Non-CO_2 abatement in the UK agricultural sector by 2050

Summary report submitted to support the 6th carbon budget in the UK

December 2020

Eory, V., Maire, J., MacLeod, M., Sykes, A., Barnes, A., Rees, R.M., Topp, C.F.E., Wall, E.

Scotland's Rural College

SRUC

Prepared for the Committee on Climate Change

Table of Contents

Abbreviations

3NOP	3-nitrooxypropanol
CCC	Committee on Climate Change
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
GHG	Greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
MACC	Marginal abatement cost curve
N	Nitrogen
NH_3	Ammonia
N_2O	Nitrous oxide
NUE	Nitrogen use efficiency

1 Background

In 2019 the UK adopted a binding target to achieve Net Zero greenhouse gas (GHG) emissions by 2050. Accordingly, the 6th carbon budget, which is going to set the emission envelope for 2033-2037, needs to increase the ambition in every sector, including agriculture and land use.

Agricultural activities were responsible for 10% of total UK GHG emissions (45.4 of 451 $MtCO_2e$) in 2018, while forests and grasslands sequestered 27 $MtCO_2e$, and other land use activities released 17 $MtCO_2e$ emissions (Brown *et al.*, 2020)[1]. To achieve the Net Zero emission target, agriculture will need to reduce emissions from its production activities and increase its potential to sequester carbon, both directly, on agricultural land, and indirectly, via increasing its productivity and thus reducing demand for land.

For the 6th carbon budget, building on the land use scenarios developed by Thomson *et al.* (2018), the Committee on Climate Change established seven potential food consumption and production pathways, estimating the cropland and grassland areas and livestock numbers between 2020 and 2050. The aim of this study was to estimate the potential GHG mitigation achievable within the agricultural sector, given the change in agricultural activities (e.g. changes in cropland area, grassland area and livestock numbers). This report documents the methodology and the results, which were subsequently used to inform the CCC's 6th carbon budget advice.

[1] Based on the current Global Warming Potential values of AR4.

2 Methodology

To quantify the on-farm agricultural abatement potential the marginal abatement cost curve methodology (described in in Eory *et al.* (2015) and Eory *et al.* (2019)) was used, which aims to qunatify the mitigation and costs of farm practices, and calculates the cost-effectiveness of them as well as the cumulative GHG abatement (considering interactions between the mitigation measures). The analysis presented here converted the CH_4 and N_2O emissions using the GWP_{100} values with climate change feedback, i.e. 34 and 298, respectively (IPCC, 2013).

The abatement was estimated by applying possible mitigation measures on the predicted agricultural area and livestock numbers (activity scenarios) provided by the CCC. Therefore, the mitigation only considered the agricultural area, and did not include potential further abatement from any land released from agriculture.

The assumptions about the GHG effects and costs of the mitigation measures are based on the agricultural MACC for the 5th carbon budget (Eory *et al.*, 2015) and on the "Delivery of Clean Growth through Sustainable Intensification" project funded by Defra (due to finish in December 2020).

2.1 Agricultural activity scenarios

Changes in consumer and farmer behaviour can release land from agriculture. The CCC considered two broad groups of changes that could release land, while maintaining a strong food production sector to feed a population that increases in the UK to 73.6 million by 2050:

- Behavioural change: diet change and food waste reduction (considering population growth and constant trade).
- Improvements in agricultural practices: crop yield improvements, stocking densities and moving horticultural production indoors.

The CCC prepared five scenarios and two sensitivities, which varied the ambition of the each of the five land release measures outlined above (Table 1):

- The Balanced Net Zero Pathway represents the CCC's central scenario and is the basis of the CCC's advice for the level of the Sixth Carbon Budget.
- The 'exploratory scenarios' (Headwinds, Widespread Engagement and Widespread Innovation) reflect different levels of ambition on behavioural change or improvements in technology and productivity.
- A further exploratory scenario (Tailwinds) assumes considerable success on both innovation and societal / behavioural change.

- Two sensitivities were applied to the Headwinds scenario: declining crops yields and a very high level of diet change (implied by Public Health England's EatWell Guide).

The projected change in crop and livestock activity between 2020-2050 for the UK under each scenario (and sensitivity) is shown in Figure 1 and Figure 2. These changes in activity data imply a reduction in agricultural emissions in all scenarios.

Table 1 Agricultural activity scenarios by 2050

	Balanced Net Zero	Headwinds	Widespread Engagement	Widespread Innovation	Tailwinds	Crop sensitivity	Diet sensitivity
Diet change: livestock product replacement with plant-based food	35% all meat; 20% all dairy to plant-based	20% all meat; 20% all dairy to plant-based	50% all meat; 50% all dairy to plant-based	50% meat (30% switch to lab-grown meat, 20% to plant-based), 50% dairy products.	As in Widespread Innovation	As in Headwinds	80% all meat; 20% all dairy to plant-based
Food waste reduction	As in Innovation	50% by 2030 and constant to 2050	50% by 2030 70% by 2050	50% by 2030 60% by 2050	As in Engagement	As in Headwinds	As in Headwinds
Average wheat yield[2] (t DM ha^{-1})	As in Headwinds	11.0	11.0	13.0	As in Innovation	6.0	As in Headwinds
Indoor horticulture	As in Headwinds	10% of production indoors	10% of production indoors	50% of production indoors	As in Innovation	As in Headwinds	As in Headwinds
Grazing intensity	As in Headwinds	Decrease livestock in upland grazing areas by redistributing to other grassland, with an overall increase in the stocking rate on the remaining grassland of 10% (medium ambition)	Decrease livestock in upland grazing areas by redistributing to other grassland, with an overall increase in the stocking rate on the remaining grassland of 5% (low ambition)	Increase in stocking density across all grassland, with an additional 10% increase in the stocking density of the reduced area of upland grassland, and a 10% increase in stocking density on improved grassland (high ambition)	As in Innovation	As in Headwinds	As in Headwinds
Dairy productivity increase	As in Headwinds	0.6% y^{-1} 2020-2050	0.6% y^{-1} 2020-2050	2.9% y^{-1} 2020-2030, 0.6% y^{-1} 2030-2050	As in Innovation	As in Headwinds	As in Headwinds
Other livestock productivity	No change	No change	No change	No change	No change	No change	No change

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

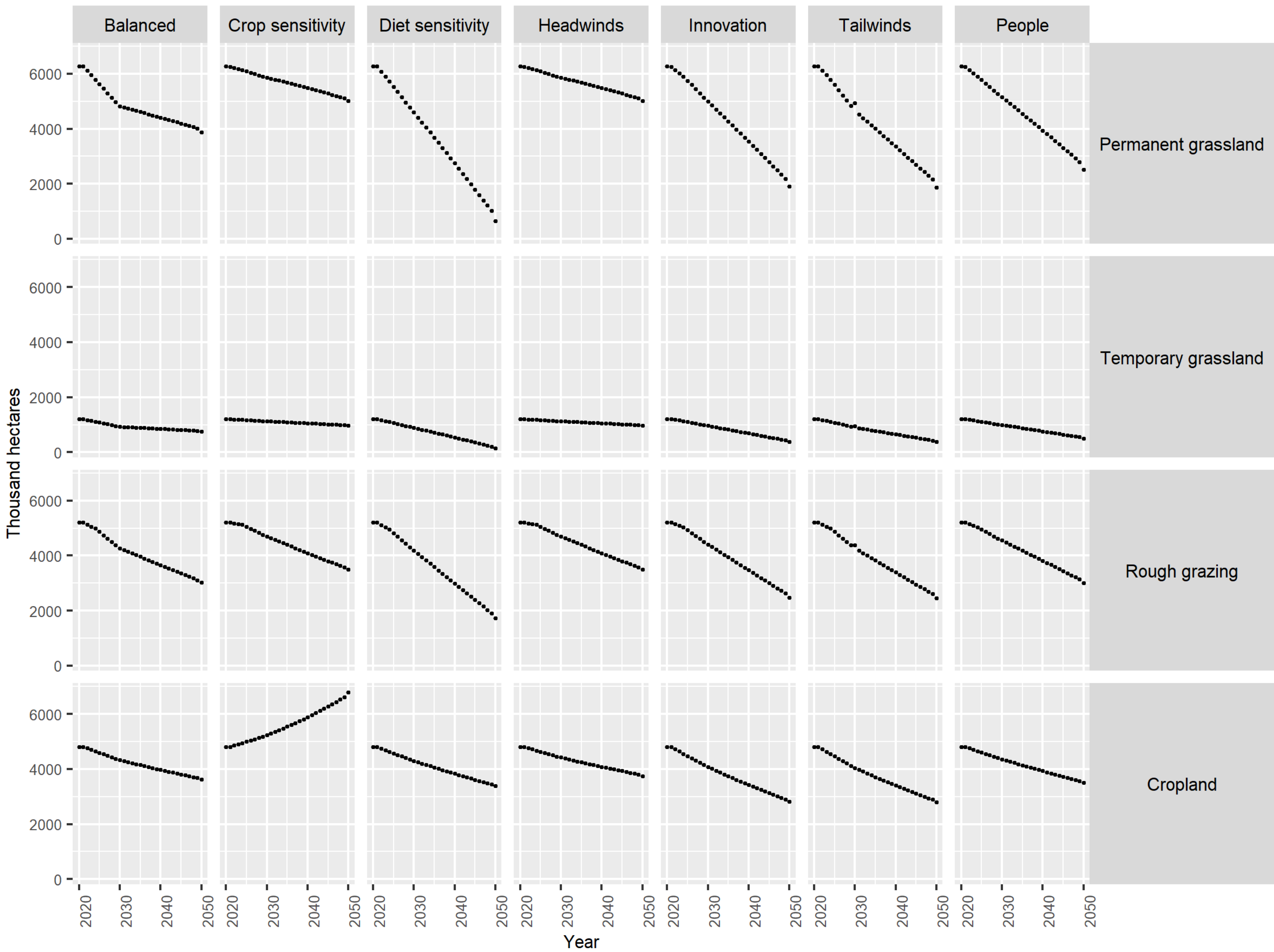

Figure 1 Crop and grass areas according to the activity scenarios in the UK

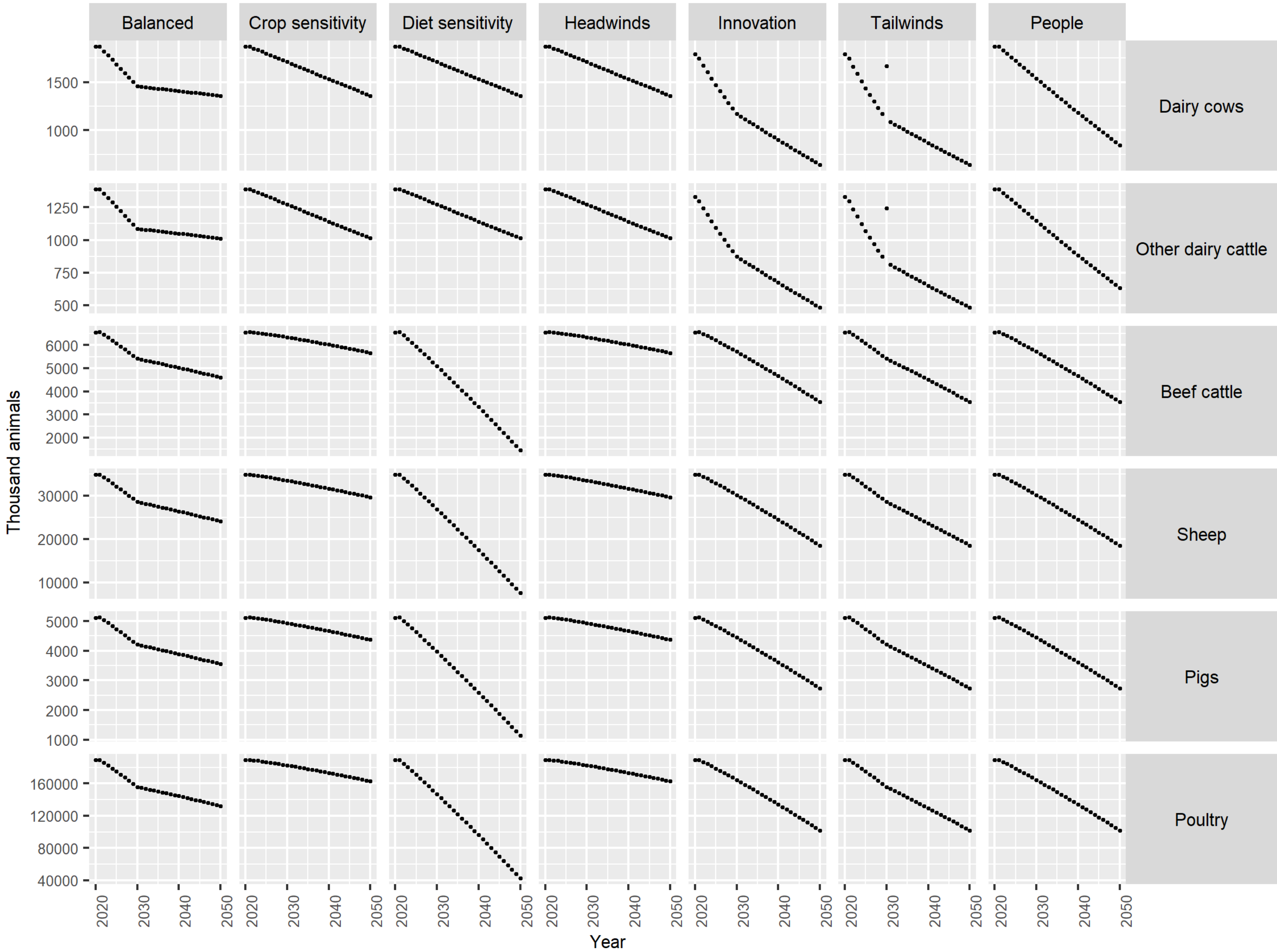

Figure 2 Livestock numbers according to the activity scenarios in the UK

2.2 Mitigation measures

Thirty-one mitigation measures were selected for this study, based on the Delivery of Clean Growth through Sustainable Intensification project (Table 2). However, not all of them were applied to every agricultural activity scenario.

Table 2 Mitigation measures selected for analysis in this report

ID	Mitigation measure
MM1	Improved crop varieties
MM2	Catch/cover crops
MM3	Keeping pH at an optimum for plant growth (e.g. liming)
MM5	Biostimulants
MM7	Crop health
MM8	Integrating grass leys in rotation
MM10	Precision farming
MM11	Avoiding N excess
MM12	Nitrification inhibitors
MM15	Analyse manure prior to application
MM16	Improving/renovating land drainage on mineral soils
MM18	Take stock off from wet ground
MM20	Biological N fixation (grass-legume mixtures)
MM21	Higher sugar content grasses
MM22	Anaerobic digestion of cattle manure
MM23	Methane capture and combustion
MM25	Covering slurry with permeable plastic cover
MM26	Breeding with genomics - current breeding goal
MM27	Breeding with genomics - lower emissions intensity breeding goal
MM28	Gene modified cattle for reducing enteric methane emissions
MM29	Higher uptake of current genetic improvement practices
MM30	Better health planning for cattle
MM31	High starch diet for dairy cows
MM32	Precision feeding
MM35	3NOP as feed additive
MM37	Increased milking frequency
MM45	Nitrate as feed additive
MM46	Slurry acidification
MM47	Covering slurry with impermeable plastic cover
MM48	Better health planning for sheep
MM49	Anaerobic digestion of pig manure

The activity scenarios in Table 1 have already assumed certain improvements in agricultural practice without specific description of changing practices. In reality such increases in yield are likely to result from the adoption of GHG mitigation practices which focus on productivity changes. Applying all the mitigation measures for these scenarios would have resulted in double counting of possible improvements and thus GHG mitigation. Therefore those mitigation measures which cumulatively resulted in a comparable yield change as assumed in the scenario were excluded from the analysis (Table 3).

