Farm-level Interventions to Reduce Agricultural Greenhouse Gas Emissions

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The report was funded by the Sustainable Agriculture Workstream of the WWF-UK and Tesco Partnership.

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Executive Summary

This report assesses interventions that UK farmers can implement to reduce greenhouse gas (GHG) emissions on their farms and provides advice to policymakers (and other key stakeholders) for how they can support uptake. Reducing food waste (that is not generated on farms) and encouraging dietary shifts away from animal products are recognised as key to reducing agricultural emissions but are out of scope of this report as they are driven by consumer changes.

E.1.0 Key Recommendations

1) Develop more **holistic GHG emissions accounting** to understand our priorities:
    a. Incorporating the climate impact of occupying land for UK agriculture (in the UK and overseas) to prioritise interventions that improve land-use efficiency.
    b. Considering shorter-timescales when assessing global warming potential (GWP) to prioritise interventions that reduce methane.
2) Accelerate **targeted research and development** (R&D) to deliver change where the potential impact is greatest:
    a. Reducing methane via feed additives for ruminants.
    b. Reducing the land area required for animal feed production by using alternative protein sources (e.g. insects and microbial protein).
3) Improve **support for farmers** to reduce their GHG emissions:
    a. Robust, impartial, consistent, and tailored advice.
    b. Financial incentives to fund both capital and ongoing costs.
4) Ensure **open access** to data to establish a central evidence base to support R&D and provide consistent advice for farmers.
5) Deliver **system change** to enable farmers to reduce on-farm food waste (as well as off-farm food waste and dietary shifts, although out of scope for this report).

Further detail on these recommendations and the relevant stakeholders needed to drive each action are discussed in Section 4.0.

E.2.0 Understanding Key Emission Sources

In order to assess the GHG reduction potential of farm-level interventions, it is first crucial to understand the extent and key sources of agricultural emissions. The largest emission sources provide the greatest reduction potential. According the CCC's Sixth Carbon Budget, agricultural emissions are responsible for 54.6 tCO_2e per year (in 2018),[1] which is around 10% of total UK emissions. According to the CCC, the key sources of these emissions are:

- Enteric fermentation (53%) – primarily methane.

[1] Climate Change Committee (2020) *The Sixth Carbon Budget: Methodology Report*

- Agricultural soils (22%) – primarily nitrous oxide and carbon dioxide.
- Wastes and manure management (16%) – primarily methane and nitrous oxide.
- Mobile and stationary farm machinery (8%) – primarily carbon dioxide.
- Other (2%)

However, this breakdown does not recognise the climate impact of occupying land for agricultural use, which is huge. Therefore, interventions that increase land use efficiency are not considered impactful, yet our analysis suggests these should be a top priority. A global perspective is needed because large areas of land overseas are required to support aspects of UK agriculture, primarily imported soy for animal feed. Replacing imported soy with locally grown grains without increasing land use efficiency will simply shift production of other products overseas. Additionally, reducing agricultural land use efficiency in the UK, without an equivalent reduction in demand, will displace production overseas and this needs to be recognised.

Furthermore, current emissions estimates assess the Global Warming Potential (GWP) of GHGs over a 100-year timescale. However, given the urgency of the climate crisis, GWP could be considered over shorter timescales. This timescale adjustment would substantially increase the relative importance of methane (a potent but short-lived GHG). This may shift our priorities further towards interventions that reduce methane.

This report predominantly assesses the GHG abatement potential of interventions based on current emissions accounting methods. However, to start to consider interventions that can improve global land use efficiency we have included an intervention that would replace soy in animal feed with alternatives that have lower land requirements.

E.3.0 Pathways to GHG Reduction Targets

Several agricultural GHG reduction targets have been published, including:

- **National Farmers' Union (NFU)**: Net Zero by 2040 (including 21% reduction by 2040).
- **The Food, Farming & Countryside Commission (FFCC)**: 38% reduction by 2050.

These targets are based on current emissions accounts and therefore may not sufficiently drive action to improve global land use efficiency or to address short-term emissions from methane. In addition, these targets are based on what is deemed achievable with current technology. However, this report highlights the substantial potential of research and development to deliver deep emission reductions. WWF is still in the process of establishing its emission reduction target. Therefore, there is an opportunity for WWF to take a lead and base their target on new emissions accounting methods that consider both land use and metrics recognising more urgent timescales, and to increase the level of ambition by incorporating the potential of further R&D.

E.4.0 Summary of Potential Interventions

20 interventions were short-listed (see E.4.1.1) and assessed based on both academic literature (to understand potential impact) and farmer insights from a farmer workshop (to

understand feasibility and key barriers). Each intervention was characterised according to four key variables:

1. National GHG abatement potential (qualitative score 0-5)
2. Cost of abatement (£/tCO_2)
3. Farmer views on 'cost-benefit' (qualitative score 0-5)
4. Farmer views on 'likelihood of implementation' (qualitative score 0-5)

When presented graphically (see Figure E- 1) interventions resolved into three distinct clusters: 'potential easy wins?', 'more challenging?', and 'further research needed?'. The potential "easy wins" seem promising but farmers highlight that even these interventions face a range of challenges. Within these clusters three high impact 'big hitters' emerged:

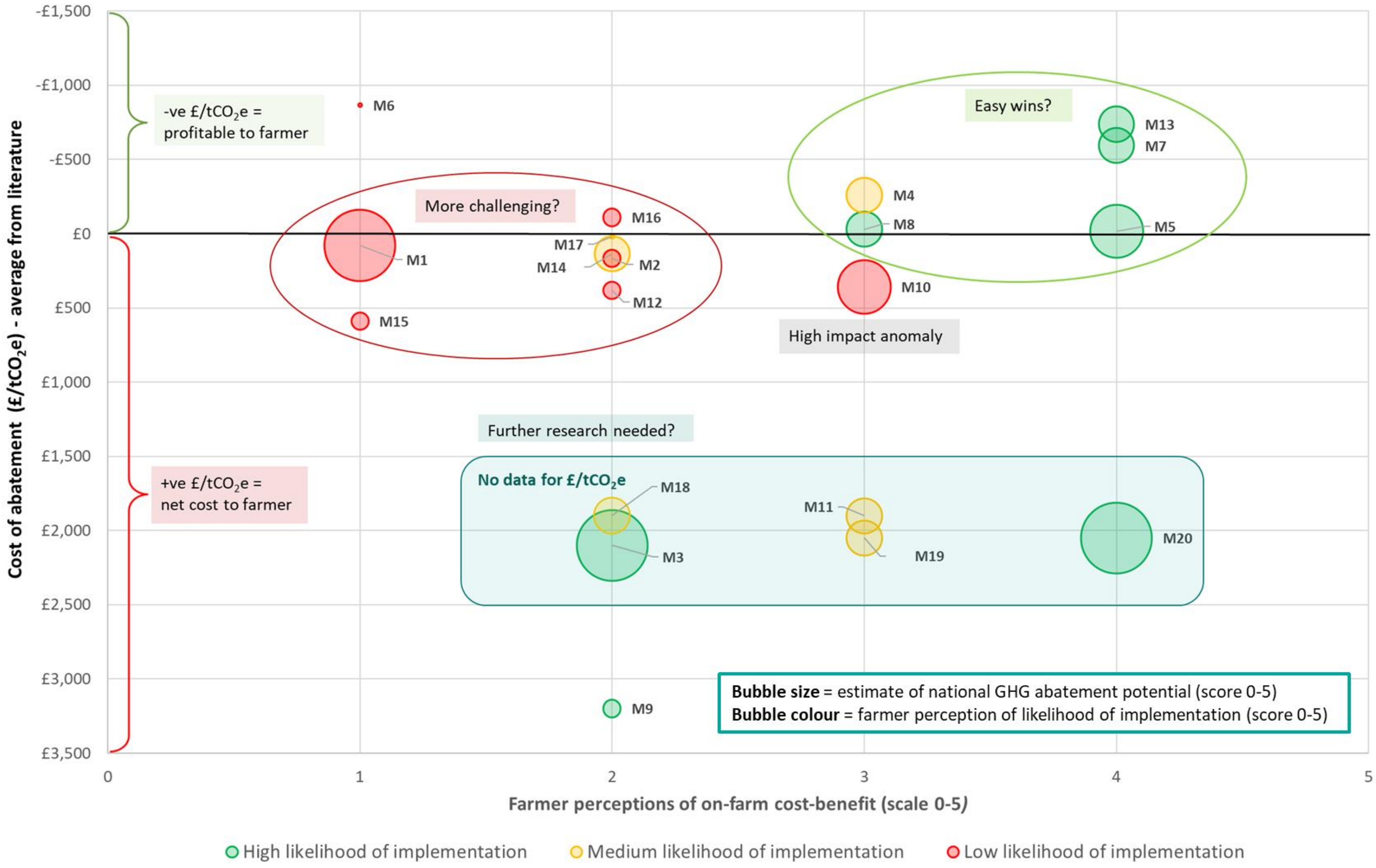
- feed additives for ruminants to reduce methane;
- novel animal feed alternatives that reduce land use; and
- on-farm food waste reduction.

None of these big hitters fell into the 'easy wins' cluster. The first two primarily require further research and development, the third largely (but not exclusively) requires system change to reduce product specification requirements. If assessing GWP over a shorter timescale then interventions that reduce methane become an even higher priority. Manure management has been less of a focus in previous reports but our analysis suggests low cost and highly effective methane destruction methods, such as biogas flaring, are worthy of further consideration.

E.4.1.1 List of interventions:

- **M1** Feed additives for ruminants
- **M2** Low cellulose diets for ruminants
- **M3** Novel animal feed alternatives to soy
- **M4** Livestock breeding
- **M5** Improving livestock health
- **M6** Increased milking frequency
- **M7** Grass-legume mixtures in pasture
- **M8** Keeping pH at an optimum for plant growth
- **M9** Cover crops in arable rotations
- **M10** Grain legumes in arable rotations
- **M11** Reduced tillage
- **M12** Integrating grass leys in arable rotation
- **M13** Precision fertiliser applications + avoiding excess N
- **M14** Controlled release fertilisers
- **M15** Nitrification/urease inhibitors
- **M16** AD for heat and power
- **M17** Covering slurry stores with impermeable cover
- **M18** Alternative low carbon fuel farm machinery
- **M19** Low carbon heating/cooling - dairies and greenhouses
- **M20** On-farm food waste reduction

Figure E- 1 Comparing interventions by GHG abatement potential, cost of abatement, and farmer perceptions



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1.0 The Challenge

1.1 The need to reduce agricultural emissions

According to current emissions accounting methods, agriculture is responsible for around 10% of total greenhouse gas (GHG) emissions in the UK (54.6 $MtCO_2e$ in 2018 measured as CO_2 equivalents)[2] largely due to releases of two highly potent GHGs, nitrous oxide (N_2O) and methane (CH_4).[3, 4] Consequently, reducing these emissions has an important role to play in meeting the UK's commitment to achieving Net Zero emissions by 2050[5,6] as well as several agriculture specific climate targets.

1.2 Understanding and rethinking key emissions sources

Before assessing methods for reducing agricultural emissions it is crucial to understand the extent and key sources of agricultural emissions. How we account for emissions has a huge influence on which interventions we consider to be most impactful and therefore which we consider to be our top priorities. According the CCC's Sixth Carbon Budget, the key sources of agricultural emissions are:[7]

- Enteric fermentation (53%) – primarily methane.
- Agricultural soils (22%) – primarily nitrous oxide and carbon dioxide.
- Wastes and manure management (16%) – primarily methane and nitrous oxide.
- Mobile and stationary farm machinery (8%) – primarily carbon dioxide.
- Other (2%).

However, these estimates do not account for the climate impact of global agricultural land use associated with UK agriculture; they underestimate the importance of short-lived GHGs, notably methane; and they do not consider the manufacturing emissions associated with agricultural inputs, primarily fertiliser.

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[2] Carbon dioxide equivalent (or CO_2e) is a metric used to compare the emissions from various greenhouse gases, including CH_4 and N_2O, on the basis of their global-warming potential (GWP).
[3] Climate Change Committee (2020) *The Sixth Carbon Budget: The UK's path to Net Zero*
[4] In the UK agriculture produces 70% of N_2O emissions and around half (49%) of methane emissions, but only 1.6% of CO_2 emissions.
[5] A Net Zero target refers reaching a point where total GHG emissions are equal to emissions removed from the atmosphere. This is achieved via a combination of emission reduction and sequestration measures.
[6] Climate Change Committee (2020) *Reaching Net Zero in the UK*, https://www.theccc.org.uk/uk-action-on-climate-change/reaching-net-zero-in-the-uk/
[7] Climate Change Committee (2020) *The Sixth Carbon Budget: Methodology Report*

1.2.1 Should we account for global land use associated with UK agriculture?

Occupying land for agriculture has a huge climate impact.[8] Existing agricultural land use prevents carbon sequestration through natural regeneration, whilst agricultural expansion drives land use change, such as deforestation, which causes GHG emissions. Reducing agricultural land use will be key to reducing the climate impact of agriculture. The complication is that land use change sits in between reducing emissions (preventing agricultural expansion) and sequestering carbon (releasing land from agriculture). In purely carbon terms, although deforestation is seen as an emission and reforestation is seen as sequestration, they are opposite sides of the same coin. Clearly, they operate on different timescales, but they are driven by the same factor – the expansion or contraction of agricultural land take and the efficiency of land use.

When considering land use, it is imperative we take a global perspective for two reasons. Firstly, large areas of land overseas are required to support many aspects of UK agriculture, for example imported animal feed (primarily soy). If imported animal feed is not considered then we may substantially underestimate the climate impact of the pig and poultry sectors in the UK. Secondly, any reduction in land use efficiency in the UK will simply displace production overseas, unless matched by an equivalent reduction in demand. Similarly, replacing imported animal feed with locally grown feed without increasing land use efficiency will simply displace the production of other crops overseas, which may ultimately lead to deforestation in new frontiers. If global land use is not considered in emissions accounts, then we underestimate the GHG abatement potential of an entire class of interventions that might increase global land use efficiency. Yet these should be a top priority.

Searchinger et al. (2018)[9] attempted to quantify the climate impact of agricultural land use, which they refer to as the 'Carbon Opportunity Cost' (COC). COC is the amount of carbon that could be sequestered if land was released from agriculture, or the amount of carbon that could be emitted if new land were brought into agricultural production. They then compare the COC of various agricultural products with the direct production emissions to indicate the importance of COC. For example, the direct production emissions associated with growing 1kg of fresh soybeans are 0.26 kg CO_2e per kg fresh weight, whereas the COC is 5.9 kg CO_2e. In other words, 96% of the climate impact of soybean production is associated with land use and only 4% is associated with production emissions. Transport-linked emissions are also de-minimis in comparison to

[8] Searchinger et al. (2018) Assessing the efficiency of changes in land use for mitigating climate change. *Nature* **564**, 249–253.
[9] Ibid

COC.[10,11] If we consider COC, then the emissions associated with imported soy in the UK (this includes direct emissions but not transport emissions) are 20.1 Mt CO_2e/year (see Appendix A.1.1). To provide a sense of scale this is double the emissions associated with UK agricultural soils (11.5 Mt CO_2e/year). The land use associated with grazing ruminants is also substantial.

1.2.2 Should methane be a higher priority?

There are two important types of GHGs: 'short-lived climate pollutants' (SLCPs) that have a short life in the atmosphere but may have a major effect during that life (notably methane), and 'long-lived climate pollutants' (LLCPs) that accumulate in the atmosphere (notably carbon dioxide). A problem arises when trying to assess the impact of these using a common metric.

The IPCC adopted a metric called GWP100 for national emissions accounting. GWP100 measures how much heat a GHG traps in the atmosphere ('radiative forcing') over 100 years, relative to carbon dioxide. However, given the urgency of the climate problem and the need to avoid climate tipping points, GWP100 arguably underestimates the short-term importance of SLCPs (primarily methane). GWP20 is an alternative metric that uses 20 years as the time period, placing greater emphasis on SLCPs. Using GWP20, the relative importance of methane increases.[12] Emissions associated with enteric fermentation increase from 28.9 to 73.2 MtCO_2e/year and emissions from wastes and manure management increase from 8.7 to 24.1 MtCO_2e/yr (see Appendix A.1.3).

However GWP20 may underemphasise the importance of cumulative long-lived GHGs and thus create greater problems further down the line. It is important also to recognise that although methane is rapidly destroyed, the warming it creates during its short life influences the future development of the rest of the climate system as indicated by Allen et al. (2018) who state.[13]

> *"Peak warming under a range of mitigation scenarios is determined by a linear combination of cumulative CO_2 emissions to the time of peak warming and non-CO2 radiative forcing immediately prior to that time."*

Both GWP100 and GWP20 pose issues around capturing the different behaviours of SLCPs and LLCPs and their impact on global mean surface temperature. These issues are largely overcome by the emerging metric GWP*. This metric equates an increase in the

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[10] Sui et al. (2020) Fuel Consumption and Emissions of Ocean-Going Cargo Ship with Hybrid Propulsion and Different Fuels over Voyage. *Marine Science and Engineering* 8, 588.

[11] COC of 1 tonne of soybeans is 5.9tCO_2e (Searchinger et al, 2018). Using 10.11 gms/tonne mile of CO_2(e) = 60.66 kg/tonne over 6,000 nautical miles (i.e. from Sao Paulo to Southampton) (Sui et al, 2020). This is around 0.06tCO_2e per tonne of soybean, in other words a factor of 100 lower.

[12] Over a 100-year time period methane is 34 times more potent than CO_2, whereas over a 20-year period it is 84 times more potent.

[13] Allen et al. (2018) A solution to the misrepresentations of CO2-equivalent emissions of short-lived climate pollutants under ambitious mitigation. *npj Clim Atmos Sci* 1, 16.

continuous emission rate of an SLCP with a one-off "pulse" emission of CO_2.[14] [15] However, the GWP* metric is still evolving and not yet standardised. Additionally, GWP* requires a very different approach to GHG accounting. It equates an emission reduction of 'x' tonnes per year of methane with a single one-off removal of 'y' tonnes of CO_2. For this reason, this report retains the use of GWP20 (alongside GWP100) as an important measurement metric to emphasise the extreme importance of methane and the urgency of dealing with its emissions, whilst recognising the need in future work to incorporate new metrics (such as GWP*) as they become standardised.

1.2.3 Should product manufacturing emissions be considered?

The manufacturing emissions associated with agricultural inputs, particularly fertilisers, are substantial but are considered industrial not agricultural. Nevertheless, farm-level change will be required to reduce the need for these inputs. Manufacturing emissions may be generated within the UK or overseas and so may or may not be included in national accounts. The manufacturing emissions associated with nitrogen fertilisers used on UK farms are ~3 Mt CO_2e per year (see Appendix A.1.2). To provide a sense of scale this is similar to the scale of emissions from agricultural machinery in the UK (4.4 Mt CO_2e per year). If we do not account for fertiliser manufacturing emissions, then the GHG abatement potential of interventions that reduce fertiliser use may be underestimated. Nevertheless, the scale of these emissions is much smaller than those associated with agricultural land use and they are not a major focus for this report.

1.2.4 Visualising the scale of emission sources

Figure 1 shows two illustrative pie charts that provide a sense of the relative scales of key agricultural emission sources in the UK, including some sources not considered in the CCC 6th Carbon Budget. Figure 1 is not intended to be a rigorous and complete emissions analysis, as there are several key limitations. Firstly, emissions associated with imported soy have been estimated including the Carbon Opportunity Cost (COC) of soy producing land (see Appendix A.1.1). Yet, COC (both national and international) has not been considered for any other aspects of UK agricultural production (notably grazing land for ruminants). Secondly, nitrogen manufacturing emissions (national and overseas) have been estimated (see Appendix A.1.2) but the manufacturing emissions associated with other farm inputs have not been included. Thirdly, the second chart adjusts methane emissions (from enteric fermentation and waste and manure management) for GWP20, which greatly increases the impact of methane (see Appendix A.1.3). However, none of the other gasses have been adjusted. If GWP20 is used for all gases, methane would be even more dominant, as the relative impact of CO_2 would be reduced.

