↑[p]	↔	↑[px]	↑[y]	↑[αγ]	↔
M11	Reducing soil compaction	↔[a]	↔	↑[p]	↔	↑[p]	↔	↑	↔
M12	Improved drainage	↔[a]	↑	↓[θ]↑[p]	↔	↑[p]	↓	↔	↔
M13	Nitrification inhibitors	↔[a]	↔	↓[q]↑[m]	↔	↓[q]↑[m]	↑[y]	↑[α]	↔
M14	Catch/cover crops	↔[a]	↔	↑[r]	↔	↑[x]	↑[f]	↑[α]	↔
M15	Improved N use varieties	↔[a]	↔	↔↑[m]	↔	↑[m]	↑[y]	↑[α]	↔
M16	Legumes in rotations	↔[a] ↓[b]	↔	↑[r]	↔	↑[m]	↑[f]	↑[α]	↔
M17	Legumes in grassland	↔[a] ↓[c]	↑↓[h]	↑[r]	↔	↑[x]	↑[f]	↑↑[α]	↔
M18	Fuel use efficiency	↔	↔	↔	↑[v]	↔	↔	↑[γ]	↑[ε]
M19	Better ruminant nutrition	↔[d]	↑[h]	↔	↔	↔	↑[y]	↑[δ]	↔
M20	Probiotic feed additives	↔[d]	↑[h]	↔	↔	↔	↑[y]	↑[δ]	↔
M21	Nitrate feed additives	↔[d]	↓[h]	↔	↔	↔	↑[y]	↑[δ]	↔
M22	High fat (lipid) diets	↔[d]	↑↓[h]	↔	↔	↔	↑[y]	↑[α]	↔
M23	3NOP feed additive	↔	↔	↔	↔	↔	↔	↔	↔
M24	Improve cattle health	↔[d]	↑[h]	↔	↔	↔	↔	↑[δ]	↔
M25	Improve sheep health	↔[d]	↑[h]	↔	↔	↔	↔	↑[δ]	↔
M26	Breeding selection	↑	↑↓[i]	↔	↔	↔	↑[l]	↑[δ]	↔
M27	Improved grazing managem.	↔	↑[h]	↑[s]	↔	↑[x]	↑[z]	↑[δ]	↔

ID	Impact Description	Yields	Animal welfare	Bio-diversity	Air (NH_3, NO_x)	Soil health	Water quality	Conserve resource	Social
M28	Precision feeding	↔[d]	↑[h]	↔↑[m]	↔	↑[m]	↑[y]	↑[α]	↔
M29	Slurry acidification	↔[a]	↔	↓[n]	↑[u]	↓[n]	↓[y]	↑[α]	↔
M30	Slurry store covering	↔[a]	↔	↓[n]	↓[u]	↓[n]	↓[y]	↑[α]	↔
M31	Anaerobic digestion	↔[a]	↔	↓[n]	↓[u]	↓[n]	↓[y]	↑[α]	↔
M32	Slurry aeration	↔[a]	↔	↑[p]	↑[u]	↑[p]	↑[y]	↑[α]	↔
M33	Compost/cover solid manure	↔[a]	↔	↑[p]	↑[u]	↑[p]	↑[y]	↑[α]	↔
M34	Conservation agriculture	↔[a]	↔	↑[pr]	↔	↑[px]	↑[y]	↑[αγ]	↑[ζ]
M35	Organic farming	↓[e]	↑[i]	↑[pr]	↑[u]	↑[px]	↑[y]	↑[αβγδ]	↑[εζη]
M36	Pasture-fed livestock	↓[f]	↑[i]	↑[s]	↔	↑[px]	↑[yz]	↑[αγδ]	↑[εζ]
M37	Agroforestry	↑↓[g]	↑[jk]	↑[pr]	↑[w]	↑[px]	↑[yz]	↑[αβγδ]	↑[εζ]
I	Reduce food losses	↑↑	↑[l]	↑[t]	↑[lt]	↑[x]	↑[y]	↑↑[αβγδ]	↑[εζ]

Key: ↑ increase/improve/benefit; ↓ reduce/worsen/harm; ↔no impact

[a] nitrogen loss reduction benefits realised as reduced fertiliser input, not increased yield
[b] reduced area of other crops
[c] reduced total N applications
[d] improved nutritional efficiency reflected in reduced feed inputs not increased outputs
[e] combination of reduced yields/stocking rates per ha and reduced areas of tillage crops
[f] for livestock due to using lower digestibility feeds
[g] increased total biomass but reduction in crop/livestock output due to area occupied by trees
[h] impacts on nutrition and health
[i] some breeding objectives may have negative welfare impacts
[j] free range
[k] shelter and diversified nutrition
[l] livestock numbers reduced
[m] limited benefits for organisms in soil and aquatic ecosystems
[n] impacts of concentrated nutrients, ammonia and acids on soil organisms, in particular earthworms
[o] benefits for farmland birds and non-crop plant species of rebalance spring and winter cropping
[p] benefits for soil organisms, in particular earthworms
[q] short term impact on specific soil microorganisms
[r] flowering plants, insects and pollinators
[s] longer grass growth and shorter grazing periods in rotational systems
[t] landuse change from agriculture to wildlife
[u] ammonia/odour on spreading
[v] reduced diesel NOx emissions
[w] ammonia capture by trees
[x] organic matter supply/conservation
[y] nitrate leaching and eutrophication
[z] due to organic matter accumulation
[α] fossil energy for fertiliser manufacture
[β] phosphorus reserves
[γ] fossil energy for mechanisation
[δ] non-renewable resources for feed production
[ε] public health
[ζ] public engagement, recreation
[η] rural incomes and employment
[θ] wetland biodiversity

3 Applicability, adoption requirements, barriers, timescales and sequencing

The measures outlined in Chapter 2 are all potential contributors to the 35% by 2045 target for GHG emissions reduction. However, they vary widely in terms of applicability to different farm types, information and investment requirements, and farmer responses. In this Chapter, we address the question:

Can these mitigation measures be sequenced in terms of priority and feasibility of deployment and what are the relative contributions of each of these measures to the 35% target over time?

The analysis is divided into three sections:

a) *Applicability:* This considers the regions and farm types appropriate (or not) for a particular measure, as well as current levels of adoption that provide a baseline on which to build. This information was used in the previous Chapter to assess the potential of 100% uptake of each measure.
b) *Adoption characteristics:* This considers the factors that will either encourage or discourage uptake of the measures in the context of farmer attitudes and behaviours, and the drivers (regulatory, business or public support) that will influence the decision to adopt or not.
c) *Contribution, timescales and priority:* Based on a) and b) we estimate the potential actual uptake of the measures over different timescales, and the resulting contribution to GHG emissions reduction. This analysis provides, together with the farm level and wider impact analysis in the previous chapter, provides a basis for prioritising the measures.

As in the previous Chapter, we have relied on the previous studies of in mitigation measures as our starting point for assessing applicability and adoption characteristics (see Section 2.3 for details).

Concerning timescales, we have divided the period 2020-2045 into five five-year periods (P1: 2020-2024; P2: 2025-2029; P3:2030-2034; P4: 2035-2049; P5:2040-2044). We are assuming that post-Brexit policy changes will influence the earlier periods, so that P1 would be focused on innovation and testing of new options, P2 on implementing new policies and P3 onwards would be focused on review, as well as implementation of longer-term options.

Only measures that have indicated potential to reduce emissions by ca. 50 kt CO_2e with 100% adoption are evaluated further in this Chapter.

Discussion of the information presented in these tables is included in Chapter 5.

Table D: Applicability

ID	*Description*	*Farm type*	*Cropping*	*Livestock*	*Exclusions*	*Total units (ha/hd)*	*Current uptake*
M1	Improve synthetic N use	C, GC, D, H, HL, LL, M, PP	[c] 100% wheat, barley, oilseeds, pots. 75% oats, other crops 95% tillage average 85% rotational grass 70% permanent grass 75% all grass 80% all tillage and grass	n/a	Rough grazing[a]	Tillage: 562 kha Grass: 989 kha	[d] pH testing: • tillage 64% • grass 30% nutrient plan: • tillage 42% • grass 17%
M2	Controlled release ferts						[e]Very limited
M3	Precision fertiliser application				Fallow, rotational and permanent grass, rough grazing	Tillage only: 525 kha	[e]10-20% (GB) 10% assumed
M1-M3	Combined				Combined	Combined	Combined
M6	Better organic N plan		[c]24% of grassland receiving slurry 16% of tillage and grassland receiving manures	All	Rough grazing[a]	Tillage/ grass: 765 kha	See M1 7% manure analysis 10% assumed
M7	Low emission spreading				See M6 Some manures will be applied to growing forage where ploughing or injection not possible.		[d]55% of slurry bandspread/ injected, 45% broadcast (est.) [d]55% of all manure/slurry NOT ploughed in or injected 50% overall compliance
M6, M7	Combined						10% plans and 50% low emission spreading
M11	Reducing soil compaction		[e]20% of tillage and grassland assessed as compacted	n/a	Rough grazing	Tillage/ grass: 382 kha	All compacted land needs to be addressed
M15	Improved N use varieties	C, GC, H	Wheat, barley, oilseed rape, potatoes, vegetables, rotational grass	n/a	Fallow, perm. grass, rough grazing	Specified crops:690 kha	[e]Very limited due to lack of breeding programmes
M16	Legumes in rotations	C, GC, D, H, HL, LL, M, PP	Tillage land (focus on grain legumes, rotational grass covered in M17)	n/a	Fallow, rotational and perm. grass, rough grazing[b]	Tillage ex fallow: 553 kha	4kha peas/beans grown
M17	Legumes in grassland		Rotational and permanent grassland	All	Rough grazing, tillage crops	Grass: 1.32 Mha	[d]20% temp grass low-N seed/ 13% unfertilised [e]45% permanent grass with clover/ 31% unfertilised)
M18	Fuel use efficiency		All crops	n/a		Tillage/grass: 1.91 Mha	Not known, assumed limited

ID	Description	Farm type	Cropping	Livestock	Exclusions	Total units (ha/hd)	Current uptake
M19	Better ruminant nutrition	Mainly D, HL, LL, M	n/a	Cattle & sheep	Pigs and poultry (non-ruminants)	1.8M cattle 7.0M sheep	[e]93% of dairy and 40% of other cattle and sheep
M21	Nitrate feed additives					1.24M cattle	Limited, not relevant to sheep
M22	High fat (lipid) diets					Concs. Fed: 98% (0.27M) D 45% (0.44M) B 15% (0.54M) S	Limited
M23	3NOP feed additive			Cattle	Not other livestock	80% (0.14M) D 40% (0.43M) other cattle	New product, no current uptake
M24	Improve cattle health			Cattle		1.8M cattle all types	95% of dairy herds and 60% of other cattle farms have health plans. Sheep not known. Health status varies on different holdings, but still possible to improve health on all
M25	Improve sheep health			Sheep		7.0M sheep all types	
M26	Breeding selection			Cattle	Pigs and poultry (non-ruminants), sheep less potential to exploit	1.78M head	Limited for beef cattle, better for dairy
M27	Improved grazing man.		Rotational/ permanent grassland (potentially also rough grazing)	All stock	Tillage crops	1.3 Mha grass (3.7 Mha RG)	Limited (no readily available data, may be 10-20%?)
M29	Slurry acidification		n/a (all crops potentially can be treated with acidified slurry)	Cattle Pigs	Solid manures	2740 holdings with slurry tanks	Not yet used in UK – uptake in DK due to limits on ammonia emissions
M32	Slurry aeration		n/a			2740 holdings with slurry tanks	5% cattle, 10% pigs working assumption
M34	Conservation agriculture	C, GC, H, M	Tillage crops	n/a	Rotational, permanent grass and rough grazing[b]	592 kha tillage	Limited (ca. 5%/30 kha)
M35	Organic farming	C, GC, D, H, HL, LL, M, PP	All	All	None	1.91 Mha tillage/ grass (+ rough graz.)	100 kha certified 2017
M36	Agroforestry		All	All	None		Limited

