Greenhouse gas abatement in UK agriculture, 2024-2050

Report submitted to support the 7th carbon budget in the UK

Vera Eory, Daniel Fletcher, Michael Macleod, Carol-Anne Duthie, Robert Rees, Kairsty Topp

SRUC

February, 2025

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Executive Summary

In 2023 agriculture in the UK provided 62% of the UK food supply for all food and 75% for indigenous foods (those that can be grown in the UK) (Defra 2024). It is also an important source of export revenue and a pillar of rural livelihoods in some areas. At the same time, agriculture is exposed to the effects of climate change while being one of the sectors where greenhouse gas mitigation has been stagnating (Brown et al. 2024). As highlighted by the Climate Change Committee, past policy efforts have been insufficient in the interlinked areas of agricultural production, land use and dietary behaviours (Climate Change Committee 2024).

The increasing need to reduce agricultural and food related emissions underlines the importance of estimating the mitigation potential in agricultural production in the wider context of emission reductions achievable with changing dietary patterns, land use and the agricultural production mix. This report provides estimates for the mitigation achievable in the latter, i.e. on farms, in the next 25 years in the UK, based on two production scenarios provided by the Climate Change Committee: (a) Business as usual (continuation of recent trends in productivity and no change in demand) and (b) Balanced Pathway (faster improvements in productivity and reduced demand for commodities with higher carbon footprints).

In the Business as Usual Case production scenario, the SRUC MACC model estimates agricultural GHG emissions in the UK (excluding emissions from poultry, goats, horses, deer and emissions from non-mobile machinery) to be 41 Mt CO_2e both in 2025 and in 2050. Implementing those on-farm mitigation measures where the abatement cost is lower than the social cost of carbon could save 6.1 Mt CO_2e in 2035 and 6.4 Mt CO_2e in 2050 in this scenario.

The food chain transition in the Balanced Pathway scenario (which involves dietary shift away from high emission intensity products, a reduction in food waste and more efficient crop production), would drastically reduce agricultural emissions due to land use change, and cost-effective on-farm mitigation measures would provide further 4.0 Mt CO_2e savings annually. Emission and mitigation trends follow similar patterns across the four countries of the UK, with slightly higher mitigation achievable in Northern Ireland. (These results do not include the potential carbon removal on the land area no longer used for agriculture.)

The total on-farm annual costs of the mitigation is -512 M£ and -36 M£ (negative costs imply a saving) in 2050 in the UK in the BAU and BP scenarios, respectively. The annual cost is composed of substantial savings due to numerous measures improving efficiency, and a varying level of capital investment (317-563 M£/year in the BAU and 51-232 M£/year in the BP scenario, respectively). On-farm measures with the highest abatement potential are ‘Grass legume mix’, ‘Faster finishing beef’ and ’Increased milking frequency’, as well as ‘3NOP feed additive’ for beef and dairy and ‘Lower emission breeding goal, dairy’.

The modelling assumed 50-75% uptake of the mitigation measures, which would necessitate a strong shift in agri-environmental policy. Beyond the potentially negative impacts of the measures on farm finances and large investment costs to implement the mitigation measures, a large array of other barriers currently prevent the wider uptake of the mitigation measures, including limited suitability to the farming operations, risk in and effort of changing farm management and low levels of robust and relevant information and advice.

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Abbreviations

Abbreviation	Definition
3NOP	3-nitrooxypropanol
AD	Anaerobic digestion
BNF	Biological nitrogen fixation
CB6	6^{th} Carbon Budget
CB7	7^{th} Carbon Budget
CCC	Climate Change Committee
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
FAO	Food and Agriculture Organization
FAOSTAT	Food and Agriculture Organization Corporate Statistical Database
GHG	Greenhouse gas
GLEAM	Global Livestock Environmental Assessment Model
GWP	Global warming potential
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 the path to achieve net zero emissions in the UK by 2050, the Climate Change Committee has been advising the UK Government on the level of carbon budgets appropriate for every 5-year period. The 7th carbon budget will define the emission cap for the period between 2038 and 2042.