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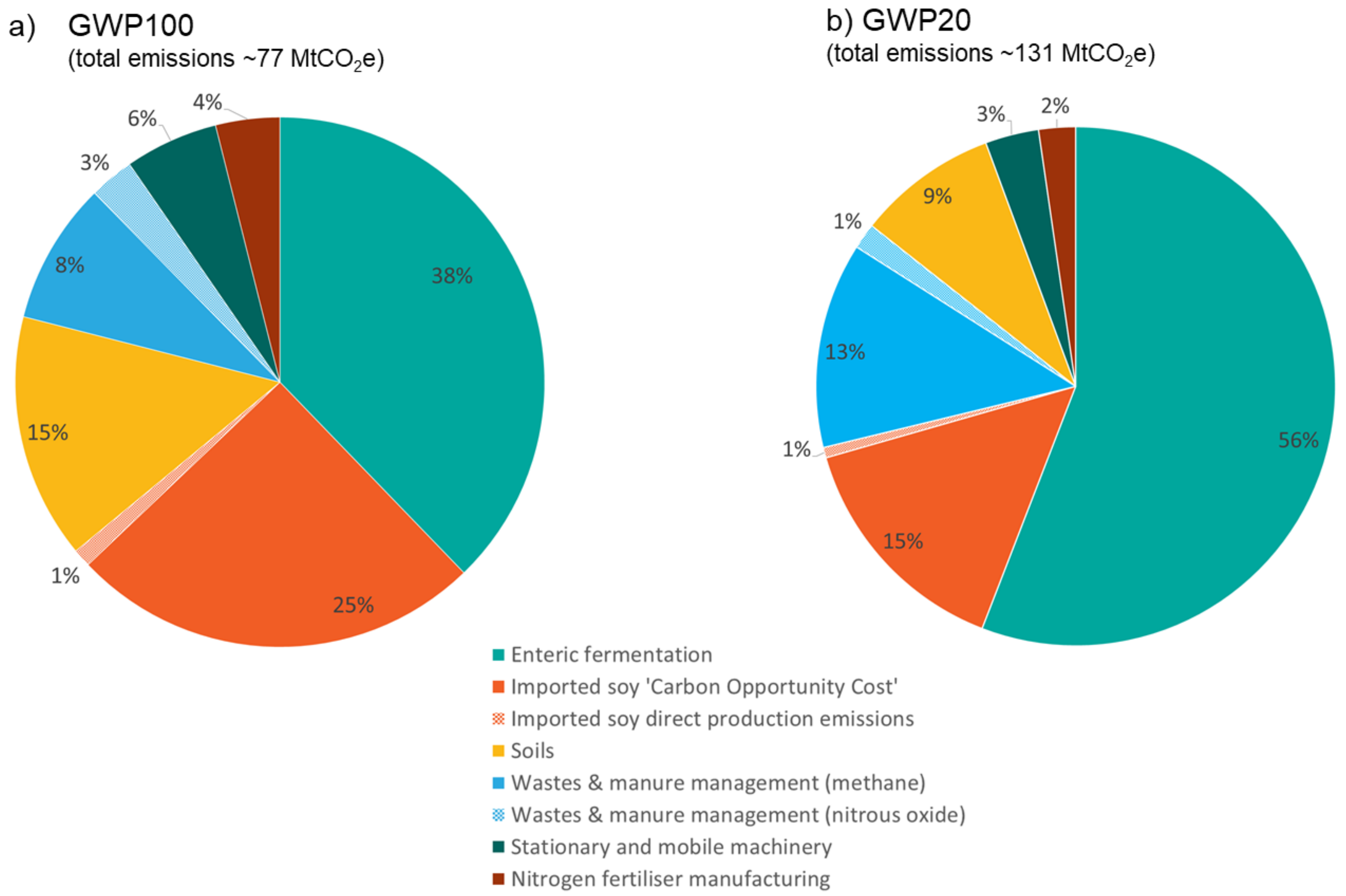
[14] Lynch et al. (2020) Demonstrating GWP*: a means of reporting warming-equivalent emissions that captures the contrasting impacts of short- and long-lived climate pollutants, *Environ. Res. Lett*. 15 044023
[15] Cain et al. (2019) Improved calculation of warming-equivalent emissions for short-lived climate pollutants. *npj Clim Atmos Sci* 2, 29.

Figure 1 Key sources of UK agricultural emissions, including the Carbon Opportunity Cost associated with imported soy, nitrogen manufacturing emissions and considering impacts at both GWP100 and GWP20[16]



[16] These charts are illustrative and provide a sense of scale to key emission sources. They are NOT a rigorous and complete emissions analysis. See Section 1.2.4 for explanation of limitations.

1.2.5 This review

This review analyses farm-level interventions that reduce greenhouse gas (GHG) emissions in the UK covering all major agricultural sectors: dairy, beef and lamb, pig, poultry, fresh produce (fruit and veg / horticulture), combinable crops and sugar beet. The review considers the GHG reduction capacity, on-farm practicality, and economic impact of each intervention. The aim is to provide **actionable** materials for farmers and policymakers to enable the implementation of these interventions. The second output of this review is a farmer facing guide produced by Innovation for Agriculture titled: "*Reducing Greenhouse Gas Emissions at the Farm Level: The Go-To Guide*".

Scope

The review focusses on interventions that **reduce agricultural GHG emissions**, rather than those that sequester carbon. The assessment of GHG reduction impact is primarily based on current national agricultural emissions accounts, as this reflects how they are assessed in existing literature. However, to start to consider interventions that can improve global land use efficiency (which sits between reducing emissions and sequestering carbon) we have considered, as an example, an intervention that would replace soy in animal feed with alternatives that have lower land requirements. Additionally, we recognise that if interventions were assessed using GWP20 or GWP* then those that tackle methane emissions may become a higher priority. We also recognise that if fertiliser manufacturing emissions were to be considered, then interventions that reduce nitrogen fertiliser use may have a greater abatement potential than estimated in the literature.

The report focusses on interventions that are **within the control of farmers and their supply chain**. Changing consumer behaviour (via dietary shifts and 'off-farm' food waste reduction) could have a major impact on reducing agricultural GHG emissions (primarily by releasing land from agricultural production) but are not the focus of this report.

Summary of our approach

Information for this report was gathered from a literature review of interventions, farmer insights, and expert judgement and analysis. Exploring the views of farmers was an important aspect of our approach, as this provided important insights into what farmers considered practical/achievable and helped us understand the actions needed to steer increased uptake.

There have been several recent reports and further ongoing studies which assess farm-level interventions to reduce GHG emissions.[17,18,19] Given that per unit (per hectare or per head of livestock) abatement potentials were not available, this review has sought to compare the results from these previous studies and provide a qualitative indication of national GHG abatement potential. Figure 2 outlines the key steps of our approach, and further detail on the methodology is included in Appendix A.1.0.

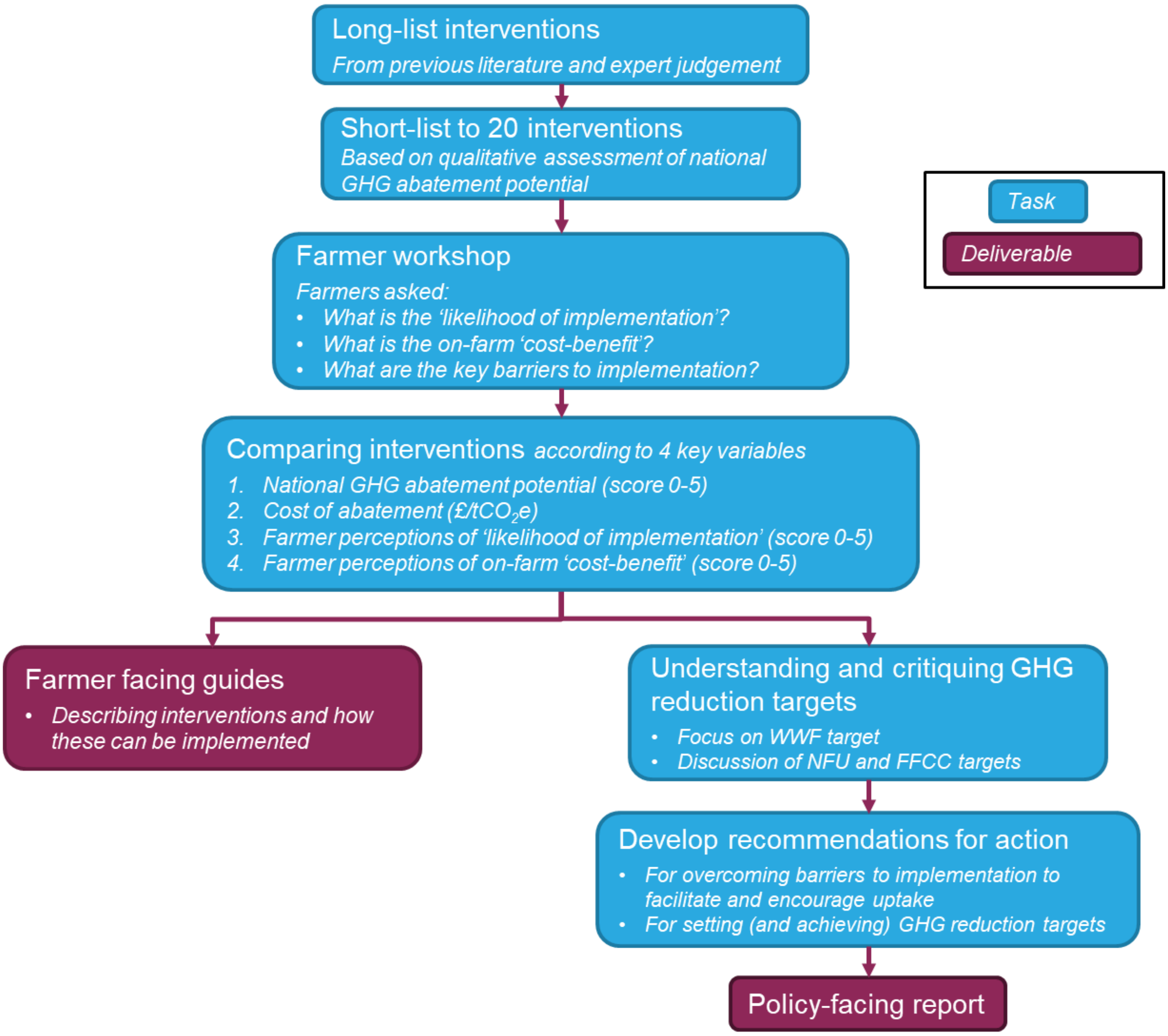
Outline of the report

The following sections provide:

1. A summary of our approach to long listing and short-listing interventions.
2. A comparative analysis of the 20 short-listed interventions characterised in terms of the four key variables:
    a) National GHG abatement potential (qualitative score 0-5).
    b) Cost of abatement in (£/tCO_2e).
    c) Farmer views on ‘cost-benefit’ (qualitative score 0-5).
    d) Farmer views on the ‘likelihood of implementation’ (qualitative score 0-5).
3. A summary of the key barriers to implementation identified by farmers.
4. A discussion around the importance of recognising ‘system-change’ both on and off the farm.
5. An overview and critique of agricultural GHG emission reduction targets, focussing on WWF’s target, but also including targets set by the NFU and FFCC.
6. Recommendations for action for government, NGOs and industry bodies to help increase intervention uptake and reduce agricultural GHG emissions.

[17] Eory et al. (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.*
[18] Lampkin et al. (2019). *Delivering on Net Zero: Scottish Agriculture*. Organic Policy, Business and Research Consultancy.
[19] Eory et al. (2020). *Non-CO2 abatement in the UK agricultural sector by 2050.*

Figure 2 Outline of key steps to produce this report



2.0 Review of interventions

2.1 Our approach

2.1.1 Long-listing interventions

Three key reports previously assessed farm-level interventions to reduce GHG emissions within the UK:

1. **Eory et al. (2015)** - commissioned by CCC to feed into UK's Fifth Carbon Budget. [20]
2. **Lampkin et al. (2019)** - commissioned by WWF to assess how Net Zero could be delivered in Scottish agriculture.[21]
3. **Eory et al. (2020)** - commissioned by CCC to feed into UK's Sixth Carbon Budget.[22]

In addition, emerging results from Defra's upcoming Clean Growth for Sustainable Intensification (CGSI) project were considered. The results of Defra's CGSI report will be published in full this year and further detail on the carbon savings and mitigation trajectories can be found there once available.

Each report assessed slightly different lists of interventions, and most were included in the long list as a starting point. The Lampkin et al. (2019) report considered some interventions relating to farm system change, namely conservation agriculture, organic farming, pasture-fed livestock production, agroforestry and afforestation. These were considered to be 'bundles' of individual interventions and therefore were not included in the long list. However, systems thinking is important and discussed further in Section 2.5. Additionally, Appendix A.2.0 outlines which of the individual short-listed interventions relate to the key systems highlighted by Lampkin et al. (2019).

Our long list included four additional interventions that our experts considered important emerging areas that had not previously been assessed, namely:

- Novel animal feed alternatives to soy which would reduce global agricultural land use.
- Alternative low carbon fuel machinery.[23]
- Low carbon heating/cooling in greenhouses/dairies.
- On-farm food waste reduction.

[20] Eory et al. (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.*
[21] Lampkin et al. (2019). *Delivering on Net Zero: Scottish Agriculture*.
[22] Eory et al. (2020). *Non-CO2 abatement in the UK agricultural sector by 2050*. Scotland's Rural College.
[23] Agricultural machinery was assessed in the CCC Sixth Carbon Budget but was not considered a 'low carbon farming measure' and thus was not assessed in the Eory et al. (2020) report.

2.1.2 Short-listing interventions based on national GHG abatement potential

To create a manageable list for analysis and discussion at the farmer workshop, a short list of 20 interventions was created focussing on those with greatest national GHG abatement potential. Some similar interventions, that were assessed separately in previous reports (e.g., different types of feed additives), were grouped into a single intervention in this report to help streamline the short-list. A summary of each short-listed intervention is provided in Table 2 and longer one-page summaries are provided in Appendix A.3.0.

Short-listing based on impact was challenging because per unit GHG abatement potentials (i.e., $ktCO_2$/yr per hectare or per animal) were generally not available and the national GHG abatement potentials ($ktCO_2e$/yr) reported in the different source documents are **not necessarily comparable.** This is due to differences in the scale of application and the assumptions about land use change, uptake rates, interaction between measures, and the GHGs assessed. A summary of these differences is outlined in Table 1.

The two Eory et al reports provided multiple results for a range of 'scenarios' based on different assumptions. Our choice of scenario is based on the following considerations:

- In the Eory et al (2020) report, the Crop Sensitivity Scenario was chosen because it was the only scenario to assess the abatement of all interventions (the other scenarios did not assess measures relating to increased nitrogen use efficiency).[24]
- Where possible we used data that reflected 100% uptake rates, as we were aiming to assess the maximum GHG abatement potential of interventions if implemented in all applicable areas. For the Eory et al (2020) report, data was adjusted by Eunomia to 100% uptake.
- Where possible we used data that reflected minimal land use change. This ensured greater comparability between data sets. In Eory et al (2020) the Crop Sensitivity scenario assumes some land use change, but this is the lowest of all the scenarios assessed.
- Where possible we used data that accounted for interactions between measures as we recognise the importance of these synergies. Data accounting for interactions was not available from the Lampkin et al (2019) report.

[24] For the other scenarios, measures relating to efficient nitrogen use are not assessed because these scenarios already assume a more efficient use of nitrogen (and moderate increase in crop yields). Therefore, including the abatement potential of these measures would be considered double counting.

Table 1 Assumptions and scale associated with previous reports

Assumption	Eory et al. (2015) *Maximum Feasible Potential Scenario*	Lampkin et al. (2019)	Eory et al. (2020) *Crop Sensitivity Scenario*
Geography	UK	Scotland	UK
Future land use change	None Total area of agricultural land held constant at 2014 value, some change in composition of agricultural land, e.g., increase in proportion of certain arable crops	None	**Dietary shift**: 20% less meat and dairy by 2050 **Food waste reduction**: 50% reduction in food waste by 2030 (no further reduction by 2050) **Other land release measures**: 10% of horticulture shifted indoors by 2050; 10% increase in stocking rates on grassland by 2050
Uptake rate	100% (by 2035)	100% (by 2045)	Between 50-75% assumed for all measures by 2050, but these were adjusted (by Eunomia) to 100%
Interaction between interventions	With interactions	Without interactions	With interactions
GHGs assessed	Methane (CH_4), nitrous oxide (N_2O), carbon dioxide (CO_2)	Methane (CH_4), nitrous oxide (N_2O), carbon dioxide (CO_2)	Methane (CH_4), nitrous oxide (N_2O)

To enhance comparability, we normalised the national GHG abatement potentials. Normalisation means dividing each value for the abatement potential of an intervention in each study (in ktCO_2e) by the highest abatement potential of any intervention within each study to put all values on a scale from 0-1. The scale was then expanded to 0-5 to make it comparable with the outputs of the farmer workshop (discussed in Section 2.2.2). It is important to note that whilst normalization helps provide a consistent and rational approach to comparing data, these scores should be seen as a rough indication of impact, not absolute values and must be interpreted with the assumptions and national scales in mind.

The normalised scores from the three key reports were used to inform an overall impact score (from 0-5) for each of the 20 short-listed interventions (although not all interventions were assessed in all reports). It is worth noting that the 'grouped interventions' provided a slight complication as there is some impact variation within sub-interventions. This has been taken into account as far as possible when establishing the overall scores. An explanation of the potential discrepancies between the different scores, particularly between the two similar Eory et al. reports, is provided in Appendix A.1.0.

2.2 Comparing interventions

Interventions were compared using four variables:

1. Normalised national GHG abatement potential (qualitative score 0-5; as described above)
2. Cost of abatement (£/tCO_2e)
3. Farmer views of cost-benefit (qualitative score 0-5)
4. Farmer views on likelihood of implementation (qualitative score 0-5).

This information is summarised in Table 3 at the end of this section.

2.2.1 Cost of abatement (£/tCO_2e)

The cost of abatement in £ per tonne of CO_2e is a key metric for informing government policy as it indicates where resources should be allocated most cost-effectively.

This information was provided in all but the Lampkin report, with the cost relating to on-farm cost only (i.e., it does not include public administration costs of mitigation policies and other wider cost/benefit values). As such, interventions that have a net cost to farmers and save CO_2 have a positive abatement cost. Interventions that are inherently profitable to a farmer and save CO_2 have a negative abatement cost.[25]

As cost of abatement values are per unit (£/tCO_2e), they are largely not influenced by geography and future land use change assumptions. Therefore, we calculated the average cost of abatement for each intervention based on data from the two Eory reports. For the grouped interventions, we calculated an average cost of abatement weighted by impact from the sub-interventions within that group. Further information on this process is included in Appendix A.1.0. We recognise that national location, extent of interaction between measures, and the GHGs assessed may have some influence on the cost of abatement. Therefore, these values should once again be seen as indications rather than accurate values.

Cost of abatement values are not yet available for five of the interventions. These include the four interventions that were not previously assessed in the literature and M11 - Minimum till, which is the only intervention that was assessed in Lampkin et al. (2019) but not in the other reports.

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[25] Given £/tCO_2e is determined by both the cost to the farmer and the CO_2 saving of a measure, £/tCO_2e the value does not tell you about the extent of on-farm cost or profit, just whether the measure is profitable to a farmer or a net cost. For example, two different feed additives may have the same cost per cow, but different CO_2e savings – so the two interventions would have different abatement costs per tonne of CO_2 (£/tCO_2), whilst having the same cost to the farmer.

Table 2 Summary of short-listed interventions assessed in this report

Ref	GHG reduction intervention	Description
M1	Feed additives for ruminants *(e.g., nitrate, 3NOP, biochar, seaweed)*	Adding small quantities of specific additives to ruminant feed can reduce methane production without substantially changing diet. In previous reports, individual feed additives are usually considered as separate interventions. However, given they would broadly be applied in the same way, and achieve a similar outcome (although to varying extents), they have been grouped into a single intervention in this report. The two additives explored in the literature are nitrate and 3NOP. However, there are a number of emerging additives that our experts identified, including biochar and seaweed.
M2	Low cellulose diets for ruminants *(high fat, sugar, or starch)*	Cellulose is a major component of ruminant diets and breakdown of cellulose in the rumen is a major cause of methane production. Reducing the proportion of cellulose in ruminant diets (by increasing starches, sugars and fats, either in feed rations or by modifying pasture composition) can reduce methane production. However, feeding diets that are too low in fibre can have adverse effects on animal health and thus yields.
M3	Low-carbon animal feed alternatives to imported soy	There are currently three main low carbon animal feed alternatives, with varying impact. The first is **increasing the land use efficiency of growing soy/ or alternative protein rich pulses**. Pulses could be grown locally rather than imported but this will likely only reduce global deforestation if land use efficiency is increased. This increased efficiency could possibly be achieved by replacing non-grain legumes (e.g., clover) used as cover crops with grain legumes (relates to M10 – grain legumes in arable rotations). This might provide both the N fixation benefit and animal feed without displacing production. The second option is **insect larvae fed on food waste**. However, processed insect meal is not currently legal for terrestrial agricultural livestock, there is still some energy loss converting food waste to insect protein, and ultimately the aim is to reduce food waste (to release land for sequestration). The third option with potentially the highest impact is **microbial protein**. This can either be grown by feeding the microbes with CO_2 from flue gas, green hydrogen and nitrogen or by bacterial fermentation of plants using the Crassulacean Acid Metabolism (e.g., cacti) grown in semi-arid areas of low biodiversity value and limited capacity to grow and store carbon.
M4	Livestock breeding	Livestock breeding is particularly confusing as different reports have divided it up in different ways. For the purposes of this report, we have taken livestock breeding to refer to reducing the emissions intensity per unit output. This may mean that emissions per animal remain the same but yield per animal increases. Equally, it may mean that emissions per animal decrease but yield per animal remains the same. The literature has only referred to breeding for cattle, but it may also be important for sheep and if we consider emissions from non-ruminant feed, then improving the feed conversion ratios of pigs and poultry may be significant.
M5	Improving livestock health	Improving livestock health can help reduce emissions intensity per unit output by improving yields, feed conversion ratios and reducing mortality rates. Previous reports have only referred to cattle and sheep health, but if we consider emissions from non-ruminant feed, then improving the feed conversion ratios of pigs and poultry may also be significant.
M6	Increased milking frequency	Increasing milking frequency can improve feed use efficiency (thus freeing up land from agriculture) and improve N utilisation (thus reducing N2O emissions from excreta). This measure only applies to dairy cows.