Farm type: C cereals; GC general cropping; D dairy; H horticulture; HL hill and upland (LFA) livestock; LL lowland (non-LFA) livestock; M mixed; PP pigs and poultry;
[a] no synthetic N/organic manures applied to rough grazing; [b] not cultivated; [c] British Survey of Fertiliser Practice, 2017, Scotland values; [d] Scottish Survey of Farm Structure and Methods, 2016; [e] Eory et al. 2015

Table E: Adoption characteristics

ID	*Description*	*Requirements*	*Barriers*	*Drivers*	*Feasibility (HML)*
M1	Improve synthetic N use	Soil analysis N planning (tools and data exist) Advice (if needed) Increased liming for pH correction	Analysis and correction costs Knowledge Access to services IT skills	Buyer requirements Cross-compliance Profitability,	H
M2	Controlled release ferts	Slight adjustment to timing of applications Possible savings from increased efficiency	10-20% higher fertiliser cost Knowledge of impacts	Information Profitability	H
M3	Precision fert application	GPS adapted machinery Soil and yield mapping	Capital investment (may be contracted) Knowledge IT skills	Profitability Innovation	M
M1-M3	Combined	As M1-M3	As M1-M3	As M1-M3	M
M6	Better organic N plan	As M1 plus manure/slurry analysis	As M1 Perceived low value of benefits	As M1	H
M7	Low emission spreading	Suitable machinery (on farm or contractors)	Capital investment (may be contracted) Labour costs (slower process) Some land not suitable, in part due to buyer food hygiene constraints on applicable crops	Buyer requirements Costs Practical constraints	M
M6, M7	Combined	As M6, M7	As M6, M7	As M6, M7	M
M11	Reducing soil compaction	Soil profile examination Appropriate cultivations Low pressure wheels Avoid traffic on wet soils Avoid poaching by livestock	Capital investment (may be contracted) Soil examination skills Weather conditions impacting timeliness	Cross-compliance Improved productivity	M
M15	Improved N use varieties	Suitable varieties from breeders	Lack of breeding programmes Timescales	Policy priorities Buyer preferences	L
M16	Legumes in rotations	Suitable varieties Technical knowledge Markets, including for wider range of grain legumes for human consumption Substitution of imported grain legumes for livestock feed	Disease and pest susceptibility Rotational constraints Prices not high enough to cover costs of production (likely to decrease as production expands)	Market conditions Risk	L

ID	*Description*	*Requirements*	*Barriers*	*Drivers*	*Feasibility (HML)*
M17	Legumes in grassland	Suitable varieties Technical knowledge	Seed costs Technical knowledge	Improved forage nutritional value reduced N requirement	H
M18	Fuel use efficiency	Skills training Technical support and advice Prioritisation of maintenance	Behaviours, e.g. poor driving style Poorly maintained equipment Access to energy tracking tools/data	Diesel costs	M
M19	Better ruminant nutrition	Access to animal nutrition advice, planning tools and forage analysis	Technical knowledge	Financial benefits of improved nutrition	H
M21	Nitrate feed additives	Thorough mixing as part of total mixed ration Feed mixer wagon	Potentially toxic if applied incorrectly Capital cost of feed mixers Not applicable if no concs. Fed No regulatory approval yet	Financial benefits of improved nutrition	L
M22	High fat (lipid) diets	Integration of oilseed or linseed with concentrates	Max 6-7% DM fat in diet = max 10% DM oilseed in diet Not applicable if no concs. fed	Financial benefits of improved nutrition	M
M23	3NOP feed additive	Regulatory approval for 3NOP at EU/UK levels Suppliers as market develops	New product adoption Possibly cost – data not yet available?	Government policy Financial benefits	M
M24	Improve cattle health	Veterinary input Training and advice Animal health plans Testing/diagnosis Premium Cattle Health Scheme membership Management input for health prevention Capital investment in housing improvements	Costs of implementation Lack of knowledge and awareness Lack of skilled/trained labour Physical resource constraints (e.g. housing, land, location)	Government policy for animal health Farm assurance schemes and buyer requirements Consumer demands re animal welfare	H
M25	Improve sheep health	Veterinary input Training and advice Animal health plans Testing/diagnosis Premium Sheep Health Scheme membership Management input for health prevention Capital investment in housing improvements	Costs of implementation Lack of knowledge and awareness Lack of skilled/trained labour Physical resource constraints (e.g. housing, land, location)	Government policy for animal health Farm assurance schemes and buyer requirements Consumer demands re animal welfare	H
M26	Breeding selection	Breeding programmes, supported by better performance recording and appropriate breeding indices linked to improved financial performance Sexed semen	Lack of knowledge and awareness Lack of breeding programmes/ indices Lack of evidence of financial benefits	Productivity (including financial) benefits	M

ID	*Description*	*Requirements*	*Barriers*	*Drivers*	*Feasibility (HML)*
M27	Improved grazing man.	Knowledge, advice Fencing, water, tracks Diversified seed mixtures Management and labour inputs	Lack of knowledge/ information Contradictory advice Productivity impact concerns Visual/aesthetic concerns	Soil health, carbon sequestration Grassland productivity	M
M29	Slurry acidification	Appropriate acids and technology for application	Lack of market readiness Health and safety issues Impacts of acidified slurry on soil organisms Capital investment costs	Productivity gains from slurry use	L
M32	Slurry aeration	Aeration equipment installation	Capital investment costs Technological constraints Ammonia loss risks Management and labour input Lack of knowledge and awareness	Soil health benefits Regulatory requirement for odour reduction	M
M34	Conservation agriculture	Knowledge of grain legumes, catch crops, reduced tillage Equipment for reduced tillage Herbicides for reduced tillage	Cost and yield impact perceptions Mindset with respect to seedbed preparations	Soil health Weed control/ herbicide resistance	M
M35	Organic farming	Knowledge of organic farming methods Reintroduction of livestock (and related services/ facilities) onto arable farms Reliance on clover/legumes for nitrogen fixation Husbandry approaches to maintain crop and livestock health and productivity Premium markets to sustain financial viability	Mindset with respect to eliminating agrochemical inputs Financial risks/ access to premium markets Lack of availability of advice, training, research and information Certification requirements	Consumer demand Policy support Soil health Animal welfare	L
M37	Agroforestry	Knowledge of tree management practices Sacrifice of some (10%) of crop/grassland for trees but potential increased overall biomass yield Appropriate establishment, weed control, browsing protection	Landlord resistance to perennial crops Establishment costs and long payback periods Lack of information on financial and some technical aspects	System health and productivity	M

Table F: Contribution, timescale and priority

ID	*Description*	*Potential uptake*	*Timescales*	*Contribution kt CO_2e*	*Priority (Rank)*	
					Total	*Cost/unit*
M1	Improve synthetic N use	Tillage: 50%*562=281 kha Grass: 75%*989=742 kha	P1:50% P2:50%	63	15	24 (-39.4)
M2	Controlled release ferts	[e]70% of land receiving fertiliser Tillage: 393 kha, Grass: 692 kha	P1:50% P2:50%	176	7	15 (-5.5)
M3	Precision fertiliser application	10% of tillage land area each period 50% over 25 years (=60% total by 2045); Tillage: 50%*562=281 kha	P1-P5	41	20	9 (-2.5)
M1-M3	Combined	As M1-M3	As M1-M3	258	4	18 (-13.5)
M6	Better organic N plan	90% over 10 years (=100% total) Tillage and grass area: 690 kha	P1:50% P2:50%	52	17	12 (-3.4)
M7	Low emission spreading	Remaining 50% potentially, reduced to 25% due to land practicalities issue. 25%*765=191 kha	P1:50% P2:50%	34	23	8 (-2.3)
M6, M7	Combined	Combined	P1:50% P2:50%	86	12	11 (-3.0)
M11	Reducing soil compaction	20% of total tillage and grassland = 382 kha	P1:50% P2:50%	58	16	5= (+2.2)
M15	Improved N use varieties	50% of 690kha applicable crops = 345 kha	End P5	50	18	7 (+0.5)
M16	Legumes in rotations	50% of 1/6th of tillage area = 46 kha peas/beans	End P3	37	22	21 (-21.9)
M17	Legumes in grassland	Additional 40% of rotational (to 53%) and perm. grass (to 71%) = 528 kha	End P3	295	5	10 (-2.6)
M18	Fuel use eff.	50% of farms	End P2	38	21	4 (+5.1)
M19	Better ruminant nutrition	40% of other cattle (0.7M) and sheep (2.8M), not dairy cattle	P1:50% P2:50%	29	24	2 (+12.9)
M21	Nitrate feed additives	50% of dairy cows and replacements (0.14 Mhead); 20% of beef cows, other beef cattle >12 months (0.19Mhd) Not for calves < 1 year and sheep	P1:50% P2:50%	105	10	25 (-40.4)
M22	High fat (lipid) diets	50% (0.09M) dairy cows; 25% (0.27M) other cattle > 12months; no sheep	P1:50% P2:50%	48	19	23 (-32.3)
M23	3NOP feed additive	80% (0.14M) dairy cows, 40% (0.43M) other cattle > 12months	P1:50% P2:50%	265	3	19 (-14.0)
M24	Improve cattle health	40 % of beef cattle 20% uptake in periods 1,2 (0.6M cattle total)	P1:50% P2:50%	94	11	1 (+15.7)
M25	Improve sheep health	40 % of sheep, 20% uptake in each P =2.8M sheep total	P1:50% P2:50%	107	9	5= (+2.2)
M26	Breeding selection	50% (0.89 Mhead) dairy/beef cattle reduced by 10% by end P3	P1 20% P2/3: 40%	165	8	3 (+8.5)
M27	Improved grazing man.	50% (0.65 Mha) grassland by end P3	End P3	242	6	14 (-4.5)
M29	Slurry acidification	All 2760 farms with slurry tanks (80% of all farms with slurry)	End P3	67	14	20 (-21.5)
M32	Slurry aeration	Additional 20% of 2760 farms in 10 years, 50% in 20	P2: 40% P4:100%	22	25	22 (-27.3)
M34	Conservation agric.	50% of tillage land = 296 kha (10% in each period)	End P5	74	13	17 (-9.3)
M35	Organic farming	40% (764 kha) of tillage and grassland (5% each P1, P2; 10% each P3-P5)	P2:25% P5:100%	731	1	13 (-4.3)
M37	Agroforestry	Systems applied on 30 % (573 kha) of tillage and grassland	End P5	569	2	16 (-6.4)

4 Agricultural implications

The aim of this Chapter is to address the physical and financial productivity implications for farmers of the individual measures applied over the next 25 years, based on the scheduling and uptake levels projected in Chapter 3.

The assessment was undertaken using published statistical data sources[69,70] and farm management planning handbooks[71,72]. For the statistical data sources, we relied on group average data, not individual farm data. Excel spreadsheets were used to undertake the modelling.