Table 3 Mitigation measures included in the scenarios (empty cells indicates that the measure is not included in the scenario)

ID	Headwinds	Widespread Engagement	Widespread Innovation	Crop sensitivity	Diet sensitivity	Balanced Pathway	Tailwinds
MM1				Yes			
MM2	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MM3				Yes			
MM5				Yes			
MM7				Yes			
MM8	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MM10				Yes			
MM11				Yes			
MM12	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MM15	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MM16				Yes			
MM18	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MM20	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MM21	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MM22	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MM23	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MM25	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MM26	Yes	Yes		Yes	Yes	Yes	
MM27	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MM28	Yes		Yes	Yes	Yes	Yes	Yes
MM29	Yes	Yes		Yes	Yes	Yes	
MM30	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MM31	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MM32	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MM35	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MM37	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MM45	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MM46	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MM47	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MM48	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MM49	Yes	Yes	Yes	Yes	Yes	Yes	Yes

The uptake rates were provided by the CCC for each scenario and mitigation measure, as shown in Table 4.

Table 4 Uptake rates (proportion of the area/livestock where the measure is applicable)

ID	Headwinds	Widespread Engagement	Widespread Innovation	Crop sensitivity	Diet sensitivity	Balanced Pathway	Tailwinds
MM1	0.5	0.5	0.6	0.5	0.5	0.5	0.6
MM2	0.75	0.8	0.75	0.75	0.75	0.75	0.8
MM3	0.75	0.8	0.75	0.75	0.75	0.75	0.8
MM5	0.6	0.6	0.75	0.6	0.6	0.6	0.75
MM7	0.6	0.75	0.6	0.6	0.6	0.6	0.75
MM8	0.5	0.5	0.6	0.5	0.5	0.5	0.6
MM10	0.6	0.6	0.75	0.6	0.6	0.6	0.75
MM11	0.75	0.8	0.75	0.75	0.75	0.75	0.8
MM12	0.6	0.6	0.75	0.6	0.6	0.6	0.75
MM15	0.6	0.75	0.6	0.6	0.6	0.6	0.75
MM16	0.5	0.5	0.6	0.5	0.5	0.5	0.6
MM18	0.75	0.8	0.75	0.75	0.75	0.75	0.8
MM20	0.75	0.8	0.75	0.75	0.75	0.75	0.8
MM21	0.75	0.8	0.75	0.75	0.75	0.75	0.8
MM22	0.6	0.6	0.75	0.6	0.6	0.6	0.75
MM23	0.5	0.5	0.6	0.5	0.5	0.5	0.6
MM25	0.75	0.8	0.75	0.75	0.75	0.75	0.8
MM26	0.5	0.5	0.6	0.5	0.5	0.5	0.6
MM27	0.6	0.6	0.75	0.6	0.6	0.6	0.75
MM28	0.5	0.5	0.6	0.5	0.5	0.5	0.6
MM29	0.5	0.5	0.6	0.5	0.5	0.5	0.6
MM30	0.6	0.75	0.6	0.6	0.6	0.6	0.75
MM31	0.75	0.8	0.75	0.75	0.75	0.75	0.8
MM32	0.75	0.75	0.8	0.75	0.75	0.75	0.8
MM35	0.5	0.5	0.6	0.5	0.5	0.5	0.6
MM37	0.6	0.6	0.75	0.6	0.6	0.6	0.75
MM45	0.6	0.6	0.75	0.6	0.6	0.6	0.75
MM46	0.5	0.5	0.6	0.5	0.5	0.5	0.6
MM47	0.75	0.8	0.75	0.75	0.75	0.75	0.8
MM48	0.6	0.75	0.6	0.6	0.6	0.6	0.75
MM49	0.6	0.6	0.75	0.6	0.6	0.6	0.75

As the mitigation measures differ in their readiness for deployment (i.e. when could the farmers start using the measure) and also in how fast policies might be able to achieve the targeted uptake, the uptake pathway of each measure was defined considering these aspects Table 5.

Table 5 Deployment and full policy implementation time

ID	Full policy implementation time (years from start of deployment)	Start of deployment (years from 2020)
MM1	10	10
MM2	5	2
MM3	10	2

ID	Full policy implementation time (years from start of deployment)	Start of deployment (years from 2020)
MM5	10	10
MM7	10	2
MM8	10	2
MM10	10	2
MM11	5	2
MM12	10	2
MM15	5	2
MM16	10	2
MM18	10	2
MM20	10	2
MM21	5	2
MM22	10	2
MM23	10	10
MM25	5	2
MM26	10	2
MM27	10	10
MM28	10	20
MM29	10	2
MM30	10	2
MM31	5	2
MM32	5	2
MM35	10	5
MM37	10	2
MM45	10	5
MM46	10	5
MM47	5	2
MM48	10	2
MM49	10	2

2.2.1 Improved crop varieties

Improving the efficiency of crops to utilise the N fertiliser is key in mitigating N_2O emissions as well as reducing the economic loss as unrecovered nitrogen. Nitrogen use efficiency (NUE) can be defined as yield per unit of N available to the crop (Moll *et al.*, 1982). Barraclough *et al.* (2010) demonstrated that season and N input had a significant effect on NUE, but crop variety choice also contributed to NUE variation. It has been proposed that NUE can be improved both via adopting improved crop, soil and fertiliser management practices and through plant breeding (Barraclough *et al.*, 2010; Hawkesford, 2014; Hawkesford, 2017; Sylvester-Bradley and Kindred, 2009). The latter is possible as NUE varies between plants and some of this variation is linked to phenotypic traits and genotypic markers (Bingham *et al.*, 2012). This variation can be as much as three-fold (from 27 to 77 kg DM (kg N)$^{-1}$), as Barraclough et al. (Barraclough *et al.*, 2010) found in wheat varieties from four different countries in Europe.

Despite the yield plateau of the last two decades (Knight *et al.*, 2012), experimental results show that there has been a continuous improvement in NUE in the past decades. The economics of grain price and fertiliser costs are two potential causes of the yield plateau, resulting in stagnating N applications in the past two decades for newer varieties which require higher N rates to manifest their full yield improvement (Knight *et al.*, 2012). This suggests that the improvement might continue as a baseline in the future, and there is scope to accelerate these gains. The assumption in this report is that these improvements can be achieved faster and adopted on larger growing areas, given increased incentives to breeding companies, research and farmers to develop and adopt such cultivars. The measure considers three major crops in the UK: wheat, barley and oilseed rape.

In this modelling the yield improvement is converted to a reduction in N application to keep the land area constant. The annual, cumulative N reduction is -0.13%, and the cost of the measure is a 10% increase in seed price.

2.2.2 Cover crops

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

The GHG effects are modelled as 1.06 t CO_2e ha^{-1} y^{-1} C sequestration and 45% reduction in nitrogen leaching. Annual maintenance costs are seed purchase, and cover crop planting and destruction (net annual cost estimated to be £139 ha^{-1} y^{-1}).

2.2.3 Keeping an optimal pH (liming)

Good management of soil acidity (soil pH) is essential for optimal crop productivity. Most crops are more productive in soils with a pH between 5.5 to 7.0. Outside of this range productivity decreases and the utilisation of nutrients added – including nitrogen fertilisers – becomes less efficient. Additionally, in more acid soils there is a higher ratio of N_2O:dinitrogen emission (Liu *et al.*, 2014). Thus, in soils that have a tendency to produce N_2O by denitrification, more acid conditions are likely to lead to a higher N_2O emissions (Goulding, 2016; Šimek *et al.*, 1999; Zhu *et al.*, 2019). Evidence suggests that lime application may, modify soil microbial communities (Goulding, 2016) and increase organic matter inputs (Fornara *et al.*, 2011; Jokubauskaite *et al.*, 2016) with the effect of increasing soil carbon stocks (SOC) (Fornara *et al.*, 2011; Li *et al.*, 2019).

Liming has an impact on CO_2 emissions, most notably pre-farm emissions arising from the extraction and transportation of lime, and direct CO_2 emissions from fieldwork. In some circumstances, the inorganic C in lime ($CaCO_3$) may remain in long-term storage (Fornara *et al.*, 2011; Hamilton *et al.*, 2007), though lime application is typically considered a direct net source of C (IPCC, 2006).

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

Modelling pH management was achieved by increasing the yield in response to lime application by 6.22%, assuming 766 kg CO_2e ha^{-1} y^{-1} of carbon sequestration and 215.70 kg CO_2e ha^{-1} y^{-1} CO_2 emissions derived directly from the lime application. The estimated cost of lime purchase and spreading is £92.3 ha^{-1} in every five years.

2.2.4 Biostimulants

Biostimulants are microorganism(s) and/or substance(s) which can stimulate the plants' natural processes to enhance nutrient uptake, nutrient efficiency, tolerance to abiotic stress, and crop quality (Colantoni *et al.*, 2017). The range is these microorganisms and substances are very wide, and their mechanism of action can differ greatly. The AHDB biostimulant report lists eleven groups of biostimulants, from seaweed extracts through noon-pathogenic fungi to protozoa and nematodes, also including very wide groups like "complex organic materials" (Storer *et al.*, 2016). Biostimulants have been used in horticultural production and, sporadically, in cereal and oilseed production.

Due to the huge variety of different types of biostimulants and the scarcity of studies on their GHG effects it is not be possible to provide an overall conclusion of the effect of biostimulant use on the GHG emissions arising from crop production. Therefore, a typical effect of biostimulant in the yield of crops in cool and temperate climate was estimated based on available literature. Field experiments on cereals in cool and temperate regions found that the yield with biostimulants is 73%-233% of untreated crops (Al-Karaki *et al.*, 2004; Çakmakçi *et al.*, 2007; Clarke and Mosse, 1981; Cozzolino *et al.*, 2013; Dunstone *et al.*, 1988; Freepons, 1996; Kettlewell *et al.*, 2010; Khaliq and Sanders, 2000; Mohamed, 2012; Ögüt *et al.*, 2005; Roques *et al.*, 2012; Storer *et al.*, 2016;

Taylor *et al.*, 1990; Travaglia *et al.*, 2010; Wang *et al.*, 2015; Weerasinghe *et al.*, 2016; Xudan, 1986; Zhang *et al.*, 2016). As a cautious assumption in the current analysis 5% yield increase was assumed with a parallel reduction in the soil N_2O emissions of (EF_1) 1%. The cost was modelled as £0.12 ha^{-1} (0.1 kg ha^{-1} application at a price of £1,200 t^{-1}).

2.2.5 Improving crop health

Pests and pathogens cause reduce the crop's ability to intercept radiation and the efficiency of the plant of producing dry matter from the radiation (Johnson, 1987). With climate change these problems are believed to increase across Europe (Olesen *et al.*, 2011) and specifically in the UK (Cannon, 1998; Evans *et al.*, 2007; Madgwick *et al.*, 2011). Eventually, pests and pathogens cause yield quality and/or quantity loss, leading to higher GHG emissions and land use requirements to achieve the same yield. A combination of plant breeding for disease resistance and physical, biological and chemical control is used to combat pests and diseases.

Crop health improvement consists of multiple prevention actions applicable to the variety of crops. As a detailed approach focusing on individual agents and control mechanisms was not within the scope of this work, a top-down estimate for cereal production is derived from yield gap studies. In North-West Europe approximately 25% of the attainable wheat yield would be lost without controlling animal pests, pathogens and viruses, and the actual loss is 6%, i.e. 75% of the losses are prevented, while for potato the loss prevention is 53% efficient (Oerke, 2006). If control practices could improve the control efficiency by another 12.5% for wheat, then the yield gap would decrease to 3%, creating a yield increase of 3.2% compared to actual yield. In the modelling a 3% yield increase is assumed across crops.

Evidence on the marginal benefits of pesticides on crop productivity and farm profitability are contradictory; some authors suggesting that current level of pesticide application is essential for maintaining crop production and profitability (Cooper and Dobson, 2007; Jess *et al.*, 2014). Other authors argue that pesticide use can be decreased on a large proportion of farms without adverse effects on crop production (Lechenet *et al.*, 2017). Integrated pest management (IPM) can provide alternatives and complements to pesticide use, increasing plant health status (Hillocks, 2012), but there are costs associated with IPM too. Emerging remote sensing and variable rate application technologies also suggest that improvement in targeting crop protection can be expected over the coming decades from the increasing use of precision farming solutions. Given this mixed evidence, we cannot assume that a substantial increase in plant protection costs is needed to achieve a higher level of control. As an approximation, a 5% increase in plant protection costs is considered here.

2.2.6 Integrating grass leys in rotations

The introduction of perennial plants, including grass leys, into an arable crop rotation can increase the positive effects of rotation practices (Gentile *et al.*, 2005; Prade *et al.*, 2017). 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 (Prade *et al.*, 2017). Diversification of arable cropping systems with grass leys serves to increase the quantity and continuity of below-ground residue returned to the soil (Fu *et al.*, 2017; West and Post, 2002). This in turn can support microbial activity and diversity, and ensures continuity of root-derived C inputs to soil, increasing soil organic matter (SOM). A key issue in the integration of grass leys into arable rotations is loss of crop production (Maillard *et al.*, 2018).

In this study we assumed that there is no net change in the grassland and arable land area, but by relocation a maximum of 10% of the temporary grassland area can be integrated into a 4-year arable rotation (combining with 3 times larger arable area). The carbon sequestration gained on the land which was arable before is 202 kg CO_2e y^{-1} and the yield increased by 0.12% y^{-1}, incurring a financial loss of £94.25 ha^{-1} y^{-1} due to the loss in gross margin.

2.2.7 Precision farming

Precision farming, as applied to crop production, is a wide group of rapidly developing technologies enabling the farmer to respond to inter- and intra-field and temporal variability in crop needs when applying inputs (e.g. seed, fertiliser, water, pesticides), increasing input use efficiency (Aubert *et al.*, 2012; Diacono *et al.*, 2013).

Precision farming technologies belong to three broad categories: guidance, recording and reacting technologies (Schwartz *et al.*, 2010). Guidance technologies (e.g. controlled traffic farming, machine guidance) help to make machinery movement more precise, recording technologies (e.g. soil mapping, canopy sensing) collect information from the field before, during or after the growing period and reacting technologies turn the recorded data into decisions guiding the input applications (e.g. variable rate irrigation, variable rate pesticide application) (Balafoutis *et al.*, 2017). Precision farming can reduce GHG emissions and GHG emission intensity of crop production in multiple ways: increasing yield with while reducing N fertiliser application, reducing tillage and thus increasing soil carbon sequestration, reducing fuel consumption and reducing other inputs to field operations (impacting off-farm emissions) (Balafoutis *et al.*, 2017).

As the complexity and range of possible system specifications is large and the evidence on the environmental performance of the various systems is only sporadic, a specific combination of technologies is selected for further evaluation which is likely to have the biggest impact on GHG emissions machine guidance with variable rate nitrogen application (Balafoutis *et al.*, 2017). These systems can be used both for crop and grass production (Berry *et al.*, 2017). Based on previous estimates (Eory *et al.*, 2015), the implementation of a medium accuracy system, capable of 10 cm accuracy, is assumed (including auto-steering, yield mapping and variable rate nitrogen application).

Experimental evidence on the N fertiliser use and yield effect shows a large variation, between -57% and +1% and -2% to 10%, respectively (Ehlert *et al.*, 2004; Link *et al.*, 2008; Mantovani *et al.*, 2011; Welsh *et al.*, 2003a; Welsh *et al.*, 2003b). Most potato and wheat farmers in the UK perceived a -5% - +5% effect of the technology on N fertiliser and fuel use, and a 5-10% increase in wheat yield (Barnes *et al.*, 2017). When modelling the effects in this report the N use was assumed to be 5% lower, the yield 7.5% higher, and fuel use 3% lower.