Ref	GHG reduction intervention	Description
M7	Grass-legume mixtures in pasture	Legumes biologically fix N and so integrating them into pasture mixes can reduce need for nitrogen fertiliser (synthetic or organic) and thus reduces direct N_2O emissions (also reduces nitrogen fertiliser manufacturing emissions if synthetic). A more diverse pasture mix can also be beneficial to animal health.
M8	Keeping pH at an optimum for plant growth	Optimizing pH (e.g., via liming) helps maximise crop N use efficiency and yield, which can reduce N_2O emissions and release land from agriculture (also reduces nitrogen fertiliser manufacturing emissions if fertiliser is synthetic).
M9	Cover crops in arable rotations	Cover crops are usually sown in Autumn/Winter and are not harvested to be sold. They can absorb excess N left over in the soil from the previous crop thus minimising the risk of 'excess' nitrogen in the soil to turn into N_2O. If the cover crops are legumes, then they also reduce the need for N fertilisers in subsequent crop. If these fertilisers are synthetic, then there is the added benefit of reducing manufacturing emissions. Cover crops can also help build soil organic matter.
M10	Grain legumes in arable rotations	Grain legumes both fix nitrogen and simultaneously produce a high value cash crop. The GHG reduction benefit is through reduced fertiliser use. If these fertilisers are synthetic then added benefit of reducing nitrogen fertiliser manufacturing emissions. There is also potential for this intervention to link into M3 – low carbon animal feed alternatives, as locally grown grain legumes can be used as an alternative to imported soy.
M11	Reduced tillage	This measure includes both minimum till and direct drilling. Minimum till refers to cultivation techniques that do not include deep inversion ploughing. Direct drilling has no prior cultivation and refers to drilling straight into stubble. Reducing soil disturbance can reduce CO_2 emissions from soil, can reduce nitrogen leaching (due to improved soil structure) and can reduce fuel use associated with cultivation.
M12	Integrating grass leys in arable rotation	Planting grass in fallow fields for a full year, as part of an arable rotation. Root residues help improve soil carbon and improve soil health with maintains yields in long-term. They can also improve soil N content reducing need for N fertilisers (reduce N_2O emissions from excess N and also nitrogen fertiliser manufacturing emissions if synthetic). A key issue is the short-term loss of production, both in terms of loss of income and potential leakage (i.e., shifting production to another site).
M13	Precision fertiliser applications + avoiding excess N	Accounting for the spatial (inter and intra field) and temporal fertiliser needs of a given crop and only applying the quantity of fertiliser required in that place at that time. This will reduce excess nitrogen inputs thus reducing N_2O emissions, as well as reducing requirement for fertiliser which, if synthetic, reduces emissions from nitrogen fertiliser manufacturing.
M14	Controlled release fertilisers	These are fertilisers that provide plant-available N more slowly and thus improve N use efficiency. This reduces N_2O emissions and, if reducing synthetic fertiliser, also reduces emissions from nitrogen fertiliser manufacturing.
M15	Nitrification/urease inhibitors	Nitrification inhibitors decrease the activity of nitrifying bacteria and thus reduce conversion of ammonium to nitrate, which is subsequently denitrified to form N_2O. Urease inhibitors (used with urea fertilisers) delay the conversion of urea to ammonium carbonate which is subsequently converted to N_2O. Both inhibitors reduce direct N_2O emissions from soils.

Ref	GHG reduction intervention	Description
M16	AD for heat and power	Anaerobic decomposition of manure to biogas (a mixture of CO_2 and methane) which is captured for energy generation. In literature this intervention is often split by manure type (mainly cattle and pig, but also some poultry), but this report groups all together. The principal benefit of AD is the conversion of methane to CO_2, in effect reducing the global warming potential (GWP100) by a factor of 30. Whilst displacing fossil fuels was historically a major benefit, the decarbonisation of the UK electricity grid, plus the fact that all AD plants leak methane, means that the net benefit of this is marginal. Consequently, whilst biogas flaring is seen as possibly wasteful, it may be an alternative and low-cost way of delivering the GHG reduction benefit. Nevertheless, biogas flaring is not included in this measure.
M17	Covering slurry stores with impermeable cover	The involves covering slurry stores with an impermeable membrane to exclude oxygen. Animal manure decomposes to form a mixture of CO_2, N_2O and methane during storage. 80% of the GHG potential of emissions from manure storage comes from methane with the balance mostly from N_2O. Reductions are difficult to quantify with very few studies showing statistically significant data. Overall, it seems that covering slurry stores with impermeable cover can increase N_2O emissions but decrease methane emissions, but this seems to vary. Covering slurry stores reduces ammonia volatilisation (but ammonia is not a GHG) and increased ammonia concentrations in the slurry can suppress methanogenesis.
M18	Alternative low carbon fuel farm machinery	This relates to all machinery used for on-farm operations, such as harvesting, preparing land, herding animals and so on. Alternative low carbon fuel farm machinery will most likely be electric, or potential hydrogen, powered.
M19	Low carbon heating/cooling - dairies and greenhouses	Replacing fossil fuel use for heating greenhouses/dairies with low-carbon renewable heat alternatives, primarily heat pumps (which require electricity).
M20	On-farm food waste reduction	Reducing the amount of on-farm food waste will reduce some direct emissions associated with production, but the main benefit is releasing land from agriculture (i.e., reducing the COC). This COC is not accounted for in UK national emission estimates and thus the main benefit of reducing food waste will not be recognised by emission reduction targets.

2.2.2 Farmer views on cost-benefit and likelihood of implementation

The short-listed interventions were discussed in a farmer workshop, representing all the key agricultural sectors in the UK. This participatory aspect was a key part of our approach and added substantial practical value to the data from the literature. Further detail about the workshop is provided in Appendix A.1.0. Farmers were asked to score each intervention based on two questions:

1. How likely are you to implement this intervention?
2. What is the cost-benefit?

The results were translated into scores of 0-5 for each intervention (with 5 being highly likely to implement and high cost-benefit) and are presented in Table 3. In other words, the higher the score the more attractive the intervention to farmers. These scores are qualitative and therefore should be considered rough indications rather than absolute quantitative values.

It is important to note that the questions posed may have been interpreted by farmers in a range of different ways. Likelihood of implementation can be influenced by both palatability (whether farmers would be interested in doing something) and feasibility (whether the correct conditions exist for them to actually do it). Farmer perceptions of on-farm cost-benefit are likely to be primarily financial (i.e., a higher score reflects a more profitable intervention). However, some farmers may have considered wider environmental benefits.

Farmers were also asked key barriers to implementation (see Section 2.3 for an overview of the key barrier themes and see Appendix A.4.0 for barriers identified for each intervention).

2.2.3 Summarising interventions

Table 3 summarises the 20 short-listed interventions in terms of the following four key variables:

1. Normalised national GHG abatement potential (qualitative score 0-5, with 5 being high impact).
2. Average cost of abatement (£/tCO_2e).
3. Farmers views of on-farm cost-benefit (score 0-5, with 5 being high cost-benefit).
4. Farmer views on likelihood of implementation (score 0-5, with 5 being highly likely to implement).

Table 3 Comparison of interventions using normalised national abatement potential, cost of abatement, and farmer views

Reference in this report	Farm level intervention to reduce GHG emissions	Normalised national GHG abatement potentials from literature (scale 0-5)			Summary	Cost of abatement (£/tCO_2e)	Outputs of farmer workshop	
		Eory et al (2015) *UK, 100% uptake*	Lampkin et al (2019) *Scotland, 100% uptake*	Eory et al (2020) *UK, adjusted to 100% uptake*	Overall estimate of abatement potential based on literature and expert judgement	Average estimate of cost of abatement from the literature	Farmer view on cost-benefit (scale 0-5)	Farmer view on likelihood of implementation (scale 0-5)
M1	**Feed additives for ruminants**				**[4]**	£78	**[1]**	**[2]**
	Nitrate	5	1	2				
	3NOP		2	5				
	Seaweed							
	Biochar							
M2	**Low cellulose diets for ruminants**				**[1]**	£165	**[2]**	**[2]**
	High fat	2	1					
	High sugar			0				
	High starch			0				
M3	**Low-carbon animal feed alternatives to imported soy**				**[4]**		**[2]**	**[4]**
M4	**Livestock breeding**				**[2]**	-£260	**[3]**	**[3]**
	Higher uptake of current genetic improvement practices (cattle only)			0				
	Breeding with genomics - current breeding goal (cattle only)			1				
	Breeding with genomics - lower emissions intensity goal (cattle only)			0				
	Selection for balanced breeding goals (cattle only)	1	4					
	Further breeding for higher feed conversion (pigs, poultry and sheep)							
M5	**Improving livestock health**				**[3]**	-£16	**[4]**	**[5]**
	Improving cattle health	5	3	2				
	Improving sheep health	2	2	1				
	Improving pig health							
	Improving poultry health							

Reference in this report	Farm level intervention to reduce GHG emissions	Normalised <u>national</u> GHG abatement potentials from literature (scale 0-5)			Summary	Cost of abatement (£/tCO$_2$e)	Outputs of farmer workshop	
		Eory et al (2015) *UK, 100% uptake*	Lampkin et al (2019) *Scotland, 100% uptake*	Eory et al (2020) *UK, adjusted to 100% uptake*	Overall estimate of abatement potential based on literature and expert judgement	Average estimate of cost of abatement from the literature	Farmer view on cost-benefit (scale 0-5)	Farmer view on likelihood of implementation (scale 0-5)
M6	**Increased milking frequency**			0	**[0]**	-£866	**[1]**	**[2]**
M7	**Grass-legume mixtures in pasture**	1	5	2	**[2]**	-£594	**[4]**	**[5]**
M8	**Keeping pH at an optimum for plant growth**			2	**[2]**	-£31	**[3]**	**[4]**
M9	**Cover crops in arable rotations**	0	0	1	**[1]**	£3,199	**[2]**	**[4]**
M10	**Grain legumes in crop rotations**	4	1		**[3]**	£358	**[3]**	**[2]**
M11	**Reduced tillage**		0		**[2]**		**[3]**	**[3]**
M12	**Integrating grass leys in arable rotation**			1	**[1]**	£383	**[2]**	**[2]**
M13	**Precision fertiliser applications + avoiding excess N**				**[2]**	-£738	**[4]**	**[4]**
	Precision fertiliser applications	2	1	0				
	Improving synthetic N use/ 'avoiding excess N'	0	1	0				
M14	**Controlled release fertilisers**	2	2		**[2]**	£135	**[2]**	**[3]**
M15	**Nitrification/urease inhibitors**	0		1	**[1]**	£590	**[1]**	**[2]**
M16	**AD for heat and power**				**[1]**	-£110	**[2]**	**[2]**
	AD (cattle manure + maize) for heat and power	1	0	2				
	AD (pig manure + maize) for heat and power			1				
	AD (pig + poultry manure, + maize) for heat and power	1						
	AD (maize) for heat and power	1						
M17	**Covering slurry stores with impermeable cover**		0	0	**[0]**	£20	**[2]**	**[3]**
M18	**Alternative low carbon fuel farm machinery**				**[2]**		**[2]**	**[3]**
M19	**Low carbon heating - dairies and greenhouses**				**[2]**		**[3]**	**[3]**
M20	**On farm food waste reduction**				**[4]**		**[4]**	**[4]**

2.3 High impact “Big Hitters”

Based on the qualitative scores for national GHG abatement potential in Table 3, the three highest impact ‘big hitters’ (scoring 4 out of 5) are:

- M1 – Feed additives for ruminants;
- M3 – Low carbon animal feed alternatives to imported soy; and
- M20 – On-farm food waste reduction.

Feed additives relate to small additions of certain compounds to ruminant diets to suppress methane production. Methane from enteric fermentation in ruminants is considered the single largest source of agricultural emissions in the UK (53% of total emissions).[26] Therefore, it is unsurprising that feed additives that reduce these emissions come out as a big hitter and if we consider emissions at GWP20, their impact is even greater. Feed additives are still relatively innovative and their impact variable, but new compounds are continually being identified. For example, seaweed is a novel feed additive that has not been assessed in previous literature but shows substantial promise with potentially over 80% reduction in methane emissions.[27] The potential of seaweed is outlined in a paper that WWF contributed to and a recent workshop series that WWF helped facilitate.[28,29]

There are currently three main **low carbon animal feed alternatives to soy**, with varying impact. The first is increasing the land use efficiency of growing soy/ or alternative protein rich pulses. Pulses could be grown locally rather than imported but this will likely only reduce global deforestation if land use efficiency is increased. This increased efficiency could possibly be achieved by replacing non-grain legumes (e.g., clover) used as cover crops with grain legumes (relates to M10 – grain legumes in arable rotations). This may provide both the N fixation benefit and animal feed without displacing production. Simply replacing imported soy with pulses grown locally without increasing land use efficiency will displace production of other crops elsewhere, which may ultimately lead to deforestation overseas.

The second and third options relate to insects fed on food waste and microbial protein. These are much more innovative and likely to have a more transformative impact. Insect larvae are a high protein animal feed that can be produced by feeding the larvae with food waste, as outlined in a recent WWF report.[30] However, there are some constraints: processed insect meal is not currently legal for terrestrial agricultural livestock in the UK; there is still some energy loss converting food waste to insect protein; and ultimately, we are aiming to reduce food waste (to release land for sequestration).

The third option with potentially the highest impact is microbial protein. This can either be grown by feeding the microbes with CO_2 from flue gas, green hydrogen and nitrogen or by bacterial fermentation of plants using the Crassulacean Acid Metabolism (e.g., cacti) grown

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[26] Climate Change Committee (2020) *The Sixth Carbon Budget: Methodology Report*
[27] Roque et al. (2021) Red seaweed (Asparagopsis taxiformis) supplementation reduces enteric methane by over 80 percent in beef steers. *PLoS ONE* 16(3): e0247820.
[28] Vijn et al. (2020) Key Considerations for the Use of Seaweed to Reduce Enteric Methane Emissions From Cattle. *Front. Vet. Sci.* 7:597430.
[29] WWF (2020) *The Potential for Seaweed as a Livestock Feed: 2020 Workshop Series Outcomes.*
[30] WWF (2021) *The Future of Feed: A WWF Roadmap to Accelerating Insect Protein in UK feeds.*

in degraded semi-arid areas.[31] In the first case there is effectively zero land use requirement, and in the second case using highly water and nutrient efficient novel crops allows degraded and semi-arid areas to be brought into efficient productive use. Potential negative biodiversity implications of these interventions should be considered. However, there are substantial areas of highly degraded semi-arid land that may benefit from additional biomass to aid soil restoration. Microbial protein is still extremely innovative and not yet ready for commercialisation, but the impact could be substantial.

On-farm food waste reduction will reduce direct production emissions and will reduce the 'Carbon Opportunity Cost' by releasing land from agriculture. Given that COC is not accounted for in existing emission accounts this benefit is not recognised by emission reduction targets.[32] Nevertheless, this measure was considered highly impactful by the expert panel and its importance is outlined in a recent WWF report (although this looks at on-farm food waste at global, rather than UK, level).[33] "Off-farm" food waste (e.g. food wasted by consumers or retailers) is also a huge issue. Although out of scope for this report, if reduced it could substantially reduce food demand and thus reduce emissions on farms.

A substantial amount of farm produce (particularly arable crops) is wasted because it does not meet food processor and retailer specification requirements. Farmers end up over-producing food to ensure they can meet contract demands within these specifications. Therefore, reducing on-farm food waste is likely to require a substantial change to these requirements. Additional issues that contribute to on-farm food waste include inability to store food and market price fluctuations (sometimes produce is too low value to be worth harvesting).

Although not an intervention in our short-list, if we assess emissions using GWP20, **biogas flaring** is potentially an important manure management approach. Ultimately, methane breaks down to carbon dioxide (and water) in the atmosphere. Burning the methane that is emitted from slurry stores simply speeds up this process by converting methane to carbon dioxide. This conversion reduces the GWP by 97% (if assessed using GWP20).[34] Biogas flaring is generally seen as a waste of energy and many would argue that if methane is being burnt, it should be used to generate heat or power. However, as the electric grid decarbonises the GHG reduction benefit from displacing fossil fuels becomes increasingly marginal and electricity grid connections are logistically challenging and expensive. Although there is possibly a role for biomethane in the gas grid, in reality the cost of clean-up, compression, transport and injection from small AD plants is prohibitive. The consequence will likely be AD plants supplemented with energy crops (which may displace food production) in order to make the scale viable. There are additional issues of dealing with the digestate.

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[31] Oxford Smith School of Enterprise and the Environment (2021) *The Climate Impact of Alternative Proteins: Final 25% Series Paper.*

[32] Searchinger et al. (2018) Assessing the efficiency of changes in land use for mitigating climate change. *Nature* **564**, 249–253.

[33] WWF (2021) *Driven to Waste: The Global Impact of Food Loss and Waste on Farms*.

[34] The GWP20 of methane is 86 on a kg/kg basis. Adjusting for the relative molecular weights of CO_2 and CH_4, the GWP20 of methane on a molar basis is 86*16/44 = 31.3. Thus burning 1kg of methane reduces the GWP by 1/31.3 = 3.2%. This equates to a 96.8% reduction.

Furthermore, almost all anaerobic digestion (AD) plants leak methane. An estimate from a sample of plants in the UK, suggests that on average 3.7% of methane produced via AD is leaked.[35] Although there is a considerable range in leakage rates with the smaller farm AD plants tending to be leakier. Leakage from AD plants can be reduced but widespread use of smaller scale AD will make this difficult to implement and to monitor. Furthermore, methane slip in engines is a separate and material issue.[36] Biogas flaring is an easier and lower cost way to deliver the GHG benefit.

The final big hitter, which is out of scope of this report, is **dietary change** to reduced meat and dairy consumption. This reduces both the direct emissions from livestock (enteric fermentation and manure management) and the Carbon Opportunity Cost of grazing land and feed production. Dietary shift was considered out of scope of this report because the focus is on farm-level interventions, rather than consumer changes. However, any change to demand for meat and dairy products will inevitably influence farmers. Farmers need to supported through this transition, as discussed in Section 2.6.3.

2.4 Emerging clusters

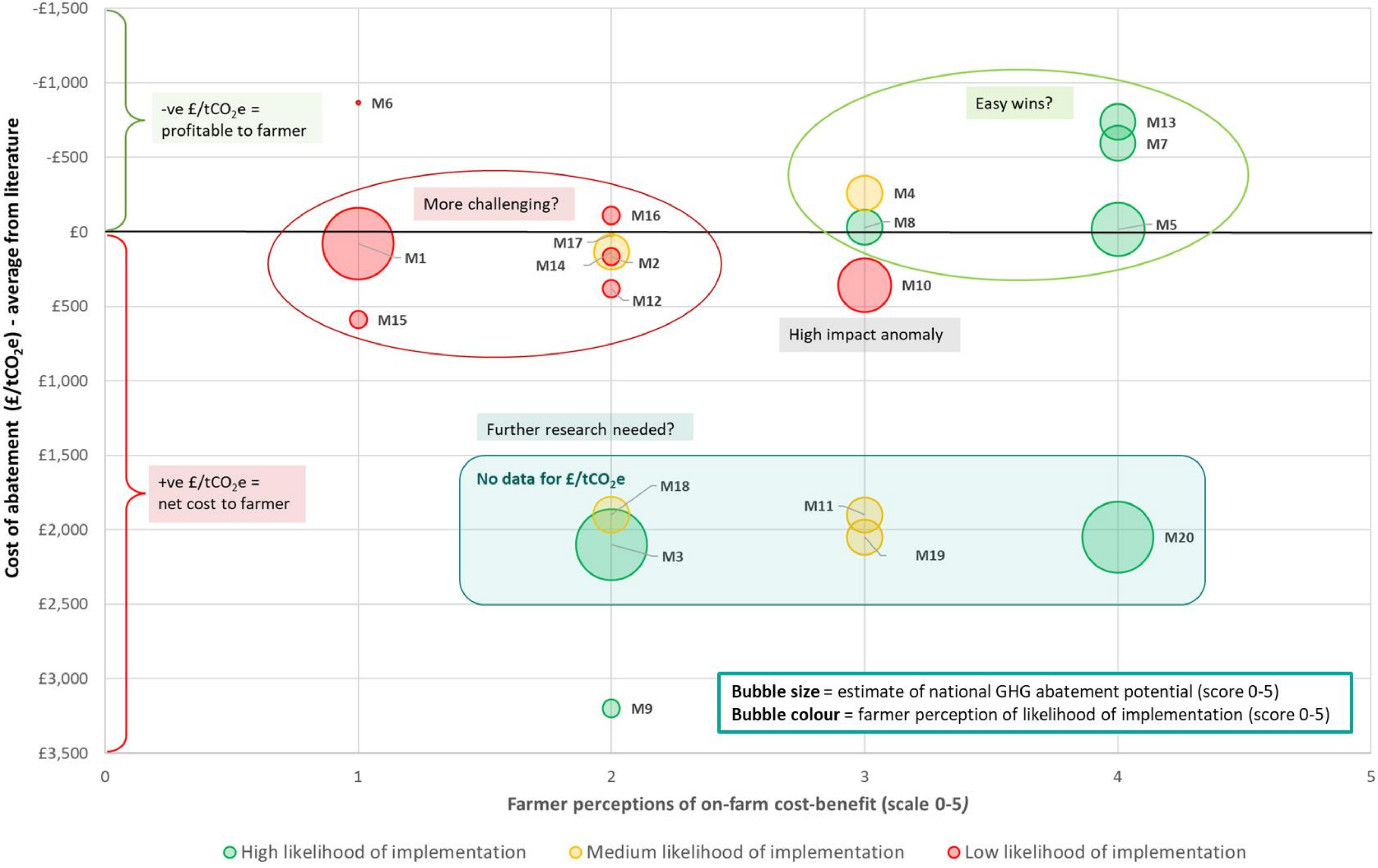
The four key variables used to characterise the 20 short-listed interventions (summarised in Table 3) are presented graphically in Figure 3. The graph is explained as follows:

- The **X-axis** relates to perceived cost benefit to farmers. Farmers are likely to have interpreted cost-benefit as financial cost-benefit. Therefore, interventions located to the right-hand side of the graph are likely considered more profitable to an individual farm business.
- The **Y-axis** relates to cost of abatement (£/tCO_2e). This metric demonstrates cost-effectiveness to society, so is an economic assessment at a national level, rather than a financial assessment at the farm level. The axis has been inverted so that measures with a higher cost-effectiveness (i.e., a more negative £/tCO_2e) are located towards the top of the graph. As explained in Section 2.2.1, measures located above the zero line (i.e., a negative £/tCO_2e) are likely to be profitable to a farmer and those located below the zero line (i.e. positive £/tCO_2e) are likely to be a net cost.
- The **size of the bubble** relates to the qualitative scores of national GHG abatement potential. A larger bubble indicates a more impactful intervention.
- The Red-Amber-Green **colour of the bubble** relates to farmers perceptions of ‘likelihood of implementation’. In general, measures with a lower perceived cost-benefit seem to have a lower likelihood of implementation. Likelihood of implementation seems to largely, but not exclusively, correlate with perceived cost-benefit.

The presentation of the interventions in Figure 4 allows us to identify three key ‘clusters’ of interventions, which are discussed in turn in the following text.

[35] Bakkaloglu et al. (2021) Quantification of methane emissions from UK biogas plants. *Waste Management*, 124, pp.82-93.
[36] Woess-Gallasch, S. et al. (2010) Greenhouse Gas Benefits of a Biogas Plant in Austria.