The analysis is based on robust/main farm types (Cereals, General cropping, Mixed, Dairy, Non-LFA cattle/sheep and LFA cattle, cattle/sheep and sheep). Horticulture, pigs and poultry types are not covered by the Farm Business Survey publications, and in any case are small sectors in relation to GHG emissions, so we have not attempted to analyse the impacts on these sectors.

In most cases a partial budgeting approach was used, with the aim of estimating the direct cost increases/savings and income changes associated with the measure and applying these to the Farm Business Income results for the relevant farm type groups.

In Table G, we have set out the key assumptions that we used for our analysis.

Table G: Agricultural Impact Analysis Assumptions

ID	*Description*	*Farm type*	*Uptake units (ha/hd)*	*Assumptions to be analysed*
M1	Improve synthetic N use	All	50% tillage = 281 kha; 75% grass = 742 kha	Access to tools, advice, soil analysis (£10/ha)[a] Reduced N fertiliser input (10%x50% fertiliser costs)[b] Liming for pH correction (£25/ha annual average)[c] No yield reductions
M2	Controlled release fertilisers	All	70% fert. land= 393 kha tillage 692 kha grass	Cost increase for N fertiliser inputs (20%x50% of fertiliser costs for additional area)[b] No yield reductions
M3	Precision fertiliser application	All	50% tillage = 281 kha	Costs of machinery investment/contracting (+£3/ha)[d] Cost of IT systems, yield monitoring etc. (£12/ha)[a,e] Fertiliser input reductions (20%x50% of fertiliser costs for additional area)[b] No yield reductions
M1-M3	Combined	All	Combined	Sum of M1-M3 per hectare costs plus sum of fertiliser change values: 100% M1, 90% M2, 90% M3
M6	Better organic N planning	All	90% manured land = 690 kha tillage and grass	Cost for access to tools and advice (£3/ha)[a] Cost for manure/slurry analysis (£1/ha) Cost savings for reduced fertiliser inputs (10%x50% fertiliser costs as approximation)[b] No yield reductions
M7	Low emission spreading	All	191kha tillage and grass	Additional slurry spreading costs 50% of £2.33[d]/m^3 @ 28 m3/ha on 25% of grassland receiving slurry (24% of total grassland) No additional costs for manure incorporation Fertiliser saving 0.5kg/m^3 slurry or t manure applied No yield reductions
M6, M7	Combined	All	As M6	M6+M7

[69] Scottish Agricultural Census 2017 and Scottish Survey of Farm Structure and Methods 2016
[70] Scottish Farm Business Survey 2017
[71] SRUC Farm Management Handbook 2017/18
[72] Lampkin N, Measures M, Padel S (2017) 2017 Organic Farm Management Handbook. Organic Research Centre.

ID	Description	Farm type	Uptake units (ha/hd)	Assumptions to be analysed
M11	Reducing soil compaction	All	20% of total tillage and grass = 382kha	Cost of sub-soiling/additional cultivations every 10 years £10/ha Fuel use improvement not included Yield improvement 2% tillage, 1 % grass £15/ha
M15	Improved N use varieties	All	345kha applicable crops	20% reduction in N fertiliser use 10% increase in seed costs No increase in yield
M16	Legumes in rotations	All tillage	46 kha	Change in gross margins other crops v. grain legumes. Reduced fertiliser costs: no N on grain legumes, 20kg N/ha reduction on subsequent crop
M17	Legumes in grassland	All	528 kha	No nitrogen fertiliser on 40% grassland @ 54p/kgN 20kg/ha less N fertiliser on crops following 40% of rotational grassland @ 54p/kgN Additional cost for clover seed/slot-seeding £10/ha Yield reduction/nutritional benefits –net 5% reduction
M18	Fuel use efficiency	All	955 kha tillage and grassland	10% reduction in machinery running costs Additional costs for training, monitoring, maintenance, approx. £2500 per farm
M19	Better ruminant nutrition	D, HL, LL, M	0.7M other cattle; 2.8M sheep	Advice £250/farm annually Analysis £100/farm annually 2% increase in non-dairy cattle and sheep output
M21	Nitrate feed additives	All	1.14 M cattle	Cost of nitrates and induced changes in ration = 1.5% of 17.5t FW/year (2.5t concs, 15t forage) = 0.26t/cow @ £500/t = £130/cow (estimate, actual current price not available) Potentially also: Feed mixers (£15-40k) Additional feed storage facilities
M22	High fat (lipid) diets	All	0.09M dairy, 0.27M other cattle	Cost of oilseed inclusion = £10/t DM or £40/head
M23	3NOP feed additive	All	0.14M dairy, 0.43M other cattle	Cost of 3NOP inclusion not yet available as new product – illustrated using £15/t DM or £60/head
M24	Improve cattle health	All	0.6M cattle (no dairy)	Animal health plan £500/farm Scheme membership £100/farm Diagnostic tests £100/farm Training £300/farm 10% increase in output incl. QMS farm assured premium
M25	Improve sheep health	All	2.8M sheep (all types)	Animal health plan £500/farm Scheme membership £250/farm Diagnostic tests £100/farm Training £300/farm 10% increase in non-LFA sheep output 20% increase in LFA sheep output Incl. QMS farm assured premium
M26	Breeding selection	All	50% of cattle = 0.89M head	Reduce cow numbers, but increase performance for remaining cows by 10% - no net change in output Replacement costs increased by 10% Other livestock and forage costs reduced by 10%
M27	Improved grazing management	Cattle focus	50% grassland = 660 kha	Increased fencing, water, track costs £50/ha Increased labour for fencing/stock movmt 1h=£15/ha Increased cost for diversified mixes/slot seeding £5/ha Increased grass (livestock margin) output 10%
M29	Slurry acidification	All	2740 holdings	Cost of acid and application technology estimated at £3/t slurry

ID	Description	Farm type	Uptake units (ha/hd)	Assumptions to be analysed
M32	Slurry aeration	All	2740 holdings	£8000 initial investment, £2.50/t cost amortised and running
M34	Conservation agric.	C, GC, M	50% (296 kha) tillage	M1 net costs (tillage area only) M16 net costs Catch crops: £50/ha seed costs, 2 years in six Reduced tillage: £50/ha annual cost savings[f]
35	Organic farming[g]	All	40% (764kha) tillage/grass	Crop output reductions: 40% Fertiliser/spray cost reductions: 90% Organic crop price premiums: 75% Crop margin reductions due to reduced tillage area: 25% cereals/general cropping, 10% mixed Livestock margin reductions: 20% Organic purch. feed price increase: 75% Organic livestock price premiums 25% Organic livestock margin on new rotational grassland: varies by farm type Fixed cost increases: 10% cereals/general cropping, 5% other Conversion/maintenance support payments not included
M37	Agroforestry[h]	All	30% (573 kha) tillage/grass	Crop and livestock margin reduction: 10% Establishment costs: £4000/ha over 30 years Annual management costs: £4000/ha over 15 years Additional revenue: £2000/ha over 15 years based on woodchip for fuel – more with fruit/nuts

[a] Eory et al. (2015)

[b] 2017/18 Scottish Farm Business Survey data, apportioned using British Fertiliser Survey results

[c] 2017/18 SRUC Farm Management Handbook

[d] National Association of Agricultural Contractors Contractor Charges 2017

[e] https://www.futurefarming.com/Tools-data/Articles/2017/9/Precision-farming-trial-to-reveal-true-cost-of-technology-1582WP/

[f] Jarvis PE, Woolford AR (2017) Economic and ecological benefits of reduced tillage in the UK. Allerton Project report. GWCT

[g] Lampkin N, Measures M, Padel S (2017) Organic farm management handbook, Organic Research Centre, Newbury

[h] Smith J (2019) pers. comm. and Raskin B, Osborn S (2019) The Agroforestry Handbook. Soil Association, Bristol

Table H: Baseline farm structural data (land areas and livestock numbers) by farm type

Item	*Detail*	*All farms*	*Cereals*	*General copping*	*Mixed*	*Dairy*	*Lowland sheep & cattle*	*LFA cattle*	*LFA cattle & sheep*	*LFA sheep*
Farms	Number in sample	492	64	57	78	41	26	122	53	51
Size	ha total	339	161	188	150	170	135	156	528	1,115
Of which	Tillage	49	133	157	79	12	23	11	4	1
	Cereals	36	109	105	64	6	20	8	2	0
	Potatoes	4	1	28	2	0	0	0	0	0
	Oilseeds	2	11	7	2	0	0	0	0	0
	Other	2	4	9	3	0	0	0	0	0
	Fodder	4	8	8	8	6	3	2	2	0
	Grass	79	22	28	64	146	96	105	113	68
	Rough grazing	211	6	3	8	12	16	41	411	1,047
Livestock	Head total	357	43	45	232	432	382	330	719	688
Of which	Ewes	218	19	10	89	9	179	119	580	669
	Suckler cows	36	5	8	39	1	51	72	59	9
	Dairy cows	16	0	0	0	211	0	8	0	0
	Other cattle	87	19	27	104	211	152	131	80	10
	LU total	141	20	27	120	351	177	183	198	116
Stocking rate	LU/forage ha incl. 25% RG	1.04	0.64	0.74	1.63	2.26	1.71	1.57	0.91	0.35
	LU excl. sheep	109	17	26	107	349	150	165	111	16

Source: Scottish Farm Business Survey, 2017/18

Table I: Baseline financial data (£/farm) by farm type

Item	*Detail*	*All farms*	*Cereals*	*General copping*	*Mixed*	*Dairy*	*Lowland sheep & cattle*	*LFA cattle*	*LFA cattle & sheep*	*LFA sheep*
Outputs	**Total**	**176,718**	**184,524**	**341,117**	**171,415**	**526,652**	**141,706**	**115,246**	**110,947**	**42,769**
Of which	Crops	65,903	140,153	302,425	71,401	7,502	16,872	6,486	767	997
	Livestock	98,482	15,418	16,991	83,241	510,187	119,016	101,493	99,868	37,071
	Milk	*33,046*	-	-	-	*443,499*	-	*14,281*	-	-
	Cattle	*46,989*	*10,741*	*13,114*	*65,369*	*65,551*	*94,665*	*73,367*	*50,185*	*5,344*
	Sheep & wool	*17,315*	*4,677*	*1,230*	*11,608*	*1,034*	*23,922*	*13,822*	*49,451*	*31,840*
	Miscellaneous	12,334	28,953	21,702	16,773	8,963	5,817	7,267	10,313	4,702
Subsidies	**Total**	**42,819**	**33,892**	**37,853**	**37,829**	**39,703**	**36,164**	**45,255**	**58,924**	**45,680**
Of which	Basic/commodity	35,474	32,951	36,398	35,501	35,342	33,318	35,954	40,996	32,451
	Agri-environment	6,110	311	466	1,923	3,800	2,618	7,672	14,254	12,427
	Other direct/P2	1,236	630	989	405	560	228	1,628	3,674	802
Inputs	**Total**	**188,288**	**192,309**	**319,797**	**187,253**	**494,914**	**148,093**	**139,034**	**138,870**	**71,765**
Of which	Crops	30,076	54,000	93,890	34,098	27,948	15,606	14,891	9,904	2,820
	Fertilisers	*13,952*	*22,947*	*29,464*	*16,065*	*21,083*	*10,152*	*10,168*	*7,664*	*2,205*
	Crop protection	*6,776*	*17,618*	*26,567*	*7,692*	*2,041*	*1,791*	*1,129*	*453*	*185*
	Livestock	46,865	9,107	8,019	39,509	238,964	54,874	45,326	49,152	23,410
	Purchased feeds	*29,348*	*4,529*	*4,696*	*18,160*	*183,611*	*29,185*	*26,508*	*29,164*	*12,715*
	Other fixed costs	111,347	129,201	217,887	113,646	228,002	77,613	78,817	79,814	45,534
	Machinery running	*28,862*	*36,562*	*57,530*	*30,529*	*62,248*	*21,824*	*19,481*	*17,758*	*9,574*
Diversify	**Margin**	**4,136**	**9,133**	**6,914**	**7,060**	**1,704**	**1,969**	**3,268**	**1,648**	**1,547**
Profit (FBI)	**Farm bus. income**	**35,385**	**35,240**	**66,088**	**29,051**	**73,144**	**31,745**	**24,734**	**32,649**	**18,231**