In England 2-22% of farms use precision farming technologies and 16% use variable rate application, though only 11% uses yield mapping (Defra, 2013). The implementation rates are higher for cereal and cropping farms, lower for dairy and mixed farms and lowest for pigs and poultry and cattle farms. With expected advances in the technology and concurrent reduction in the cos of the technology the uptake is assumed to reach 50% on arable areas and 20% on improved grassland by 2050 without specific policy support.

The financial implications consist of the capital and maintenance cost of the equipment, the subscription costs to data providers and software costs. Savings can be expected from reduction in fertiliser and fuel use, and income can increase from improved yield quantity and quality. Further gross margin impacts can include a change labour requirement. The cost calculations are based on assuming an average farm size of 120 ha (the capital costs were not assumed to change with the farm size as precision farming operations can be done by contractors). The capital costs consist of the cost difference for auto-steer (£5,000 every 5 years), and yield monitor (£5,000 every 15 years), with 5% maintenance costs. Training costs are £750 every 5 years. The signal and data costs are £250 y^{-1}, and reduced overlaps decrease variable costs by 3%.

2.2.8 Avoiding nitrogen excess

Crops' yield response to fertilisation is sharply increasing at low fertilisation rates, but as fertilisation rate increases the additional gain in yield diminishes. At the economic optimum the cost of the additional N fertiliser results in the same amount of additional income from the sales of the product (AHDB, 2019). The yield response depends on a variety of well predictable and less predictable factors (e.g. crop variety, plant-available N content of the fertiliser and soil, soil pH, growth conditions during the season, pests and diseases). Most farmers use decision rules and tools to optimise their fertiliser use (Beegle *et al.*, 2000; Defra, 2018a). Nevertheless farmers might keep an over-application margin as a protection from potential yield penalties which could happen with better than expected growing conditions. Under fertilisation might also happen, resulting in suboptimal utilisation of land, though this measure considers only over fertilisation.

The measure requires farmers planning their fertiliser needs based on a recommendation system, considering field and crop characteristics (i.e. creating and using a nutrient management plan). The abatement arises from the reduced synthetic N application, combining savings both in organic and synthetic N use.

Though in reality the relationship between N rate and N_2O emissions is not linear (Cardenas *et al.*, 2019), the modelling in this study use a linear relationship. The reduction in the N use is estimated to be 10% of the applied synthetic N, based on similar past studies (ADAS, 2017; Eory *et al.*, 2015; MacLeod *et al.*, 2010; Pellerin *et al.*, 2013).

The cost of the measure is estimated as the cost of creating a nutrient and manure management plan (£560 for an 80 ha farm) and its annual update (£100) with the help of a farm advisor. Soil sampling, which is required to the plan, is £14 per sample, on average one to be taken from every 4 ha (SAC, 2014) in every 5 years (Soil Associaton, 2018). Additionally, the savings in N costs are also included in the calculations.

Given the lack of direct information over fertilisation in the UK, the uptake of the measure is approximated by the existence and use of nutrient management plans and manure management plans as reported for England and Wales (Defra, 2018a). 78% of the farm area has nutrient management plans and 78% has manure management plans in England and Wales across farm types (where it is applicable). Of those having a nutrient management plan 5% never uses it, so the current uptake can be estimated as 73%.

2.2.9 Nitrification inhibitors

Nitrification inhibitors depress the activity of nitrifying bacteria, improving the availability of nitrogen fertiliser to the plant, reducing N_2O emissions and nitrate leaching in high rainfall areas (Akiyama *et al.*, 2010), though in some cases they can increase ammonia (and hence indirect N_2O) emissions (Lam *et al.*, 2017). Various compounds have been identified as nitrification inhibitors, probably the most widely studied ones are dicyandiamide (DCD), 3,4-dimethyl pyrazole phosphate (DMPP) and nitrapyrin. Furthermore, urea based fertilisers have a high rate of ammonia volatilisation when applied to soils, due to the urease enzyme released by soil bacteria. This leads not only to ammonia (and indirect N_2O) emissions, but reduces the N plants can utilise. Urease inhibitors delay urea hydrolysis to ammonia, reducing ammonia emissions (Harty *et al.*, 2016). Using urea in combination with urease inhibitors and nitrification inhibitors can therefore further reduce N_2O emissions.

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

In our analysis, we considered the application of nitrification inhibitors with ammonium nitrate fertiliser and nitrification and urease inhibitors with urea applications, and expressed the effect as a change in the soil N_2O emission factor (ammonium nitrate and urea EF_1 reduced by 25% and 50%, respectively). The cost of the inhibitor is estimated at £0.1 (kg N)$^{-1}$.

2.2.10 Analyse manure prior to application

In terms of reducing GHGs, the purpose of analysing the manure prior to application is to ensure that the N applied to the crop as organic and inorganic N matches the requirement of the crop. An accurate assessment of the N available from the manure means that the potential for losses of N from the system is minimised. This requires that samples are taken and sent for analysis shortly before application as the period of storage of the manure can affect the N content.

The measure is applicable to all farmers who are applying manure to their land, which is approximately 30% of the sown area (Defra, 2018b). This applicability is applied universally across all crops. Solid manures and slurry account for 66% and 32% of the manure applied (Defra, 2018b). It is assumed that this measure does not apply to solid manures that are applied to winter crops.

The mitigation is expressed as a reduction in the synthetic N used (-5.5 kg ha^{-1} y^{-1}), as more organic N is utilised. The manure analysis is estimated to cost £0.5 ha^{-1} y^{-1}, based on two manure analysis (spring and summer, £15 each, on a farm area of 60ha). The current uptake is assumed to be 23%.

2.2.11 Improving/renovating land drainage on mineral soils

Drainage prevents soil waterlogging, reducing the risk of structural damage and poaching occurring on mineral soils (Lilly *et al.*, 2012). Well drained soils tend to have lower N_2O emissions as a result of changes in nitrification and denitrification processes (Bouwman *et al.*, 2002; Dobbie and Smith, 2006; Krol *et al.*, 2016). Waterlogging also reduces yield (MacLeod *et al.*, 2010), therefore this measure has the potential to increase the crop yield without an increase in other inputs. Implementing this measure requires the construction of field drains, or the renovation and maintenance of existing but deteriorated systems.

To model the N_2O effect the soil N_2O emission factor (EF_1) is reduced by 64%. This is based on emission differences on Krol *et al.* (2016), who reported that soils with moderate drainage, as compared to well drained soils, had 1.5—2.2 fold higher N_2O emissions in spring and summer, and 3.5 fold higher N_2O emissions in autumn as compared to well drained soils, with even higher differences for poorly drained soils. Lilly *et al.* (2012) suggest that maintaining the water table below 35cm is likely to reduce N_2O emissions by 50%. The yield increase was modelled as 11%

(while not increasing the crop residue N, as the assumption is that the yield increase is a result from avoided losses that were mostly a consequence of unworkable fields where crops were growing already) (MacLeod *et al.*, 2010). The average investment cost is £3,500 ha^{-1}, and the lifetime of the system is 20 years. There is an £125 ha^{-1} maintenance cost in every 5 years (MacLeod *et al.*, 2010).

2.2.12 Take stock off from wet ground

In many parts of the UK, livestock are routinely allowed to graze pastures throughout the winter period, providing advantages like reduced housing and feed costs. However, the livestock, particularly in wet periods, can cause soil compaction, increasing water pollution and promoting hotspots of N_2O emissions. Moving stock from wet ground during periods when soil water content exceeds a threshold value can help prevent soil compaction. Animals can be relocated to specially designated stand-off pads (Buss *et al.*, 2011). A New Zealand study demonstrated a reduction of up to 12% of total GHG emissions could be achieved by removing cattle from wet ground (Van der Weerden *et al.*, 2017). It was also shown that the maximum emissions savings would be achieved with this management approach was applied to poorly drained soils.

The construction of such standoff pads represents a considerable capital investment, but it has been estimated to cost one tenth of the capital costs of a conventional built housing (construction cost: £654 $animal^{-1}$, lifetime 15 year, maintenance: £32 $animal^{-1}$ y^{-1}). The abatement is estimated via changing the proportion of manure in the different manure management systems corresponding to 8.3% decrease in the time spent grazing; and via decreasing the emission factor that describes the proportion of N converted to N_2O from urine and dung deposited during grazing by 5%. The current uptake is assumed to be 1.5%.

2.2.13 Biological nitrogen fixation (grass-legumes mixtures)

N_2O emissions arising from the use of synthetic N fertilisers can be reduced by relying more on biologically fixed nitrogen in crop production (Lüscher *et al.*, 2014). Biological nitrogen fixation occurs as legumes form symbiotic relationships with bacteria (*Rhizobia*) in the soil that allows them to transform atmospheric dinitrogen to nitrogen compounds they can utilise, diminishing their need for synthetic fertilisers. Besides the fixed nitrogen supporting the growth of the legume crop (e.g. clover), part of the nitrogen also becomes available to the grass, reducing their need for fertiliser. This effect becomes substantial above a clover content of around 20%-30% in the sward.

The measure entails using grass-clover mixes for sowing (white clover seed rate 1-4 kg ha^{-1}, red clover seed rate 7 kg ha^{-1}) in temporary grasslands and keeping the fertilisation at the recommended level. In permanent grasslands clover can be introduced (or clover content can be increased) by various techniques without cultivation (e.g. direct drilling), using a clover seed rate of 4 kg ha^{-1}.

The measure is modelled by reducing the nitrogen fertilisation rate by 200 kg ha^{-1} y^{-1}, considering the fuel use effects (net annual CO_2 effect +5.73 and -4.07 kg CO_2e ha^{-1} for permanent and temporary grassland, respectively). The seed cost is £10 ha^{-1} at an annual basis, savings from one less fertiliser spreading is £-10.16 ha^{-1} y^{-1} and the cost of direct drilling for permanent grassland is £52.86 ha^{-1} every 5 years.

2.2.14 Higher sugar content grasses

The incorporation of high sugar grasses into swards is a management option for pasture-based systems. These are ryegrass varieties that have been bred to express elevated concentrations of water-soluble carbohydrate. When digested by ruminants, they have the potential to increase the efficiency of the use of N released from the digested forage (Parsons *et al.*, 2011). Consequently, HSGs have the potential to reduce the proportion of ingested N lost in the form of urine, which results in a reduction in N lost through leaching and N_2O emissions (Foskolos and Moorby, 2017; Parsons *et al.*, 2004). However, the water soluble carbohydrate (WSC): crude protein (CP) ratio of the grass is critical in controlling the N excreted (Parsons *et al.*, 2011).

To estimate the changes in GHG emissions associated with this measure, the milk yield of the cows was increased by 6.8% (total production was kept constant, i.e. livestock numbers have decreased in this option), and the digestible energy content of the roughage was also increased (overall 9% decrease in the N excretion relative to energy corrected milk). The seed price difference is modelled as £36/ha for 5 years (assuming an average 1.8 livestock unit ha^{-1} stocking density). The current uptake is assumed to be 9%.

2.2.15 Anaerobic digestion of cattle and slurry manure

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

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

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

This study modelled the anaerobic digestion of cattle manure (MM22) and pig and poultry manure (MM49), both co-digested with maize silage.

The energy (electricity and heat) and GHG production and cash flow of the plants were based on key parameters detailed in Table 6. The capital cost and operating costs were estimated according to Mistry *et al.* (2011):

$$Capital\ cost\ (£) = 79.5 * capacity\ (fresh\ t\ y^{-1}) + 516{,}000 \quad Eq.\ 1$$

$$Operating\ cost(£) = 218 * [capacity\ (fresh\ t\ y^{-1})]^{(1-0.306)} \quad Eq.\ 2$$

Table 6 Key assumptions used in the AD calculations

Parameter	Value	Unit	Reference
Volatile solid content of the manure	0.01-5.4 for livestock 0.282 for maize silage	kg VS (head * day)$^{-1}$ for livestock kg VS (kg fresh matter)$^{-1}$ for maize silage	(Eggleston *et al.*, 2006; Mistry *et al.*, 2011; Webb *et al.*, 2014)
Methane production potential	0.24-0.523	m^3 CH_4 (kg VS)$^{-1}$	(Eggleston *et al.*, 2006; Mistry *et al.*, 2011; Webb *et al.*, 2014)
CH_4 losses in storage before digestion	0.05	-	(Bangor University and Thunen Institute, 2015)
CO_2 losses in storage before digestion	0.05	-	(Møller *et al.*, 2004)
CH_4 leakage from digester	0.05	-	(Bangor University and Thunen Institute, 2015)
CH_4 ratio of the biogas	0.53	-	(Bangor University and Thunen Institute, 2015)
Efficiency of electricity generation	0.38	of CH_4 energy content	(Bangor University and Thunen Institute, 2015)
Efficiency of heat generation	0.43	of CH_4 energy content	(Bangor University and Thunen Institute, 2015)
Electricity used by the anaerobic digester	0.78	MJ nm^{-3} biogas produced	(Bangor University and Thunen Institute, 2015)
Heat used by the anaerobic digester	1.64	MJ nm^{-3} biogas produced	(Bangor University and Thunen Institute, 2015)
Operational engine hours	7000	kWh year^{-1} kW^{-1}	(Velghe and Wierinck, 2013)
Lifetime	20	years	
Electricity price	0.18	£ kWh^{-1}	

Parameter	Value	Unit	Reference
Heat price	0.09	£ kWh^{-1}	
Long-run marginal emission factor of electricity	0.03	kg CO_2e kWh^{-1}	(DECC, 2014)
Fuel emission factor (diesel)	0.269	kg CO_2e kWh^{-1}	(BEIS, 2019)
Transport cost	1.78	£ km^{-1}	
Average travel distance	10	km	
Truck load	11	t fresh matter	

2.2.16 Methane capture and combustion

Biogas flaring is similar to anaerobic digestion as it is based on converting the CH_4 generated during storage to the less potent GHG CO_2 (Pellerin *et al.*, 2013). However, unlike in a digester, in methane capture and combustion maximising the CH_4 production is not a goal, therefore no specific storage conditions are required. To collect the CH_4 an airtight, impermeable cover is used. One option is to purify the gas and sell the CH_4, while a technologically simpler solution is flaring the gas on site. As with slurry covers, NH_3 emissions are also greatly mitigated. The more N available in the manure can lead to increased emissions from manure spreading unless low NH_3 spreading technologies are used.

The measure requires an airtight cover (e.g. flexible HDPE membrane) which can be installed on slurry tanks and also on small and medium sized slurry lagoons (VanderZaag *et al.*, 2015). A pumping system is needed to collect the biogas, this also keeps a vacuum under the cover, reducing the risk of wind damage. Pumps above the cover are needed to remove the accumulating rainwater.

As no study was found which reported on GHG emissions from biogas flaring systems, we used the assumptions of the GHG and NH_3 effects of impermeable covers (see next section), combined with the GHG effects of flaring (assuming 90% flaring efficiency (Cherubini *et al.*, 2015)). The capital cost is £16 m^{-3} (10 years lifetime) with 2% maintenance cost, based on 3.5m slurry depth (VanderZaag *et al.*, 2015).

2.2.17 Covering slurry

Animal excreta stored in liquid systems is an important source of ammonia and methane emissions, as during the storage nitrogen and the volatile solids excreted turn into these gaseous compounds. In these systems (unless the slurry is aerated) direct N_2O formation is less important as the anaerobic environment blocks denitrification (Sommer *et al.*, 2000), however, a small portion of ammonia emissions turns into N_2O (indirect emissions). Several factors affect the rate of ammonia, CH_4 and N_2O emissions, including the airflow over the manure. Thus by covering the store these emissions can be reduced (Hou *et al.*, 2014; VanderZaag *et al.*, 2015).