Figure 3 Comparing interventions by GHG abatement potential, cost of abatement, and farmer perceptions



The three clusters of interventions can be classified as:

- Easy wins?
- More challenging?
- Further research needed?

2.4.1 "Easy wins?"

Interventions falling into this cluster are:

- M4 Livestock breeding;
- M5 Improving livestock health;
- M7 Grass-legume mixtures in pasture;
- M8 Keeping pH at an optimum for plant growth; and
- M13 Precision fertiliser applications + avoiding excess N.

Farmers perceive these interventions to have a high cost-benefit for their farm and indicate they are likely to implement them. The cost of abatement values suggest these interventions are likely to be profitable to farmers and the cost-effectiveness to society is high. The GHG abatement potential scores indicate that there are **no big hitters** in this category, but most measures seem to have a moderate, and not insignificant, impact.

Increasing uptake of these interventions - where they are not already being implemented - may be relatively 'easy' compared to other interventions. Knowledge was identified as a key barrier and therefore 'enabling' approaches (aimed at sharing information and good practice) are likely to be effective to help encourage uptake. A further obstacle is the need for capital investment (e.g., for precision fertiliser applications). Although farmers recognise the long-term cost-benefit, they may not be in a position to make the investments needed. Thus, farmers may need some modest level of financial support to secure high levels of uptake of some easy wins. Recommendations for improving farmer advice and funding investments are covered in more detail in Section 4.0.

2.4.2 "More challenging?"

Interventions falling into this cluster are:

- M1 Feed additives for ruminants;
- M2 Low cellulose diets for ruminants;
- M12 Integrating grass leys in arable rotation;
- M14 Controlled release fertilisers;
- M15 Nitrification/urease inhibitors;
- M16 AD for heat and power; and
- M17 Covering slurry stores with impermeable cover.

Farmers perceive these interventions to have a low cost-benefit for their farm and indicate they are less likely to implement them. The cost of abatement values suggest they are a net cost to a farmer (with the exception of M16). Although the measures in this group are less cost-effective to society than those in the 'easy wins' cluster, they are still relatively cost-effective. The majority of interventions in this cluster seem to have a relatively low impact with the exception of M1 (feed additives) which is **a big hitter**. Nevertheless, some low impact interventions such as M15 (nitrification/urease inhibitors) may be low priority from a climate perspective, but the co-benefits for reducing nitrogen leaching may make them higher priority. This is discussed further in Section 2.6.1.

Increasing uptake of these interventions, is likely to be 'more challenging' and may require approaches to 'encourage' behaviour change through, for example, financial incentives. Farmers identified ongoing costs with no clear farm benefit as a particularly challenging barrier. Substantial financial support will likely be needed to fund these ongoing costs (outlined further in Section 4.0).

Furthermore, as outlined in Section 2.3, M1 (feed additives) is a big hitter that needs substantial further research. Although included in the 'more challenging' category, it could also fall into the 'further research needed' cluster. It is also important to note that costs associated with more innovative measures are often high initially and then reduce as supply chains develop and production efficiencies are realised. Therefore, the cost effectiveness (£/tCO_2e) of M1 may be underestimated.

2.4.3 "Further research needed?

Interventions falling into this cluster are:

- M3 Low-carbon animal feed alternatives to imported soy;
- M11 Minimum till;
- M18 Alternative low carbon fuel farm machinery;
- M19 Low carbon heating - dairies and greenhouses; and
- M20 On-farm food waste reduction.

Other than M11, these interventions have not been assessed in the three previous reports reviewed. We were unable to find cost of abatement values for these interventions and they are therefore presented as a separate category. The impact scores are based primarily on expert judgement and wider literature. Although there seems to be a spread of perceived cost-benefit to farmers, all the measures seem to have a medium to high perceived likelihood of implementation. Notably M3 (low carbon animal feed alternatives) performs relatively poorly on cost-benefit but has a high likelihood of implementation. The measures in this cluster are all considered relatively high impact with **two big hitters**, namely M3 (low carbon animal feed alternatives) and M20 (on-farm food waste reduction).

The need for further research can be interpreted in two main ways: (1) further research into quantifying the national abatement potentials and cost of abatement values for established technologies and (2) further research into the technologies themselves to make them commercially available and reduce production costs.

The technology already exists to implement M11, M18, and M19 and in many cases, they are already in use. However, further research is needed into quantifying their costs and national abatement potentials. M20 does not require 'technology' as such, instead it requires a change in market dynamics throughout the supply chain, notably food processor and retailer specification requirements. Nevertheless, further research is needed to understand the full abatement potential of reducing on-farm food waste in the UK (a recent WWF report assess this at a global, not UK, level).[37]

Both M3 and M18 need further research into the technologies themselves and/or supply chain development. For M18 although some small electric tractors are emerging on the market, there is still substantial R&D needed to both develop new products and drive down production costs. Within M3, two potentially very significant alternatives to soy (insects fed on food waste and microbial protein) are not yet available on the market. The technology around insects is relatively well understood but processed insect meal is not currently legal for terrestrial agricultural livestock in the UK.[38] Furthermore, the potential supply of insect-based protein is limited, and the supply chains not yet established. Microbial proteins, by contrast, have arguably unlimited global supply potential but still need substantial further research before commercialisation.[39]

2.4.4 Anomalies

There are three anomalies that fall outside these three clusters. One of these (M10 – grain legumes) is considered moderately high impact, the others are considered low impact. There are **no anomalous big hitters**.

- M10 (grain legumes in crop rotations) has a relatively high impact and a moderate cost-effectiveness to society and so is worth further consideration. It has a high perceived cost-benefit to farmers, yet a positive cost of abatement suggesting it is a net cost to farmers. This indicates there is some disparity between farmers views of profitability and the data in the literature. Most notably, it has a low perceived likelihood of implementation. Key barriers identified by farmers include the extent of farm system change required to incorporate grain legumes into their rotations.
- M6 (increased milking frequency) has a high cost-effectiveness to society but is considered very low impact and so deemed low priority.
- M9 (cover crops in arable rotations) has both a low cost-effectiveness to society and is considered low impact and so deemed low priority.

2.5 Farmer views on barriers to implementation

In the farmer workshop, farmers were asked to identify key barriers to uptake, focussing on the interventions they considered less likely to implement (the "more challenging" cluster). However, farmers highlighted that even the interventions considered potential "easy wins" face a range of challenges. Key barriers were also explored in an expert

[37] WWF (2021) *Driven to Waste: The Global Impact of Food Loss and Waste on Farms.*
[38] WWF (2021) *The Future of Feed: A WWF Roadmap to Accelerating Insect Protein in UK feeds.*
[39] Oxford Smith School of Enterprise and the Environment (2021) *The Climate Impact of Alternative Proteins: Final 25% Series Paper.*

discussion around emerging results from the Defra GSI research (also based on farmer views). Many of the barriers reported by farmers were common to a range of interventions and are discussed in the following text. Barriers for individual interventions are outlined in Appendix A.4.0.

Insufficient free, robust, independent, consistent, and tailored advice, on both best farm practice and best climate practice. This applies to almost all interventions where farmers are asked to be innovative or to change long-standing practices. Some measures lack advice that is based on robust scientific evidence. If this evidence does not yet exist, then further research is needed. Farmers noted that they can feel ‘at the mercy’ of agri-business salespeople with vested interests and it can be hard to access free and independent advice. Farmers also felt that there is a multitude of fragmented, often conflicting, information sources on what they should be doing on their farm, and it can be hard to know which sources to use. Finally, each farm is different, and farmers often need tailored, not generic, advice that is specific to their farm situation.

Concerns about making financial investments for long-term benefit. Financial investments include capital investments, for example purchasing new machinery, as well as losses in productivity, for example integrating grass leys to improve long-term soil health. Farmers face a variety of risks including weather, climate, market price, policy change and disease. Therefore, their discount rates are high, and they do not know what will happen down the line that may affect their ability to pay back an investment. One farmer commented ‘cash in hand now is better than cash promised at an unspecified later date'. Furthermore, a large proportion of farmers are tenant farmers with relatively short-term land tenure. This further reduces the incentive to invest in measures with a long-term benefit. The need for capital investment was highlighted as a barrier for interventions in both the ‘easy wins’ and ‘more challenging’ clusters. For the ‘easy wins’, although farmers recognise the long-term cost-benefit, they may not be in a position to make the investments needed.

Increased ongoing costs with no clear benefit to farmers. Farmers generally implement measures that are financially beneficial to their farm business. Measures with an ongoing cost and no clear financial benefit represent poor business decisions and therefore generally scored low for both perceived cost-benefit and likelihood of implementation. A particularly notably example was feed additives which may have a substantial climate benefit but reducing methane emissions alone has no clear benefit to farmers. Some companies, such as Rumitech, are currently promoting feed additives that they claim also improve animal health,[40] yet it appears farmers may not trust these claims. For interventions such as controlled release fertilisers (CRFs), there may be some benefit to farmers, in this case a reduction in the quantity of fertiliser needed, but this

[40] Harbro (2021) Beef Nutritional Solutions: Rumitech, available at https://www.harbro.co.uk/what-we-do/species/beef/, accessed Aug 2021.

benefit is outweighed by the additional cost of CRFs compared to conventional fertilisers.

Resistance to farm-system change and high levels of risk. Some interventions require more substantial change than others and the greater the change, the greater the risk. Furthermore, if any individual intervention is seen to have an element of risk, combining multiple interventions into a whole system change has the effect of multiplying those risks together. Thus, although farmers may think about their farm as an integrated system, changing to an alternative system has a much higher barrier to overcoming risk than simply changing one element of their existing system.

Lack of market availability of improved products. Some measures are not yet readily available for farmers to buy and therefore farmers cannot implement them. For example, insect and microbial protein alternatives to imported soy are not yet commercially available. Similarly, several potentially highly effective feed additives have been identified but are still in the early stages of testing and are not yet market available. Unless there is an incentive to bring new GHG reducing products to market, agribusiness is unlikely to develop new supply chains and relevant products.

2.6 Understanding System Change

There is a danger that by focussing on the GHG abatement potentials of individual farm-level interventions, the bigger picture is overlooked. It is imperative to recognise the synergies between different interventions, their other environmental co-benefits, their international impact and the relationship between farmers, consumers, and the supply chain.

2.6.1 Farm-level system change and co-benefits

Farmers tend to make strategic decisions in terms of their overall farm-system – i.e., how different interventions interact across their operation and business. This emphasises the extent to which discrete interventions, as modelled in these reports, are often better evaluated as part of a 'farming-system' approach rather than treated in isolation. Many farming systems, such as organic farming and pasture-fed livestock, comprise packages of measures that are intended to stack up operationally, nutritionally and economically. The extent to which the interventions we have assessed relate to a selection of key farming systems is outlined in Appendix A.2.0.

Furthermore, we need to recognise the co-benefits of certain interventions within the farm-system, such as GHG sequestration, biodiversity, and water quality etc. If we separate out our analyses of these, then farmers may be faced with conflicting advice around which are the top priority interventions. For example, several measures relating to reduced nitrogen fertiliser use seem to have a low GHG abatement potential and thus may be considered low priority. Yet, their environmental co-benefits are substantial. Reduced nitrogen leaching can substantially improve water quality and surrounding biodiversity. If these co-benefits are considered, then their priority for implementation may be much higher. Measures to improve nitrogen management are outlined further in a report commissioned by WWF and in preparation by York University. Examples of notable win-wins across the two reports include: precision fertiliser applications, cover crops and improving livestock health.

2.6.2 Global impacts of individual farm level change

In a globally commoditised marketplace, unless land use efficiency is increased or demand is reduced, any reduction in deforestation in one area (e.g., replacing Amazonian soy with locally grown pulses) will displace the crops previously grown on that land elsewhere. Given the constraints on available land this is most likely to shift land conversion to a new frontier. Likewise, any reduction in land-use efficiency (e.g., via reduced stocking rates) without a reduction in demand is likely to increase land conversion for agriculture (likely via deforestation). Some of the major GHG reduction benefits claimed for systems such as organic and pasture-fed livestock relate to reducing stocking rates.[41] Such systems may reduce emissions at a farm-level but may actually increase emissions at a global level. This highlights the need to recognise that individual farm systems are part of a globally interconnected system, and the climate crisis is a global crisis.

2.6.3 System change amongst consumers and retailers

To ensure that farm-systems reducing stocking densities have the desired GHG benefit, these changes need to be accompanied by consumer dietary shifts. Whilst these are considered out of scope for this report, they are intrinsically linked with food production systems. Significant dietary shifts will drive farm-system change and livestock farmers will need to be supported through this transition.

Finally, there is a major opportunity to reduce GHG emissions by reducing on-farm food waste (M20), as outlined in a recent WWF report.[42] This change is not solely within the remit of farmers. For example, a key cause of the problem is the tight produce specifications required by buyers. These are in turn focussed on delivering perceived consumer requirements. Implementation of this intervention is likely to require collaboration from all parts of the food supply chain, including farmers, food processors, retailers and consumers. Changing consumer attitudes towards what produce should look like will be key.

3.0 Pathways to targets

Emission reduction targets help to inform and prioritise the actions that must be taken to achieve them. In order to make a material difference, it is important to be clear about what emissions need to be reduced, the extent of reduction possible and the timescales

[41] Lampkin et al. (2019) *Delivering on Net Zero: Scottish Agriculture*.
[42] WWF (2021) *Driven to Waste: The Global Impact of Food Loss and Waste on Farms.*

over which emissions should be assessed. Several agricultural climate and sustainability targets have been set in recent years. This section outlines what these targets are, their limitations, and ideas for improving them. The main focus is on the WWF target, but we also acknowledge the Food, Farming and Countryside Commission (FFCC) and National Farmers' Union (NFU) targets.

3.1 Understanding WWF's Initial Target

3.1.1 Setting the target

WWF are still in the process of determining their agricultural emissions reduction target. They initially considered basing their target on the CCC's Widespread Engagement (WE) Scenario (one of five different agricultural GHG emission reduction scenarios assessed in the CCC's Sixth Carbon Budget report). This scenario was chosen because WWF felt most aligned with its assumptions, namely a future with less reliance on bioenergy carbon capture and storage (BECCS), high levels of farmer and consumer engagement, and less reliance on future technological innovation.

If the changes assumed under the Widespread Engagement Scenario are all achieved, then agricultural emissions will be reduced by 24% (13 $MtCO_2e$/yr) by 2030 and by 50% (27 $MtCO_2e$/yr) by 2050, as shown in Figure 4. WWF used this extent of GHG reduction as their initial target. However, WWF is currently exploring its preferred pathway for achieving this target. This could be via the WE scenario or via another pathway that could also achieve, or even exceed, the target. This is covered in more detail in a separate piece of work commissioned by WWF and currently in preparation by the University of Aberdeen.

3.1.2 Pathway for achieving target assumed under Widespread Engagement Scenario

To determine whether WWF should aim to achieve this target via the Widespread Engagement Scenario, it is first important to understand what that pathway entails. The CCC report has divided the 'methods for reducing GHG emissions' into four categories and within these categories assumptions have been made as to the extent of change as outlined in Table 4.

Figure 4 Emissions pathways for the agriculture sector as outlined in the CCC Sixth Carbon Budget

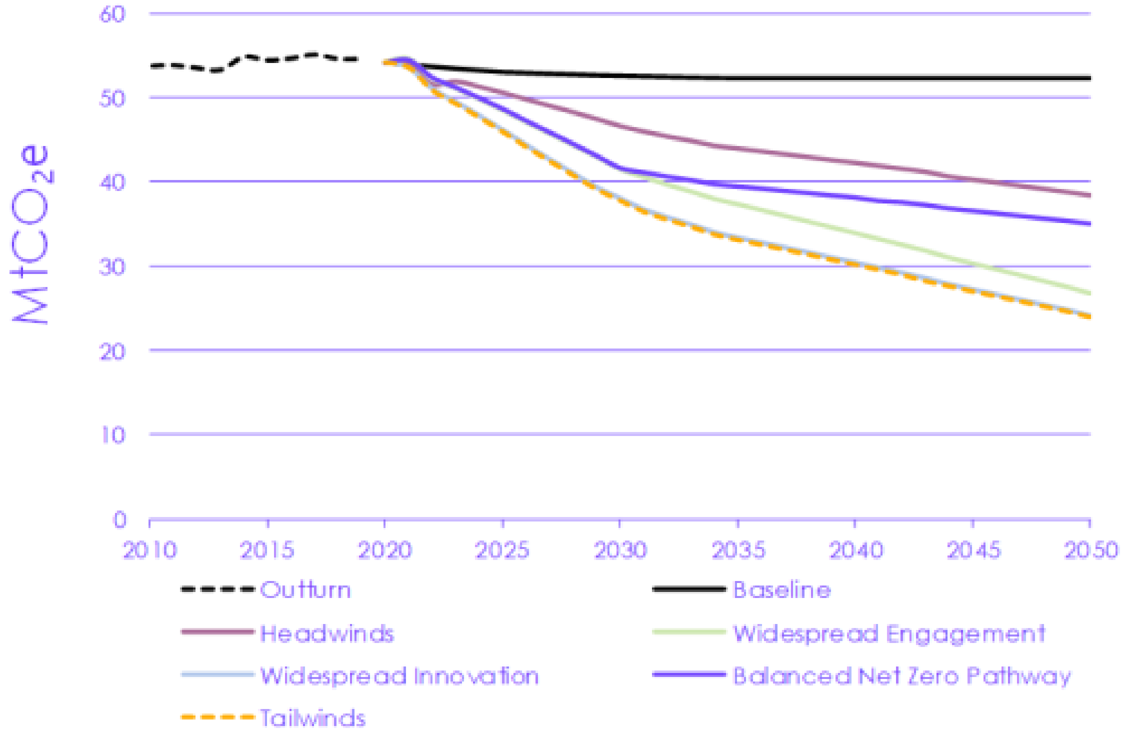


Table 4 GHG reduction categories and extent of change assumed under Widespread Engagement Scenario

GHG reduction 'category'	Extent of change assumed within this category
Dietary change and food waste reduction	• 50% less meat and dairy by 2050 • 50% reduction in food waste (including on-farm waste) by 2030 and 70% by 2050
Other land release measures	• Moderate increase in crop yields (to 13 $tDMha^{-1}$ by 2050) and 'a more efficient use of N' • 5% increase in stocking rate for grazing animals by 2050 • 0.6% yr^{-1} increase in dairy productivity between 2020 and 2050 • 10% of horticulture production moved indoors by 2050
Agricultural machinery	• Increase in electrification and use of biofuels in agricultural machinery

Low-carbon farming measures	18 low carbon farming measures were selected as the most 'cost-effective to society' (in £/tCO_2e). These were divided into interventions that require 'behavioural change' and those that are 'innovative'. The abatement potential of these interventions is only assessed in terms of non-CO_2 GHGs (i.e., nitrous oxide and methane). • 50-75% uptake of 'behavioural' measures by 2050 • 60-80% uptake of 'innovative' measures by 2050

3.2 Considerations if diverging from the WE scenario

WWF may decide to change some of the assumptions made under the WE scenario to achieve (or exceed) their current GHG reduction ambitions, for example by prioritising different farm-level interventions. However, if WWF change some, but not all, of the assumptions made under the WE then there are several factors that need to be considered.

Firstly, there is a danger of double counting. The WE scenario has a number of GHG reduction 'categories' as outlined in Table 4. One of these is 'low-carbon farming', which includes 18 farm-level interventions shortlisted by cost-effectiveness in £/tCO_2e. In this report we developed a list of 20 farm-level interventions shortlisted by national GHG abatement potential. Some of our short-listed interventions are not included in the WE scenario 'low-carbon farming' category but overlap with assumptions made in one of the other three 'GHG reduction categories'. If these interventions are included as low carbon farming measures within the WWF's pathway model (without changing the other WE scenario assumptions) this will lead to double counting. These measures are as follows:

- 'On-farm food waste reduction' (M20) overlaps with the food waste reduction assumption in the 'dietary change and food waste' category.
- Interventions relating to efficient/reduced fertiliser use (M10, M8, M13, M14, M9, M15) overlap with the increase in crop yields and nitrogen efficiency assumption in 'other land release measures' category.[43]
- 'Alternative low carbon fuel farm machinery' (M18) overlaps with the increase in electrification and use of biofuels in agricultural machinery in the 'agricultural machinery category'.

[43] The CCC Sixth Carbon Budget report says *"our scenarios exclude the take-up of four crop and soil related measures assessed by SRUC […]. Our assumptions on crop yield improvements, already imply a more efficient use of nitrogen and adding these to our scenarios would be double-counting. Although we have not included the abatement savings from these measures, it is important that farmers are encouraged to take these up to reduce emissions from crops and soils."* See p.14 of the sector summary for Agriculture and land use, land use change and forestry, https://www.theccc.org.uk/wp-content/uploads/2020/12/Sector-summary-Agriculture-land-use-land-use-change-forestry.pdf .

Secondly, the emission reduction potential of ‘low carbon farming’ measures may need to be adjusted depending on which farm-level interventions are included. Two interventions (precision feeding and GM cattle) were assessed in the WE scenario due to high cost-effectiveness (in £/tCO_2e) but were not included in our short-list due to low GHG abatement potential. If these are omitted from the low-carbon farming measures category, then the emissions reductions from 'low-carbon' farming will be reduced slightly. However, if new higher impact interventions are included then the emissions reductions from ‘low carbon’ farming will increase.

Thirdly, the influence of land use change on the national GHG abatement potential of farm-level interventions must be recognised. Dietary shifts away from animal products will likely release land from agriculture, which in turn will reduce the area of land on which farm-level interventions are applicable. Whilst the per unit (per hectare or per animal) impact of interventions will remain unchanged, their national potential may decrease. Therefore, more ambitious assumptions around dietary shifts will likely reduce the overall reduction potential of ‘low carbon farming’ measures, despite having positive climate impact.

3.3 Challenging and rethinking the WWF target

WWF’s emission reduction target overlooks three key factors that are not considered in current national emissions accounts (as outlined in Section 1.2). These factors are the ‘Carbon Opportunity Cost’ (COC) of global land use associated with UK agriculture; additional metrics to GWP100 (e.g., GWP20 or GWP*); and fertiliser manufacturing emissions. Disregarding these factors may lead to different, and perhaps misjudged, priorities for emissions reduction.