Source: Scottish Farm Business Survey, 2017/18

Table J: Impact of individual mitigation measures on Farm Business Income (FBI £/ha) by farm type

Item	*Detail*	*All farms*	*Cereals*	*General copping*	*Mixed*	*Dairy*	*Lowland sheep/cattle*	*LFA cattle*	*LFA cattle/sheep*	*LFA sheep*
Baseline	**FBI (£/farm)**	**35,385**	**35,240**	**66,088**	**29,051**	**73,144**	**31,745**	**24,734**	**32,649**	**18,231**
M1	*Improve synthetic N use*				*Cost/benefit ratio (Change in all farms FBI/change in ktC02e):* **-39.4**					
Changes	Increased costs	2,938	2,907	3,495	3,050	4,052	2,926	2,933	3,030	1,787
	Cost savings	457	614	793	492	770	356	370	284	82
	Farm Income +/-	-2,481	-2,293	-2,702	-2,559	-3,282	-2,570	-2,563	-2,746	-1,704
	As % of baseline FBI	-7.0%	-6.5%	-4.1%	-8.8%	-4.5%	-8.1%	-10.4%	-8.4%	-9.3%
Final	Net FBI	32,904	32,947	63,386	26,493	69,862	29,175	22,171	29,903	16,527
M2	*Controlled release fertilisers*				*Cost/benefit ratio (Change in all farms FBI/change in ktC02e):* **-5.5**					
Changes	Increased costs	977	1,606	2,062	1,125	1,476	711	712	537	154
	Cost savings	-	-	-	-	-	-	-	-	-
	Farm Income +/-	-977	-1,606	-2,062	-1,125	-1,476	-711	-712	-537	-154
	As % of baseline FBI	-3%	-5%	-3%	-4%	-2%	-2%	-3%	-2%	-1%
Final	Net FBI	34,409	33,634	64,025	27,927	71,668	31,034	24,023	32,112	18,077
M3	*Precision fertiliser application*				*Cost/benefit ratio (Change in all farms FBI/change in ktC02e):* **-2.5**					
Changes	Increased costs	366	1,001	1,178	590	93	172	80	31	5
	Cost savings	266	986	1,248	443	82	98	47	13	1
	Farm Income +/-	-100	-14	+ 69	-146	-11	-74	-33	-17	-4
	As % of baseline FBI	0%	0%	0%	-1%	0%	0%	0%	0%	0%
Final	Net FBI	35,285	35,225	66,157	28,905	73,134	31,670	24,701	32,632	18,227
M1-M3	*Combined*				*Cost/benefit ratio (Change in all farms FBI/change in ktC02e):* **-13.5**					
Changes	Increased costs	4,183	5,353	6,529	4,652	5,473	3,737	3,654	3,544	1,931
	Cost savings	696	1,502	1,916	891	844	444	412	296	83
	Farm Income +/-	-3,487	-3,851	-4,613	-3,761	-4,629	-3,293	-3,242	-3,248	-1,847
	As % of baseline FBI	-10%	-11%	-7%	-13%	-6%	-10%	-13%	-10%	-10%
Final	Net FBI	31,898	31,388	61,474	25,290	68,515	28,451	21,492	29,401	16,384
M6	Better organic N planning				*Cost/benefit ratio (Change in all farms FBI/change in ktC02e):* **-3.4**					
Changes	Increased costs	462	559	668	513	571	429	415	420	246
	Cost savings	284	305	366	303	375	275	272	279	164
	Farm Income +/-	-178	-253	-301	-210	-195	-154	-143	-141	-82
	As % of baseline FBI	-0.5%	-0.7%	-0.5%	-0.7%	-0.3%	-0.5%	-0.6%	-0.4%	-0.4%
Final	Net FBI	35,207	34,987	65,786	28,841	72,949	31,591	24,591	32,508	18,149

Table J: Impact of individual mitigation measures on Farm Business Income (FBI £/ha) by farm type (cont.)

Item	*Detail*	*All farms*	*Cereals*	*General copping*	*Mixed*	*Dairy*	*Lowland sheep/cattle*	*LFA cattle*	*LFA cattle/sheep*	*LFA sheep*
Baseline	**FBI (£/farm)**	**35,385**	**35,240**	**66,088**	**29,051**	**73,144**	**31,745**	**24,734**	**32,649**	**18,231**
M7	*Low emission spreading*				*Cost/benefit ratio (Change in all farms FBI/change in ktC02e):* ***-2.3***					
Changes	Increased costs	-156	-43	-56	-125	-287	-189	-206	-222	-133
	Cost savings	79	85	102	84	104	76	76	78	46
	Farm Income +/-	-77	+42	+46	-41	-183	-113	-130	-144	-87
	As % of baseline FBI	-0.2%	+0.1%	+0.1%	-0.1%	-0.3%	-0.4%	-0.5%	-0.4%	-0.5%
Final	Net FBI	35,308	35,282	66,134	29,010	72,961	31,632	24,604	32,505	18,144
M6+M7	*Combined*				*Cost/benefit ratio (Change in all farms FBI/change in ktC02e):* ***-3.0***					
Changes	Increased costs	618	602	724	638	858	618	621	642	379
	Cost savings	363	390	468	387	480	352	348	357	210
	Farm Income +/-	-255	-211	-256	-251	-378	-266	-273	-285	-169
	As % of baseline FBI	-0.7%	-0.6%	-0.4%	-0.9%	-0.5%	-0.8%	-1.1%	-0.9%	-0.9%
Final	Net FBI	35,130	35,029	65,832	28,800	72,766	31,478	24,462	32,364	18,062
M11	*Reducing soil compaction*				*Cost/benefit ratio (Change in all farms FBI/change in ktC02e):* ***+2.2***					
Changes	Increased costs	256	310	371	285	317	238	231	234	137
	Increased output	385	466	557	427	476	357	346	350	205
	Farm Income +/-	+128	+155	+186	+142	+159	+119	+115	+117	+68
	As % of baseline FBI	0.4%	0.4%	0.3%	0.5%	0.2%	0.4%	0.5%	0.4%	0.4%
Final	Net FBI	35,513	35,395	66,273	29,194	73,303	31,864	24,850	32,766	18,300
M15	*Improved N use varieties*				*Cost/benefit ratio (Change in all farms FBI/change in ktC02e):* ***+0.5***					
Changes	Increased costs	304	503	1,341	315	98	110	80	45	11
	Cost savings	332	833	982	486	118	177	112	77	39
	Farm Income +/-	+27	+330	-359	+171	+20	+67	+31	+32	+28
	As % of baseline FBI	+0.1%	+0.9%	-0.5%	+0.6%	+0.0%	+0.2%	+0.1%	+0.1%	+0.2%
Final	Net FBI	35,648	35,847	66,806	29,474	73,343	31,948	24,827	32,718	18,268
M16	*Legumes in rotations*				*Cost/benefit ratio (Change in all farms FBI/change in ktC02e):* ***-21.9***					
Changes	Crop GM reduction	847	1,121	4,631	703	43	154	59	17	2
	Cost savings	37	104	124	58	5	16	7	2	0
	Farm Income +/-	-810	-1,017	-4,507	-645	-38	-137	-52	-15	-2
	As % of baseline FBI	-2.3%	-2.9%	-6.8%	-2.2%	-0.1%	-0.4%	-0.2%	-0.0%	-0.0%
Final	Net FBI	33,535	29,693	60,705	25,790	72,837	30,748	24,305	32,526	18,216

Table J: Impact of individual mitigation measures on Farm Business Income (FBI £/ha) by farm type (cont.)

Item	*Detail*	*All farms*	*Cereals*	*General copping*	*Mixed*	*Dairy*	*Lowland sheep/cattle*	*LFA cattle*	*LFA cattle/sheep*	*LFA sheep*
Baseline	**FBI (£/farm)**	**35,385**	**35,240**	**66,088**	**29,051**	**73,144**	**31,745**	**24,734**	**32,649**	**18,231**
M17	*Legumes in grassland*				*Cost/benefit ratio (Change in all farms FBI/change in ktC02e):* **-2.6**					
Changes	Incr. costs/red. Inc.	2,287	396	453	1,920	10,788	2,765	2,448	2,448	1,012
	Cost savings	1,523	422	549	1,236	2,815	1,854	2,000	2,155	1,293
	Farm Income +/-	-765	+26	+96	-684	-7,973	-911	-448	-293	+281
	As % of baseline FBI	-2.2%	+0.1%	+0.1%	-2.4%	-10.9%	-2.9%	-1.8%	-0.9%	+1.5%
Final	Net FBI	34,621	35,266	66,183	28,368	65,171	30,834	24,286	32,356	18,512
M18	*Fuel use efficiency*				*Cost/benefit ratio (Change in all farms FBI/change in ktC02e):* **+5.1**					
Changes	Increased costs	1,250	1,250	1,250	1,250	1,250	1,250	1,250	1,250	1,250
	Cost savings	1,443	1,828	2,877	1,526	3,112	1,091	974	888	479
	Farm Income +/-	+193	+578	+1,627	+276	+1,862	-159	-276	-362	-771
	As % of baseline FBI	+0.5%	+1.6%	+2.5%	+1.0%	+2.5%	-0.5%	-1.1%	-1.1%	-4.2%
Final	Net FBI	35,578	35,818	67,714	29,328	75,007	31,586	24,458	32,287	17,460
M19	*Better ruminant nutrition*				*Cost/benefit ratio (Change in all farms FBI/change in ktC02e):* **+12.9**					
Changes	Increased costs	140	n/a	n/a	140	n/a	140	140	140	140
	Cost savings	514	n/a	n/a	616	n/a	949	698	797	297
	Farm Income +/-	+374	-	-	+476	-	+809	+558	+657	+157
	As % of baseline FBI	+1.1%	-	-	+1.6%	-	+2.5%	+2.3%	+2.0%	+0.9%
Final	Net FBI	35,760	35,240	66,088	29,527	73,144	32,553	25,292	33,306	18,389
M21	*Nitrate feed additive*				*Cost/benefit ratio (Change in all farms FBI/change in ktC02e):* **-40.4**					
Changes	Increased costs	4,238	624	910	3,718	19,227	5,278	5,798	3,614	494
	Cost savings	-	-	-	-	-	-	-	-	-
	Farm Income +/-	-4,238	-624	-910	-3,718	-19,227	-5,278	-5,798	-3,614	-494
	As % of baseline FBI	-12.0%	-1.8%	-1.4%	-12.8%	-26.3%	-16.6%	-23.4%	-11.1%	-2.7%
Final	Net FBI	31,147	34,616	65,178	25,333	53,917	26,467	18,936	29,035	17,737
M22	*High fat (lipid) diets*				*Cost/benefit ratio (Change in all farms FBI/change in ktC02e):* **-32.3**					
Changes	Increased costs	1,550	240	350	1,430	6,340	2,030	2,190	1,390	190
	Cost savings	-	-	-	-	-	-	-	-	-
	Farm Income +/-	-1,550	-240	-350	-1,430	-6,340	-2,030	-2,190	-1,390	-190
	As % of baseline FBI	-4.4%	-0.7%	-0.5%	-4.9%	-8.7%	-6.4%	-8.9%	-4.3%	-1.0%
Final	**Net FBI**	33,835	35,000	65,738	27,621	66,804	29,715	22,544	31,259	18,041

Table J: Impact of individual mitigation measures on Farm Business Income (FBI £/ha) by farm type (cont.)