Greenhouse gas (GHG) emissions from agricultural production contribute with a slowly increasing share to the overall UK emissions, as the sector has achieved very limited mitigation in the past decades. Agricultural GHG emissions were 42.0 Mt CO_2e in 2022, or 10.2% of UK emissions, compared with 43.6 Mt CO_2e in 2010 (7.1%) (Brown et al. 2024). These emissions mainly consist of non-CO_2 GHG gases, namely methane (CH_4) and nitrous oxide (N_2O), which arise from biological processes in crop and livestock production and are difficult to reduce. Still, GHG mitigation and increased carbon sequestration in the sector, along with dietary shift toward a carbon intensive diet is possible and also essential for achieving the UK's net zero target (Climate Change Committee 2024).

This report presents an assessment of GHG mitigation options within agricultural production in the period between 2025 and 2050, providing technical background to the 7th carbon budget recommendation by the Climate Change Committee. It documents the methodology and presents the key results.

2

Methodology

2.1. Modelling overview

The mitigation potential and mitigation cost were estimated using a bottom-up marginal abatement cost curve method, following earlier agricultural mitigation estimates provided for carbon budget developments in the UK (Eory et al. 2015; Eory et al. 2020). In this method the GHG mitigation and abatement cost are estimated for the individual mitigation measures for the whole farming area in the geographic region, and they are subsequently aggregated to estimate the total abatement achievable in the region. The GHG mitigation of each measure is calculated from the mitigation efficacy (e.g. a reduction in fertiliser-use or in an emission factor), its applicability and potential additional uptake in the future. The cost of the measures is estimated from adding up technical costs and any benefits from savings in resources or increases in income, over the time period of the investment. The methodology is described in detail in (Eory et al. 2015). Below is a summary of the approach as well as the description of improvements since the version used in that report.

2.1.1. Non-mitigated greenhouse gas emissions

The model uses IPCC GHG inventory equations for calculating greenhouse gas emissions based on agricultural activity data (e.g. number of dairy calves, milk yield, hectares of wheat and nitrogen fertiliser dose) and parameters associated with emissions specific to each country's agriculture (e.g. nitrogen fertiliser emission factors or manure management emissions factors). The emission parameters are obtained from the UK GHG inventory, courtesy of the Inventory Team. The main features of the analysis are presented in Table 2.1.

Table 2.1: Summary of the GHG modelling approach

GHG sources included	N_2O emissions from i) soils due to inorganic and organic nitrogen application and residual crop N, and ii) manure storage. CH_4 emissions from i) enteric fermentation, ii) manure storage, and iii) leaks from anaerobic digesters. CO_2 emissions from machinery use Carbon sequestration in soils. Avoided CO_2 emissions from energy generation.
GHG sources excluded	Upstream and downstream emissions (such as fertiliser production or product processing) Emission changes arising from direct and indirect land use change Emissions from poultry (omitted due to limited GHG mitigation options) Emissions from goats, horses, deer (omitted due to limited role in GHG emissions).
GHG equivalency	GWP100 (AR6): GWP(N_2O)=273 CO_2e; GWP(CH_4)=27.2 CO_2e.
Spatial resolution	4 countries in the UK.
Temporal resolution	Annual, 2025-2050.
Calculation approach	The total mitigation is the difference between GHG emissions in the absence of mitigation measures and with mitigation measures applied.
Aggregation of mitigation effects: interactions between measures	The model reduces the mitigation effect of the measures if they are applied together and act on the same emission source.