Overlooking ‘**Carbon Opportunity Cost’ (COC)** could severely underestimate the potential of a whole class of interventions that improve global land use efficiency, such as replacing soy in animal feed with alternatives with a lower land requirement and reducing on-farm food waste. Although COC may be considered difficult to quantify, work done by Searchinger et al (2018) suggests this could be possible.[44] Given the globalised nature of agriculture, it is imperative we take a global perspective to COC to understand how actions on UK farms can deliver a net global benefit. This helps avoid misplaced recommendations such as replacing imported soy with pulses grown in the UK without increasing land-use efficiency. Reducing the impact of imported soy is particularly relevant to WWF given their advocacy for reducing deforestation in the Amazon and a recent report on using insect protein in animal feed.[45] WWF should consider how their targets for reducing UK agricultural emissions and deforestation

[44] Searchinger et al. (2018) Assessing the efficiency of changes in land use for mitigating climate change. *Nature* 564, 249–253.
[45] WWF (2021) *The Future of Feed: A WWF Roadmap to Accelerating Insect Protein in UK feeds.*

should be linked, whilst recognising the dangers of simply displacing one crop for another.

The recently released IPCC AR6 report highlighted that the timescales for averting tipping points are even shorter than previously anticipated.[46] The use of **alternative metrics to GWP100** been discussed widely but by convention all policy and activity is based on the internationally accepted GWP100. There is an opportunity for WWF to take a lead and set a target that also considers GWP20, or the emerging metric GWP*, to emphasise the urgency of the challenge. Such an approach would increase the relative importance of methane emissions, and the interventions that reduce them.

Nitrogen **fertiliser manufacturing emissions** are an important area globally and contribute around 1.4% to global GHG emissions.[47] For this reason, they need to be included in WWF's targets, though they are a relatively modest contributor to UK emissions and should not be a major priority at this stage.

Based on the results of first part of the IPCC AR6, the WWF target is **not as ambitious** as it could be.[48] WWF are already considering increasing the dietary shift ambition to 50% reduction in meat and dairy by 2030 (rather than 2050 as assumed under the WE Scenario). If GHG accounting methods are updated to include global COC (associated with UK agriculture) and to consider GWP20 or GWP* in addition to GWP100, then the GHG impact of dietary shifts will be even greater than currently estimated. Nonetheless, increased ambition around dietary shifts should not detract from measures to reduce on-farm emissions.

There may be other areas for increasing ambition, in particular, through **research and development**. WWF chose the Widespread Engagement Scenario in part because it has less focus on innovation. However, as outlined in Section 2.3, two of the most impactful interventions (i.e., "the Big Hitters"), namely novel feed additives (e.g. seaweed and derivatives) and novel feed alternatives to soy (e.g. microbial protein), require substantial further research and development. WWF in the USA recently facilitated a workshop looking at the potential of seaweed as a feed additive.[49] If the GHG reduction potential of research and development is recognised then the WWF target could be more ambitious. Note that the abatement potential of novel animal feed alternatives will only be relevant if the target is adjusted to consider global COC.

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[46] IPCC (2021) Climate Change 2021: *The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate*. Cambridge University Press. In Press.

[47] Kanter et al. (2020) Building on Paris: integrating nitrous oxide mitigation into future climate policy, *Current Opinion in Environmental Sustainability*, 47, pp 7-12

[48] IPCC (2021) Climate Change 2021: *The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate*. Cambridge University Press. In Press.

[49] WWF (2020) *The Potential for Seaweed as a Livestock Feed: 2020 Workshop Series Outcomes.*

The abatement potentials of the low-carbon farming measures assessed by the CCC are based on **non-CO_2 GHGs only**. Therefore, some interventions may have been underestimated, or not assessed at all (e.g., M11 - minimum till). Although CO_2 is not one of the dominant emissions sources of on farm emissions, it is the key component of COC and of the manufacturing emissions associated with synthetic fertilisers. If WWF are to include these emissions in their target, then they should also ensure that CO_2 is included.

The WE scenario uses a **fragmentary approach** to assessing interventions. Although the interactions between interventions have been accounted for (as far as possible) when estimating abatement potentials, the analysis does not recognise the synergies between interventions and how they complement one another within farm-systems. The WE scenario also does not recognise other environment co-benefits beyond GHGs. Furthermore, WWF need to recognise that farmers tend to may make strategic decisions in terms of their overall farm-system, so promoting individual interventions may not be the most constructive approach to encouraging uptake.

Low carbon farming measures in the WE Scenario were **short-listed based on cost-effectiveness to society (£/tCO_2e)**, whereas in this report, interventions were short-listed based on GHG abatement potential as ultimately the aim is to have maximum impact. Although cost effectiveness is important, it is also important to note that costs associated with more innovative measures are often high initially and then reduce as supply chains develop and production efficiencies are realised. For very innovative measures such as feed additives, the costs are often relatively unknown at the early stage. When developing their pathway WWF needs to decide whether to prioritise interventions that are most cost-effective (in £/tCO_2e) or that have the most impact.

The **uptake rates** of the 18 low carbon farming measures assessed in the WE Scenario are outlined in below. These uptake rates are based on farmer feedback from workshops run by Defra (in the unpublished CGSI report). We have provided an analysis of whether we think these uptake rates are cautious, realistic, or ambitious, based on feedback from our own farmer workshop. Table 5 also flags which of our interventions are either not considered in WE Scenario at all or are not included in the low carbon farming measures section of WE Scenario.

Table 5 Assumed uptake rates in Widespread Engagement Scenario

(measures in blue were assessed in this report but are either not considered in WE scenario or are not included in the low carbon farming measures section of WE scenario)

Farm-level GHG reduction intervention	Uptake rate assumed under WE Scenario	Farmer view on likelihood of implementation (scale 0-5)	Comments
M1 Feed additives for ruminants		**2**	Ambitious (given both these feed additives are still in development).
3NOP	50%		
Nitrate additives	60%		
Biochar	N/A		Not considered
Seaweed	N/A		Not considered
M2 Low cellulose diets		2	Ambitious (60% may be more realistic given dominance of outdoor rearing on unimproved pastures
High fat	N/A		
High sugar diet	80%		
High starch diet	80%		
M3 Low carbon animal feed alternatives to imported soy	N/A	4	Not considered.
M4 Livestock breeding		3	Broadly realistic (although would question whether uptake of 'low emissions breeding goal' will be higher than 'current breeding goal')
Increased uptake of current genetic improvement practices	50%		
Breeding with genomics - current breeding goal	50%		
Breeding with genomics - low methane breeding goal	60%		
Selection for 'balanced breeding goals' (i.e. reduced emissions intensity per unit meat)	N/A		This is a different way to consider improved livestock breeding. It is a combination of breeding for improved feed conversion/improved yields and reduced emissions intensity, also uses selective breeding not genomics.
Selective breeding for higher feed conversion (pigs, poultry, sheep)	N/A		Not considered.
M5 Livestock health		5	Potentially cautious
Improving cattle health	75%		
Improving sheep health	75%		
Improving pig health	N/A		Not considered
Improving poultry health	N/A		Not considered
M6 Increased milking frequency	60%	2	Ambitious

Farm-level GHG reduction intervention	Uptake rate assumed under WE Scenario	Farmer view on likelihood of implementation (scale 0-5)	Comments
M7 Grass-legume mixture in pasture	80%	5	Potentially cautious
M8 Keeping pH at an optimum for plant growth	N/A	4	Considered double counting due to assumed increases in crop yields + nitrogen efficiency (part of 'land release measures' GHG reduction category)
M9 Cover crops in arable rotations	80%	4	Ambitious (likely more like 50% as not practical in some cropping situations and or on some heavy clay soils)
M10 Grain legumes in crop rotations	N/A	2	Not considered
M11 Reduced tillage	N/A	3	Not considered. WE scenario only considers non-CO_2 GHG abatement potential from low carbon farming measures (primary benefit of M11 is reducing soil CO_2 emissions)
M12 Grass leys in arable rotations	50%	2	Ambitious
M13 Precision fertiliser applications + avoiding excess N		4	Considered double counting due to assumed increases in crop yields + nitrogen efficiency (part of 'land release measures' GHG reduction category)
Precision fertiliser applications	N/A		
Avoiding excess N	N/A		
M14 Controlled release fertilisers	N/A	3	
M15 Nitrification/urease inhibitors	N/A	2	
M16 Anaerobic digestion		2	Ambitious
AD pig manure	60%		
AD cattle manure	60%		
M17 Covering slurry stores	80%	3	Ambitious
M18 Alternative low carbon fuel farm machinery	N/A	3	Considered double counting as part of agricultural machinery GHG reduction category
M19 Low carbon heating	N/A	3	Not considered
M20 On-farm food waste reduction	**N/A**	4	Considered double counting as part of dietary change/food waste GHG reduction category
Genetic modification of cattle.	*Not specified*	Not assessed in our report due to low GHG abatement potential but included the WE Scenario due to high cost-effectiveness (in £/tCO_2e).	
Precision feeding	75%		

3.4 Other targets

3.4.1 NFU

The NFU has set a target of achieving Net Zero emissions by 2040.[50] The NFU's report makes clear that the 2040 ambition is a national aspiration, not an expectation that every farm can, or will, reach net zero. They aim to reach net zero via three main 'pillars':

1) Productivity/efficiency improvements to save 11.5 $MtCO_2e$/year.
2) Farmland carbon storage, to save 9 $MtCO_2e$/year.
3) Bioeconomy-based measures, to save 26 $MtCO_2e$/year.

The first pillar relates primarily to GHG reductions and accounts for 25% of this target. The interventions identified in this report focus on GHG reductions and therefore will mostly contribute to this pillar and *"enable farmers to produce the same quantity of food, or more, with less inputs"*. The following interventions are identified in the NFU Net Zero report as examples of measures falling within this Pillar 1 category that overlap with the short-listed interventions in this report:

- Feed additives for ruminants (a more challenging 'Big Hitter').
- Improved livestock health (a potential 'easy win').
- Precision fertiliser applications (a potential 'easy win').
- Controlled release fertilisers (potentially 'more challenging').
- Nitrification and urease inhibitors (potentially 'more challenging').
- Anaerobic digestion of animal manures and crop waste (potentially 'more challenging').

The terminology 'production/efficiency improvements' is slightly confusing as some interventions, such as feed additives, reduce emissions but do not necessarily improve the efficiency of land use or inputs.

The second two pillars primarily relate to GHG removals and account for the majority (75%) of the target. The key message here is that the level of ambition for GHG reductions is relatively low, compared to GHG removals, and is less ambitious than the WWF target, which currently aims for a 13$MtCO_2e$ reduction by 2030 and 27$MtCO_2e$ reduction by 2050. Additional reductions could be achieved through wider engagement with and advice for farmers to implement the 'easy wins' measures identified in this report, alongside further research and financial incentives to implement the 'more challenging' interventions. Furthermore, perhaps the NFU should consider the importance of global COC and whether this should be integrated into their target. This would be particularly important for pig and poultry farmers in terms of finding alternative animal feed products. Additionally, if GHGs are assessed using GWP20 then

[50] National Farmers' Union (2020) *Achieving Net Zero, Farming's 2040 goal*, https://www.nfuonline.com/nfu-online/business/regulation/achieving-net-zero-farmings-2040-goal/ accessed July 2021.

greater ambition around methane reduction may be needed to achieve Net Zero by 2040.

A large proportion of the GHG reductions in the WWF target relate to dietary shifts and reduction in food waste, not just low-carbon farming measures. Dietary shifts are not considered in the NFU target and although some discussions around waste have been had, no specific target has been clearly publicised.

Finally, the NFU does not provide a clear pathway for achieving this level of reduction. They outline examples of measures that could be used to achieve each pillar but do not seem to have modelled national abatement potentials and uptake scenarios to verify a clear pathway required to achieve the target, as was done for the WE scenario used to inform the WWF target.

3.4.2 FFCT's 10 years to transition to agroecology

The Food, Farming & Countryside Commission has set out a 10-year transition to agroecology target, which aims to grow enough healthy food for a future population whilst achieving the following targets:[51]

- Reduce agricultural GHG emissions by 38% by 2050.
- Eliminate synthetic fertilizers and pesticides.
- Release 7.5% land from agriculture (for sequestration opportunities).
- Nearly double amount of land available for 'green and ecological infrastructure' (ponds, hedges, meadows etc).
- All without compromising food security or offshoring food production.

The assumptions associated with this transition include a 10% reduction in food waste by 2050 and a limit of 35g animal protein (out of max 50g protein) per person per day. This equates to more than 50% reduction for men and just under 50% reduction for women.

The emission reduction target here is lower than the WWF target, aiming for a 20.7 $MtCO_2e$ reduction by 2050 as opposed to WWF's 27 $MtCO_2e$ reduction by 2050. Nevertheless, the FFCT's target is taking a more holistic, agroecological and systems-based approach to achieving GHG emission reduction. Although less ambitious, it may prioritise interventions which maximize a range of outcomes, not just GHG reduction.

[51] Food, Farming & Countryside Commission (2021) *Farming For Change, Mapping a route to 2030,* https://ffcc.co.uk/assets/downloads/FFCC_Farming-for-Change_January21-FINAL.pdf.

4.0 Key Recommendations

This section includes recommendations for overcoming the key barriers to uptake identified by farmers (see Section 2.5), including the need for further R&D, lack of suitable advice, capital and ongoing costs, and tight product specification requirements. We also include recommendations concerning the need to rethink GHG emissions accounting, to provide open access to information, and to encourage sustainable consumer attitudes towards food.

4.1 Develop more holistic GHG emissions accounting

1) **NGOs and research organisations should develop a clear methodology for accounting for GHG emissions that considers global Carbon Opportunity Costs (associated with UK agriculture), shorter timescales by reflecting GWP20 or GWP* to complement GWP100, and perhaps fertiliser manufacturing emissions.**
2) **Government and NGOs should use this more complete perspective to set GHG emission reduction targets that recognise the global impact of reducing national emissions (to ensure emissions are not simply being shifted elsewhere), maximise opportunities for avoided deforestation and carbon sequestration, and reflect the need for urgent action.**
3) **Government should support action to improve the measurement of GHG emissions from farming practices, to enable more accurate emissions calculation. This is particularly true for long-term processes, such as those related to soils including the impact of reducing tillage.**

To establish GHG reduction priorities and establish useful targets, it is important to account for the extent and key sources of UK agricultural emissions. As outlined in Section 1.2, there are three key factors that are currently not accounted for in national emissions estimates: global Carbon Opportunity Cost (associated with UK agriculture); alternative metrics that increase the relative importance of short-lived GHGs, and fertiliser manufacturing emissions. If these are not incorporated into emission accounts and thus reduction targets, there is a danger we prioritise the wrong things.

Carbon Opportunity Costs (COC), due to agricultural land use, are a particular concern. If these are not incorporated into GHG emission reduction targets, the GHG abatement potential of interventions that reduce the area of land required for food production are underestimated. We may also make misplaced recommendations about shifting the production of crops (such as soy) that cause international deforestation to the UK, without increasing land use efficiency or reducing demand. This points to a need to recognise the global impact of changes to ensure we are not shifting emissions elsewhere.

Using metrics that better account for short and long-lived GHGs. Given the urgency of the climate problem, accounting for the GWP of GHGs over a 100-year timescale may not be sufficient, and a 20-year time horizon is perhaps more relevant. If we consider GWP20 then the relative importance of methane increases substantially and the priorities for GHG reduction from agriculture shifts to increase focus on interventions that reduce methane. We recognise the emergence of GWP* as an alternative method for equating short and long-term GHGs. However, although it simplifies the metrics in some respects it adds the complication of equating a single pulse of CO_2 to a change in the continuous rate of methane emissions. This is an important area for further discussion and debate.

Fertiliser manufacturing emissions are considered industrial but the need for fertiliser is reduced at a farm level. Acknowledging these emissions when considering farm-level interventions to reduce GHGs will place greater emphasis on interventions that reduce fertiliser use.

Finally, there is a need to improve the measurement of GHG emissions from farming practices, to enable more accurate emissions calculation. This is particularly true for long-term processes, such as those related to soils.

4.2 Accelerate targeted R&D to deliver 'Big Hitters'

4) **Research councils should be given a mandate to accelerate targeted R&D to reduce emissions from key sources, namely**
   a. **reducing methane via feed additives for ruminants;**
   b. **reducing the land area required for animal feed production by using alternative protein sources (e.g. insects and microbial protein).**

Farmers identified lack of robust scientific evidence and lack of market availability as key barriers for implementing two big hitters M1 (feed additives that reduce methane from enteric fermentation) and M3 (animal feed alternatives with reduced land requirement). Sizeable reductions in methane emissions and agricultural land use will be needed at speed, to be consistent with IPCC AR6.[52] Two important strands of research which have the potential to materially reduce these emissions are:

1) Novel feed-additives, such as bromoform compounds from seaweed.
2) Novel protein sources, such as microbial protein.[53]

Although these technologies are still largely experimental, they have considerable potential for emission reduction. Research efforts should be accelerated to make a material difference within the relevant timescales. Research should focus on improving

[52] IPCC (2021) Climate Change 2021: *The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate*. Cambridge University Press. In Press.

[53] Oxford Smith School of Enterprise and the Environment (2021) *The Climate Impact of Alternative Proteins: Final 25% Series Paper.*

our understanding of emerging products/techniques that have already been identified and identification of new products/techniques.

4.3 Provide robust, impartial, consistent, and tailored advice to farmers on how to reduce GHG emissions.

All have a role to play in this:

5) **The Government should provide impartial agricultural advisory services with a clear remit to deliver GHG reduction and well-trained local advisors to tailor guidance at a farm level.**
6) **The Government should fund activities to support greater peer-to-peer learning amongst farmers and bottom-up farmer-led advisory initiatives as an effective way of sharing good practice particularly for those interventions seen as cost-effective.**
7) **All organisations undertaking research in this area, including WWF, should pool resources and share research to create a common and consistent evidence base.**
8) **Focussed research must be accelerated (see above) to create a robust and up-to-date evidence base. Farmer participation should be included to ensure relevance.**
9) **Government advice should support system changes, not just individual interventions, and recognise synergies between interventions and other environmental co-benefits.**
10) **Government farm advisors should promote interventions that have a positive global impact**

Farmers identified a lack of **robust, consistent, impartial, and tailored advice**, on best farming practice and best climate practice, as a key barrier to implementation for a wide range of measures across all the clusters. Therefore, provision of this advice is a core recommendation.

To ensure this advice is **impartial**, it is important that research and advice is provided by organisations without vested interests (i.e. non-agri business). This could be achieved by introducing legislation to prohibit sales organisations providing advice or making impartial advisory schemes more widely available (as was the case historically in the UK). Organisations providing taxpayer funded advice should clearly demonstrate a separation from sales. Local and tailored advice is still available to farmers in catchments sensitive to water pollution under the Catchment Sensitive Farming Initiative (CSF). Defra has also recently announced the next round of its fully funded "advisory support programme" as part of its Future Farming Resilience Fund (FFRF) which will run from August 2021 to February 2022. This will provide participating farmers and land managers with free, **tailored** one to one advice, events and skills development workshops to help navigate the changes brought about by the Agricultural Transition.[54] Both of these mechanisms could be extended to provide farmers with information on how to reduce their GHG emissions. Impartial advice could also usefully be achieved by supporting more **peer-to-peer learning** and bottom-up farmer-led advisory initiatives. Farmers sharing their skills, technical knowledge and experience may be key to embracing new, more sustainable farming techniques as farmers tend to trust the experience of their peers, which is considered more impartial and ground-truthed. For example, interventions falling into the 'Easy Wins' cluster (improved livestock health and livestock breeding, use of grass-legume mixtures and optimising pH and fertiliser applications) are considered attractive, cost-effective to farmers and relatively well understood. The main barrier is likely to be knowledge. Farmers could make each other aware of new advice on good practices and outline their experiences of it.

For other interventions further research is needed to provide more **robust** information on climate benefits and to reassure farmers that the measures do not pose a significant risk for their farms. This is particularly true for more innovative interventions such as feed additives. It is also true for a number of more established measures such as minimum till, for which little is known about their climate impact. Ideally research would include farmer participation to ensure its relevance. It is also important that research and information is shared between organisations, to ensure everyone has access to most up to date data. Furthermore, much of the data on emissions factors in agriculture is out of date relative to current practice, so there is a risk that modelled mitigation estimates are incorrect.

To ensure this advice is **consistent**, it is crucial that we join up agricultural and non-agricultural business-related advice to avoid mixed messaging. As described, research efforts should be channelled into a consistent advisory service to ensure information is up to date and collated in a central place. There are a number of initiatives seeking to lead the way on this, for example, the Evidence for Farming Initiative (EFI) and Agricology.[55] To avoid further fragmentation of advisory information, all organisations undertaking research in this area, including WWF, should work to share resources and outputs. For example, the EFI are currently conducting a pilot project assessing farm-level interventions to reduce and sequester GHG emissions (across range of sectors) and aiming to present the outputs in a farmer friendly format;[56] WWF should reach out to EFI to explore options for supporting each other.

Farmers tend to make strategic decisions in terms of their **overall farm-system**. Therefore, framing interventions within the context of systems may help better engage

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[54] ADAS (2021) *Future Farming Resilience Fund – how farmers can access free support for their business*, available at https://www.adas.uk/News/future-farm-resilience-fund-how-farmers-can-access-free-support-for-their-business, accessed August 2021.

[55] Agricology (n.d) *Welcome to Agricology: practical farming regardless of labels*, available at https://www.agricology.co.uk/, accessed August 2021.

[56] For further information contact jon.foot@ahdb.org.uk.

farmers. Furthermore, to ensure farmer advice is consistent (as highlighted in Section 4.1), farmers should be advised which systems (and in some cases individual interventions) are highest priority to achieve maximum benefit across a range of different outcomes. This avoids confusion surrounding different lists of interventions that prioritise different outcomes (GHG reduction, or sequestration, or reduced nitrogen leaching etc). WWF should consider a separate study that looks at farm-system change in more detail. The study could also bring in more detail on the co-benefits from some of these wider changes – although it is noted that environmental appraisal methodologies are relatively poorly developed on many aspects such as biodiversity. This should also look at how farm-system change could be better supported.