Item	*Detail*	*All farms*	*Cereals*	*General copping*	*Mixed*	*Dairy*	*Lowland sheep/cattle*	*LFA cattle*	*LFA cattle/sheep*	*LFA sheep*
Baseline	**FBI (£/farm)**	**35,385**	**35,240**	**66,088**	**29,051**	**73,144**	**31,745**	**24,734**	**32,649**	**18,231**
M23	*3NOP feed additive*					*Cost/benefit ratio (Change in all farms FBI/change in ktC02e):* **-14.0**				
Changes	Increased costs	3,720	576	840	3,432	15,216	4,872	5,256	3,336	456
	Cost savings	-	-	-	-	-	-	-	-	-
	Farm Income +/-	-3,720	-576	-840	-3,432	-15,216	-4,872	-5,256	-3,336	-456
	As % of baseline FBI	-10.5%	-1.6%	-1.3%	-11.8%	-20.8%	-15.3%	-21.2%	-10.2%	-2.5%
Final	Net FBI	31,665	34,664	65,248	25,619	57,928	26,873	19,478	29,313	17,775
M24	*Improve cattle health*					*Cost/benefit ratio (Change in all farms FBI/change in ktC02e):* **+15.7**				
Changes	Increased costs	400	400	400	400	400	400	400	400	400
	Increased income	1,880	430	525	2,615	2,622	3,787	2,935	2,007	214
	Farm Income +/-	+1,480	+30	+125	+2,215	+2,222	+3,387	+2,535	+1,607	-186
	As % of baseline FBI	+4.2%	+0.1%	+0.2%	+7.6%	+3.0%	+10.7%	+10.2%	+4.9%	-1.0%
Final	Net FBI	35,105	34,960	65,808	28,771	72,864	31,465	24,454	32,369	17,951
M25	*Improve sheep health*					*Cost/benefit ratio (Change in all farms FBI/change in ktC02e):* **+2.2**				
Changes	Increased costs	460	460	460	460	460	460	460	460	460
	Increased income	693	187	49	464	41	957	1,106	3,956	2,547
	Farm Income +/-	+233	-273	-411	+4	-419	+497	+646	+3,496	+2,087
	As % of baseline FBI	+0.7%	-0.8%	-0.6%	+0.0%	-0.6%	+1.6%	+2.6%	+10.7%	+11.4%
Final	Net FBI	35,045	34,900	65,748	28,711	72,804	31,405	24,394	32,309	17,891
M26	*Breeding selection*					*Cost/benefit ratio (Change in all farms FBI/change in ktC02e):* **+8.5**				
Changes	Increased costs	760	50	80	390	5,285	510	920	590	90
	Cost savings	2,161	531	584	2,030	12,514	2,619	2,425	1,698	261
	Farm Income +/-	+1,401	+481	+504	+1,640	+7,229	+2,109	+1,505	+1,108	+171
	As % of baseline FBI	+4.0%	+1.4%	+0.8%	+5.6%	+9.9%	+6.6%	+6.1%	+3.4%	+0.9%
Final	Net FBI	36,786	35,721	66,592	30,691	80,373	33,853	26,240	33,757	18,402
M27	*Improve grazing management*					*Cost/benefit ratio (Change in all farms FBI/change in ktC02e):* **-4.5**				
Changes	Increased costs	2,779	763	994	2,233	5,114	3,367	3,661	3,945	2,366
	Increased output	1,686	300	441	2,136	13,351	3,104	2,606	1,466	167
	Farm Income +/-	-1,093	-463	-553	-97	+8,237	-263	-1,055	-2,478	-2,199
	As % of baseline FBI	-3.1%	-1.3%	-0.8%	-0.3%	+11.3%	-0.8%	-4.3%	-7.6%	-12.1%
Final	Net FBI	34,292	34,776	65,535	28,954	81,382	31,482	23,679	30,170	16,032

Table J: Impact of individual mitigation measures on Farm Business Income (FBI £/ha) by farm type (cont.)

Item	*Detail*	*All farms*	*Cereals*	*General copping*	*Mixed*	*Dairy*	*Lowland sheep/cattle*	*LFA cattle*	*LFA cattle/sheep*	*LFA sheep*
Baseline	**FBI (£/farm)**	**35,385**	**35,240**	**66,088**	**29,051**	**73,144**	**31,745**	**24,734**	**32,649**	**18,231**
M29	*Slurry acidification*				*Cost/benefit ratio (Change in all farms FBI/change in ktC02e):* **-21.5**					
Changes	Increased costs	1,442	n/a	n/a	1,264	2,446	1,650	n/a	n/a	n/a
	Cost savings	-	n/a	n/a	-	-	-	n/a	n/a	n/a
	Farm Income +/-	-1,442	n/a	n/a	-1,264	-2,446	-1,650	n/a	n/a	n/a
	As % of baseline FBI	-4.1%	n/a	n/a	-4.3%	-3.3%	-5.2%	n/a	n/a	n/a
Final	**Net FBI**	33,944	n/a	n/a	27,788	70,698	30,095	n/a	n/a	n/a
M32	*Slurry aeration*				*Cost/benefit ratio (Change in all farms FBI/change in ktC02e):* **-27.3**					
Changes	Increased costs	600	n/a	n/a	526	1,019	687	n/a	n/a	n/a
	Cost savings	-	n/a	n/a	-	-	-	n/a	n/a	n/a
	Farm Income +/-	-600	n/a	n/a	-526	-1,019	-687	n/a	n/a	n/a
	As % of baseline FBI	-1.7%	n/a	n/a	-1.8%	-1.4%	-2.2%	n/a	n/a	n/a
Final	**Net FBI**	34,785	n/a	n/a	28,525	72,125	31,057	n/a	n/a	n/a
M34	*Conservation agriculture on arable land*				*Cost/benefit ratio (Change in all farms FBI/change in ktC02e):* **-9.3**					
Changes	Increased costs	1,906	4,013	8,035	2,410	n/a	n/a	n/a	n/a	n/a
	Cost savings	1,220	3,335	3,928	1,965	n/a	n/a	n/a	n/a	n/a
	Farm Income +/-	-686	-678	-4,108	-445	n/a	n/a	n/a	n/a	n/a
	As % of baseline FBI	-1.9%	-1.9%	-6.2%	-1.5%	n/a	n/a	n/a	n/a	n/a
Final	Net FBI	34,699	34,562	61,980	28,606	n/a	n/a	n/a	n/a	n/a
M35	*Organic farming*				*Cost/benefit ratio (Change in all farms FBI/change in ktC02e):* **-4.3**					
Changes	Incr. cost/red. incm.	25,815	32,193	67,705	21,904	71,525	16,388	13,469	12,776	5,215
	Incr. incm./red. cost	22,707	28,257	50,612	27,965	50,490	16,858	13,354	11,050	4,006
	Farm Income +/-	-3,108	-3,937	-17,093	+6,062	-21,035	+470	-116	-1,726	-1,209
	As % of baseline FBI	-8.8%	-11.2%	-25.9%	+20.9%	-28.8%	+1.5%	-0.5%	-5.3%	-6.6%
Final	Net FBI	32,277	31,303	48,995	35,113	52,109	32,215	24,619	30,923	17,022
M37	*Agroforestry*				*Cost/benefit ratio (Change in all farms FBI/change in ktC02e):* **-6.4**					
Changes	Increased costs	4,162	4,636	8,751	4,140	9,425	3,391	2,816	2,649	1,175
	Cost savings	513	621	742	570	634	476	461	467	273
	Farm Income +/-	-3,649	-4,016	-8,009	-3,570	-8,791	-2,915	-2,355	-2,182	-902
	As % of baseline FBI	-10.3%	-11.4%	-12.1%	-12.3%	-12.0%	-9.2%	-9.5%	-6.7%	-4.9%
Final	Net FBI	31,736	31,224	58,079	25,481	64,353	28,830	22,379	30,467	17,330

5 Discussion of assumptions and results

As Table B indicates, the emission mitigation options presented in Chapter 2 vary widely in terms of their potential to reduce emissions, as does their impact on other policy objectives (Table C). We have evaluated in more detail in Chapters 3 and 4 those which showed most potential to contribute to the target of a 35% reduction in Scottish GHG emissions (2.7Mt CO_2e) by 2045.

We have considered the applicability (Table D), adoption characteristics (Table E; requirements, barriers and drivers) and potential uptake (Table F; quantity, timing and priority). Based on this assessment, and excluding measures M21 (nitrate feed additives), M22 (high lipid diets) and M29 (slurry acidification) due to potential duplication with other measures, we conclude that a reduction of 2.9 Mt CO_2e or 38% of Scottish agricultural GHG emissions is achievable. This is on an annual basis, and all references to emission values in this section are also presented on an annual basis.

There are some interactions between measures that we have not been able to analyse that could reduce this total, but we do not consider them to be significant. There is also potential to exceed this amount, as there are only a few cases where we have assumed 100% uptake, and higher uptakes could be achieved under the right conditions.

For almost all the measures analysed, it is not clear how current uptake is reflected in the calculations of Scottish agricultural GHG emissions, or how future uptake could be reflected in reduced emission totals. There will be a need to address the statistical evidence gaps if real progress by farmers is to be recognised. Defra produces an annual report 'Agricultural Statistics and Climate Change'[73] which illustrates how this might be approached.

In general terms, the largest potential impacts occur where nitrogen fertiliser use is reduced significantly (e.g. M17 (legumes in grassland), and where measures involve some land use change and carbon sequestration (e.g. M27 (improved grazing management), M35 (organic farming) and M37 (agroforestry)).

In the case of nitrogen fertiliser use, modest reductions in GHG emissions can be achieved with measures 1-3 (nitrogen fertiliser use efficiency), potentially in combination delivering 258 ktCO_2e reductions annually if applied on 50-75% of tillage and grassland), with no significant impacts on output. An additional 50% emissions reduction would be delivered in the manufacturing sector. These measures are relatively easy to implement, as the technical knowledge and technologies are available and accessible, but the financial impact assessments indicate that the cost savings from reduced fertiliser use do not outweigh the implementation costs. There may be scope to encourage nitrogen efficiency measures like these as part of a baseline agri-environment scheme.

A more radical option would be to encourage widespread use of legumes (clovers etc.) in grassland combined with a substantial reduction or complete elimination of nitrogen fertiliser use (M17). Adoption on 40% of grassland could deliver 295 ktCO_2e reductions in GHG emissions, bringing with it added biodiversity benefits (including pollinators) and improved forage quality and nutritional benefits for livestock. The use of legumes is well understood, with suitable varieties readily available, so there are no significant barriers to adoption. Financially, the impacts of this measure would be modest, with low net costs or possibly even cost savings on cropping and lowland/cattle and sheep farms. The biggest negative impact would be on dairy farms, where nitrogen fertiliser use on grassland is typically highest. It might be that for these farms a reduction in, rather than elimination of, nitrogen fertiliser use should be prioritised.