Cover technologies include floating covers, rigid covers, natural crust and suspended, tent-like structures (VanderZaag *et al.*, 2015). The effects of cover solutions on direct greenhouse gas emissions are less explored though, with variable and inconclusive results (Hou *et al.*, 2014; Montes *et al.*, 2013; Sajeev *et al.*, 2018; VanderZaag *et al.*, 2008; VanderZaag *et al.*, 2015). Crust formation, straw addition and the use of granules tend to increase nitrous oxide emissions substantially, often overriding the emission savings in methane and indirect nitrous oxide emission reductions (Hou *et al.*, 2014; Sajeev *et al.*, 2018). The effects of these covers on methane emissions are variable, with a high probability of increased emissions. A review by Hout *et al.* (2014) showed that impermeable plastic covers have the potential to reduce ammonia and greenhouse gas emissions in parallel.

In this study we modelled the use of flexible plastic covers, both a permeable (MM25) and an impermeable solution. We assumed that a permeable cover reduces direct N_2O emissions by 68% and NH_3 volatilisation by 60% while increasing the CH_4 conversion factor by 2%. An impermeable cover would reduce N_2O and NH_3 emissions by 100% and 80%, respectively, and the CH_4 conversion factor by 47%. The cost of the permeable covers is £1.26 m^{-3} (5 years lifetime) with 1% maintenance cost, and the capital cost of the impermeable cover is £3.79 m^{-3} (10 years lifetime), requiring 2% maintenance cost.

2.2.18 Cattle breeding measures

Many production and fitness traits have been shown to have a genetic component and have scope to be improve ed via genetic selection. Current broader breeding goals that select on both production and fitness traits can help to mitigate GHGs from livestock systems per unit of output, due to a combination of lower feed intake, higher yield and fewer non-productive animals in the herd. GHG emissions can be reduced if the output is kept constant. The reduction in dairy cattle numbers in the past two decades in the UK was accompanied by an increase in milk production and a decrease in enteric CH_4 emissions from dairy cattle (Brown *et al.*, 2020). Similarly, increased growth rate enables beef animals to reach slaughter age quicker, reducing their lifetime emissions. Garnsworthy (2004) estimated, using modelling, that if cow fertility was restored to 1995 levels (from the 2003 level) that methane emissions from the dairy industry could be reduced by 10-15%.

So far, improvement in cattle production and efficiency using the current breeding goals has been happening. However, use of better genetic material has only reached an uptake of around 20-25% in the dairy herd, and still lower in the beef herd (Defra, 2018a). An increased uptake will lead to further improvements in efficiency. Though it is expected that the efficiency is going to continue to increase without further policy intervention, a more widespread and therefore larger increase in milk yield and growth rate can be expected from increased adoption of the best available genetic material. MM29 (Increased uptake of cattle genetic improvement practices using the current breeding goal) represents this mitigation measure.

Genetic improvement in the national herd can be enhanced by using genomic tools (MM26: Increased uptake of cattle genetic improvement practices using the current breeding goal, using genomic tools). This entails farmers collecting performance information on the individual animals and genetic testing, and feeding back this information to breeding goal development.

Literature suggests that the genetics of mammals has an influence on the micro-organisms present in the gut (Hegarty and McEwan, 2010). It is possible to select sheep for high or low CH_4 emissions, as CH_4 production is heritable to some extent (Pinares-Patiño *et al.*, 2013); selection for low emission causes changes in the animal's nutritional physiology (Goopy *et al.*, 2014). Studies indicate potential genetic selection for low CH_4 emission for dairy cattle too (de Haas *et al.*, 2011; Roehe *et al.*, 2016). Inclusion of low enteric CH_4 emission in the breeding goal (MM27: Shift to lower emissions intensity breeding goal in cattle breeding, using genomic tools) could reduce CH_4 emissions from cattle, though might limit the productivity and fitness improvements to some extent.

Genetic modification of cattle to reduce enteric methane emissions (MM28) is a mitigation measure which is speculative at the moment, assuming that genetic modification could be found which reduces enteric CH_4 emissions.

The breeding measures as modelled in the MACC cannot be applied to the same animals as MM26 assumes MM29 is implemented (and includes those effects), and both MM27 and MM28 includes both MM29 and MM26. However, they could still be applied in parallel within the national herd – this is reflected in the interactions in the MACC.

Key production, CH_4 emission and cost data are presented in Table 7 and Table 8.

Table 7 Production and GHG assumptions used in the breeding measures

Measure	Milk yield	Milk protein content	Dairy cow fertility	Beef live-weight	Beef growth rate	Beef cow fertility	Enteric CH_4 emission factor
MM26	+0.9% y^{-1}	+0.9% y^{-1}	+0.38% y^{-1}	+0.25% y^{-1}	+0.25% y^{-1}	+0.25% y^{-1}	0
MM27	+0.75% y^{-1}	+0.75% y^{-1}	+0.3% y^{-1}	+0.25% y^{-1}	+0.25% y^{-1}	+0.25% y^{-1}	-0.15% y^{-1}
MM28	+0.75% y^{-1}	+0.75% y^{-1}	+0.3% y^{-1}	+0.25% y^{-1}	+0.25% y^{-1}	+0.25% y^{-1}	-0.4% y^{-1}
MM29	+0.6% y^{-1}	+0.6% y^{-1}	+0.25% y^{-1}	NA	NA	NA	0

Table 8 Key assumptions used in the breeding measures

Measure	Dairy research investment	Cost of operating the dairy scheme	Dairy genomic testing cost	Beef research investment	Cost of operating the beef scheme	Beef genomic testing cost
MM26	£0.5M for 20 years	£0.25M for 5 years	£20 per bull, serving 500 cows	£1.5M for 20 years	£0.25M for 5 years	£20 per bull, serving 100 cows
MM27	£2.5M for 20 years	£0.5M for 5 years	£20 per bull, serving 500 cows	£2.5M for 20 years	£0.5M for 5 years	£20 per bull, serving 100 cows
MM28	£5M for 20 years	£0.5M for 5 years	£20 per bull, serving 1000 cows	£10M for 20 years	£0.25M for 5 years	£20 per bull, serving 1000 cows
MM29	£0	£0	£0	£0	£0	£0

2.2.19 Better health planning for cattle and sheep

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

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

Here we estimated the mitigation effects and costs of both improving cattle (MM30) and sheep (MM48) health. The mitigation effect was modelled with an increase in productivity (both milk yield and beef liveweight +6.38%, sheep liveweight +10.45%). The cost was estimated to be £27.8 head^{-1} and £7.70 head^{-1} for cattle and sheep, respectively (no investment is required).

2.2.20 High starch diet for dairy cows

This diet increases the digestible energy content of the diet by increasing the amount of starchy concentrates in the ration, while keeping the total crude protein content of the diet constant. This reduces the rate of enteric methane emissions. In practice, this can be achieved by replacing conserved grass with maize silage, to increase the digestibility of the ration. This will reduce enteric methane emissions and manure methane too (as less volatile solids will be excreted) (Hristov *et al.*, 2013b).

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

We assume that as grass and maize silage have the same production costs, and as grass silage will be replaced with maize silage the net costs are zero. The mitigation is represented by a 5% reduction in the rumen methane conversion factor.

2.2.21 Precision feeding

Precision feeding provides opportunities for reducing the feed conversion ratio of animals, and as less feed would be used, GHG emissions from feed production reduced. It can also reduce the rate of nitrogen and volatile solid excretion and therefore the N_2O and CH_4 emissions arising during manure management. It is applicable primarily to housed animals that can be monitored at regular intervals, and the information used to adjust rations, i.e. dairy cattle and pigs, and chicken.

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

The mitigation is estimated via reducing the gross energy requirement of dairy cows by 2% and reducing the nitrogen and volatile solid excretion of pigs by 2%. Cost estimates were not available due to the complexity of the systems and the lack of publications. Based on earlier cost-effectiveness estimates, which estimated an increase in profit (ADAS, 2017; Pellerin *et al.*, 2013; Pomar *et al.*, 2011) we assumed a small net annual benefit of £8.2 head^{-1} across animal categories (without trying to estimate the capital costs and reduction in feed costs separately).

2.2.22 Ruminant feed additive: 3NOP

3NOP (3-nitrooxypropanol) is a chemical that reduces the production of enteric methane by ruminants when added to their rations. It does so by reducing the rates at which rumen archaea convert the hydrogen in ingested feed into methane. Specifically, 3NOP inhibits methyl-coenzyme M reductase, the final step of CH_4 synthesis by archaea (Duin *et al.*, 2016). In a meta-analysis, Dijkstra *et al.* found that the effect on enteric CH_4 emissions was -38.8%+/-5.5% for dairy and -17.1%+/-4.2% for beef cattle (2018).

The measure entails the ingestion of a small amount of 3NOP each day, typically in the range of 0.05-0.2 g NOP for each kg of dry matter intake (Jayanegara *et al.*, 2018). For housed animals the 3NOP could be mixed in with the ration. The enteric CH_4 of dairy and beef animals were reduced by 30% and 20%, respectively. The current uptake is assumed to be 0%. The cost is modelled as £38 head^{-1} y^{-1}.

2.2.23 Increased milking frequency

Increased milking frequency increases milk yield and at the same time improves the amino acid and nitrogen utilisation of the animal, reducing its nitrogen excretion (Moorby *et al.*, 2007). The reduced nitrogen excretion reduces both direct and indirect N_2O emissions from manure management.

The measure can be implemented by the use of robotic milking parlours. This entails purchase of a robotic milker (typically costing £50-80k per 60 cows) and changes to stock management (e.g. keeping cattle closer to the milking parlour).

In the modelling we assumed 10% increase in the milk yield (Moorby *et al.*, 2007) and £125.000 capital investment for 120 cows (15 year lifetime).

2.2.24 Ruminant feed additive: nitrate

Enteric fermentation in ruminants is a major source of agricultural GHG emissions. During the fermentation process hydrogen is generated, and, via a microbial process, it reacts with CO_2 in the rumen, forming CH_4. The rumen processes can be modified, for example with chemical compounds which serve as an alternative hydrogen sink (Hristov *et al.*, 2013a; Leng, 2008).

The measure can be implemented by mixing 1.5% nitrate homogeneously into ruminant diets. The nitrate would (partially) replace non-protein nitrogen sources (e.g. urea), or, if NPN is not present in the diet, then high protein content components, like soya. It would also (partially) replace limestone as a calcium source.

The enteric CH_4 conversion factor is reduced by 17.5% and the cost is £27 animal^{-1} y^{-1}, based on the dairy cow cost estimate of replacing urea (£388 t^{-1}) and limestone (£35 t^{-1}) with Bolifor© (63.1% nitrate content, £620 t^{-1}) (Eory *et al.*, 2015).

2.2.25 Slurry acidification

The GHG reduction of acidifying slurry is based on the pH dependency of CH_4 and NH_3 emissions from slurry. Reducing the pH of the slurry with acids to 4.5-6.8 can significantly reduce the emissions of these two gases from storage, reducing NH_3 emissions also from field application, though increasing N_2O emissions from that stage. According to a review 67-90% of manure CH_4 emissions can be avoided when using strong acids (sulphuric or hydrochloric acid) (Fangueiro *et al.*, 2015). Acidification can be done at any phase of manure management: in the animal house, to the storage tank or before field application.

This analysis assessed acidification of the slurry in the storage tank. The storage emissions are modelled with a 75% reduction in the CH_4 conversion factor and a 70% reduction of the N volatilisation from slurry. The N_2O emission increase from field application is assumed to be off-set by the reduction in NH_3 emissions from the field. It is a measure not yet used in the UK, and the applicability is estimated as 94%, 72% and 95% of dairy cattle, beef cattle and pig manure stored in tanks, respectively (not applying it on smaller farms). The cost is modelled using the assumption of Kai *et al.* (2008), who suggested an annualised value of £43 y^{-1} for a 500 kg livestock unit.

3 Results

3.1 Total abatement

The total abatement under the CCC assumed carbon value (which rises from £72 (t $CO_2e)^{-1}$ in 2020 to £181 (t CO2e)$^{-1}$ in 2035, and to £241 (t CO2e)$^{-1}$ in 2050, CCC *pers. comm.*) increases until around 2035 when it starts a steep or gentle decline, depending on the scenario. The increasing trend corresponds with the increasing uptake of the mitigation measures as they become available for deployment and their uptake reaches the full uptake during the full policy implementation time. Once full uptake of most of the measures are reached the reduction in agricultural activities (which is the predicted trend in all five scenarios and the two sensitivities) result in a decrease in total abatement.

The highest abatement is predicted for the Crop sensitivity scenario (in which average crop yields decline to 6 t ha^{-1} by 2050), peaking above an annual 5.0 Mt CO_2e y^{-1} and providing more than 4.5 Mt CO_2 e in 2050 in the UK. This is the scenario where all the mitigation measures were included, since the crop yield was not assumed to increase by unspecified agronomic improvements in the agricultural activity scenario. At the same time this scenario has the highest livestock numbers (along with the Headwinds scenario, Figure 2) and an increasing cropland area towards 2050 (Figure 1), providing more scope for mitigation (though, at the same time, also higher land use).

On the other hand, the Diet sensitivity, Widespread Innovation, Widespread Engagement and Tailwinds scenarios provide much smaller total mitigation (4 – 4.2 Mt CO_2e y^{-1}) at their peak in 2035 and decline to 2.3 – 2.5 Mt CO_2e in 2050 in the UK. In these scenarios the number of beef cattle, pigs and poultry drops by more than one third by 2050 (in the Diet sensitivity scenario with 78%). At the same time, less land is used for agriculture, increasing the supply for land-based carbon sequestration activities. The Balanced Pathway provides a medium level abatement, peaking at 4 Mt CO_2e in 2035 and declining to around 3.5 Mt CO_2e by 2050.