Government farm advisors must also consider the **global impact** of farm-level interventions, particularly with regards to land use (e.g. more locally grown animal feed or reduced stocking densities). As highlighted in Section 2.5, in a globally commoditised marketplace, unless land use efficiency is increased or demand is reduced, any reduction in deforestation or land-use efficiency in one area will likely shift deforestation into a new frontier in another area. It is the role of government advisers to be able to look beyond the farm and promote systems that increase land use efficiency.

4.4 Provide financial incentives to support GHG reductions

4.4.1 Funding Investments – making capital affordable & available

11) **Government should create mechanisms to support farmers overcome the initial investment costs of GHG reduction interventions by providing non-traditional and sub-commercial capital to farmers (both tenants and landlords). Approaches to consider include:**
    a) **creating specialist agricultural lenders;**
    b) **de-risking future cash flows through use of contracts; and**
    c) **providing a grant scheme**
    d) **Private firms may have a role albeit this is likely to need underwriting by Government.**
12) **Government should provide long-term secure carbon prices to support interventions that increase ongoing costs.**

Farmers identified capital cost as a key barrier for a number of interventions, both within the 'easy wins' and the 'more challenging' cluster. There are several distinct but interdependent elements that need to be in place to allow farmers, already facing cost pressures and substantial risks, to invest in GHG reducing interventions.

- **Reducing Risk.** Farmers face a range of risks including weather, climate, market price, disease and policy change. Measures that help reduce these risks, or at least reduce the financial impact they may have on farmers, can help farmers have more confidence in capital investments for long-term benefits. Lower risk investments also attract lower interest rates.

- **Making Capital Affordable and Available**. Many farmers (particularly tenant farmers) have insufficient collateral, or too high a risk profile, to raise the capital needed for many of the interventions. Many are also risk adverse. Defra should be encouraged to establish a low return green fund for investing in capital and/or an incentive to encourage green loans. Regardless of availability, capital must be affordable. In today's low interest environment interest rates are only a modest proportion of the cash flows needed to fund investment. Capital repayment is often dominant. This can be mitigated by long term loans that are attached to the farm not the farmer – especially for interventions such as soil health improvement which may have 10–20-year time horizons for having an effect. The actual practicalities of how this could be done need further thought. Private firms may have a role, as per the sustainability finance programme operated by Santander. This could be expanded to farms to give better payment terms or interest rates for farmers investing to reduce GHG emissions, particularly those adopting the more challenging practices, albeit this is likely to need underwriting by government.[57]

Carbon pricing is often seen as a suitable market mechanism for funding GHG mitigation, but it may not address these barriers. Future carbon prices are uncertain and introduce new market and policy risks to an already risky operating environment.

Defra should be encouraged to create mechanisms to support farmers overcome the initial investment costs. Possible policy approaches to be considered include:

- **establishing specialist agricultural lenders** whose low cost and long-term lending to GHG reducing interventions is underwritten by government;
- **de-risking future cash flows** for farmers who rely on future revenue streams to pay for GHG reducing investment. In the latter case an example may be seen in the 'Contract for Difference' approach used to de-risk renewable energy investments. Such an approach can be used to insure against the effects price falls, or even weather or other adverse effects, whilst not costing government in good years; and
- **offering grants** – though these tend to be blunt instruments that may be difficult to monitor and manage. They can also distort the market and therefore low interest and long-terms loans (discussed above) may be preferrable.

4.4.2 Funding ongoing costs - Grants, Subsidy, or Carbon Prices

Farmers identified ongoing costs as a key barrier, particularly for interventions in the 'more challenging' cluster. The mechanisms that deal with capital intensive but cost saving interventions are not suitable for interventions that have long term cost

[57] Global Trade Review (2021) Santander sets up sustainability-linked supply chain finance programme for Tesco, available at https://www.gtreview.com/news/sustainability/santander-sets-up-sustainability-linked-supply-chain-finance-programme-for-tesco/, accessed August 2021.

implications for farmers. They cannot deal with issues such as feed additives to reduce enteric methane emissions – which are likely to always be an additional cost of operation with no on-farm benefit. For these, subsidy is likely to be required, or a clear carbon price. This could be a carbon price as a reward for measures that reduce emissions, without reducing system efficiency. The issue with a carbon price as a tax is that it can drive production to other untaxed places.

Carbon pricing for such interventions works because farmers can make decisions in real time about what they wish to spend to reduce emissions. Similarly, subsidy to feed manufacturers would allow low carbon feeds, or feeds that reduce enteric emissions, to be competitive with traditional feeds. Subsidy may be the only alternative for interventions that reduce emissions not generated on farm for which there is no proposed market mechanism in discussion and is probably the more viable option in the short term.

4.5 Ensure open access to data

13) **All data on the impact of farm-level interventions (particularly per unit data) should be publicly available at no cost, including clear explanations of the methods, data and assumptions used.**
14) **Data on uptake levels should be monitored and made publicly available to track progress against targets and, if necessary, to direct further action to boost behaviour change.**

This work was hampered by lack of access to core per unit data on GHG emissions from interventions. This information should be openly accessible to all as a baseline from which people can derive their own scenarios aligned to tailored assumptions. Large elements of work in this area have been publicly funded through Defra, who should ensure in future that the outputs are not only available, but also accessible to others. One option for harmonising and opening access to data would be to make core data available via common platforms such as Hestia.[58] There is also an opportunity for retailers (or other businesses) to upload anonymised farm GHG footprint data into a platform such as Hestia, to build the databank on farm-level activities. Going forward, we would also recommend that Defra, regularly and openly, monitor intervention uptake levels to track progress against target and, if necessary, take steps to boost behaviour change.

[58] Oxford Martin School (2021) Food Sustainability Analytics: The Challenge, available at https://www.oxfordmartin.ox.ac.uk/food-sustainability-analytics/, accessed August 2021.

4.6 Work together to deliver system change and encourage sustainable consumer attitudes to food

15) **WWF should continue to encourage retail and supply chains to provide guidance and support to farmers to reduce their emissions.**
16) **Governments, NGOs and retailers must work together to change consumer attitudes towards food.**
17) **NGOs, Government and industry need to support livestock farmers through the system changes associated with dietary shifts.**

A key barrier to reducing on-farm food waste (M20) is tight produce specification requirements set by food processors and retailers. NGOs, and potentially farmers, should apply pressure on supermarkets to change these rigid requirements to enable farmers to reduce out of specification production.

WWF should encourage retail and supply chains, such as Tesco, to build on existing producer relationships to provide guidance and support towards net zero on farms. This will help food companies meet their own climate targets and enhance their public image. In the past, retailer/supply-chain-driven initiatives have successfully incentivised participation in sustainable farming initiatives, such as improving animal welfare and reducing antibiotic use. Given the existing relationship that WWF have with Tesco, this dissemination route is likely to make a distinctive contribution.

Since specification requirements are driven by consumer expectations, retailers and NGOs must also work together to help consumers understand the impact of their demands for perfect products at all times and to change attitudes, for example towards buying ‘wonky veg’. This will avoid shifting the food waste problem off-farms and into supermarkets. Given heightened public awareness around food waste and dietary choices, aligning with this change is likely to have the benefit of presenting a positive public image for all involved.

NGOs, government, and industry need to encourage dietary shifts. This will both reduce direct emissions from livestock farming and enable increased uptake of sustainable agroecological systems that revolve around low density livestock farming, without having the negative global emissions impacts discussed above. Dietary shifts will hugely impact livestock farmers. To ensure a thriving and sustainable farming community, farmers need to be supported on the journey through dietary system change.

APPENDICES

A.1.0 Methodology

The section summarises the methods used to:

1) Estimate emissions from imported soy.
2) Estimate emissions from nitrogen manufacturing
3) Adjust for GWP20.
4) Estimate national GHG abatement potential and short-list interventions.
5) Calculate the average cost of abatement (£/tCO_2e) values for each intervention
6) Assess farmer views on 'cost-benefit' to their farm, 'likelihood of implementation' and key barriers to implementation via a farmer workshop.
7) Identify key policy recommendations.

A.1.1 Estimating emissions from imported soy

The UK imports 2,005,000 tonnes of soy meal per year and 757,000 tonnes of soybeans per year.[59] To make soy meal, the oil is removed from the soybeans. Given the beans consist of 20% oil, the equivalent weight of UK soy meal imports as fresh soybean is 2,506,250 tonnes per year. Therefore, total UK soybean imports are 3,263,250 tonnes per year. The global average direct operating emissions are 0.26 tonnes of CO_2e per tonne of soybean; and the global average Carbon Opportunity Cost of soy production is 5.90 tonnes of CO_2e per tonne of soybean.[60] Therefore, the total direct operating emissions associated with UK soy imports are 848,445 tonnes of CO_2e per year. The total Carbon Opportunity Cost associated with UK soy imports is 19,253,175 tonnes of CO_2e per year.

A.1.2 Estimating emissions from nitrogen fertiliser manufacturing

The total UK use of nitrogen in fertiliser is approximately 1,000,000 tonnes per year.[61] Emissions per tonne of nitrogen manufactured are 3.3 tCO_2e per year (in Europe) and 10.9 tonnes CO_2e per year in China.[62] Therefore, the lower estimate of UK emissions from imported synthetic nitrogen fertiliser production is 3.3 million t CO_2 per year.

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[59] Efeca (2019) *UK Roundtable on Sustainable Soya: Annual progress report.*

[60] Searchinger et al. (2018) Assessing the efficiency of changes in land use for mitigating climate change. *Nature* 564, 249–253.

[61] Agricultural Industries Confederation (2020) *Fertiliser consumption in UK.*

[62] International Fertiliser Society (2018) *The carbon footprint of fertiliser production: regional reference values.*

A.1.3 Adjusting for GWP20

The GWP100 of methane is 34 (i.e. it is 34 times more potent than CO_2). The GWP20 of methane is 86.[63] Therefore, to rescale the impact of methane for GWP20 it is necessary to take the contribution at GWP100, and scale it by a factor of 86/34, which equals 2.53. In other words, the relative impact of methane compared to CO_2 is almost three times as great over 20 years than over 100 years.

The GHG emissions from enteric fermentation are assumed to be 100% methane, therefore this calculation is straightforward. For manure management the situation is more complex because emissions from manure comprise both methane and nitrous oxide. Nitrous oxide is a variable proportion of emissions, albeit much the minor proportion. There is a key paper that estimates the N_2O contribution from manure management at around 16% using GWP 100.[64] Using this percentage split, only the methane proportion of emissions from manure management have been rescaled as above.

A.1.4 Estimating national GHG abatement potential and short-listing interventions

The long-listing process is explained in Section 2.1.1 in the main body of the report. A short list of 20 interventions was created based on national GHG abatement potential (sometimes referred to in this report as ‘impact’) and were taken forward to the farmer workshop. Some similar interventions were grouped to streamline this list. For example, 3NOP and nitrate feed additive were both grouped as ‘feed additives’.

As outlined in Section 2.1.2, short-listing based on impact was challenging because per unit GHG abatement potentials (i.e. $ktCO_2$/yr per hectare or per animal) were generally not available and the national GHG abatement potentials ($ktCO_2e$/yr) reported in the different source documents are **not necessarily comparable.**

The normalised scores for the measures that did not make the short-list are presented in Table 6 below. The absolute values before normalisation measures are presented in Table 7 for short-listed measures and in Table 8 for measures that did not make the long list.

Note that in Table 3 the normalised scores for a particular intervention in the two Eory reports may well appear to be inconsistent, even though inspection of the original data (Table 7) shows the absolute abatement potential ($ktCO_2e$) of that intervention to be similar. The reason for this is that the Eory et al (2020) includes an additional

[63] Myhre et al. (2013). Chapter 8: Anthropogenic and Natural Radiative Forcing. In Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. pp. 659–740.
[64] https://core.ac.uk/download/pdf/29225569.pdf.

intervention (3NOP – a feed additive), for which its abatement potential is substantially larger than any other intervention. The process of normalising the data from this report consequently reduces the score of all other interventions. Although apparently inconsistent this has the correct outcome of reducing the relative importance of the other interventions and promoting that of feed additives. It is important to bear in mind that these scores provide relative and not absolute assessments, and their purpose is to help focus on the most impactful interventions rather than quantify them.

Table 6 Normalised scores for the measures that did not make the short-list

Reference in this report	Farm level intervention to reduce GHG emissions	Normalised national GHG abatement potentials from literature (scale 0-5)			Summary
		Eory et al (2015) *UK, 100% uptake*	Lampkin et al (2019) *Scotland, 100% uptake*	Eory et al (2020) *UK, adjusted to 100% uptake*	Overall estimate of abatement potential based on literature and expert judgement
	Improving/renovating land drainage on mineral soils			0	**[0]**
	Crop health			0	**[0]**
	Precision feeding		0	0	**[0]**
	Biostimulants			0	**[0]**
	Slurry acidification	2	1	0	**[0]**
	Take stock off from wet ground			0	**[0]**
	Plants with improved N use efficiency	1	1	0	**[0]**
	Covering slurry with permeable plastic cover			0	**[0]**
	Biogas flaring		0	0	**[0]**
	Gene modified cattle for reducing enteric methane			?	**[0]**
	Analyse manure prior to application			?	**[0]**
	Improving organic N planning	0	1		**[0]**
	Low emission manure spreading	1	1		**[0]**
	Shifting autumn manure applications to spring	0	0		**[0]**
	Reducing soil compaction	2	1		**[0]**
	Probiotics for ruminants	1	0		**[0]**
	Behavioural change in fuel efficiency of mobile machinery	0	1		**[0]**
	Cultivate land for crops in spring rather than autumn		0		**[0]**
	Conservation agriculture		N/A		System
	Organic farming		N/A		System
	Pasture-fed livestock production		N/A		System
	Agroforestry		N/A		System
	Afforestation	N/A			Sequestration

Table 7 Absolute national GHG abatement potential values from literature (in ktCO$_2$e/yr) for short-listed measures

Reference in our report	GHG reduction intervention	National GHG abatement potential (ktCO$_2$e/yr)		
		Eory et al (2015) *UK, 100% uptake*	Lampkin et al (2019) *Scotland, 100% uptake*	Eory et al (2020) *UK, adjusted to 100% uptake*
M1	**Feed additives for ruminants**			
	Nitrate	719	145	769
	3NOP		265	2,185
	Seaweed			
	Biochar			
M2	**Low cellulose diets for ruminants**			
	High fat	390	118	
	High sugar			73
	High starch			9
M3	**Low-carbon animal feed alternatives to imported soy**			
M4	**Livestock breeding**			
	Higher uptake of current genetic improvement practices (cattle only)			83
	Breeding with genomics - current breeding goal (cattle only)			247
	Breeding with genomics - lower emissions intensity goal (cattle only)			24
	Selection for balanced breeding goals (cattle only)	101	390	
	Further breeding for higher feed conversion (pigs, poultry and sheep)			
M5	**Improving livestock health**			
	Improving cattle health	784	308	776
	Improving sheep health	363	269	419
	Improving pig health			
	Improving poultry health			
M6	**Increased milking frequency**			109
M7	**Grass-legume mixtures in pasture**	170	540	753
M8	**Keeping pH at an optimum for plant growth**			1,077
M9	**Catch/cover crops in arable rotations**	8	9	319
M10	**Grain legumes in crop rotations**	602	77	
M11	**Reduced tillage**		12	
M12	**Integrating grass leys in arable rotation**			481
M13	**Precision fertiliser applications + avoiding excess N**			
	Precision fertiliser applications	362	82	145
	Improving synthetic N use/ 'avoiding excess N'	26	100	8
M14	**Controlled release fertilisers**	239	252	
M15	**Nitrification/urease inhibitors**	n/a	n/a	244
M16	**AD for heat and power**			
	AD (cattle manure + maize)	100		777
	250kW		18	
	500kW		4	
	1000kW		10	
	AD (pig manure + maize)			484
	AD (pig + poultry manure, + maize)	156		
	AD (maize)	136		
M17	**Covering slurry stores with impermeable cover**		9	189
M18	**Alternative low carbon fuel farm machinery**			
M19	**Low carbon heating - dairies and greenhouses**			
M20	**On farm food waste reduction**			

Table 8 Absolute national GHG abatement potential values from literature (in $ktCO_2e/yr$) for measures that did not make the short-list

Reference in our report	GHG reduction intervention	National GHG abatement potential ($ktCO_2e/yr$)		
		Eory et al (2015) *UK, 100% uptake*	Lampkin et al (2019) *Scotland, 100% uptake*	Eory et al (2020) *UK, adjusted to 100% uptake*
	Improving/renovating land drainage on mineral soils		n/a	148
	Crop health			62
	Precision feeding		1	33
	Biostimulants			33
	Slurry acidification	271	67	33
	Take stock off from wet ground			25
	Plants with improved N use efficiency	184	100	5
	Covering slurry with permeable plastic cover			0
	Biogas flaring			84
	Gene modified cattle for reducing enteric methane			
	Analyse manure prior to application			
	Improving organic N planning	18	58	
	Low emission manure spreading	163	68	
	Shifting autumn manure applications to spring	63	1	
	Reducing soil compaction	374	58	
	Probiotics for ruminants	113	14	
	Behavioural change in fuel efficiency of mobile machinery	75	77	
	Cultivate land for crops in spring rather than autumn		14	
	Conservation agriculture		143	
	Organic farming		1,827	
	Pasture-fed livestock production		484	
	Agroforestry		1,897	
	Afforestation	4,064		

A.1.5 Calculating average cost of abatement values

For each intervention with no constituent components the estimated cost of abatement is simply the mean average of the cost of abatements reported by the two Eory reports.[65,66]

For each of the interventions that were comprised of a group of similar interventions, a weighted average cost of abatement was calculated as follows:

- The average cost of abatement was calculated for each of the constituent interventions using data from the two Eory reports, as described above. The average impact of each intervention was calculated as the average of its normalised impact scores (from the three key reports). These scores were based solely on data from the literature and did not involve any expert judgement.
- The estimated cost of abatement of the composite groups was then calculated by taking the average cost of abatement for each constituent intervention, weighted by its average normalised national GHG abatement potential.

We recognise that national location, extent of interaction between measures, and the GHGs assessed may have some influence on the cost of abatement. We also recognise that the average normalised abatement potential is subject to a variety of assumptions. Therefore, these values should be seen as indications rather than accurate values.

A.1.6 Farmer workshop

An online farmer workshop was hosted by Innovation for Agriculture to get direct feedback from farmers on the practicality of the short-listed interventions. Farmers were asked to provide a Mentimeter[67] ranking for each intervention in response to the following two questions:

1) What is the 'likelihood of implementation'?
2) What is the on-farm 'cost benefit'?

Farmers were also asked about the key barriers to implementing interventions (focussing on those high impact interventions considered less likely to be implemented) and their answers were recorded using Mural, an online whiteboard tool. Due to time constraints, barriers were not able to be discussed for each intervention in this workshop.

[65] Eory et al. (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.*
[66] Eory et al. (2020). *Non-CO2 abatement in the UK agricultural sector by 2050*.
[67] An on-line polling tool. https://www.mentimeter.com/features

The workshop was attended by 21 farming stakeholders representing the following sectors:

- Poultry laying sector x 4;
- Poultry meat sector x 2;
- Pig sector x 1;
- Cattle beef sector x 1;
- Cattle dairy sector x 5;
- Sheep sector x 1;
- Mixed farming sector x 2;
- Arable x 1; and
- Fresh produce/horticulture sector x 4.

A.1.7 Identifying key policy change recommendations

All results from the earlier steps were presented at an expert workshop to sense-check the main findings and discuss recommendations needed to address barriers to uptake and achieve targets.