The contribution of livestock to GHG emissions has received widespread attention. Almost half (3.7 MtCO_2e) of Scottish agricultural GHG emissions are attributed to methane from enteric fermentation (digestion), while a further 17% (1.3 MtCO_2e) is related to manure management and application as well as urine and faecal deposits on grassland. These values contrast with the 1.1 MtCO_2e arising from nitrogen fertiliser use, leaching and run-off, as well as liming (some of which is needed to correct the soil acidification resulting from nitrogen fertiliser use). 55% of nitrogen fertiliser applications in Scotland were

[73] Defra (2019) Agricultural Statistics and Climate Change. 9th edition. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/835762/agriclimate-9edition-02oct19.pdf

on grassland, so at least 5.6 Mt CO_2e (almost 75% of Scottish agricultural emissions) can be attributed to livestock. Given the importance of livestock and grassland in Scottish agriculture, this is perhaps not surprising, but it explains why livestock production is a focus for attention. At the same time, the role of grassland in sequestering carbon is also significant, and livestock are often able to utilise land that is not suitable for crop production. It is therefore important to identify options to reduce emissions from livestock production, possibly with some reductions in numbers, rather than argue for the elimination of livestock entirely.

One option to reduce emissions from livestock while maintaining output is to reduce the methane from enteric fermentation (digestion) through the use of feed additives. Some, albeit limited, benefits have been attributed to the tannins in clovers and other herbage species that reduce the breakdown of nitrogen in the rumen, permitting the proteins to be broken down later in the digestion process with reduced methane emissions. Recent research has focussed on the use of feed additives such as 3NOP (M23), nitrates (M21), probiotics (M20), dietary lipids (M22) and seaweed derivatives (not assessed). While M20 and M22 are relatively well developed and easy to implement, their impact is relatively small. 3NOP and nitrates offer potentially greater impacts, with 3NOP potentially offering a 265 ktCO_2e reduction if adopted for 80% of dairy cows and 40% of other cattle. However, 3NOP is not yet approved as a feed additive, and its use is not sufficient to identify potential downsides, so some caution is needed. The use of nitrates has potential animal health implications if applied inappropriately, so its applicability is constrained. For 3NOP, cost estimates are difficult to make as the product is not on the market – we have attempted to illustrate a possible scenario, but in the long run the product may be much more affordable than our assumption. We have also not identified for these additives cost savings in terms of improved nutrition and productivity, which might help to make the case for their utilisation. Again, the relatively high use of livestock feeds by the dairy sector means that the negative financial impacts would fall primarily on this sector.

Improved animal health (M24, M25) and breeding (M26) in combination show significant promise to reduce emissions as a result of improved yields, growth rates, feed conversion efficiency and reduced requirements for replacements. These measures have the potential to maintain the output of meat and milk products while reducing the total number of livestock, creating a win-win situation with both opportunities for reduced emissions (combined total of 366 ktCO_2e with 40-50% uptake) and improved profitability. As a result, these measures were among the highest scoring for cost-effectiveness in our prioritisation rankings (Table F). We assume in this assessment that the land spared by reducing stock numbers remained as grassland. There would be potential to combine the reduced need for grassland with the use of legumes to reduce N fertiliser use (see above) and with approaches such as agroforestry (see below).

A further significant opportunity to reduce livestock-related emissions and sequester carbon is the use of rotational grazing (M 27) in combination with diversification of herbage species. If adopted on 50% of grassland, emissions could be reduced by 242 ktCO_2e. This would also work well in combination with M17, potentially delivering total reduction benefits of over 540 ktCO_2e. The financial impacts of the two measures are largely complimentary, including the potential on dairy farms for increased output from rotational grazing to compensate the impact on output of reduced fertiliser use with legumes. The potential of this combination suggests that the assumption that grass-fed livestock are worse for emissions than grain-fed due to high fibre diets generating more methane emissions need to be reassessed, and that there would be a case for investigating further the potential of pasture-fed livestock production (M36) in future work.

Livestock manures and slurries are also a focus for attention due to the release of both methane and ammonia, with indirect impacts on N_2O emissions, but measures aimed at reducing losses during storage may be negated by increased losses on application, so it is necessary to consider these options together. Better planning of organic manure utilisation (M6) and low emission spreading techniques (M7) in combination have the potential to reduce emissions by 86 ktCO_2e at relatively low cost. However, many of the measures suggested for improved storage of manures and slurries, including anaerobic digestion (M31), slurry-store covering (M30), composting (M33) and slurry aeration (M32) offer relatively low mitigation potential. Slurry acidification appears to offer more potential – up to 67 ktCO_2e in our estimates, but there are concerns about the environmental and health and safety implications of this approach. At present it is not widely used in the UK, but in Denmark uptake is over 20%. Given the greater potential for mitigation elsewhere, it may be that manure and slurry management should not be the central focus of a future strategy.

In part given the relatively low significance of crop production in Scottish agricultural emissions (18% or 1.4 $MtCO_2e$), measures focused specifically on crop production, including reducing soil compaction (M11), improved drainage (M12), reduced/zero tillage (M10), spring crop cultivations (M9), use of improved nitrogen-use efficiency varieties (M15) and the use of catch crops (M14) and grain legumes in crop rotations (M16) all make relatively small contributions to the overall challenge. The combination of a number of these measures in a conservation agriculture (M34) approach to arable production may offer the best approach, with the potential also for biodiversity and other benefits. We estimated that uptake of conservation agriculture on 50% of tillage land could achieve a modest reduction of 74 $ktCO_2e$. If combined with the more efficient use of machinery (M18), this could be increased to 112 $ktCO_2e$. Although yields can be maintained, there is a net financial cost to the approach, which in our analysis is particularly high on general cropping farms, as a consequence of high prevalence of potato production and the assumption that all crops would be reduced pro rata to allow for an increase in grain legumes. In practice, it likely that the potato area on these farms could be maintained, and other less profitable crops reduced instead. The combination of GHG and other public benefits could make this option worth considering for future agri-environmental support.

The highest single emissions reduction opportunity identified is organic farming (M35), with 40% uptake potentially resulting in a reduction of 731 $ktCO_2e$. This is a consequence of a) the elimination of synthetic nitrogen fertiliser use, b) the conversion of tillage land to rotational grassland on more crop focused farm types and c) the 20% reduced stocking rates on grassland, leading to an overall reduction in livestock numbers of 10%. There would also be manufacturing sector benefits in terms of agrochemical use reduction, but these have not been estimated here. As can be seen from the financial calculations, this measure also involves the largest changes, both plus and minus, which can act to inhibit uptake, particularly where there is uncertainty over market premiums. We have not included current support payments for organic farming in our calculations. Two farm types show significant income losses: general cropping (due to the prevalence of potatoes) and dairy. A higher price premium for these commodities could help address this issue. Lack of availability of information and advice is also a key issue affecting uptake.

Agroforestry (M37) offers the second best mitigation potential, at 569 $ktCO_2e$ based on 30% uptake. Nearly 75% of this gain is a result of carbon sequestration from the tree component, with the balance mainly a result of reduced livestock output. The financial assessment shows that the establishment costs and lost income from cash crops and livestock can be quite high, with limited opportunities for replacement income unless profitable options like fruit or nuts can be established. There is therefore a need to adapt systems to specific situations to minimise the financial impacts, and to consider support packages that address the upfront establishment costs and the long lead in times before new income can be generated.

In most cases, the measures analysed involve no reduction in output, so there is limited risk of exporting emissions to other countries as a result of increased reliance on imports. The livestock health and breeding measures (M24, M25, M26) even have the potential to reduce total feed requirements including feed imports, therefore offering some additional benefits in other countries. But some of the measures analysed do involve output reductions. The use of legumes in rotations (M16) and in grassland (M17) have modest output reductions due to the replacement of other crops by grain legumes in M16 and the reduced forage yields in M17. The output reductions from M16 also then apply to conservation agriculture (M34). Larger reductions in output are associated with agroforestry (M37) due to the replacement of 10% of the farmed area with trees, but yields and stocking rates may be increased on the remaining land to compensate.

The largest potential output reductions are associated with organic farming (M35), given the assumption of a 40% reduction in crop yields, a 25% reduction of the cropped area on cereals and general cropping farms, a 10% reduction of cropped area on mixed farms, and a 10% overall reduction in livestock output. This represents a significant trade off against the substantial mitigation benefits identified, although a range of biodiversity and other environmental benefits also need to be considered. This issue has been highlighted most recently by Smith et al. (2019)[74] in a study of 100% conversion to organic farming in England and Wales. However, this study assumed that food demands would be unaltered, and it is possible that a substantial adoption of organic farming would be accompanied by both changes in human and animal diets and reductions in food waste which could moderate the impact of at least some of the output reductions.

In most cases, the financial costs identified are regular annual costs not requiring an initial investment. Often where specialist machinery is required, this can be provided by contractors. For M1, M6, M24 and M25, initial nutrient and health planning are required, but the costs of this are relatively low. In some cases, such as M17 (legumes in grassland), slot-seeding of permanent grassland at 10 year intervals has been assumed, with the costs averaged over the 10 year period. M27 (improved grassland management) would have an upfront requirement for investment in fencing, tracks etc. which has been included in the annual costs estimated. M37 (agroforestry) establishment costs would also be concentrated in the early years, and any support programmes would need to accommodate this. For M35 (organic farming) there are significant additional costs associated with system restructuring and lack of access to premium prices during the 2-3 year conversion period that have not been assessed here. These are reflected in the current higher support payments for conversion to organic production.

[74] Smith LG, Kirk GJD, Jones PJ, Williams AG (2019) The greenhouse gas impacts of converting food production in England and Wales to organic methods. *Nature Communications* 10, 4641.

6 Policy options

The aim of this Chapter is to review the policy mechanisms required from Scottish Government to help the agriculture sector transition to a 35% reduction in emissions by 2045, including the framework of regulation, advice and incentives and how can they be appropriately sequenced.

The policy mechanisms available will to some extent depend on the outcome of current Brexit discussions, at least in the short term. Scotland, as other parts of the UK, is considering a post-Brexit agricultural policy which emphasises public money for public goods – the extent to which emission (negative externality) reductions can be considered part of this will depend on where boundaries are set.

In addition to the Scottish Government's own initiatives[75,76], various organisations have published policy proposals[77,78,79,80] for the future of Scottish agriculture in the last couple of years. We have considered these as part of this analysis.

6.1 Farming system payments for innovative approaches (whole or part farm)

As our analysis indicates, farming system-based approaches including pasture fed livestock (integrating M17 and M27), agroforestry (M37), organic farming (M35) and, to a lesser extent, conservation agriculture (M34) provide the opportunity to generate substantial reductions in GHG emissions. Offering payments to support the establishment and maintenance of these systems would be justified both in terms of climate objectives and the delivery of other environmental public goods. This is a conclusion also supported by the latest IPCC report on Climate Change and Land[81].

Revising the current agroforestry scheme provided by the Scottish Government[82], in particular to reduce the tree numbers per ha requirement, would be an important first step, as currently the minimum density under the scheme is 200-400 trees per hectare, which excludes farmers from payment under the Common Agricultural Policy-based Basic Payment Scheme (BPS) and potentially could lead to the land being fully removed from agriculture once the tree canopy closes.

Support schemes need to be adaptable to enable appropriate implementation of systems on different farm types and locations, and where systems, such as organic farming, have a significant market interaction, the design and implementation of the schemes needs to be sensitive to market impacts[83].