Crop categories	‘Vegetables (other non-legumes)’, ‘Potatoes (maincrop)’, ‘Root crops for stockfeed’, ‘Winte barley malting’, ‘Forage maize’, ‘Wheat’, ‘Miscanthus’, ‘Fruit mixed top and soft fruit’, ‘Linseed’, ‘Wheat non-milling’, ‘Sugar beet’, ‘Field beans and peas combined (not Vining peas)’, ‘Winter barley non-malting’, ‘Other fodder crops’, ‘Winter oats’, ‘Winter oilseed rape’, ‘Maize’, ‘Minor cereals’, ‘Spring barley malting’, ‘Improved Temporary Grass’, ‘Other field crops’, ‘Grain maize’, ‘Leafy forage crops’, ‘Wine grapes’, ‘Spring barley’, ‘Oilseed rape’, ‘Field beans (harvested dry)’, ‘Soft Fruit’, ‘Vegetables (not differentiated)’, ‘Winter barley’, ‘Spring oats’, ‘Top Fruit’, ‘Willow short rotation coppice’, ‘Spring oilseed rape’, ‘Vegetables brassicas’, ‘Improved Permanent Grass’, ‘Vegetables legumes’, ‘Spring barley non-malting’, ‘Oats’, ‘Wheat milling’, ‘Potatoes seed or earlies’, ‘Other horticultural crops’, ‘Field peas (harvested dry)’ (Unfertilised permanent grassland (rough grazing) is not included).
Livestock categories	**Cattle**: ‘Dairy Calves Female’, ‘Dairy Replacements Female’, ‘Dairy In Calf Heifers’, ‘Dairy Cows’, ‘Beef Heifers for Breeding’, ‘Beef Females for Slaughter’, ‘Beef Bulls for Breeding’, ‘Beef Cereal Fed Bull’, ‘Beef Steers’, ‘Beef Cows’; **Sheep**: ‘Lamb’, ‘Mature Ram’, ‘Mature Ewe’; **Pig**: ‘Sows’, ‘Other pigs’.
Heterogeneity in farming	Country-level heterogeneity is included, along with heterogeneity by livestock and crop categories and manure management systems; other heterogeneity is not represented (e.g. by soil types, weather parameters, livestock productivity levels or farm size and structure).
Agricultural activity scenarios	The CCC provides two ‘land-use scenario’ projections for key crop and livestock categories up until 2050. These projections are used to create detailed activity data for the scenarios based on crop and activity ratios of 2021 in the UK agricultural GHG inventory.

Agricultural practices	Main areas of activities: • crop yield and fertilisation rates by country and fertiliser type. • livestock weight and milk yield by country and livestock category. • manure management system proportions by country and livestock category. • grazing proportion by country and livestock category.
Agricultural emission parameters	The model uses UK agricultural GHG inventory values (from 2016 and 2021), and thus follows the emission calculation levels in the inventory: Enteric CH_4 of cattle and sheep: Tier 3 (country-specific parameters); pigs Tier 1 (default IPCC parameters); Manure emissions of cattle, sheep and pigs: Tier 2 (mix of country-specific and default IPCC parameters); Direct soil N_2O: Tier 1 and Tier 2 (mix of country-specific and default IPCC parameters); Indirect soil N_2O: Tier 1 (default IPCC parameters). Main areas of parameters: • Cattle enteric CH_4: emissions percentage (Ym [% gross energy]), feed composition (roughage vs concentrate), grazing percentage, digestible energy of feed, nitrogen content of feed • Cattle manure emissions: manure CH_4 potential (B0), manure management emission factors by system (CH_4, direct and indirect N_2O), pasture range and paddock CH_4, direct and indirect N_2O emission factors. • Sheep: enteric CH_4 emissions factor [kgCH_4/head], volatile solids and nitrogen excretion rates, manure management emission factors by system (CH_4, direct and indirect N_2O), pasture range and paddock emission factors (CH_4, direct and indirect N_2O). • Pigs: volatile solids and nitrogen excretion rates, manure management emission factors by system (CH_4, direct and indirect N_2O), pasture range and paddock emission factors (CH_4, direct and indirect N_2O). • Soil N_2O: synthetic and organic N_2O emission factors, NH_3 volatilisation fraction, leaching, nitrogen residuals.