Table 9 Cost of abatement (£/tCO₂e) absolute values from literature and average calculations

Reference	GHG reduction intervention	Normalised GHG abatement potentials (scale 0-5): Average of normalised values from literature	Normalised GHG abatement potentials (scale 0-5): Standard deviation	Cost of abatement (£/tCO₂e): Eory et al (2015)	Cost of abatement (£/tCO₂e): Eory et al (2020)	Cost of abatement (£/tCO₂e): Average estimate of cost of abatement	Cost of abatement (£/tCO₂e): Weighted average cost of abatement	Cost of abatement (£/tCO₂e): Standard deviation
M1	**Feed additives for ruminants**						£78	
	Nitrate	2.6	*1.5*	£81	£55	£68		*£18*
	3NOP	3.7	*1.5*		£86	£86		
	Seaweed							
	Biochar							
M2	**Low cellulose diets for ruminants**						£165	
	High fat	1.8	*1.0*	£221		£221		
	High sugar	0.2	*0.0*		-£416	-£416		
	High starch	0.0	*0.0*		£0	£0		
M3	**Low-carbon animal feed alternatives to imported soy**						N/A	
M4	**Livestock breeding**						-£260	
	Higher uptake of current genetic improvement practices (cattle only)	0.2			-£1,176	-£1,176		
	Breeding with genomics - current breeding goal (cattle only)	0.6			-£579	-£579		
	Breeding with genomics - lower emissions intensity goal (cattle only)	0.1			-£1,838	-£1,838		
	Selection for balanced breeding goals (cattle only)	2.1	*1.7*	-£52		-£52		
	Further breeding for higher feed conversion (pigs, poultry and sheep)							
M5	**Improving livestock health**						-£16	
	Improving cattle health	3.2	*1.5*	-£42	-£41	-£41		*£1*
	Improving sheep health	1.9	*0.9*	£30	£23	£26		*£5*
	Improving pig health							
	Improving poultry health							

Reference	GHG reduction intervention	Normalised GHG abatement potentials (scale 0-5)		Cost of abatement (£/tCO_2e)				
		Average of normalised values from literature	Standard deviation	Eory et al (2015)	Eory et al (2020)	Average estimate of cost of abatement	Weighted average cost of abatement	Standard deviation
M6	**Increased milking frequency**	0.3	*0.0*		-£866	-£866	-£866	
M7	**Grass-legume mixtures in pasture**		*1.9*	-£45	-£1,143	-£594	-£594	*£776*
M8	**Keeping pH at an optimum for plant growth**	2.5	*0.4*		-£31	-£31	-£31	
M9	**Catch/cover crops in arable rotations**	0.3	*0.4*	£6,269	£130	£3,199	£3,199	*£4,341*
M10	**Grain legumes in crop rotations**	2.3	*2.2*	£358		£358	£358	
M11	**Reduced tillage**	0.1					N/A	
M12	**Integrating grass leys in arable rotation**	1.1	*0.5*		£383	£383	£383	
M13	**Precision fertiliser applications + avoiding excess N**						-£738	
	Precision fertiliser applications	1.1	*0.9*	-£107	-£1,436	-£771		*£940*
	Improving synthetic N use/ 'avoiding excess N'	0.4	*0.4*	£174	-£1,445	-£635		*£1,145*
M14	**Controlled release fertilisers**	1.9	*0.6*	£135		£135	£135	
M15	**Nitrification/urease inhibitors**	0.6	*0.1*		£590	£590	£590	
M16	**AD for heat and power**						-£110	
	AD (cattle manure + maize)	1.2	*0.7*	£169	-£177	-£4		*£245*
	250kW	0.2						
	500kW	0.0						
	1000kW	0.1						
	AD (pig manure + maize)	1.1	*0.6*		-£250	-£250		
	AD (pig + poultry manure, + maize)	1.0		-£19		-£19		
	AD (maize)	0.9		-£41		-£41		
M17	**Covering slurry stores with impermeable cover**	0.3	*0.2*		£20	£20	£20	
M18	**Alternative fuel farm machinery**						N/A	
M19	**Low carbon heating - dairies and greenhouses**						N/A	
M20	**On farm food waste reduction**						N/A	

A.2.0 Systems thinking and relevant interventions

Table 10 shows which of the short-listed interventions are most relevant to the key farming systems identified in Lampkin et al (2019).[68]

Table 10 Key farming systems and individual interventions driven by them

System	Description of system	Relevant interventions driven by system change
Conservation agriculture	A farming system that promotes minimum soil disturbance, maintenance of a permanent soil cover, (and diversification of plant species?)	• Reduced till • Cover crops in arable rotations • Grain legumes in crop rotations • Grass-legume mixtures in pasture • Integrating grass leys in arable rotations? • Keeping pH at optimum for plant growth (liming) • Precision fertiliser applications • Controlled release fertilisers • Nitrification/urease inhibitors
Organic farming	A farming system that aims to eliminate synthetic inputs (primarily artificial fertilizers, pesticides and antibiotics); maintain long-term soil health; and enhance on-farm biodiversity. *(N.B need to recognise that without demand reduction, reduced stocking densities can lead to GHG emission 'leakage', as production shifted elsewhere)*	• Grain legumes in crop rotations • Grass-legume mixtures in pasture • Keeping pH at optimum for plant growth (liming) • Cover crops in arable rotations • Integrating grass leys in arable rotations • Improving livestock health (but not via antibiotics)
Pasture-fed livestock production	Self-explanatory	• Improving livestock health • Livestock breeding • Grass-legume mixtures in pasture • Low carbon animal feed alternatives to imported soy

[68] Lampkin et al. (2019). *Delivering on Net Zero: Scottish Agriculture*.

System	Description of system	Relevant interventions driven by system change
Agroforestry	A farming system that combines trees and shrubs, livestock (and crop) production	• Improving livestock health • Low carbon animal feed alternatives to imported soy • Integrating grass leys in arable rotations • Reduced till

A.3.0 One-page summaries for each intervention

This Appendix provides a one-page summary for each intervention covering:

- an overview of the intervention and explanation of how it reduces GHG emissions;
- a discussion of its likely palatability and key barriers for farmers; and
- a short outline of non GHG related environmental co-benefits, such as benefits to biodiversity or water quality.

M1 - Feed additives for ruminants

National GHG abatement potential	Average cost of abatement ($£/tCO_2e$) based on literature	Farmer views on cost-benefit	Farmer views on likelihood of implementation	Key barriers
(Big hitter)	£78			• Ongoing cost • Further R&D required / on-farm risk • Lack of impartial advice • Applicability

What is it and how does it reduce GHG emissions?

Adding small quantities of specific additives (e.g. 3NOP, nitrate, seaweed, biochar) to ruminant feed can reduce methane production without substantially changing diet. Ruminants produce methane using bacteria to break down cellulose in the rumen. This produces both H_2 and CO_2 which other organisms (called archaea) combine to make methane. Various feed additives are able to influence the number and activity of the archaea, thus reducing methane production.

In previous reports, individual feed additives are usually considered as separate interventions. However, given they would broadly be applied in the same way, and achieve a similar outcome (although to varying extents), they have been grouped into a single intervention in this report. The two additives explored in the literature are nitrate and 3NOP. However, there are a number of emerging additives that our experts identified, including biochar and seaweed.

Palatability and key barriers

Farmers considered feed additives low palatability and it falls within the 'more challenging' cluster in Figure 3. Feed additives are an emerging science. Whilst the methane inhibiting effects of feed additives have been shown to be substantial in trials, the specific mechanisms with which they reduce emissions is still somewhat disputed. Consequently, the science is still unclear about what factors may increase or reduce the effects of these additives in different situations. Similarly, the impacts of these additives on yield and meat/milk composition are still unclear. Thus, farmers have no clarity as yet of the performance or consequences of different choices in their specific farm situation.

Furthermore, most ruminants in UK are pasture-fed and therefore adding feed additives to their diets is practically unsuitable if most feed is forage based and no mechanical mixing is done on farm allowing addition of feed additives. Finally, all additives will have a cost, albeit possibly minimal. However, whilst avoiding the loss of carbon to methane may improve the available energy and increase yields, it is also possible that methane suppression may have small negative effects on yield.

Environmental co-benefits

None significant.

M2 - Low cellulose diets for ruminants

National GHG abatement potential	Average cost of abatement (£/tCO_2e) based on literature	Farmer views on cost-benefit	Farmer views on likelihood of implementation	Key barriers
	£165			• Ongoing cost • Lack of knowledge • Risk of negative effect on livestock health

What is it and how does it reduce GHG emissions?

Cellulose is a major component of grass and other plants that make up the majority of ruminant diets. This measure refers to reducing the proportion of cellulose in ruminant diets by increasing starches, sugars and fats, either in feed rations or by modifying pasture composition.

Ruminants produce methane using bacteria to break down cellulose in the rumen. This produces both H_2 and CO_2 which other organisms (called archaea) combine to make methane. If ruminants are fed a lower proportion of cellulose, they will produce a lower quantity of methane. Some food components, such as fats, may also act as methane suppressing additives as well providing non-cellulose sources of energy.

Palatability and key barriers

Farmers considered low cellulose ruminant diets to be low palatability and therefor it falls within the ‘more challenging’ cluster in Figure 3. The key barriers to shifting ruminant diets are largely a matter of the potential negative effects on livestock health.

A key problem, currently much debated, stems from the impacts on animal health. Ruminants evolved to digest feed high in fibre. Thus feeding diets that are too low in fibre and too high in easily digestible alternative energy sources can have well known adverse effects on animal health and thus yields.

Furthermore, it is reasonable to assume that current practice is ‘efficient’ in the economic sense – i.e. close to lowest cost per unit output. It is therefore likely that any shift to a substantially different diet will be likely to have a net cost, perhaps through a reduction in yield.

Notwithstanding the cost, there is no clear guidance in the literature about what constitutes best practice in what circumstances.

Environmental co-benefits

None significant.

M3 - Low-carbon animal feed alternatives to imported soy

National GHG abatement potential	Average cost of abatement (£/tCO_2e) based on literature	Farmer views on cost-benefit	Farmer views on likelihood of implementation	Key barriers
(Big hitter)	N/A			• Not market ready • Lack of impartial advice • Ongoing cost

What is it and how does it reduce GHG emissions?

Production of grain-based animal feed, commonly soy due to its high protein content, has a huge climate impact, primarily from the Carbon Opportunity Cost of the land under cultivation. In particular, imported soy from Brazil is linked to Amazonian deforestation. Replacing soy with alternatives that have a lower land requirement could substantially reduce GHG emissions, particularly from the pig and poultry sectors.

There are currently three main low carbon animal feed alternatives, with varying impact. The first is **increasing the land use efficiency of growing soy/ or alternative protein rich pulses**. Pulses could be grown locally rather than imported but this will likely only reduce global deforestation if land use efficiency is increased. This increased efficiency could possibly be achieved by replacing non-grain legumes (e.g., clover) used as cover crops with grain legumes (relates to M10 – grain legumes in arable rotations). This might provide both the N fixation benefit and animal feed without displacing production. The second option is **insect larvae fed on food waste**. However, there is still some energy loss converting food waste to insect protein, and ultimately the aim is to reduce food waste (to release land for sequestration). The third option with potentially the highest impact is **microbial protein**. This can either be grown by feeding the microbes with CO_2 from flue gas, green hydrogen and nitrogen or by bacterial fermentation of plants using the Crassulacean Acid Metabolism (e.g. cacti) grown in semi-arid areas.

Palatability and key barriers

Despite having a relatively low perceived cost-benefit, this measure was still considered highly palatable by farmers. For the farmer there is generally no substantial operational change, although this is context specific. However, it is not clear what the cost of these alternatives would be. Furthermore, the alternatives are not yet market available. Insect protein fed on food waste is a proven technology, but it needs production development, and regulatory approval for use in the human food chain. Microbial proteins are still experimental and need further research before commercialising.

Environmental co-benefits

Substantially reducing the land needed to produce protein-rich animal feed would allow some of the most biodiverse regions of the world – e.g. the Amazon rainforest, to be conserved and even re-established.

M4 – Livestock breeding

National GHG abatement potential	Average cost of abatement (£/tCO_2e) based on literature	Farmer views on cost-benefit	Farmer views on likelihood of implementation	Key barriers
●	-£260	●	●	• Out of farmer control • Extent of farm-system change • Lack of knowledge

What is it and how does it reduce GHG emissions?

Livestock breeding is a particularly confusing intervention in the literature as different reports have divided it up in different ways. For the purposes of this report, we have taken livestock breeding to refer to reducing the emissions intensity per unit output. This may mean that emissions per animal remain the same but yield per animal increases. Equally, it may mean that emissions per animal decrease but yield per animal remains the same. The literature has only referred to breeding for cattle, but it may also be important for sheep and if we consider emissions from non-ruminant feed, then improving the feed conversion ratios of pigs and poultry may be significant. Reducing the amount of feed needed to produce a given output, reduces the emissions associated with producing that feed. This often also leads to higher growth rates, so reducing the number of animals that need to be kept. For ruminants, reducing the feed per unit of product can also reduce the direct methane production and the emissions from manure.

Palatability and key barriers

This measure is moderately palatable and just manages to fall within the 'easy wins' cluster in Figure 3. Genetic improvements to farmed livestock have been ongoing since the first domestications and the trend continues. Any improvements that save costs on inputs are attractive for farmers. However not all farmers are aware or have access to the latest developments. In fact, uptake of the 'best genetic material' for high yields and feed conversion ratios is only 20-25% in UK dairy sector, and still lower in the beef.[69] Additionally, breeding strategies have historically not focused on emission reduction per unit of product. There is no current incentive to do this, nor any agency whose mission it is to deliver low emission livestock lines. Emissions reduction as a breeding goal has a less clear benefit to farmers than increased yields or feed conversion ratios.

Environmental co-benefits

Reduction of the period of growth, and feed inputs, will free up land for natural regeneration and biodiversity.

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[69] Eory et al. (2020) *Non-CO2 abatement in the UK agricultural sector by 2050.*

M5 - Improving livestock health

National GHG abatement potential	Average cost of abatement (£/tCO_2e) based on literature	Farmer views on cost-benefit	Farmer views on likelihood of implementation	Key barriers
●	-£16	●	●	• Lack of knowledge • Ongoing and capital costs • No further improvements

What is it and how does it reduce GHG emissions?

Improving livestock health (e.g. by prophylactic health management, improved housing conditions and improved screening and monitoring) can help reduce emissions intensity per unit output by improving yields, feed conversion ratios and reducing mortality rates. Previous reports have only referred to cattle and sheep health, but if we consider emissions from non-ruminant feed, then improving the feed conversion ratios of pigs and poultry may also be significant.

According to Eory et al. (2015) the emissions intensity of ruminant meat and milk production is sensitive to changes in key production aspects, such as maternal fertility rates, mortality rates, milk yield, growth rates and feed conversion ratios.[70] All of these parameters are influenced by health status, so improving health status is expected to lead to reductions in emission intensity.

Palatability and key barriers

Farmers considered this intervention highly palatable, and it falls within the 'easy wins' cluster in Figure 3. In fact, most farmers are already thinking about this, and some indicated that they think there are no further improvements to be made. This suggests there may be a knowledge gap where they are not aware of new measures that they could implement to improve best practice. Furthermore, improving livestock health can be expensive and this increased cost may not always be outweighed by proportionally increased yields. The costs include be operating costs, both in terms of purchased inputs, and of time and labour, and frequently capital costs required to change systems to improve housing and allow routing screening and monitoring.

Environmental co-benefits

Generally improved animal welfare.

[70] Eory et al. (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.*

M6 - Increased milking frequency

National GHG abatement potential	Average cost of abatement (£/tCO_2e) based on literature	Farmer views on cost-benefit	Farmer views on likelihood of implementation	Key barriers
	-£866			• Lack of knowledge • Capital cost • Ongoing cost

What is it and how does it reduce GHG emissions?

Increasing milking frequency (e.g. from two to three times a day) can improve feed use efficiency (thus freeing up land from agriculture and reducing COC) and improve N utilisation (thus reducing N_2O emissions from excreta). This measure only applies to dairy cows.

Palatability and key barriers

Farmers considered this measure low palatability. (It does not fall within the 'more challenging cluster in in Figure 3 due to high cost-effectiveness to society (£/tCO_2e), but it is so low impact that it is considered a low priority anomaly).

Farmers were generally unclear of the science that supports increased milking frequency. They were also conscious of potentially substantially increased costs. If increased milking frequency is achieved via robots, then requires capital investment in expensive new machinery. If milking is done by hand, then increased frequency is an additional labour cost. It is unclear whether the additional milk yield and improved nitrogen use efficiency will outweigh the cost of extra labour.

Environmental co-benefits

Air and water quality benefits from reduced nitrogen excretion, as less NH_3 emissions and nitrate leaching.

M7 - Grass-legume mixtures in pasture

National GHG abatement potential	Average cost of abatement (£/tCO₂e) based on literature	Farmer views on cost-benefit	Farmer views on likelihood of implementation	Key barriers
	-£594			• Capital (/ongoing?) cost • Lack of knowledge/ advice

What is it and how does it reduce GHG emissions?

Legumes are a family of plants that can biologically fix nitrogen in their root nodules. Examples include clover, lucerne and tall fescue. The fixed nitrogen supports both the growth of the grass and the legume, reducing the need for nitrogen fertiliser (either organic or synthetic). Legumes use the nitrogen they fix to grow, but the surrounding grass does not immediately have access to it. When the legumes die and decompose the nitrogen is transferred to the soil and becomes accessible to the grass. In grass-legume mixtures with clover, the clover content begins to have a substantial effect above 20-30% of the sward (dry matter at an annual average).[71]

By reducing the need for N fertiliser and fixing nitrogen within the plant structure, legumes can reduce N_2O emissions. They can also reduce emissions associated with synthetic fertiliser production, although this is only true if they are reducing inputs of synthetic, not organic, fertiliser.

Palatability and key barriers

Farmers considered this measure highly palatable, and it falls within the ‘easy wins’ cluster in Figure 3. The costs associated with introducing or increasing legume content in grassland depend on whether the grassland is permanent or temporary. As well as additional seed costs, permanent grasslands would also require drilling every five years. However, integrating legumes into pasture can reduce fertiliser requirements. Additionally, it can be beneficial for both animal health and long-term soil health.

Environmental co-benefits

Reducing nitrogen fertiliser application will reduce nitrogen leaching into waterways, which will reduce eutrophication.

[71] Eory et al. (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.*

M8 - Keeping pH at an optimum for plant growth

National GHG abatement potential	Average cost of abatement (£/tCO_2e) based on literature	Farmer views on cost-benefit	Farmer views on likelihood of implementation	Key barriers
●	-£31	●	●	• Capital and ongoing cost

What is it and how does it reduce GHG emissions? If the pH of the soil is outside the optimum range for crop productivity, plant nitrogen use efficiency decreases and crop yield is reduced. This can reduce N_2O emissions from excess fertiliser application and release land from agriculture. It also reduces nitrogen fertiliser manufacturing emissions if fertiliser is synthetic.

If the pH is below the optimum range (5.5-7.0 for most crops), lime can be applied to the soil to increase the pH back to optimum levels and increase crop productivity. Generally, it is adequate to apply lime every four years, however, the amount and frequency of lime application depends on factors such as crop type, soil type, and current pH of the soil. The soil would have to be sampled and analysed to determine if liming would be beneficial.

There are some CO_2 emissions associated with the lime itself, arising from the fieldwork needed for the application as well as the extraction and transportation of the lime.

Palatability and key barriers

Farmers considered this measure to be relatively palatable and it falls within the 'easy wins' cluster in Figure 3. There is a substantial increased cost associated with lime purchase and spreading as often as is necessary (on average every four years). However, a potential reduction of fertiliser use and an increase in crop yield could counteract the extra costs associated with liming in the long-term.

Environmental co-benefits

Reducing excess N fertiliser application will reduce nitrogen leaching into waterways, which will reduce eutrophication. The potential increase in crop yield could release land from agriculture for natural regeneration.

M9 - Cover crops in arable rotations

National GHG abatement potential	Average cost of abatement (£/tCO_2e) based on literature	Farmer views on cost-benefit	Farmer views on likelihood of implementation	Key barriers
● (red)	£3,199	● (amber)	● (green)	• Need tailored advice • Ongoing cost

What is it and how does it reduce GHG emissions? Catch/cover crops are grown during fallow periods to maintain soil cover and reduce nitrogen leaching. The crops can be sown in late summer or early autumn after the harvest of arable crops in late summer and are not harvested to be sold. They provide protection to the soil over winter and are most applicable to light to medium textured free draining soils as these provide better germination and growth. Cover crops can absorb excess N left over in the soil from the previous crop thus minimising the risk of 'excess' nitrogen in the soil to turn into N_2O. If the cover crops are legumes, then they also reduce the need for N fertilisers in subsequent crop. If these fertilisers are synthetic, then there is the added benefit of reducing manufacturing emissions. Cover crops can also help build soil organic matter.

Cover crops also increase soil carbon sequestration as the crops are not harvested but ploughed into the soil when it is time for the spring crops to be sown.

Palatability and key barriers

Despite a relatively low perceived cost-benefit, farmers considered this highly likely to implement. It was considered an anomaly in Figure 3 due to a particularly low cost-effectiveness to society. Key barriers include the need for context specific, tailored advice and the cost of seeds for cover crops, planting and destruction.

Environmental co-benefits

Cover crops can reduce nitrogen leaching by 30-60% which will reduce eutrophication of the waterways.[72] Furthermore, cover crops also reduce the risk of soil erosion and can improve soil structure, which can support soil biodiversity.

[72] Eory et al. (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.*

M10 - Grain legumes in arable rotations

National GHG abatement potential	Average cost of abatement (£/tCO_2e) based on literature	Farmer views on cost-benefit	Farmer views on likelihood of implementation	Key barriers
	£358			• Capital cost • Farm system change • Applicability

What is it and how does it reduce GHG emissions?

Grain legumes are a plant within the legume family that simultaneously fix atmospheric nitrogen within their root nodules and produce a protein rich grain/bean which can be harvested. If sown into arable rotations they both reduce the need for nitrogen fertilisers and reduce soil erosion, whilst also producing a nutritious high-value crop. Examples of grain legumes include peas, broad beans, and lentils. The nitrogen fixing potential varies with the type of crop with beans fixing twice as much nitrogen than peas in a given area.

The GHG reduction benefit is through reduced fertiliser use. If these fertilisers are synthetic, then added benefit of reducing manufacturing emissions. There is also potential for this intervention to link into M3 – low carbon animal feed alternatives, although this is not included in the national GHG abatement potential estimate. Locally grown grain legumes can be used as an alternative to imported soy. However, this will only reduce the Carbon Opportunity Cost of animal feed if production of local grain legumes is matched by an increase in land use efficiency or reduction in demand. Without one of these, production of grain legumes may simply shift other production elsewhere. An increase in land use efficiency can be achieved by replacing non-grain legumes (e.g. clover) used as cover crops with grain legumes. This provides both the N fixation benefit and animal feed without displacing production.

Palatability and key barriers

Despite a moderate perceived cost-benefit, farmers considered this 'low likelihood of implementation'. A reduction in fertiliser use will reduce ongoing operational costs and grain legumes themselves are a high protein cash-crop. Farmers the extent of farm system change as a key barrier, with a potential change in harvest timing and change of product. They also noted that there may be a need to change harvesting machinery. There are also applicability challenges in that the type of soil will limit the type of legume that can be sown.

Environmental co-benefits

Reducing the use of N fertiliser will reduce nitrogen leaching into waterways, which will reduce eutrophication.

M11 - Reduced till

National GHG abatement potential	Average cost of abatement (£/tCO2e) based on literature	Farmer views on cost-benefit	Farmer views on likelihood of implementation	Key barriers
●	N/A	●	●	• Capital cost • Applicability • Weed management

What is it and how does it reduce GHG emissions?

This measure includes both minimum till and direct drilling. Minimum till refers to cultivation techniques that do not include deep inversion ploughing. Direct drilling has no prior cultivation and refers to drilling straight into stubble. Reducing soil disturbance can reduce CO_2 emissions from soil, can reduce nitrate leaching due to improved soil structure (by up to 20%),[73] and can reduce fuel use associated with cultivation.