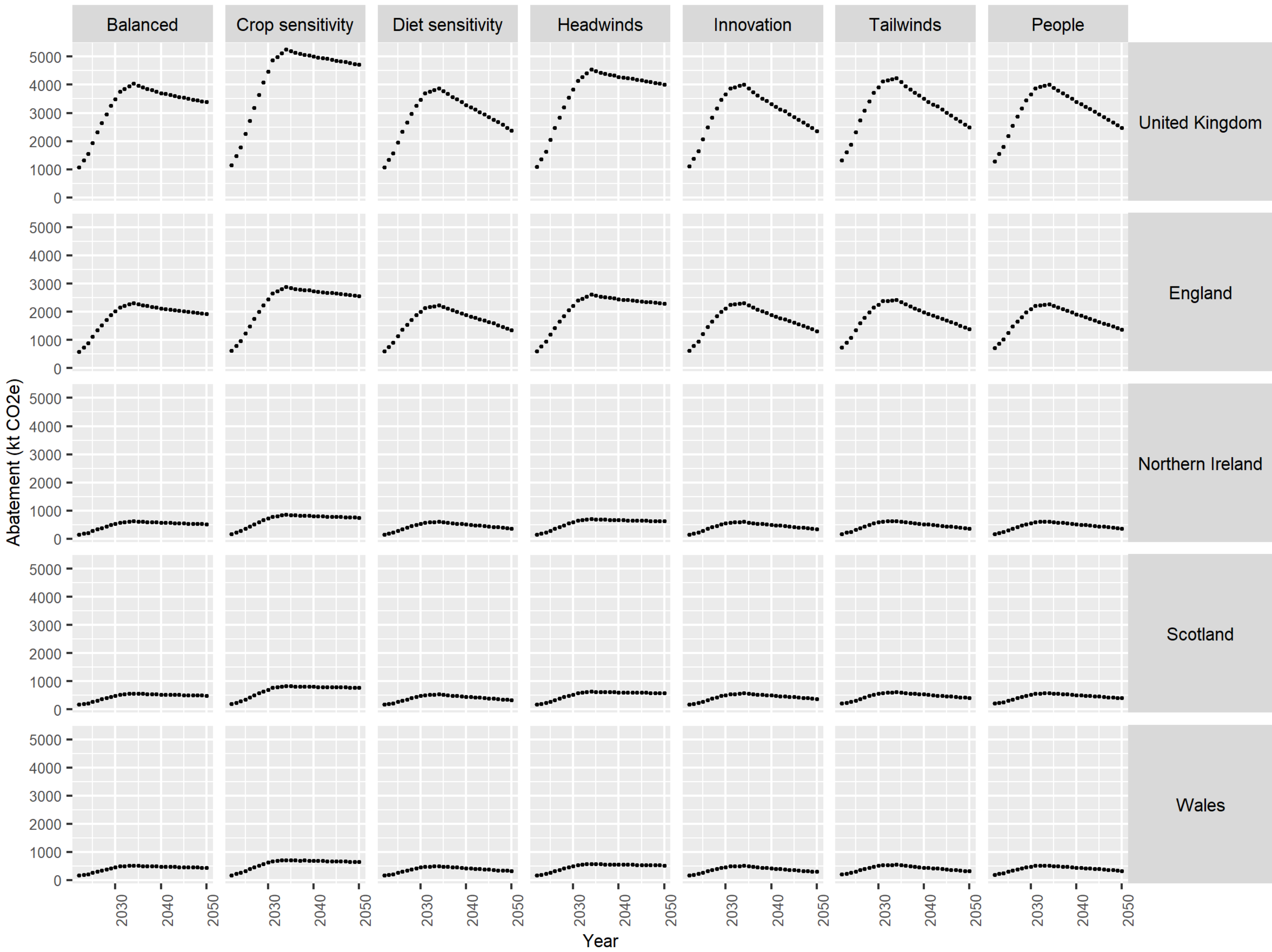

Figure 3 Total abatement under the carbon price in the seven activity scenarios and four UK countries

3.2 Marginal abatement cost curves

Table 9 and Table 10 show the cost-effectiveness and abatement potential of the mitigation measures in the UK in 2035 and 2050 in the Balanced Pathway scenario (see the other scenarios in the Annex). Within a year the cost-effectiveness of the mitigation measures is very similar between the scenarios, the main differences can be found in the abatement values, reflecting the underlying assumptions about agricultural activities.

Using grass-clover mixtures, the cattle genomic breeding, better health planning for cattle health and manure anaerobic digestions are the mitigation measures that are estimated to provide savings to the farmers and contribute to the abatement with more than 200 kt CO_2e y^{-1} across scenarios and years. Better health planning for sheep, covering slurry with impermeable cover, ruminant feed additives (3NOP and nitrate) could also provide important contribution to the mitigation effort with costs below the carbon price. Amongst the most expensive measures (with cost-effectiveness above the carbon price) are biogas flaring, nitrification inhibitors and slurry acidification.

Table 9 UK MACC, Balanced Pathway, 2035 (measures with cost-effectiveness under the C price are indicated with light blue shading)

	ID	Cost-effectiveness with interactions (£ (t CO_2e)$^{-1}$)	Abatement with interactions (kt CO_2e y^{-1})
GrassLegumesMix	MM20	-1038.0	524.4
BreedingGenomics	MM26	-578.4	224.8
BreedingCurrent	MM29	-1177.2	75.8
BreedingLowMethane	MM27	-1851.3	21.8
IncreaseMilkFreq	MM37	-851.8	60.8
HighSugarGrasses	MM21	-416.0	49.6
ADPigs	MM49	-250.0	249.4
ADCattle	MM22	-177.3	424.6
HealthCattle	MM30	-44.1	410.0
PrecisionFeeding	MM32	-15.3	22.7
HighStarchDiet	MM31	0.0	6.0
CoverSlurryImperm	MM47	20.8	126.7
HealthSheep	MM48	22.8	216.0
NitrateAdd	MM45	55.3	416.5
3NOP	MM35	85.5	956.4
CoverCrop	MM2	124.0	187.3
GrassLeys	MM8	364.3	188.8
NitrifInhibitor	MM12	561.4	118.3
BiogasFlaring	MM23	705.4	37.3
SlurryAcid	MM46	1662.5	14.5

	ID	Cost-effectiveness with interactions (£ (t $CO_2e)^{-1}$)	Abatement with interactions (kt CO_2e y^{-1})
StockOffWet	MM18	4553.5	16.4
CoverSlurryPerm	MM25	14798.0	0.0
Cumulative abatement under C price			**3972.6**
Cumulative abatement from all measures			**4348.0**

Table 10 UK MACC, Balanced Pathway, 2050 (measures with cost-effectiveness under the C price are indicated with light blue shading)

	ID	Cost-effectiveness with interactions (£ (t $CO_2e)^{-1}$)	Abatement with interactions (kt CO_2e y^{-1})
GrassLegumesMix	MM20	-1023.9	405.7
BreedingGenomics	MM26	-609.8	338.6
BreedingCurrent	MM29	-1232.5	117.3
BreedingLowMethane	MM27	-1167.3	96.0
IncreaseMilkFreq	MM37	-1271.6	41.3
GMCattle	MM28	-1265.2	26.6
HighSugarGrasses	MM21	-594.5	31.6
ADPigs	MM49	-244.9	181.4
ADCattle	MM22	-163.6	319.8
HealthCattle	MM30	-64.2	320.4
PrecisionFeeding	MM32	-54.3	13.4
HighStarchDiet	MM31	0.0	3.9
CoverSlurryImperm	MM47	19.8	106.6
HealthSheep	MM48	22.8	171.4
NitrateAdd	MM45	60.9	312.2
3NOP	MM35	88.4	743.6
CoverCrop	MM2	123.9	155.6
GrassLeys	MM8	208.4	137.6
NitrifInhibitor	MM12	550.5	98.5
BiogasFlaring	MM23	677.3	52.1
SlurryAcid	MM46	1993.4	9.9
StockOffWet	MM18	4553.5	12.9
CoverSlurryPerm	MM25	17643.7	0.0
Cumulative abatement under C price			**3385.6**
Cumulative abatement from all measures			**3696.5**

References

ADAS 'Farmscoper Version 4 – August 2017 – Description', ADAS, (2017).

AHDB 'Nutrient management guide (RB209)', AHDB, (2019).

Akiyama, H., Yan, X., and Yagi, K. 'Evaluation of effectiveness of enhanced-efficiency fertilizers as mitigation options for N_2O and NO emissions from agricultural soils: Meta-analysis', *Global Change Biology*, Vol. 16, (2010) pp. 1837-1846.

Al-Karaki, G., McMichael, B., and Zak, J. 'Field response of wheat to arbuscular mycorrhizal fungi and drought stress', *Mycorrhiza*, Vol. 14, (2004) pp. 263-269.

Alliaume, F., Rossing, W.A.H., Tittonell, P., Jorge, G., and Dogliotti, S. 'Reduced tillage and cover crops improve water capture and reduce erosion of fine textured soils in raised bed tomato systems', *Agriculture, Ecosystems & Environment*, Vol. 183, (2014) pp. 127-137.

Aubert, B.A., Schroeder, A., and Grimaudo, J. 'IT as enabler of sustainable farming: An empirical analysis of farmers' adoption decision of precision agriculture technology', *Decision Support Systems*, Vol. 54, (2012) pp. 510-520.

Bacenetti, J., Sala, C., Fusi, A., and Fiala, M. 'Agricultural anaerobic digestion plants: What LCA studies pointed out and what can be done to make them more environmentally sustainable', *Applied Energy*, Vol. 179, (2016) pp. 669-686.

Balafoutis, A., Beck, B., Fountas, S., Vangeyte, J., van der Wal, T., Soto, I., Gomez-Barbero, M., Barnes, A., and Eory, V. 'Precision agriculture technologies positively contributing to GHG emissions mitigation, farm productivity and economics', *Sustainability*, Vol. 9, (2017) pp. 1339.

Bangor University and Thunen Institute 'Comparative lifecycle assessment of anaerobic digestion', Report no. Defra AC0410, Defra, (2015).

Barnes, A., Eory, V., and Sinclair, R. 'Deliverable 5: Survey Results', Report no. Deliverable 5 in the study called "The contribution of Precision Agriculture technologies to farm productivity and the mitigation of greenhouse gas emissions in the EU", with reference JRC/SVQ/2015/J.4/0018/OC., (2017).

Barraclough, P.B., Howarth, J.R., Jones, J., Lopez-Bellido, R., Parmar, S., Shepherd, C.E., and Hawkesford, M.J. 'Nitrogen efficiency of wheat: Genotypic and environmental variation and prospects for improvement', *European Journal of Agronomy*, Vol. 33, (2010) pp. 1-11.

Beegle, D.B., Carton, O.T., and Bailey, J.S. 'Nutrient management planning: Justification, theory, practice', *Journal of Environmental Quality*, Vol. 29, (2000) pp. 72-79.

BEIS 'Greenhouse gas reporting: conversion factors 2019', (2019).

Berry, P.M., Holmes, H.F., and Blacker, C. 'Development of methods for remotely sensing grass growth to enable precision application of nitrogen fertilizer', Vol. 2017/06/01, (2017) pp. 758-763.

Bingham, I.J., Karley, A.J., White, P.J., Thomas, W.T.B., and Russell, J.R. 'Analysis of improvements in nitrogen use efficiency associated with 75 years of spring barley breeding', *European Journal of Agronomy*, Vol. 42, (2012) pp. 49-58.

Blombäck, K., Eckersten, H., Lewan, E., and Aronsson, H. 'Simulations of soil carbon and nitrogen dynamics during seven years in a catch crop experiment', *Agricultural Systems*, Vol. 76, (2003) pp. 95-114.

Bouwman, A.F., Boumans, L.J.M., and Batjes, N.H. 'Modeling global annual N_2O and NO emissions from fertilized fields', *Global Biogeochemical Cycles*, Vol. 16, (2002).

Brown, P., Cardenas, L., Choudrie, S., Jones, L., Karagianni, E., MacCarthy, J., Passant, N., Richmond, B., Smith, H., Thistlethwait, G., Thomson, A., Turtle, L., and Wakeling, D. 'UK Greenhouse Gas Inventory, 1990 to 2018', Report no. ED62689/0/CD9487/PB, Ricardo Energy & Environment, Department for Business, Energy & Industrial Strategy, (2020) London.

Buss, J., Chadwick, D., Davies, L., Smith, Ken, and Vickers, M. 'Improved design and management of woodchip pads for sustainable out-wintering of livestock', EBLEX, (2011).

Çakmakçi, R., Dönmez, M., and Erdo, Ü. 'The effect of plant growth promoting Rhizobacteria on barley seedling growth, nutrient uptake, some soil properties, and bacterial counts', *Turkish Journal of Agriculture and Forestry*, Vol. 31, (2007) pp. 189-199.

Cannon, R.J.C. 'The implications of predicted climate change for insect pests in the UK, with emphasis on non-indigenous species', *Global Change Biology*, Vol. 4, (1998) pp. 785-796.

Cardenas, L.M., Bhogal, A., Chadwick, D.R., McGeough, K., Misselbrook, T., Rees, R.M., Thorman, R.E., Watson, C.J., Williams, J.R., Smith, K.A., and Calvet, S. 'Nitrogen use efficiency and nitrous oxide emissions from five UK fertilised grasslands', *Science of the Total Environment*, Vol. 661, (2019) pp. 696-710.

Chadwick, D., Sommer, S., Thorman, R., Fangueiro, D., Cardenas, L., Amon, B., and Misselbrook, T. 'Manure management: Implications for greenhouse gas emissions', *Animal Feed Science and Technology*, Vol. 166-67, (2011) pp. 514-531.

Cherubini, E., Zanghelini, G.M., Alvarenga, R.A.F., Franco, D., and Soares, S.R. 'Life cycle assessment of swine production in Brazil: a comparison of four manure management systems', *Journal of Cleaner Production*, Vol. 87, (2015) pp. 68-77.

Cicek, H., Martens, J.R.T., Bamford, K.C., and Entz, M.H. 'Late-season catch crops reduce nitrate leaching risk after grazed green manures but release N slower than wheat demand', *Agriculture, Ecosystems & Environment*, Vol. 202, (2015) pp. 31-41.

Clarke, C. and Mosse, B. 'Plant growth responses to vesicular-arbuscular mycorrhiza. XII. Field inoculation responses of barley at two soil P levels', *New Phytologist*, Vol. 87, (1981) pp. 695-703.

Colantoni, A., Recchia, L., Bernabei, G., Cardarelli, M., Rouphael, Y., and Colla, G. 'Analyzing the environmental impact of chemically-produced protein hydrolysate from leather waste vs. enzymatically-produced protein hydrolysate from legume grains', *Agriculture*, Vol. 7, (2017) pp. 62.

Cooper, J. and Dobson, H. 'The benefits of pesticides to mankind and the environment', *Crop Protection*, Vol. 26, (2007) pp. 1337-1348.

Cozzolino, V., Di Meo, V., and Piccolo, A. 'Impact of arbuscular mycorrhizal fungi applications on maize production and soil phosphorus availability', *Journal of Geochemical Exploration*, Vol. 129, (2013) pp. 40-44.

Dabney, S.M., Delgado, J., Meisinger, J.J., Schomberg, H., Liebig, M.A., Kaspar, T., Mitchell, J., and Reeves, W. 'Using cover crops and cropping systems for nitrogen management', Advances in Nitrogen Management for Water Quality. (2011) Soil and Water Conservation Society, Ankeny, IA, USA, pp. 230-281.

De Baets, S., Poesen, J., Meersmans, J., and Serlet, L. 'Cover crops and their erosion-reducing effects during concentrated flow erosion', *Catena*, Vol. 85, (2011) pp. 237-244.

de Haas, Y., Windig, J.J., Calus, M.P.L., Dijkstra, J., de Haan, M., Bannink, A., and Veerkamp, R.F. 'Genetic parameters for predicted methane production and potential for reducing enteric emissions through genomic selection', *Journal of Dairy Science*, Vol. 94, (2011) pp. 6122-6134.

DECC 'Valuation of energy use and greenhouse gas emissions for appraisal', DECC, (2014).

Defra 'Farm practices survey October 2012 - Current farming issues', Defra, (2013).

Defra 'Farm practices survey 2018 - Greenhouse gas mitigation', National Statistics, (2018a).

Defra 'The British survey of fertiliser practice. Fertiliser use on farm crops for crop year 2017', Defra, (2018b).

Diacono, M., Rubino, P., and Montemurro, F. 'Precision nitrogen management of wheat. A review', *Agron Sustain Dev*, Vol. 33, (2013) pp. 219-241.

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

Dobbie, K.E. and Smith, K.A. 'The effect of water table depth on emissions of N2O from a grassland soil', *Soil Use and Management*, Vol. 22, (2006) pp. 22-28.

Duin, E.C., Wagner, T., Shima, S., Prakash, D., Cronin, B., Y+í+¦ez-Ruiz, D.R., Duval, S., R++mbeli, R., Stemmler, R.T., Thauer, R.K., and Kindermann, M. 'Mode of action uncovered for the specific reduction of methane emissions from ruminants by the small molecule 3-nitrooxypropanol', *Proceedings of the National Academy of Sciences of the United States of America*, Vol. 2016/05/02, (2016) pp. 6172-6177.