6.2 Input reduction and improved soil management

This study has highlighted the potential of reduced use of nitrogen fertilisers, fuel and other inputs, as well as better use and storage of organic manures. While individually, some of these measures only have limited emission reduction impacts, collectively they could be significant. As part of a future baseline agri-environment scheme, some targeted options could be utilised, for example:

- A nitrogen use reduction scheme including the use of better planning and catch/cover crops and legumes;

[75] Scottish Government (2018) Climate change plan third report.
[76] Climate Change (Emissions Reduction Targets) (Scotland) 2019 Act
[77] RSPB (2018) Balancing Act: How farming can support a net-zero emission target in Scotland. RSPB Scotland.
[78] NFUS (2018) Steps to Change: A new agricultural policy for Scotland. NFU Scotland.
[79] LINK (2018) 10 Principles for Future Land Management Support in Scotland. Scottish Environment LINK.
[80] SLE (2018) A new direction for Scottish land management. Scottish Land and Estates.
[81] IPCC (2019) *Climate Change and Land.* Special report on climate change, desertification, land degradation, sustainable land management, food security and greenhouse gas fluxes in terrestrial ecosystems. https://www.ipcc.ch/report/srccl/
[82] https://www.ruralpayments.org/publicsite/futures/topics/all-schemes/forestry-grant-scheme/agroforestry/#570391
[83] See also SOLMACC project policy recommendations with respect to organic farming: http://solmacc.eu/wp-content/uploads/2018/05/IFOAMEU_SOLMACC_policy-recommendations_FINAL_web_cover_20180518.compressed.pdf

- A livestock methane and ammonia reduction scheme including appropriate feed additives and improved manure and slurry management options.

Support for soil testing and advice provision through the SRUC Soil and Nutrient Network[84] and other similar support mechanisms should be continued. The RSPB has recommended making soil testing compulsory[77]. Options to better co-ordinate manure use between livestock and arable farms could also be considered[85] including potentially central manure processing plants as in the Netherlands[86].

Policy measures to support capital investment, for example in on-farm energy efficiency and heat recovery, improved manure management facilities (including anaerobic digestion where appropriate), and improved mechanisation options, should be included as part of this approach.

These schemes would also have benefits for water and air quality. Collaborative initiatives in catchment sensitive areas, with enhanced payments for co-operation between groups of land-managers, water companies and civil society organisations, should also be considered. This could be based on a Payment for Ecosystem Service (PES) approach, for example by facilitating carbon offset payments between private companies and individual farms. Current initiatives such as the Scottish Water-led Sustainable Land Management Incentive Scheme[87], the Tweed Forum Carbon Club[88], and the Dee Catchment Partnership[89] could provide valuable insights for such an approach. Funding for the promotion of partnership-building and templates for land-management contracts would help this process.

6.3 Regulatory and fiscal options

Tighter regulation could also help to encourage improved management of GHG intensive inputs such as manufactured nitrogen fertiliser. The introduction of quotas or a tax implemented in proportion to the level of non-renewable inputs to a farm could provide an effective driver for change, although care would need to be taken to avoid "emission leakage" as a result of increased reliance on imported products from countries with less efficient production systems[90].

Similarly, tradeable fossil-energy quotas could be implemented at national scale to limit purchasing of non-renewable inputs through effectively limiting the amount any one individual business can purchase in a given year[91]. This could be linked to tradeable carbon quotas (as have already been proposed for forestry in Scotland[92]) that also take account of carbon sequestration initiatives by farmers, including soil carbon building activities, conversion of tillage to grassland and practices such as agroforestry.

Payment by Results (PBR) based schemes could be used to encourage farmers to engage more directly with desired outcomes and to be innovative in how these are delivered in the context of their specific situations[93,94]. A recent report by ClimateXChange emphasised the potential of PBR scheme(s) for carbon sequestration[95]. Such schemes would require careful management to avoid excessive burdens of

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[84] https://www.farmingandwaterscotland.org/soil-nutrients/

[85] Soussana JF, Lemaire G (2014) Coupling carbon and nitrogen cycles for environmentally sustainable intensification of grasslands and crop-livestock systems. *Agriculture, Ecosystems & Environment* 190:9-17.

[86] Zwart SD (2015) Responsibility and the problem of many hands in networks. In: van de Poel I, Royakkers L, Zwart SD (eds.) *Moral Responsibility and the Problem of Many Hands*, Routledge: Abingdon pp. 131-166.

[87] Thomson K, Kerle S, Waylenk K, Martin-Ortega J (2014) Water-based payment for ecosystem services (PES) schemes in Scotland. James Hutton Institute.

[88] https://tweedforum.org/tweed-forum-carbon-club/

[89] https://www.deepartnership.org/

[90] Himics M, Fellmann T, Barreiro-Hurlé J, Witzke HP, Pérez Domínguez I, Jansson T, Weiss F (2018) Does the current trade liberalization agenda contribute to greenhouse gas emission mitigation in agriculture? *Food Policy* 76:120-129.

[91] Fleming D, Chamberlin S (2011) TEQs (Tradable Energy Quotas): A policy framework for peak oil and climate change. London: All-Party Parliamentary Group on Peak Oil, and The Lean Economy Connection.

[92] https://www.climatexchange.org.uk/research/projects/future-options-for-forest-carbon-markets-in-scotland-and-the-uk/

[93] Rayment M (2018) Paying for public goods from land management: How much will it cost and how might we pay? RSPB, the National Trust and The Wildlife Trusts.

[94] https://ec.europa.eu/environment/nature/rbaps/index_en.htm

[95] Yeluripati J, Rivington M, Lilly A, Baggaley N, McKenzie B, Aitkenhead M, Matthews K (2018) Payment for carbon sequestration in soils: A scoping study. ClimateXChange.

administration and monitoring, and should aim to be fair in recognising land management histories. Encouraging public-private partnerships in PBR schemes at regional and national level would serve to increase their appeal and uptake.

6.4 Carbon, nitrogen and sustainability auditing

Policy initiatives to encourage the use of carbon auditing support tools (e.g. AgRE Calc[96], Cool Farm Tool[97]) could help to encourage the general uptake of mitigation measures described in this report. Given the potential interactions with other environmental and social objectives identified in Table C, integrated sustainability assessment tools[98] can help ensure that carbon audit tools used in isolation do not have unintended consequences with respect to other policy objectives, and could help underpin future agri-environment-climate schemes[99]. A recent consultation on the development of a post-Brexit Sustainable Land Management (SLM) scheme in Wales[100] has suggested an annual sustainability self-assessment for the purpose of allocating subsidy based on delivery of public goods and Defra are considering the role of farmer-self assessment as part of the Environmental Land Management (ELM) scheme. A similar self-assessment initiative in Scotland could help to avoid duplication of effort and encourage uptake.

The potential for reducing the unnecessary use and losses of nitrogen, whether from synthetic fertiliser or organic sources, to reduce GHG emissions has been highlighted in this report. The inclusion of a national nitrogen balance sheet in the Climate Change (Emissions Reduction Targets) (Scotland) 2019 Act[101] reflects the significance of this, but there is also a need to make this work at a farm scale. Measures 1 and 6 in this study can incorporate a balance sheet approach as part of better nitrogen use planning, using tools such as PLANET[102]. Current work to develop a nutrient budgeting tool[103] as part of the new Common Agricultural Policy (CAP) proposals for 2021-2027 could also be relevant in this context. Consideration should also be given to extending nitrogen budgeting approaches to include soil organic matter balances.

However, many of these tools are rarely used in practice by farmers, despite research projects[104] which have explored routes for encouraging their adoption, e.g. by making them more farmer-friendly. Fitting assessments within existing workflows may help to encourage uptake[105].

6.5 Training, advice and skills

Many of the measures analysed require improvements in technical knowledge, tools and advice to support their implementation (Table E). Scotland is well placed to utilise resources within SRUC and other organisations, include the SEFARI initiative[106], to support this. Farmer-to-farmer knowledge exchange (e.g. demonstration events and on-farm workshops) can be a powerful tool to overcome gaps in knowledge that may limit the potential for some mitigation measures. Increasing the visibility and availability of existing information is also key and future developments should seek to build-on and improve current online resources (e.g. Farm Advisory Service Technical notes[107], outputs from the SRUC Animal Health Planning

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96 https://www.agrecalc.com/

97 https://coolfarmtool.org/

98 Mullender, S, Smith, LG, Padel, S (2018) Sustainability Assessment: The Case for Convergence. Sustainable Food Trust, Bristol.

99 https://www.ruralpayments.org/publicsite/futures/topics/all-schemes/agri-environment-climate-scheme/

100 https://gov.wales/sites/default/files/consultations/2019-07/brexit-consultation-document.pdf

101 http://www.legislation.gov.uk/asp/2019/15/enacted (Regional N balances for the period 1995-2017 in Germany have recently been published which contain relevant methodological considerations: Stickstoff-Flächenbilanzen für Deutschland mit Regionalgliederung Bundesländer und Kreise – Jahre 1995 bis 2017: Methodik, Ergebnisse und Minderungsmaßnahmen. Abschlussbericht. Umweltbundesamt, Germany).

102 www.planet4farmers.co.uk

103 https://ec.europa.eu/info/news/new-tool-increase-sustainable-use-nutrients-across-eu-2019-feb-19_en

104 Rose DC, Sutherland WJ, Parker C, Lobley M, Winter M, Morris C, Twining S, Ffoulkes C, Amano T, Dicks LV (2016) Decision support tools for agriculture: Towards effective design and delivery. *Agricultural Systems* 149:165-174.

105 Rose DC, Keating C, Morris C (2018) Understanding how to influence farmers' decision-making behaviour: a social science literature review. Agriculture and Horticulture Development Board, University of East Anglia, Norwich

106 https://sefari.scot/

107 https://www.fas.scot/publication/technical-notes/

System[108] and Practice Abstracts within the Agricology website[109]). Support for skills development should also be encouraged, both via online and/or face-to-face training within the Farming for a Better Climate programme[110] and similar initiatives. Providing support for modules targeting GHG mitigation within agricultural courses and universities and colleges in the UK will also help to equip future generations of farmers will the skillsets required for effective GHG mitigation.

While there are many existing initiatives that can be built on and further developed, it would be desirable to conduct a stocktake of the current support available to ensure that there are no critical gaps in provision.

6.6 Improved greenhouse gas monitoring and statistics

We have identified in Chapter 5 the need for better statistics to enable the impact of the adoption of GHG mitigation measures to be better quantified and represented in the reporting of agricultural GHG emissions. This needs a systematic review of current data collection on farming practices and their integration into the GHG inventory. The most recent (2016) Scottish Farm Structure and Methods Survey[111] is a step in the right direction, but the surveys should be carried out more frequently, with more detail, and a specific focus on interpretation in terms of climate change-related impacts. The annual reporting by Defra[73] could be used a starting point for further developments.

Within the current agricultural GHG inventory, there are also data gaps despite the recent efforts of the UK Greenhouse Gas Platform. In particular better activity data in the areas of nitrogen fertilisation of minor crops, ruminant diets, and manure and slurry management/storage information would help to improve the accuracy of the current GHG inventory for Scotland, and aid the development of effective policy support towards those areas in the most need[112]. Improved data availability would also help address some of the research needs identified below.

Benchmarking by farm type could also play a useful role in this regard, facilitating improved performance by allowing for comparison of individual farm performance against other similar farms[78].

Given that global warming is by-definition a global crisis, there should also be moves towards improved reporting systems, as the current national inventory potentially gives a misleading picture of mitigation by only accounting for GHG sources and sinks within Scotland and within the agricultural sector. Improved national reporting schemes that account for both domestic and external footprints would allow for better recommendations and support for farm practices that adequately captures overseas impact (e.g. overseas emissions from deforestation that occurs in order to produce imported soy-based feeds). Recent work by the Stockholm Environment Institute[113],[114] could help to inform improved calculations focused on consumption rather than production.