Reduced/minimum tillage can increase carbon sequestration in the soil.[74] However, there are some concerns that zero-till farming may increase indirect N_2O emissions in waterlogged or poorly aerated soils.[75]

Palatability and key barriers

Farmers considered minimum till to be relatively low palatability. The key barrier is capital cost to purchase the new machinery required to implement such approaches. Additionally, reduced tillage does not suit all soil types and full direct drilling approaches are not suitable everywhere. Finally, weed management is key barrier as one of the key purposes of ploughing is to reduced weeds. Reduce tillage systems often require herbicides to kill weeds.

Environmental co-benefits

Benefits of good soil structure as a result of reduced tillage include improved water infiltration, and thus reduced flooding. Increased SOM may lead to enhanced soil microbial activity and biodiversity.

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[73] Lampkin et al. (2019). *Delivering on Net Zero: Scottish Agriculture*.
[74] Mangalassery et al. (2014). To what extent can zero tillage lead to a reduction in greenhouse gas emissions from temperate soils?. *Sci Rep* 4, 4586.
[75] Ibid

M12 - Integrating grass leys in arable rotations

National GHG abatement potential	Average cost of abatement (£/tCO_2e) based on literature	Farmer views on cost-benefit	Farmer views on likelihood of implementation	Key barriers
🔴	£383	🟡	🟡	• Short-term cost, long-term benefit

What is it and how does it reduce GHG emissions?

According to the Eory et al (2020), loss of soil organic matter (SOM), with corresponding negative effects on crop yield and CO_2 emission, is possible if arable-only rotations are practiced over the long-term. This measure relates to planting grass in fallow fields for a full year, as part of an arable rotation. Root residues help improve soil carbon and improve soil health with maintains yields in long-term. They can also improve soil N content reducing need for N fertilisers (reduce N_2O emissions from excess N and also manufacturing emissions if synthetic).

However, this analysis of GHG abatement potential does not include the effect of displacing the short-term loss of production to another site (leakage), possibly in another country and with potentially negative consequences. In the long term this measure may result in an overall increase in carbon stored in soils, and a reduction in emissions from applied fertilisers, but the net effect cannot be analysed without addressing the larger issue of leakage and the expansion of agricultural land into areas of high biodiversity and carbon storage value.

Palatability and key barriers

Farmers considered this measure to be low palatability, and it falls within the 'more challenging' category in Figure 3. A key issue is the short-term loss of production and subsequent loss of income. Many farmers are aware of the long-term benefit this measure can have for soil health but are reluctant to financially invest in this future. This is because farmers face a variety of risks and therefore their discount rates are high.

Environmental co-benefits

Possible local biodiversity benefits for invertebrates and small mammals and birds.

M13 - Precision fertiliser applications and avoiding excess N

National GHG abatement potential	Average cost of abatement (£/tCO_2e) based on literature	Farmer views on cost-benefit	Farmer views on likelihood of implementation	Key barriers
	-£738			• Capital cost • Lack of knowledge/ impartial advice

What is it and how does it reduce GHG emissions?

A farmer must consider the spatial (inter and intra field) and temporal fertiliser needs of a given crop and only apply the quantity of fertiliser required in that place at that time. This will reduce excess nitrogen inputs.[76] The granularity of these spatial and temporal needs will vary depending on the equipment available. High granularity may require remote sensing technology, in-field electronic sensors and spatial data management systems. Lower granularity will be based on soil sampling and weather forecasts (i.e. not applying fertiliser just before a rainstorm). Consequently, the extent of N-use reduction will also vary.

Reducing excess nitrogen inputs will reduce both direct nitrous oxide emissions from soil and the manufacturing emissions associated with synthetic fertiliser production (if the fertiliser being applied is synthetic rather than organic). There is also potential that such applications will increase crop yields, which can help to free up land from agriculture and make it available for sequestration measures.

Palatability and key barriers

Farmers considered this measure to be highly palatable and it falls within the 'easy wins' cluster in Figure 3. Nevertheless, whilst farmers generally recognise the long-term cost benefit from reduced fertiliser costs and potentially improved yields, the capital cost of monitoring equipment can be high. Farmers may not be in a position to make the investments needed. Furthermore, there will be some ongoing maintenance costs, potential subscription costs to data and software. However, farmers did not flag these as a particular issue.

Environmental co-benefits

Reducing excess nitrogen application will reduce nitrogen leaching into waterways, which will reduce eutrophication.

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[76] Vecchio et al. (2020). Adoption of precision farming tools: A context-related analysis. *Land Use Policy*, 94, p.104-481.

M14 - Controlled Release Fertilisers

National GHG abatement potential	Average cost of abatement (£/tCO_2e) based on literature	Farmer views on cost-benefit	Farmer views on likelihood of implementation	Key barriers
●	£135	●	●	• Ongoing costs • Lack of knowledge/ impartial advice

What is it and how does it reduce GHG emissions?

Controlled release fertilisers (CRF) are products that provide readily available nitrogen more slowly than conventional fertilisers (over a period of 2-6 months[77]). This is achieved by coating the fertiliser prill with a material that slowly breaks down, delaying the availability of the nitrogen (N) to crops and microbes with the intention of matching nutrient release with crop demand[78]. By slowing down the rate of dissolution of N fertiliser into the soil, there is less excess N available for nitrification and denitrification. Therefore, CRFs tend to reduce soil N_2O emissions (by up to 35%).[79] Furthermore, by increasing N use efficiency, CRFs reduce the emissions associated with synthetic N fertiliser production.

Palatability, cost-effectiveness and key barriers

Farmers considered CRFs relatively low palatability, and the measure falls within the 'more challenging' cluster in Figure 3. The key barrier identified by farmers was increased ongoing costs. CRFs are generally much more expensive than regular fertilisers and therefore although they may reduce the quantity of fertiliser needed, this benefit may be outweighed by the overall increase in cost. CRFs can, in theory, be applied in all situations where synthetic N fertilisers are already used. However, there are some situations where CRFs are not as effective. For example, as CRFs have reduced water solubility compared to regular fertilisers, they perform best on soil types where there is a higher water content, so the release of the fertiliser is slowed. Therefore, CRFs have less impact in well-drained soils.

Environmental co-benefits

Reducing excess nitrogen availability will reduce nitrogen leaching into waterways, which will reduce eutrophication.

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[77] Lampkin et al. (2019). *Delivering on Net Zero: Scottish Agriculture.*
[78] Eory et al. (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.*
[79] Ibid

M15 - Nitrification/urease inhibitors

National GHG abatement potential	Average cost of abatement (£/tCO_2e) based on literature	Farmer views on cost-benefit	Farmer views on likelihood of implementation	Key barriers
🔴	£590	🔴	🟡	• Lack of knowledge/ independent advice

What is it and how does it reduce GHG emissions?

Nitrification inhibitors decrease the activity of nitrifying bacteria and thus reduce conversion of ammonium to nitrate, which subsequently become denitrified to form N_2O. Urease inhibitors (used with urea fertilisers) delay the conversion of urea to ammonium carbonate which is subsequently converted to N_2O. Both of these inhibitors reduce direct N_2O emissions from soils. The soil N_2O emission factor has been shown to be reduced by 25% for nitrification inhibitors and 50% for urea inhibitors.[80]

Palatability, cost effectiveness, and key barriers

Farmers considered this measure to be low palatability and it falls within the 'more challenging' cluster in Figure 3. For nitrification inhibitors, there are concerns that NH_3 emissions (and therefore, some N_2O emissions) could be increased, which could outweigh the benefits associated with the inhibitors. Furthermore, some components in the synthetic fertiliser are already nitrates and the inhibitors would have no effect on the nitrification and leaching from these components. Farmers highlighted that there is not enough independent advice available to be confident about the cost-benefit to the farm.

Environmental co-benefits

Reducing excess nitrogen availability will reduce nitrogen leaching into waterways, which will reduce eutrophication.

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[80] Eory et al. (2020). Non-CO2 abatement in the UK agricultural sector by 2050. Scotland's Rural College.

M16 - Anaerobic Digestion for heat and power

National GHG abatement potential	Average cost of abatement (£/tCO_2e) based on literature	Farmer views on cost-benefit	Farmer views on likelihood of implementation	Key barriers
	-£110			• Capital cost • Involvement • Lack of knowledge

What is it and how does it reduce GHG emissions?

Anaerobic digestion (AD) of manures involves accelerated biological decomposition of the manure to biogas (a mixture of CO_2 and methane) which can then be used for energy generation. The biogas can be burnt to produce onsite heat or to produce electricity to feed into the electric grid, or the biogas can be upgraded and injected into the gas grid. In literature this intervention is often separated out by manure type (mainly cattle and pig), but for the purposes of this report we have grouped all together. The principal benefit of AD is the conversion of methane to CO_2, which reduces the global warming potential (GWP) by 97% (if assessed using GWP20).[81] Whilst displacing fossil fuels was historically a major benefit, as the electric grid decarbonises the GHG reduction benefit of this has become increasingly marginal. Furthermore, most AD plants leak methane. Although there is possibly a role for biomethane in the gas grid, in reality the ongoing costs (described below) from small AD plants is prohibitive. The consequence will likely be AD plants supplemented with energy crops (which may displace production) in order to make the scale viable.

Palatability and key barriers

Farmers considered AD to be low palatability and it falls within the ‘more challenging’ cluster in Figure 3. The main barrier to AD is capital and ongoing costs. AD plants require substantial infrastructure. Electricity grid connections are logistically challenging and expensive. For biomethane in the gas grid, the cost of clean-up, compression, transport and injection from small AD plants is generally prohibitive.

Environmental co-benefits

AD is an excellent way to recycle key nutrients, particularly nitrogen and phosphates.

[81] The GWP20 of methane is 86 on a kg/kg basis. Adjusting for the relative molecular weights of CO_2 and CH_4, the GWP20 of methane on a molar basis is 86*16/44 = 31.3. Thus burning 1kg of methane reduces the GWP by 1/31.3 = 3.2%. This equates to a 96.8% reduction.

M17 - Covering slurry stores with impermeable cover

National GHG abatement potential	Average cost of abatement (£/tCO_2e) based on literature	Farmer views on cost-benefit	Farmer views on likelihood of implementation	Key barriers
🔴	£20	🟠	🟠	• Capital cost • Lack of information

What is it and how does it reduce GHG emissions?

The measure involves covering slurry stores with an impermeable membrane to exclude oxygen. Animal manure decomposes to form a mixture of CO_2, N_2O and methane during storage. 80% of the GHG potential of emissions from manure storage comes from methane with the balance mostly from N_2O.[82] Reductions are difficult to quantify – with very few studies showing statistically significant data. Overall, it seems that covering slurry stores with impermeable cover can increase N_2O emissions but decrease methane emissions – but this seems to vary. Covering slurry stores reduces ammonia volatilisation and increased ammonia concentrations in the slurry can suppress methanogenesis. [83]

Palatability and key barriers

Farmers considered this measure low palatability, and it falls within the 'more challenging' cluster in Figure 3. The uncertainties in the data, and the cost and difficulty of ensuring reliable impermeable covering, is a notable barrier. Farmers highlighted that they were unclear how this measure helps reduce GHG emissions. Of the 22 studies reviewed by Kupper, only one (for pig manure) showed statistically significant reductions in methane emissions caused by covering.[84] Furthermore, there is a capital cost associated with implementation. In particular, older slurry stores that cannot support a roof so will these have to be decommissioned and a full new store with roof installed

Environmental co-benefits

Covering manure has a positive impact on ammonia emissions, and on odour.

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[82] Kupper et al. (2020) Ammonia and greenhouse gas emissions from slurry storage - A review. Agriculture, Ecosystems & Environment.
[83]Ziyi Yang et al. (2018). Effect of ammonia on methane production, methanogenesis pathway, microbial community and reactor performance under mesophilic and thermophilic conditions; Renewable Energy, Volume 125; Pages 915-925.
[84] Kupper et al. (2020) Ammonia and greenhouse gas emissions from slurry storage - A review. Agriculture, Ecosystems & Environment.

M18 - Alternative low carbon fuel farm machinery

National GHG abatement potential	Average cost of abatement (£/tCO_2e) based on literature	Farmer views on cost-benefit	Farmer views on likelihood of implementation	Key barriers
●	N/A	●	●	• Market availability. • Capital cost

What is it and how does it reduce GHG emissions?

This relates to machinery used for all on-farm operations, such as harvesting, preparing land, herding animals and so on. Low carbon machinery will most likely be electric, or potential hydrogen, powered. Eliminating fossil fuel use would reduce direct CO_2 emissions. The measure has a relatively low abatement potential as the vast majority of agricultural emissions come from nitrous oxide and methane emissions. There is a risk that shifts to biofuels (e.g., biomethane powered tractors) can cause bioenergy crop production to displace food production thus increase Carbon Opportunity Cost.

Palatability and key barriers

Farmers considered this measure moderately palatable with a low perceived cost-benefit. The two key barriers for this measure are capital costs and lack of market availability. The purchase of new machinery is a substantial financial investment for farmers and although this may lead to reduced cost of fuel consumption, farmers did not consider this to have a worthwhile investment. Although some small electric tractors are already emerging on the market, there is still substantial R&D needed to both develop new products and drive down production costs.

Environmental co-benefits

Some air quality benefits from reduced fossil fuel emissions.

M19 - Low carbon heating (dairies & greenhouses)

National GHG abatement potential	Average cost of abatement (£/tCO_2e) based on literature	Farmer views on cost-benefit	Farmer views on likelihood of implementation	Key barriers
●	N/A	●	●	• Capital cost

What is it and how does it reduce GHG emissions?

The majority of greenhouses use gas fired boilers to supply additional heat energy to maintain year-round production of seasonal produce. This measure relates to replacing fossil fuel use for heating greenhouses/dairies with low-carbon renewable heat alternatives, primarily heat pumps (which require electricity). Heat pumps can redirect waste heat from other processes (e.g. nearby wastewater treatment or combined heat and power plants).[85] If electricity used by heat pumps is obtained from the grid, then the emissions benefit of low carbon heating is dependent on the marginal fuel mix used to produce the electricity that would have been used. If located by CHP plant, waste CO_2 can be used to 'fertilise' plants in the greenhouse, thus increasing CO_2 absorption and yields.[86]

Palatability and key barriers

Farmers considered this measure moderately palatable. The primary barrier was the capital cost of purchasing and installing new equipment, however the reduction in ongoing fuel costs can be substantial.

Environmental co-benefits

Some air quality benefits from reduced fossil fuel emissions.

[85] Greencoat capital (2019) World-first low carbon greenhouses in boost for UK agriculture, available at https://www.greencoat-capital.com/news/2019/031019-greenhouses, accessed August 2021.
[86] Vermeule & van der Lans (2010). Combined heat and power (CHP) as a possible method for reduction of the CO2 footprint or organic greenhouse horticulture. *Acta Horticulturae*. 915.

M20 – On farm food waste reduction

National GHG abatement potential	Average cost of abatement (£/tCO_2e) based on literature	Farmer views on cost-benefit	Farmer views on likelihood of implementation	Key barriers
● (Big hitter)	N/A	●	●	• Consumer preferences • Regulations

What is it and how does it reduce GHG emissions?

On-farm food waste reduction will reduce some direct emissions associated with production, but the main benefit is releasing land from agriculture (i.e. reducing the COC). This COC is not accounted for in UK national emission estimates and thus the main benefit of reducing food waste will not be recognised by emission reduction targets. Nevertheless, this measure was considered highly impactful by the expert panel and its importance is outlined in a recent WWF report (although this looks at on-farm food waste a global, rather than UK, level).[87] A substantial amount of farm produce (particularly arable crops) is wasted because it does not meet food processor and retailer specification requirements. Farmers end up over-producing food to ensure they can meet contract demands within these specifications. Therefore, reducing on farm food waste is likely to require a substantial change to these requirements. Additional issues that contribute to on farm food waste include inability to store food and market price fluctuations (sometimes produce is too low value to be worth harvesting)

Palatability and key barriers

Farmers considered this measure highly palatable. All actors in the supply chains would like to add value to 'waste' food. However, constraints range from strong consumer preferences, through constraints on shelf real-estate in retail outlets, to supply chains optimised to handle uniform products. Some of the wastage may also be caused by falling outside the EU Marketing Standards, currently still in force in the UK, and which could now be relaxed. Barriers therefore include consumer preferences, retail shelf space, tight produce specification requirements, and variability of farmer skill and management.

Environmental co-benefits

Potential biodiversity increases as a result of freeing land from commercial use.

[87] WWF (2021) *Driven to Waste: The Global Impact of Food Loss and Waste on Farms.*

A.4.0 Key barriers identified for each intervention

The table below summarises barriers identified by farmers as discouraging uptake of the interventions listed. These are derived from the farmer workshops organised as part of this research (in black text) and from an expert discussion reflecting farmer views emerging from Defra research (in maroon text).

Table 11 Key barriers for each intervention identified in farmer workshops

Reference	Intervention	Barriers identified by farmers
M1	Feed additives for ruminants	• **Ongoing cost**: with no clear benefit for farmers • **Further R&D required / on-farm risk**: scientific information unclear as to which additives to use and what effects are on yields. Need further research before farm ready. Needs long term trials and concrete data of immediate and long-term effects. Farmers were once advised to put extra P into cattle diets but that was then debunked, need to ensure same doesn't happen for feed additives such as3NOP. • **Lack of impartial advice**: farmers feel 'at the mercy' of sales reps/nutritionists with vested interests - don't get an impartial opinion on which additives best to use. • **Applicability**: unsuitable for largely grass-fed systems as no "mixer wagon"
M2	Low cellulose diets for ruminants	• Not discussed. • Risk of negative effect on livestock health identified in literature

Reference	Intervention	Barriers identified by farmers
M3	Low-carbon animal feed alternatives to imported soy	• **Not market ready**: alternatives not yet readily available. • **Lack of impartial advice**: “Agribusiness/sales rep’s constantly ‘flogging’ soy, due to vested interests - hard to find impartial advice on alternatives and nutritional implications” • **Ongoing cost**: feed is usually biggest cost in pig and poultry farming and soy is cheap, alternatives likely more expensive. Farmers at mercy of market price volatility so hard to make ethical decisions on feed sourcing whilst staying competitive.
M4	Livestock breeding	• **Out of farmer control**: some farmers feel that they have little influence here instead relying on breed societies and breeding companies to drive this forward. • **Extent of farm-system change**: changing herds not practical, culturally may farm a specific breed. • **Lack of knowledge**: not always clear what is ‘the best breed’.
M5	Improving livestock health	• **No further improvements:** most farmers already think about this, and some farmers unsure that significant improvements can be made. • **Lack of knowledge:** the above point may be a knowledge issue because farmers may be unaware that there are in fact further improvements to be made.

Reference	Intervention	Barriers identified by farmers
M6	Increased milking frequency	• **Lack of knowledge**: farmers unclear of the science that supports increased milking frequency. • **Capital cost**: If this is achieved via robots, then requires expensive new machinery • **Ongoing cost**: if milking is done by hand, then increased frequency is an additional labour cost. Unclear if the additional milk yield/ improved N use efficiency will outweigh the cost of extra labour
M7	Grass-legume mixtures in pasture	• **Capital (/ongoing?) cost**: farmers aware of long-term soil benefits but cost of seed is short-term • **Lack of knowledge/ advice**: need context-specific advice
M8	Keeping pH at an optimum for plant growth	• **Capital cost**: many farmers are aware that their fields are below optimum pH, and they know they have to apply extra N to maintain yields. But liming is expensive and not linked to short-term benefit. Whereas the application of N provides an immediate yield benefit.
M9	Catch/cover crops in arable rotations	• **Further R&D and impartial advice**: need clear and independent information • **Applicability/ need tailored advice**: very context specific, need advice tailored to specific farm systems
M10	Grain legumes in crop rotations	• **Capital cost**: possibly need to change machinery? But pulses are a cash crop and reduce fertiliser costs in long-term • **Farm system change**: Change of harvest timing and change of product.

Reference	Intervention	Barriers identified by farmers
M11	Reduced tillage	• **Capital cost**: expensive outlay; requires investment in machinery • **Applicability**: does not suit all soil types and systems; full direct drilling approaches are not suitable everywhere
M12	Integrating grass leys in arable rotation	• **Short-term cost, long-term benefit:** short-term loss of productivity (grass leys planted for a full year), for long-term improved soil health, which helps maintain yields. Farmers aware of long-term benefit but the short-term cost is a key barrier.
M13	Precision fertiliser applications + avoiding excess N	• **Capital cost**: farmers aware of long-term benefit of reduced fertiliser costs but equipment is expensive; unlikely to buy sensor equipment but farmers may pay a contractor to bring equipment to assess their farm • **Lack of knowledge/ impartial advice**: unclear what this means in practice and how it can be implemented
M14	Controlled release fertilisers	• **Ongoing costs:** generally much more expensive than standard fertilisers • **Lack of knowledge/ impartial advice:** lack of independent information about which fertilisers to use and their benefit
M15	Nitrification/urease inhibitors	• **Lack of knowledge/independent advice**: not enough independent advice available to be confident about the cost benefit
M16	AD for heat and power	• Commonly no enthusiasm for AD from farmers • **Capital cost**: grid connections and equipment expensive • **Involvement**: ongoing management and involvement required • **Lack of knowledge**: complicated and need information about how to do it well – 'noddy's guide to AD'

Reference	Intervention	Barriers identified by farmers
M17	Covering slurry stores with impermeable cover	• **Capital cost:** Cost of doing this too high for some farms, but now a legal requirement. Some older slurry stores cannot support a roof so will have to be decommissioned and a full new store with roof installed • **Lack of information**: farmers are unclear on how this helps reduce GHGs.
M18	Alternative low carbon fuel farm machinery	• **Not market ready**: alternatives not yet readily available to replace current machinery • **Capital cost**: very expensive to purchase new farm machinery especially low carbon models, although farmers aware that ongoing fuel costs may be reduced
M19	Low carbon heating - dairies and greenhouses	• **Capital cost**: very expensive investment
M20	On farm food waste reduction	• **Specification requirements**: Requirements to reliably meet strict supermarket specifications in turn driven by consumer requirements