Dunstone, R.L., Richards, R.A., and Rawson, H.M. 'Variable responses of stomatal conductance, growth, and yield to fulvic acid applications to wheat', *Australian Journal of Agricultural Research*, Vol. 39, (1988) pp. 547-553.

Eggleston, S., Buendia, L., Miwa, K., Ngara, T., and Tanabe, K. 'IPCC guidelines for national greenhouse gas inventories', Report no. 4, (2006) Hayama, Japan.

Ehlert, D., Schmerler, J., and Voelker, U. 'Variable rate nitrogen fertilisation of winter wheat based on a crop density sensor', *Precision Agriculture*, Vol. 5, (2004) pp. 263-273.

Elliott, E.T., Drake, B., Jones, G., Chatterton, J., Williams, A., Wu, Z., Hateley, G., and Curwen, A. 'Modelling the impact of controlling UK endemic cattle diseases on greenhouse gas emissions (Defra project AC0120)', 88th Annual Conference of the Agricultural Economics Society, AgroParisTech, Paris, France, (2014).

Eory, V., MacLeod, M., Topp, C. F. E., Rees, R. M., Webb, J., McVittie, A., Wall, E., Brothwick, F., Watson, C., Waterhouse, A., Wiltshire, J., Bell, H., Moran, D., and Dewhurst,

R. J. 'Review and update of the UK agriculture MACC to assess the abatement potential for the 5th carbon budget period and to 2050', the Committee on Climate Change, (2015).

Eory, V., Maire, J., Anthony, S., Topp, C. F. E., Rees, R., Hamilton, H., and Wall, E. 'Non-CO_2 abatement in the UK agricultural sector by 2050', (2019).

Evans, N., Baierl, A., Semenoov, N.A., Gladders, P., and Fitt, B.D.L. 'Range and severity of a plant disease increased by global warming', *Journal of The Royal Society Interface*, Vol. 5, (2007).

Fangueiro, D., Hjorth, M., and Gioelli, F. 'Acidification of animal slurry – a review', *Journal of Environmental Management*, Vol. 149, (2015) pp. 46-56.

Fornara, D.A., Steinbess, S., McNAMARA, N.P., GLEIXNER, G., OAKLEY, S., POULTON, P.R., MACDONALD, A.J., and BARDGETT, R.D. 'Increases in soil organic carbon sequestration can reduce the global warming potential of long-term liming to permanent grassland', *Global Change Biology*, Vol. 17, (2011) pp. 1925-1934.

Foskolos, A. and Moorby, J.M. 'The use of high sugar grasses as a strategy to improve nitrogen utilization efficiency: A meta- analysis', 8 ed. (2017) Cambridge University Press.

Freepons, D. 'Enhancing food production with chitosan seed-coating technology', in: Goosen, M.F.A. (Ed.), Applications of chitin and chitosan. (1996) CRC Press.

Fu, X., Wang, J., Sainju, U.M., and Liu, W. 'Soil carbon fractions in response to long-term crop rotations in the Loess Plateau of China', *Soil Science Society of America Journal*, Vol. 81, (2017) pp. 503-513.

Garnsworthy, P.C. 'The environmental impact of fertility in dairy cows: a modelling approach to predict methane and ammonia emissions', *Animal Feed Science and Technology*, Vol. 112, (2004) pp. 211-223.

Gentile, R.M., Martino, D.L., and Entz, M.H. 'Influence of perennial forages on subsoil organic carbon in a long-term rotation study in Uruguay', *Agriculture, Ecosystems & Environment*, Vol. 105, (2005) pp. 419-423.

Goopy, J.P., Donaldson, A., Hegarty, R., Vercoe, P.E., Haynes, F., Barnett, M., and Oddy, V.H. 'Low-methane yield sheep have smaller rumens and shorter rumen retention time', Vol. 2013/10/08, (2014) pp. 578-585.

Goulding, K.W.T. 'Soil acidification and the importance of liming agricultural soils with particular reference to the United Kingdom', *Soil Use and Management*, Vol. 32, (2016) pp. 390-399.

Hamilton, S.K., Kurzman, A.L., Arango, C., Jin, L., and Robertson, G.P. 'Evidence for carbon sequestration by agricultural liming', *Global Biogeochemical Cycles*, Vol. 21, (2007).

Harty, M.A., Forrestal, P.J., Watson, C.J., McGeough, K.L., Carolan, R., Elliot, C., Krol, D., Laughlin, R.J., Richards, K.G., and Lanigan, G.J. 'Reducing nitrous oxide emissions by changing N fertiliser use from calcium ammonium nitrate (CAN) to urea based formulations', *Science of the Total Environment*, Vol. 563-564, (2016) pp. 576-586.

Hawkesford, M.J. 'Reducing the reliance on nitrogen fertilizer for wheat production', *Journal of Cereal Science*, Vol. 59, (2014) pp. 276-283.

Hawkesford, M.J. 'Genetic variation in traits for nitrogen use efficiency in wheat', *Journal of Experimental Botany*, Vol. 68, (2017) pp. 2627-2632.

Hegarty, R. and McEwan, J. 'Genetic opportunities to reduce enteric methane emissions from ruminant livestock', 9th World Congress of Genetics Applied to Livestock Production, (2010).

Hillocks, R.J. 'Farming with fewer pesticides: EU pesticide review and resulting challenges for UK agriculture', *Crop Protection*, Vol. 31, (2012) pp. 85-93.

Hou, Y., Velthof, G.L., and Oenema, O. 'Mitigation of ammonia, nitrous oxide and methane emissions from manure management chains: a meta-analysis and integrated assessment', *Global Change Biology*, (2014) pp. n/a.

Hristov, A., Oh, J., Lee, C., Meinen, R., Montes, F., Ott, T., Firkins, J., Rotz, A., Dell, C., Adesogan, A., Yang, Wen Zhu, Tricarico, J., Kebreab, E., Waghorn, G. C., Dijkstra, J., and Oosting, S. 'Mitigation of greenhouse gas emissions in livestock production - A review of technical options for non-CO_2 emissions', Report no. FAO Animal Production and Health Paper 177, FAO, (2013a) Rome, Italy.

Hristov, A.N., Oh, J., Firkins, J.L., Dijkstra, J., Kebreab, E., Waghorn, G., Makkar, H.P.S., Adesogan, A.T., Yang, W., Lee, C., Gerber, P.J., Henderson, B., and Tricarico, J.M. 'SPECIAL TOPICS - Mitigation of methane and nitrous oxide emissions from animal operations: I. A review of enteric methane mitigation options', *Journal of Animal Science*, Vol. 91, (2013b) pp. 5045-5069.

IPCC '2006 IPCC guidelines for national greenhouse gas inventories, Prepared by the National Greenhouse Gas Inventories Programme, Volume 4: Agriculture, forestry and other land use', Institute for Global Environmental Strategies (IGES), (2006) Japan.

IPCC 'Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change', Cambridge University Press, (2013) Cambridge, United Kingdom and New York, NY, USA.

Jayanegara, A., Sarwono, K.A., Kondo, M., Matsui, H., Ridla, M., Laconi, E.B., and Nahrowi 'Use of 3-nitrooxypropanol as feed additive for mitigating enteric methane emissions from ruminants: a meta-analysis', *Italian Journal of Animal Science*, Vol. 17, (2018) pp. 650-656.

Jess, S., Kildea, S., Moody, A., Rennick, G., Murchie, A.K., and Cooke, L.R. 'European Union policy on pesticides: implications for agriculture in Ireland', *Pest Management Science*, Vol. 70, (2014) pp. 1646-1654.

Johnson, K.B. 'Defoliation, disease, and growth: a reply', *Phytopathology*, Vol. 77, (1987) pp. 1495-1497.

Jokubauskaite, I., Kar-ìauskien-ù, D., Slepetiene, A., Repsiene, R., and Amaleviciute, K. 'Effect of different fertilization modes on soil organic carbon sequestration in acid soils', *Acta Agriculturae Scandinavica, Section B ΓÇö Soil & Plant Science*, Vol. 66, (2016) pp. 647-652.

Kai, P., Pedersen, P., Jensen, J.E., Hansen, M.N., and Sommer, S.G. 'A whole-farm assessment of the efficacy of slurry acidification in reducing ammonia emissions', *European Journal of Agronomy*, Vol. 28, (2008) pp. 148-154.

Kettlewell, P., Heath, W., and Haigh, I. 'Yield enhancement of droughted wheat by film antitranspirant application: rationale and evidence', *Agricultural Sciences*, Vol. 1, (2010) pp. 143-147.

Khaliq, A. and Sanders, F.E. 'Effects of vesicularΓÇôarbuscular mycorrhizal inoculation on the yield and phosphorus uptake of field-grown barley', *Soil Biology and Biochemistry*, Vol. 32, (2000) pp. 1691-1696.

Knight, S., Kightley, S., Bingham, I., Hoad, S., Lang, B., Philpott, H., Stobart, R., Thomas, J., Barnes, A., and Ball, B. 'Desk study to evaluate contributory causes of the current 'yield plateau' in wheat and oilseed rape', Report no. HGCA Project Report No. 502, HGCA, (2012).

Krol, D.J., Carolan, R., Minet, E., McGeough, K.L., Watson, C.J., Forrestal, P.J., Lanigan, G.J., and Richards, K.G. 'Improving and disaggregating N2O emission factors for ruminant excreta on temperate pasture soils', *Science of the Total Environment*, Vol. 568, (2016) pp. 327-338.

Lal, R. 'Soil carbon sequestration to mitigate climate change', *Geoderma*, Vol. 123, (2004) pp. 1-22.

Lam, S.K., Suter, H., Mosier, A.R., and Chen, D. 'Using nitrification inhibitors to mitigate agricultural N_2O emission: a double-edged sword?', *Global Change Biology*, Vol. 23, (2017) pp. 485-489.

Lechenet, M., Dessaint, F., Py, G., Makowski, D., and Munier-Jolain, N. 'Reducing pesticide use while preserving crop productivity and profitability on arable farms', *Nature Plants*, Vol. 3, (2017) pp. 17008.

Leng, R. A. 'The potential of feeding nitrate to reduce enteric methane production in ruminants', Report no. A Report The Department of Climate Change, Commonwealth Government of Australia, (2008).

Li, Y., Cui, S., Chang, S.X., and Zhang, Q. 'Liming effects on soil pH and crop yield depend on lime material type, application method and rate, and crop species: a global meta-analysis', *Journal of Soils and Sediments*, Vol. 19, (2019) pp. 1393-1406.

Lilly, A., Baggaley, N., Rees, R., Topp, C. F. E., Dickson, I., and Elrick, G. 'Report on agricultural drainage and greenhouse gas abatement in Scotland', ClimateXChange, James Hutton Institute and SRUC, (2012).

Link, J., Batchelor, W.D., Graeff, S., and Wilhelm, C. 'Evaluation of current and model-based site-specific nitrogen applications on wheat (Triticum aestivum L.) yield and environmental quality', *Precision Agriculture*, Vol. 9, (2008) pp. 251-267.

Liu, B., Frostegård, Å., and Bakken, L.R. 'Impaired reduction of N_2O to N_2 in acid soils is due to a posttranscriptional interference with the expression of nosZ', *mBio*, Vol. 5, (2014) pp. e01383-14.

Lüscher, A., Mueller-Harvey, I., Soussana, J.F., Rees, R.M., and Peyraud, J.L. 'Potential of legume-based grassland–livestock systems in Europe: a review', *Grass and Forage Science*, Vol. 69, (2014) pp. 206-228.

MacLeod, M., Moran, D., McVittie, A., Rees, R., Jones, G., Harris, D., Antony, S., Wall, E., Eory, V., Barnes, A., Topp, Cairistiona F. E., Ball, Bruce, Hoad, Steve, and Eory, L. 'Review and update of UK marginal abatement cost curves for agriculture', Committee on Climate Change, (2010).

Madgwick, J.W., West, J.S., White, R.P., Semenov, M.A., Townsend, J.A., Turner, J.A., and Fitt, B.D.L. 'Impacts of climate change on wheat anthesis and fusarium ear blight in the UK', *European Journal of Plant Pathology*, Vol. 130, (2011) pp. 117-131.

Maillard, É., McConkey, B.G., St.Luce, M., Angers, D.A., and Fan, J. 'Crop rotation, tillage system, and precipitation regime effects on soil carbon stocks over 1 to 30 years in Saskatchewan, Canada', *Soil and Tillage Research*, Vol. 177, (2018) pp. 97-104.

Mantovani, E.C., Misiewicz, P., White, D., and Godwin, R.J. 'Results of preliminary study of spatially variable Nitrogen application rates for forage maize in the UK', LANDWARDS EVENTS 2011: High technology for Agriculture – The next phase. A series of Forward Looking Events from IAgrE, (2011).

Mistry, P., Procter, C., Narkeviciute, R., Webb, J., Wilson, L., Metcalfe, P., Solano-Rodriguez, B., Conchie, S., and Kiff, B. 'Implementation of AD in E&W – Balancing optimal outputs with minimal environmental impacts', Report no. Defra AC0409, AEAT/ENV/R/3162, Defra, (2011) London.

Mohamed, W.H. 'Effects of humic acid and calcium forms on dry weight and nutrient uptake of maize plant under saline condition', *Australian Journal of Basic and Applied Sciences*, Vol. 6, (2012) pp. 597-604.

Moll, R.H., Kamprath, E.J., and Jackson, W.A. 'Analysis and interpretation of factors which contribute to efficiency of nitrogen utilization', *Agronomy Journal*, Vol. 74, (1982) pp. 562-564.

Møller, H.B., Sommer, S.G., and Ahring, B.K. 'Biological degradation and greenhouse gas emissions during pre-storage of liquid animal manure', *Journal of Environmental Quality*, Vol. 33, (2004) pp. 27-36.

Montes, F., Meinen, R., Dell, C., Rotz, A., Hristov, A.N., Oh, J., Waghorn, G., Gerber, P.J., Henderson, B., Makkar, H.P.S., and Dijkstra, J. 'SPECIAL TOPICS – Mitigation of methane and nitrous oxide emissions from animal operations: II. A review of manure management mitigation options', *Journal of Animal Science*, Vol. 91, (2013) pp. 5070-5094.

Moorby, J. M., Chadwick, D., Schofield, C. P., Chambers, B. J., and Williams, J. R. 'A review of research to identify best practice for reducing greenhouse gases from agriculture and land management', Report no. AC0206, Defra, (2007).

Nkoa, R. 'Agricultural benefits and environmental risks of soil fertilization with anaerobic digestates: a review', *Agronomy for Sustainable Development*, Vol. 34, (2014) pp. 473-492.

Oerke, E.C. 'Crop losses to pests', *Journal of Agricultural Science*, Vol. 144, (2006) pp. 31-43.

Ögüt, M., Akdag, C., Düzdemir, O., and Sakin, M.A. 'Single and double inoculation with Azospirillum/Trichoderma: the effects on dry bean and wheat', *Biology and Fertility of Soils*, Vol. 41, (2005) pp. 262-272.

Olesen, J.E., Trnka, M., Kersebaum, K.C., Skjelvag, A.O., Seguin, B., Peltonen-Sainio, P., Rossi, F., Kozyra, J., and Micale, F. 'Impacts and adaptation of European crop production systems to climate change', *European Journal of Agronomy*, Vol. 34, (2011) pp. 96-112.

Parsons, A.J., Rasmussen, S., Xue, H., Newman, J.A., Anderson, C.B., and Cosgrove, G.P. 'Some 'high sugar grasses' don't like it hot', (2004).

Parsons, A.J., Rowarth, J., and Rasmussen, S. 'High-sugar grasses', *CAB Reviews*, Vol. 6, (2011) pp. 1-12.