6.7 Targeted research

While a lot of research has already been undertaken on the subject of climate change and agriculture, there are some significant open questions that still need to addressed so that better decisions about future mitigation options can be made. As a result of this study, we have identified a number of specific areas where further research is needed:

- <u>The potential to reduce consumption and demand</u> as a way of reducing the need for production in the first place. This is partly an issue of diet, but it is also a question about how business and technical practices adopted by supply chain actors (before and from the farm gate to retailers and caterers) and by consumers, could reduce food losses and waste.

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[108] https://www.sruc.ac.uk/info/120107/veterinary_services/295/animal_health_planning_system_sahps
[109] https://www.agricology.co.uk/resources/
[110] https://www.farmingforabetterclimate.org/
[111] https://www2.gov.scot/Topics/Statistics/Browse/Agriculture-Fisheries/Publications/FSSPubs
[112] Eory V, Topp K, Rees B (2019) Mitigation measures in the 'smart inventory': Practical abatement potential in Scottish agriculture. ClimateXChange.
[113] https://www.sei.org/topic/supply-chains/
[114] Palm V, Wood R, Berglund M, Dawkins E, Finnveden G, Schmidt S, Steinbach N (2019) Environmental pressures from Swedish consumption–A hybrid multi-regional input-output approach. *Journal Cleaner Production* 228:634-644.

- The complex interactions between livestock, pasture species and management, soil carbon and nitrogen fixation, diet, human and animal health and greenhouse gas emissions[115]. There are complex trade-offs (both synergies and conflicts) between these issues that have not been fully evaluated, including some very specific topics such as free-range pig and poultry production. More generally, there is a need to better understand how trade-offs between climate and other policy goals can be identified, quantified and evaluated. Research on the complementarity between individual mitigation measures could help to reveal the best combinations of practices and whether these could justify tailored support schemes.
- The optimal use of marginal, rough grazing lands. Almost 60% of Scottish agricultural land is classified as rough grazing of different types. The Macaulay Land Capability system focuses on the production potential of these land categories, but it is not clear from available studies what proportion of rough grazing land might be better retained for grazing, or transferred to non-agricultural uses including peatland restoration, afforestation or rewilding. All of these alternative uses have significant carbon sequestration potential, but the analysis of this was outside the scope of this study.
- Further research on the financial costs/benefits that could accrue from the uptake of the measures considered in this report would also be useful. The financial assessment approach taken within this report was necessarily rudimentary. A more detailed analysis could consider the wider uptake of practices or farming systems (e.g. through upscaling to regional or national levels) and/or follow an Economics of Ecosystem Services assessment approach building on current work within the Natural Capital Coalition[116] and The Economics of Ecosystems and Biodiversity (TEEB) project[117].
- Further research on changing attitudes and behaviour could also help to identify key leverage-points for encouraging the uptake of innovative practices that may be considered complex or infeasible in some circles (e.g. agroforestry, organic farming, 100% pasture fed livestock). Padel (2001)[118] has demonstrated that the more complex an innovation is, the slower its uptake. In particular, exploring how knowledge generation and use may be a force for reorientation in agriculture would help to drive understanding in this area. Recent work [99,119,120] has made useful recommendations on effective strategies for changing behaviour.

6.8 Dietary change and food waste reduction

A detailed exploration of the impact of dietary changes in Scotland was beyond the scope of this study, however recent reports have highlighted a clear need to eat “less and better” meat and/or the potential benefits of a move towards more plant-based diets[121,122]. At the same time, it is recognised that significant changes to diets are difficult to achieve in a free market, particularly in view of the lack of policy mechanisms to drive this (especially mechanisms that do not add to total food costs) and the lack of political will to invest the time and resources needed to transition to healthier and more sustainable

[115] Garnett, T, Godde, C, Muller, A, Röös, E, Smith, P, De Boer, IJM, zu Ermgassen, E, Herrero, M, Van Middelaar, CE, Schader, C (2017) Grazed and confused?: Ruminating on cattle, grazing systems, methane, nitrous oxide, the soil carbon sequestration question-and what it all means for greenhouse gas emissions. FCRN.

[116] https://naturalcapitalcoalition.org/

[117] http://www.teebweb.org/

[118] Padel, S (2001) Conversion to organic farming: a typical example of the diffusion of an innovation? *Sociologia Ruralis* 41:40-61.

[119] Dessart FJ, Barreiro-Hurlé J, van Bavel R (2019) Behavioural factors affecting the adoption of sustainable farming practices: a policy-oriented review. *European Review of Agricultural Economics* 46:417–471.

[120] Abson DJ, Fischer J, Leventon J, Newig J, Schomerus T, Vilsmaier U, von Wehrden H, Abernethy P, Ives CD, Jager NW (2017) Leverage points for sustainability transformation. *Ambio* 46:30-39.

[121] Bajželj B, Richards KS, Allwood JM, Smith P, Dennis JS, Curmi E, Gilligan CA (2014) Importance of food-demand management for climate mitigation. *Nature Climate Change* 4:924.

[122] Willett W, Rockström J, Loken B, Springmann M, Lang T, Vermeulen S, Garnett T, Tilman D, DeClerck F, Wood A (2019) Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *The Lancet* 393:447-492.

diets[123] Encouraging greater consumption of plant-based food products would therefore require a significant overhaul of policy support measures in the UK and Europe, which have tended to promote the (over) production of meat, sugar and dairy products, as well as their over-consumption, particularly in low income households[124]. Moves in this direction could also help to encourage more nutritionally balanced diets with associated health benefits[125].

This study has also highlighted the importance of food waste reduction in achieving a more sustainable supply of food. The Scottish Government's Food Waste Reduction Action Plan[126] is an important initiative in this context, but there is more that could be done at farm level and in the supply chain to reduce losses, particularly of horticultural products, through grade-outs and failure to harvest crops produced. Better planning, including contractual commitments to buy and utilise crops produced, would help this situation. There are also considerable opportunities for offsetting supply losses through: improving management practices in the retail sector (e.g. avoiding overstocking); technological innovations (e.g. smart-fridges); and educating consumers (e.g. the Love Food Hate Waste Campaign introduced by the Waste and Resources Action Programme (WRAP) in 2007[127]). If such measures could be implemented on a wider scale, they would help to reduce overall food demand, thereby reducing GHG emissions within the food system and allow for the wider adoption of lower-input agricultural systems, and the resource-use efficiencies accompanying them.

6.9 Conclusion

Whether or not Brexit happens, the Scottish Government will have to design new agricultural/agri-environmental policy schemes. Individual measures and/or effective combinations to delivery climate change mitigation should be included in this process. Should the UK remain in the EU after all, then the new CAP Strategic Plans and Pillar 1 eco-schemes could provide a mechanism to deliver this, although the requirement to deliver these at the Member State level may complicate negotiations. However, Member States will be free to propose measures to meet their identified needs and priorities, which may give greater flexibility than in the past.

[123] Wellesley L, Happer C, Froggatt A (2015) *Changing Climate, Changing Diets.* Chatham House, the Royal Institute of International Affairs, London.

[124] Bailey A, Lang T, Schoen V (2016) Does the CAP still fit? Food Research Collaboration, London.

[125] Williams A, Morris J, Audsley E, Hess T, Goglio P, Burgess P, Chatterton J, Pearn K, Mena C, Whitehead P (2018) Assessing the environmental impacts of healthier diets. Final report to Defra on project FO0427.

[126] https://www.gov.scot/publications/food-waste-reduction-action-plan/

[127] Priefer C, Jörissen J, Bräutigam K (2013) Technology options for feeding 10 billion people, Science and Technology Options Assessment: Options for Cutting Food Waste, p. 127. Directorate General for Internal Policies, European Parliament, Brussels.

7 Glossary of terms

Agroforestry	Farming with trees through the integration of trees on farmland and/or through the use of livestock or crops in woodlands.
Ammonia	A compound of nitrogen and hydrogen. A colourless gas with a characteristic pungent smell. Common agricultural sources include slurries, manures and fertiliser. Chemical formula = NH_3.
Ammonium nitrate	A highly water-soluble chemical compound, the nitrate salt of the ammonium cation derived by combining ammonia with nitric acid. It is a white crystal solid and predominantly used in agriculture as a high-nitrogen fertilizer. Chemical formula = NH_4NO_3, simplified to $N_2H_4O_3$.
Carbon sequestration	In agriculture, refers to the removal, through plant photosynthesis, of carbon dioxide from the atmosphere and the storage of that carbon as plant biomass and organic matter.
Catch crops	A rapidly maturing crop that is often grown between plantings of a main crop. Radishes and mustard are common examples.
Compaction	Increased density of soil through compression of pores that could otherwise transport air and water. Soil compaction often occurs as a result of the use of heavy machinery (e.g. tractors) in wet conditions.
Concentrate feed	Highly concentrated sources of nutrients for animal feed. Common forms include “straights” i.e. individual feed ingredients such as wheat or oats, “blends” i.e. mixtures of individual ingredients and “compounds” i.e. pelleted mixtures of ingredients that are often balanced to meet nutritional requirements and include supplementary minerals.
Denitrification	The microbial reduction of nitrate to gaseous N, resulting in nitrous oxide (N_2O) emissions. Occurs within the soil profile wherever there is sufficient available nitrate, labile carbon substrate, and low oxygen conditions (e.g. in slowly draining soils or in waterlogged conditions).
Field capacity	The amount of soil moisture or water content held in the soil after excess water has drained away and the rate of downward movement has decreased. This usually takes place 2–3 days after rain or irrigation in pervious soils of uniform structure and texture.
GWP	Global Warming Potential- a measure of how much heat a greenhouse gas traps in the atmosphere up to a specific time horizon, relative to carbon dioxide.
IPCC	Intergovernmental Panel on Climate Change.
Leaching	In an agricultural context refers to the loss of water-soluble plant nutrients from the soil, due to rain and irrigation.
Methane	A potent greenhouse gas. Main human derived sources are fossil fuel production, distribution and use and livestock farming. Chemical formula = CH_4.
Nitrate	A chemical that includes nitrogen and oxygen, often used as a fertiliser. Chemical formula = NO_3.
Nitrification	The process in which bacteria in the soil use oxygen to change compounds of nitrogen (e.g. from organic matter) into nitrates which plants can then absorb.
Nitrous oxide	An important anthropogenic greenhouse gas. Agriculture represents the largest source through cultivation of soils, biomass burning and N fertiliser. Chemical formula = N_2O.
Rough grazing	Unimproved grassland of mainly or entirely natural species.
Scope 1 emissions	Direct greenhouse gas emissions resulting from the activities of an organisation. Includes fuel combustion on site.
Scope 2 emissions	Indirect greenhouse gas emissions from electricity purchased and used by an organisation.
Scope 3 emissions	Greenhouse gas emissions associated with an organisation’s brought in products or services. Usually the greatest share of the carbon footprint.
Transpiration	The process of water movement through a plant and its evaporation from aerial parts.
Urea	An inexpensive form of nitrogen fertilizer manufactured with anhydrous ammonia. Chemical formula CH_4N_2O
Volatilisation	In the case of nitrogen (N) occurs at the soil surface when ammonium from urea or ammonium-containing fertilisers (e.g. urea) is converted to ammonia gas at high pH. Losses are minimal when fertiliser is incorporated, but can be high where fertiliser is surface-applied.