Pellerin, S., Bamiere, L., Angers, D., Beline, F., Benoit, M., Butault, J. P., Chenu, C., Colnenne-David, C., De Cara, S., Delame, N., Dureau, M., Dupraz, P., Faverdin, P., Garcia-Launay, F., Hassouna, M., Henault, C., Jeuffroy, M. H., Klumpp, K., Metay, A., Moran, D., Recous, S., Samson, E., and Savini, I. 'How can French agriculture contribute to reducing greenhouse gas emissions? Abatement potential and cost of ten technical measures', INRA, (2013).

Pinares-Patiño, C.S., Hickey, S.M., Young, E.A., Dodds, K.G., MacLean, S., Molano, G., Sandoval, E., Kjestrup, H., Harland, R., Hunt, C., Pickering, N.K., and McEwan, J.C. 'Heritability estimates of methane emissions from sheep', *Animal*, Vol. 7, (2013) pp. 316-321.

Pomar, C., Hauschild, L., Zhang, G.H., Pomar, J., and Lovatto, P.A. 'Precision feeding can significantly reduce feeding cost and nutrient excretion in growing animals', in: Sauvant, D., Milgen, J., Faverdin, P., and Friggens, N. (Eds.), Modelling nutrient digestion and utilisation in farm animals. (2011) Wageningen Academic Publishers, pp. 327-334.

Prade, T., Kätterer, T., and Björnsson, L. 'Including a one-year grass ley increases soil organic carbon and decreases greenhouse gas emissions from cereal-dominated rotations – A Swedish farm case study', *Biosystems Engineering*, Vol. 164, (2017) pp. 200-212.

Roehe, R., Dewhurst, R.J., Duthie, C.A., Rooke, J.A., McKain, N., Ross, D.W., Hyslop, J.J., Waterhouse, A., Freeman, T.C., Watson, M., and Wallace, R.J. 'Bovine host genetic variation influences rumen microbial methane production with best selection criterion for low methane emitting and efficiently feed converting hosts based on metagenomic gene abundance', *PLOS Genetics*, Vol. 12, (2016) pp. e1005846.

Roques, S., Kendall, S., mith, K, ewell-Price, P., and erry, P. 'A review of the non-NPKS nutrient requirements of UK cereals and oilseed rape', Report no. RR78, AHDB Cereals & Oilseeds, (2012).

Ruis, S.J. and Blanco-Canqui, H. 'Cover crops could offset crop residue removal effects on soil carbon and other properties: A review', *Agronomy Journal*, Vol. 109, (2017) pp. 1785-1805.

Rutledge, S., Wall, A.M., Mudge, P.L., Troughton, B., Campbell, D.I., Pronger, J., Joshi, C., and Schipper, L.A. 'The carbon balance of temperate grasslands part I: The impact of increased species diversity', *Agriculture, Ecosystems & Environment*, Vol. 239, (2017) pp. 310-323.

SAC 'Soil sampling', SAC, (2014).

Sajeev, E.P.M., Winiwarter, W., and Amon, B. 'Greenhouse gas and ammonia emissions from different stages of liquid manure management chains: Abatement options and emission interactions', *Journal of Environmental Quality*, Vol. 47, (2018) pp. 30-41.

Schwartz, J., Herold, L., and Polling, B. 'Typology of PF technologies', Report no. FutureFarm FP7 Project Deliverable 7.1, (2010).

Šimek, M., Hopkins, D.W., Kalcík, J., Picek, T., Šantrucková, H., Stana, J., and Trávník, K. 'Biological and chemical properties of arable soils affected by long-term organic and inorganic fertilizer applications', *Biology and Fertility of Soils*, Vol. 29, (1999) pp. 300-308.

Skuce, P. J., Houdijk, J., Hutchings, M., Waterhouse, A., and MacLeod, M. 'The impact of animal health status on greenhouse gas emissions from livestock', KnowledgeScotland, (2014).

Soil Associaton 'Measuring soil health', (2018).

Sommer, S.G., Petersen, S.O., and Sogaard, H.T. 'Greenhouse gas emission from stored livestock slurry', *Journal of Environmental Quality*, Vol. 29, (2000) pp. 744-751.

Storer, Kate, Kendall, Sarah, White, Charlotte, Roques, Susie, and Berry, Pete 'A review of the function, efficacy and value of biostimulant products available for UK cereals and oilseeds', Report no. RR89, AHDB, (2016).

Sylvester-Bradley, R. and Kindred, D.R. 'Analysing nitrogen responses of cereals to prioritize routes to the improvement of nitrogen use efficiency', *Journal of Experimental Botany*, Vol. 60, (2009) pp. 1939-1951.

Taylor, J.S., Harker, K.N., Robertson, J.M., and Foster, K.R. 'The effect of a seaweed extract containing cytokinin on the growth and yield of barley', *Canadian Journal of Plant Science*, Vol. 70, (1990) pp. 1163-1167.

Thomson, A., Misselbrook, T., Moxley, J., Buys, G., Evans, C., Malcolm, H., Whitaker, J., McNamara, N., and Reinsch, S. 'Quantifying the impact of future land use scenarios to 2050 and beyond - Final Report', (2018).

Travaglia, C., Reinoso, H., Cohen, A., Luna, C., Tommasino, E., Castillo, C., and Bottini, R.n. 'Exogenous ABA increases yield in field-grown wheat with moderate water restriction', *Journal of Plant Growth Regulation*, Vol. 29, (2010) pp. 366-374.

Van der Weerden, T.J., Laurenson, S., Vogeler, I., Beukes, P.C., Thomas, S.M., Rees, R.M., Topp, C.F.E., Lanigan, G., and de Klein, C.A.M. 'Mitigating nitrous oxide and manure-derived methane emissions by removing cows in response to wet soil conditions', *Agricultural Systems*, Vol. 156, (2017) pp. 126-138.

VanderZaag, A.C., Amon, B., Bittman, S., and Kuczynski, T. 'Ammonia abatement with manure storage and processing techniques', in: Reis, S., Howard, C., and Sutton, M. (Eds.), Costs of ammonia abatement and the climate co-benefits. (2015) Springer, pp. 75-112.

VanderZaag, A.C., Gordon, R.J., Glass, V.M., and Jamieson, R.C. 'Floating covers to reduce gas emissions from liquid manure storages: A review', *Applied Engineering in Agriculture*, Vol. 24, (2008) pp. 657-671.

Velghe, F. and Wierinck, I. 'Evaluatie van de vergisters in Nederland - Fase II', (2013) Agentschap NL, Divisie Energie & Klimaat.

Wang, M., Chen, Y., Zhang, R., Wang, W., Zhao, X., Du, Y., and Yin, H. 'Effects of chitosan oligosaccharides on the yield components and production quality of different wheat cultivars (Triticum aestivum L.) in Northwest China', *Field Crops Research*, Vol. 172, (2015) pp. 11-20.

Webb, N., Broomfield, M., Brown, P., Buys, G., Cardenas, L., Murrels, T., Pang, Y., Passant, N., Thistlethwait, G., and Watterson, J. D. 'UK Greenhouse Gas Inventory, 1990 to 2012', Report no. Ricardo-AEA/R/3407, Defra, Ricardo-AEA, (2014) London.

Weerasinghe, M.M., Kettlewell, P.S., Grove, I.G., and Hare, M.C. 'Evidence for improved pollen viability as the mechanism for film antitranspirant mitigation of drought damage to wheat yield', *Crop and Pasture Science*, Vol. 67, (2016) pp. 137-146.

Welsh, J.P., Wood, G.A., Godwin, R.J., Taylor, J.C., Earl, R., Blackmore, S., and Knight, S.M. 'Developing strategies for spatially variable nitrogen application in cereals, part I: Winter barley', *Biosystems Engineering*, Vol. 84, (2003a) pp. 481-494.

Welsh, J.P., Wood, G.A., Godwin, R.J., Taylor, J.C., Earl, R., Blackmore, S., and Knight, S.M. 'Developing strategies for spatially variable nitrogen application in cereals, part II: Wheat', *Biosystems Engineering*, Vol. 84, (2003b) pp. 495-511.

West, T.O. and Post, W.M. 'Soil organic carbon sequestration rates by tillage and crop rotation', *Soil Science Society of America Journal*, Vol. 66, (2002) pp. 1930-1946.

Xudan, X. 'The effect of foliar application of fulvic acid on water use, nutrient uptake and yield in wheat', *Australian Journal of Agricultural Research*, Vol. 37, (1986) pp. 343-350.

Zhang, X., Zhang, X., Liu, X., Shao, L., Sun, H., and Chen, S. 'Improving winter wheat performance by foliar spray of ABA and FA under water deficit conditions', *Journal of Plant Growth Regulation*, Vol. 35, (2016) pp. 83-96.

Zhu, G., Song, X., Ju, X., Zhang, J., Müller, C., Sylvester-Bradley, R., Thorman, R.E., Bingham, I., and Rees, R.M. 'Gross N transformation rates and related N2O emissions in Chinese and UK agricultural soils', *Science of the Total Environment*, Vol. 666, (2019) pp. 176-186.

Annex

The cost-effectiveness and abatement of the mitigation measures in the UK in all scenarios (see page 34 for the Balanced Pathway) are presented in Table 1 –

Table for the year 2035 and Table 15 UK MACC, Crop sensitivity applied to the Headwinds scenario, 2035 (measures with cost-effectiveness under the C price are indicated with light blue shading)

	ID	Cost-effectiveness with interactions (£ (t CO_2e)$^{-1}$)	Abatement with interactions (kt CO_2e y^{-1})
HealthCrop	MM7	-2594.5	37.4
Biostimulants	MM5	-2146.8	19.9
AvoidNexcess	MM11	-1444.6	5.9
PrecisionFarming	MM10	-1435.9	86.9
GrassLegumesMix	MM20	-1142.7	564.5
BreedingGenomics	MM26	-578.8	246.8
BreedingCurrent	MM29	-1175.8	83.3
BreedingLowMethane	MM27	-1838.2	24.2
IncreaseMilkFreq	MM37	-866.3	65.6
HighSugarGrasses	MM21	-415.6	54.5
ADPigs	MM49	-250.0	290.5
ADCattle	MM22	-177.3	466.1
HealthCattle	MM30	-40.6	465.4
pHCrop	MM3	-30.6	807.9
PrecisionFeeding	MM32	-8.6	24.9
HighStarchDiet	MM31	0.0	6.6
CoverSlurryImperm	MM47	19.9	141.4
HealthSheep	MM48	22.8	251.2
NitrateAdd	MM45	55.4	461.3
3NOP	MM35	85.5	1092.4
CoverCrop	MM2	129.7	239.0
GrassLeys	MM8	383.2	240.5
NitrifInhibitor	MM12	589.8	146.2
BiogasFlaring	MM23	709.2	42.2
ImpDrainage	MM16	1183.2	73.8
SlurryAcid	MM46	1673.6	16.3
ImpCrop	MM1	2203.1	2.3
StockOffWet	MM18	4722.1	18.4
CoverSlurryPerm	MM25	14422.4	0.1
Cumulative abatement under C price			**5196.6**
Cumulative abatement from all measures			**5975.2**

Table 14 UK MACC, Diet sensitivity scenario, 2035 (measures with cost-effectiveness under the C price are indicated with light blue shading)

	ID	Cost-effectiveness with interactions (£ (t CO_2e)$^{-1}$)	Abatement with interactions (kt CO_2e y^{-1})
GrassLegumesMix	MM20	-1025.8	425.4
BreedingGenomics	MM26	-576.0	246.7
BreedingCurrent	MM29	-1182.5	82.8
BreedingLowMethane	MM27	-1925.8	22.8
IncreaseMilkFreq	MM37	-792.2	71.7
HighSugarGrasses	MM21	-417.5	54.2
ADPigs	MM49	-250.0	200.8
ADCattle	MM22	-177.3	466.1
HealthCattle	MM30	-61.8	383.0
PrecisionFeeding	MM32	-43.9	24.7
HighStarchDiet	MM31	0.0	6.5
HealthSheep	MM48	22.8	173.2
CoverSlurryImperm	MM47	24.2	131.9
NitrateAdd	MM45	55.2	438.7
3NOP	MM35	86.0	861.4
CoverCrop	MM2	124.0	182.9
GrassLeys	MM8	368.8	147.7
NitrifInhibitor	MM12	534.0	116.0
BiogasFlaring	MM23	670.0	36.2
SlurryAcid	MM46	1619.6	14.5
StockOffWet	MM18	4553.5	13.2
CoverSlurryPerm	MM25	16630.8	0.0
Cumulative abatement under C price			**3773.0**
Cumulative abatement from all measures			**4100.6**

–

Table for the year 2050.

Table 11 UK MACC, Headwinds scenario, 2035 (measures with cost-effectiveness under the C price are indicated with light blue shading)

	ID	Cost-effectiveness with interactions (£ (t CO_2e)$^{-1}$)	Abatement with interactions (kt CO_2e y^{-1})
GrassLegumesMix	MM20	-1045.5	616.9
BreedingGenomics	MM26	-578.8	246.8
BreedingCurrent	MM29	-1175.8	83.3
BreedingLowMethane	MM27	-1838.2	24.2
IncreaseMilkFreq	MM37	-866.3	65.6
HighSugarGrasses	MM21	-415.6	54.5
ADPigs	MM49	-250.0	290.5
ADCattle	MM22	-177.3	466.1
HealthCattle	MM30	-40.6	465.4
PrecisionFeeding	MM32	-8.6	24.9
HighStarchDiet	MM31	0.0	6.6
CoverSlurryImperm	MM47	20.0	141.0
HealthSheep	MM48	22.8	251.2
NitrateAdd	MM45	55.4	461.3
3NOP	MM35	85.5	1092.4
CoverCrop	MM2	124.0	191.6
GrassLeys	MM8	361.5	226.6
NitrifInhibitor	MM12	585.2	120.7
BiogasFlaring	MM23	713.4	41.9
SlurryAcid	MM46	1673.6	16.3
StockOffWet	MM18	4553.5	19.1
CoverSlurryPerm	MM25	14536.8	0.1
Cumulative abatement under C price			**4482.4**
Cumulative abatement from all measures			**4907.1**

Table 12 UK MACC, Widespread Innovation scenario, 2035 (measures with cost-effectiveness under the C price are indicated with light blue shading)

	ID	Cost-effectiveness with interactions (£ (t CO_2e)$^{-1}$)	Abatement with interactions (kt CO_2e y^{-1})
GrassLegumesMix	MM20	-1034.0	460.0
BreedingLowMethane	MM27	-517.4	91.0
IncreaseMilkFreq	MM37	-624.5	121.4
HighSugarGrasses	MM21	-266.8	72.3
ADPigs	MM49	-250.0	296.7
ADCattle	MM22	-177.3	404.0
HealthCattle	MM30	-63.2	355.7
PrecisionFeeding	MM32	-19.8	30.6
HighStarchDiet	MM31	0.0	9.2
CoverSlurryImperm	MM47	18.1	83.5
HealthSheep	MM48	22.8	203.7

NitrateAdd	MM45	46.3	488.6
3NOP	MM35	79.4	1085.2
CoverCrop	MM2	124.0	168.3
GrassLeys	MM8	355.0	195.5
NitrifInhibitor	MM12	510.8	145.4
BiogasFlaring	MM23	797.0	34.4
SlurryAcid	MM46	1857.5	13.0
StockOffWet	MM18	4553.5	15.4
CoverSlurryPerm	MM25	13886.0	0.0
Cumulative abatement under C price			**3870.2**
Cumulative abatement from all measures			**4274.0**

Table 12 UK MACC, Tailwinds scenario, 2035 (measures with cost-effectiveness under the C price are indicated with light blue shading)

	ID	Cost-effectiveness with interactions (£ (t CO_2e)$^{-1}$)	Abatement with interactions (kt CO_2e y^{-1})
GrassLegumesMix	MM20	-1034.0	510.5
BreedingLowMethane	MM27	-517.6	91.0
IncreaseMilkFreq	MM37	-625.1	121.3
HighSugarGrasses	MM21	-266.8	80.5
ADPigs	MM49	-250.0	296.7
ADCattle	MM22	-177.3	403.9
HealthCattle	MM30	-62.5	450.5
PrecisionFeeding	MM32	-20.0	30.3
HighStarchDiet	MM31	0.0	11.0
CoverSlurryImperm	MM47	18.4	89.4
HealthSheep	MM48	22.8	254.6
NitrateAdd	MM45	46.4	487.2
3NOP	MM35	79.6	1082.4
CoverCrop	MM2	123.9	186.8
GrassLeys	MM8	356.8	194.3
NitrifInhibitor	MM12	537.0	138.2
BiogasFlaring	MM23	811.5	33.8
SlurryAcid	MM46	1891.2	12.8
StockOffWet	MM18	4553.5	16.6
CoverSlurryPerm	MM25	13997.1	0.1
Cumulative abatement under C price			**4096.0**
Cumulative abatement from all measures			**4491.7**

Table 13 UK MACC, Widespread Engagement scenario, 2035 (measures with cost-effectiveness under the C price are indicated with light blue shading)

	ID	Cost-effectiveness with interactions (£ (t CO_2e)$^{-1}$)	Abatement with interactions (kt CO_2e y^{-1})
GrassLegumesMix	MM20	-1034.4	540.4
BreedingGenomics	MM26	-579.2	200.6
BreedingCurrent	MM29	-1177.2	67.7
BreedingLowMethane	MM27	-1835.6	19.7
IncreaseMilkFreq	MM37	-867.8	53.4
HighSugarGrasses	MM21	-415.9	49.3
ADPigs	MM49	-250.0	235.3
ADCattle	MM22	-177.3	378.8
HealthCattle	MM30	-40.3	479.4
PrecisionFeeding	MM32	-9.3	20.0
HighStarchDiet	MM31	0.0	6.3
CoverSlurryImperm	MM47	19.0	130.4
HealthSheep	MM48	22.8	254.6
NitrateAdd	MM45	55.5	373.5
3NOP	MM35	85.7	883.4
CoverCrop	MM2	124.0	206.3
GrassLeys	MM8	367.9	172.7
NitrifInhibitor	MM12	586.5	110.4
BiogasFlaring	MM23	725.9	33.4
SlurryAcid	MM46	1703.5	13.0
StockOffWet	MM18	4553.5	16.6
CoverSlurryPerm	MM25	14386.2	0.0
Cumulative abatement under C price			**3899.2**
Cumulative abatement from all measures			**4245.3**

Table 15 UK MACC, Crop sensitivity applied to the Headwinds scenario, 2035 (measures with cost-effectiveness under the C price are indicated with light blue shading)

	ID	Cost-effectiveness with interactions (£ (t CO_2e)$^{-1}$)	Abatement with interactions (kt CO_2e y^{-1})
HealthCrop	MM7	-2594.5	37.4
Biostimulants	MM5	-2146.8	19.9
AvoidNexcess	MM11	-1444.6	5.9
PrecisionFarming	MM10	-1435.9	86.9
GrassLegumesMix	MM20	-1142.7	564.5
BreedingGenomics	MM26	-578.8	246.8
BreedingCurrent	MM29	-1175.8	83.3
BreedingLowMethane	MM27	-1838.2	24.2
IncreaseMilkFreq	MM37	-866.3	65.6
HighSugarGrasses	MM21	-415.6	54.5
ADPigs	MM49	-250.0	290.5
ADCattle	MM22	-177.3	466.1
HealthCattle	MM30	-40.6	465.4
pHCrop	MM3	-30.6	807.9
PrecisionFeeding	MM32	-8.6	24.9
HighStarchDiet	MM31	0.0	6.6
CoverSlurryImperm	MM47	19.9	141.4
HealthSheep	MM48	22.8	251.2
NitrateAdd	MM45	55.4	461.3
3NOP	MM35	85.5	1092.4
CoverCrop	MM2	129.7	239.0
GrassLeys	MM8	383.2	240.5
NitrifInhibitor	MM12	589.8	146.2
BiogasFlaring	MM23	709.2	42.2
ImpDrainage	MM16	1183.2	73.8
SlurryAcid	MM46	1673.6	16.3
ImpCrop	MM1	2203.1	2.3
StockOffWet	MM18	4722.1	18.4
CoverSlurryPerm	MM25	14422.4	0.1
Cumulative abatement under C price			**5196.6**
Cumulative abatement from all measures			**5975.2**

Table 14 UK MACC, Diet sensitivity scenario, 2035 (measures with cost-effectiveness under the C price are indicated with light blue shading)

	ID	Cost-effectiveness with interactions (£ (t CO_2e)$^{-1}$)	Abatement with interactions (kt CO_2e y^{-1})
GrassLegumesMix	MM20	-1025.8	425.4
BreedingGenomics	MM26	-576.0	246.7
BreedingCurrent	MM29	-1182.5	82.8
BreedingLowMethane	MM27	-1925.8	22.8
IncreaseMilkFreq	MM37	-792.2	71.7
HighSugarGrasses	MM21	-417.5	54.2
ADPigs	MM49	-250.0	200.8
ADCattle	MM22	-177.3	466.1
HealthCattle	MM30	-61.8	383.0
PrecisionFeeding	MM32	-43.9	24.7
HighStarchDiet	MM31	0.0	6.5
HealthSheep	MM48	22.8	173.2
CoverSlurryImperm	MM47	24.2	131.9
NitrateAdd	MM45	55.2	438.7
3NOP	MM35	86.0	861.4
CoverCrop	MM2	124.0	182.9
GrassLeys	MM8	368.8	147.7
NitrifInhibitor	MM12	534.0	116.0
BiogasFlaring	MM23	670.0	36.2
SlurryAcid	MM46	1619.6	14.5
StockOffWet	MM18	4553.5	13.2
CoverSlurryPerm	MM25	16630.8	0.0
Cumulative abatement under C price			**3773.0**
Cumulative abatement from all measures			**4100.6**

Table 17 UK MACC, Headwinds scenario, 2050 (measures with cost-effectiveness under the C price are indicated with light blue shading)

	ID	Cost-effectiveness with interactions (£ (t CO_2e)$^{-1}$)	Abatement with interactions (kt CO_2e y^{-1})
GrassLegumesMix	MM20	-1040.3	547.2
BreedingGenomics	MM26	-612.5	366.3
BreedingCurrent	MM29	-1228.6	127.2
BreedingLowMethane	MM27	-1062.3	115.8
IncreaseMilkFreq	MM37	-1264.4	44.9
GMCattle	MM28	-1160.9	30.2
HighSugarGrasses	MM21	-592.9	34.2
ADPigs	MM49	-244.9	236.0
ADCattle	MM22	-163.6	345.9
HealthCattle	MM30	-51.4	386.1
PrecisionFeeding	MM32	-24.5	14.7
HighStarchDiet	MM31	0.0	4.2
CoverSlurryImperm	MM47	17.5	119.3
HealthSheep	MM48	22.8	226.1
NitrateAdd	MM45	61.6	344.6
3NOP	MM35	88.5	912.1
CoverCrop	MM2	123.9	163.3
GrassLeys	MM8	204.2	198.6
NitrifInhibitor	MM12	592.8	102.7
BiogasFlaring	MM23	701.6	61.0
SlurryAcid	MM46	1999.6	11.5
StockOffWet	MM18	4553.5	16.9
CoverSlurryPerm	MM25	16483.2	0.0
Cumulative abatement under C price			**4216.7**
Cumulative abatement from all measures			**4408.9**

Table 18 UK MACC, Widespread Innovation scenario, 2050 (measures with cost-effectiveness under the C price are indicated with light blue shading)

	ID	Cost-effectiveness with interactions (£ (t $CO_2e)^{-1}$)	Abatement with interactions (kt CO_2e y^{-1})
GrassLegumesMix	MM20	-980.4	205.9
IncreaseMilkFreq	MM37	-513.1	103.0
BreedingLowMethane	MM27	-518.1	173.0
GMCattle	MM28	-429.6	76.1
HighSugarGrasses	MM21	-396.4	30.1
ADPigs	MM49	-244.9	174.6
ADCattle	MM22	-163.6	193.0
HealthCattle	MM30	-79.1	201.5
PrecisionFeeding	MM32	-33.6	13.0
HighStarchDiet	MM31	0.0	4.0
CoverSlurryImperm	MM47	11.4	50.0
HealthSheep	MM48	22.8	131.6
NitrateAdd	MM45	49.2	251.8
3NOP	MM35	81.8	634.9
CoverCrop	MM2	123.7	115.3
GrassLeys	MM8	185.5	65.6
NitrifInhibitor	MM12	471.3	99.5
BiogasFlaring	MM23	775.7	35.1
SlurryAcid	MM46	2133.2	6.5
StockOffWet	MM18	4553.5	9.8
CoverSlurryPerm	MM25	16339.9	0.0
Cumulative abatement under C price			**2423.4**
Cumulative abatement from all measures			**2574.4**

Table 19 UK MACC, Tailwinds scenario, 2050 (measures with cost-effectiveness under the C price are indicated with light blue shading)

	ID	Cost-effectiveness with interactions (£ (t $CO_2e)^{-1}$)	Abatement with interactions (kt CO_2e y^{-1})
GrassLegumesMix	MM20	-980.1	226.5
IncreaseMilkFreq	MM37	-514.0	102.9
BreedingLowMethane	MM27	-518.2	172.9
GMCattle	MM28	-430.1	76.1
HighSugarGrasses	MM21	-396.6	33.5
ADPigs	MM49	-244.9	174.6
ADCattle	MM22	-163.6	192.7
HealthCattle	MM30	-77.5	257.3
PrecisionFeeding	MM32	-33.9	12.9
HighStarchDiet	MM31	0.0	4.8
CoverSlurryImperm	MM47	11.7	53.5

HealthSheep	MM48	22.8	164.5
NitrateAdd	MM45	49.3	250.9
3NOP	MM35	81.9	633.4
CoverCrop	MM2	123.7	127.3
GrassLeys	MM8	187.7	64.1
NitrifInhibitor	MM12	487.1	95.6
BiogasFlaring	MM23	789.4	34.5
SlurryAcid	MM46	2170.1	6.4
StockOffWet	MM18	4553.5	10.5
CoverSlurryPerm	MM25	16281.3	0.0
Cumulative abatement under C price			**2547.9**
Cumulative abatement from all measures			**2694.9**

Table 15 UK MACC, Widespread Engagement scenario, 2050 (measures with cost-effectiveness under the C price are indicated with light blue shading)

	ID	Cost-effectiveness with interactions (£ (t CO_2e)$^{-1}$)	Abatement with interactions (kt CO_2e y^{-1})
GrassLegumesMix	MM20	-997.7	316.8
BreedingGenomics	MM26	-614.3	205.6
BreedingCurrent	MM29	-1231.7	71.4
BreedingLowMethane	MM27	-1045.2	66.2
IncreaseMilkFreq	MM37	-1272.2	25.2
HighSugarGrasses	MM21	-593.2	21.5
ADPigs	MM49	-244.9	138.4
ADCattle	MM22	-163.6	194.1
HealthCattle	MM30	-48.6	282.1
PrecisionFeeding	MM32	-17.8	8.3
HighStarchDiet	MM31	0.0	2.8
CoverSlurryImperm	MM47	16.3	77.2
HealthSheep	MM48	22.8	164.5
NitrateAdd	MM45	61.6	194.4
3NOP	MM35	88.7	521.9
CoverCrop	MM2	123.9	166.9
GrassLeys	MM8	218.3	86.6
NitrifInhibitor	MM12	531.1	91.9
BiogasFlaring	MM23	717.1	34.2
SlurryAcid	MM46	2037.3	6.5
StockOffWet	MM18	4553.5	10.5
CoverSlurryPerm	MM25	15929.4	0.0
Cumulative abatement under C price			**2543.9**
Cumulative abatement from all measures			**2687.0**

Table 21 UK MACC, Crop sensitivity scenario, 2050 (measures with cost-effectiveness under the C price are indicated with light blue shading)

	ID	Cost-effectiveness with interactions (£ (t CO_2e)$^{-1}$)	Abatement with interactions (kt CO_2e y^{-1})
HealthCrop	MM7	-2307.3	44.4
Biostimulants	MM5	-1818.4	38.7
AvoidNexcess	MM11	-1494.7	6.2
PrecisionFarming	MM10	-1466.6	82.7
GrassLegumesMix	MM20	-1142.1	498.4
ImpCrop	MM1	-882.3	23.1
BreedingGenomics	MM26	-612.5	366.3
BreedingCurrent	MM29	-1228.6	127.2
BreedingLowMethane	MM27	-1062.3	115.8
IncreaseMilkFreq	MM37	-1264.4	44.9
GMCattle	MM28	-1160.9	30.2
HighSugarGrasses	MM21	-592.9	34.2
ADPigs	MM49	-244.9	236.0
ADCattle	MM22	-163.6	345.9
HealthCattle	MM30	-51.4	386.1
pHCrop	MM3	-30.6	714.9
PrecisionFeeding	MM32	-24.5	14.7
HighStarchDiet	MM31	0.0	4.2
CoverSlurryImperm	MM47	17.5	119.6
HealthSheep	MM48	22.8	226.1
NitrateAdd	MM45	61.6	344.6
3NOP	MM35	88.5	912.1
CoverCrop	MM2	137.4	269.7
GrassLeys	MM8	293.1	218.1
NitrifInhibitor	MM12	584.6	166.0
BiogasFlaring	MM23	698.5	61.2
ImpDrainage	MM16	1239.2	71.2
SlurryAcid	MM46	1999.6	11.5
StockOffWet	MM18	4729.1	16.3
CoverSlurryPerm	MM25	16347.5	0.0
Cumulative abatement under C price			**4716.4**
Cumulative abatement from all measures			**5530.4**

Table 22 UK MACC, Diet sensitivity scenario, 2050 (measures with cost-effectiveness under the C price are indicated with light blue shading)

	ID	Cost-effectiveness with interactions (£ (t CO_2e)$^{-1}$)	Abatement with interactions (kt CO_2e y^{-1})
GrassLegumesMix	MM20	-845.5	110.4
BreedingCurrent	MM29	-599.4	260.7
BreedingGenomics	MM26	-1122.6	194.6
BreedingLowMethane	MM27	-1984.3	57.6
GMCattle	MM28	-1368.0	30.3
IncreaseMilkFreq	MM37	-1024.0	55.4
HighSugarGrasses	MM21	-613.6	33.1
ADPigs	MM49	-244.9	49.9
ADCattle	MM22	-163.6	345.9
HealthCattle	MM30	-152.6	201.2
PrecisionFeeding	MM32	-152.0	15.3
HighStarchDiet	MM31	0.0	3.8
HealthSheep	MM48	22.8	47.8
CoverSlurryImperm	MM47	23.7	124.4
NitrateAdd	MM45	56.9	319.1
3NOP	MM35	95.4	382.0
CoverCrop	MM2	123.9	144.0
GrassLeys	MM8	294.6	13.6
NitrifInhibitor	MM12	433.3	95.1
BiogasFlaring	MM23	523.1	40.7
SlurryAcid	MM46	2201.4	6.7
StockOffWet	MM18	4553.7	3.3
CoverSlurryPerm	MM25	45938.4	0.0
Cumulative abatement under C price			**2375.7**
Cumulative abatement from all measures			**2535.1**