Other emission parameters	• Diesel emission factors, source: Climate Change Committee • Electricity emission factors (marginal emissions intensity, commercial end-use), source: Climate Change Committee • Heat emission factors, source: (DECC, 2014)

2.1.2. Mitigation measures' effects on greenhouse gas emission

The GHG mitigation due to the implementation of the measures is represented in the model via changing the emissions parameters (e.g. nitrogen fertiliser emissions factors), the activity data (e.g. hectares of wheat receiving fertiliser), or both.

Each mitigation measure has an assumed applicability (e.g. only applicable to crops receiving ammonium nitrate) and uptake (e.g. 30% grassland is a grass-legume mix). These are expressed as a proportion of land (for crop measures) or livestock numbers. More information on the uptake-modelling approach can be found in section 2.5.

Importantly, production constraints are included in the model so that measures which increase yield reduce the number of agriculture units so that total production of commodities is constant. Similarly, if a measure reduces yield, agriculture units are increased to preserve production. This is a strong assumption and not likely to happen in reality, however, it makes it possible to aggregate the effects of GHG savings from efficiency improvements with GHG savings from altering chemical processes.

2.1.3. Cost of the mitigation measures

The net annualised cost is calculated based on partial accounting of the technical costs on the farm, i.e. adding up the estimated changes in income and costs of the farm business. Included are:

- Investment costs (referred to in the report as 'additional capital expenditure' or 'capex'), hereby defined as any cost which has a lifetime of more than one year. These costs are annualised using a 3.5% discount rate.
- Annual costs (referred to in the report as 'additional operating expenditure' or 'opex'), which can be due to i) using additional inputs (e.g. fertiliser additives), ii) changes in the amount of inputs used and iii) changes in the outputs produced.

The model does not include transaction costs (associated e.g. with monitoring the implementation of the measure, changes in the time required for farm.

2.1.4. Aggregation of the mitigation potential

The abatement potential of a mitigation measure is calculated as the difference in GHG emissions of the non-mitigated and mitigated scenarios so that positive values represent emissions savings. Similarly, cost is calculated as the difference in cost of the mitigated and non-mitigated scenarios so that positive values represent cost to the farm.

This approach produces abatement potential and cost for the mitigation measures assuming each measure is applied independently. However, some measures interact, so that their total mitigation/cost would be different than the sum of their individual mitigation/cost (for instance in the case of reducing N fertilisation excess and having a grass-legume mixed sward). The mitigation interactions are estimated in the model post hoc, as part of the ranking algorithm (the cost interactions are not considered).

To generate the marginal abatement cost curves, which visualise the total abatement from the component mitigation measures, the measures are ranked. If the abatement cost is negative, the ranking is by abatement potential (largest to smallest abatement potential), and if the abatement cost is positive, the ranking is by abatement cost (smallest to largest abatement cost); cost negative measures are ranked above cost positive measures.

To represent the interactions, an 'interaction factor' was estimated for each pair of mitigation measure, representing the change (in most cases reduction) needed in the mitigation effect of one of the measures if it is applied together with another measure. If two measures have an interaction factor, the measure which is ranked lower has its abatement potential reduced by that factor. This method reduces the risk of double counting GHG mitigation, though inflates the abatement cost of the mitigation measures which are ranked lower. In case of mutually exclusive measures (like alternative forms of CH_4 reducing feed additives) the interaction factor is 0, i.e. the second measure of the pair is assumed to generate no mitigation in the land areas/animals where they are both applied.

2.2. Changes to modelling methodology since CB6

Since CB6 the agricultural MACC model has been transferred from a Microsoft Excel model to Python. Through this process small errors in the original model were corrected, methodology has been harmonised and additional functionality has been added. It is important to track these changes so that differences between CB6 and CB7 can be explained. Here we detail these changes.

Changes in approach

- In CB6 cost was calculated as the cost per applied unit (land area of livestock) multiplied by number of applied units which resulted in a slight miscalculation of cost when the mitigation measure changed the yield and thus number of units. Now cost is calculated as the difference in cost between the non-mitigated and mitigated scenario when a proportion of units has the measure applied (see Appendix A for more detail).
- The externally provided activity data (livestock numbers/areas of crops) are now included in the model at an annual basis. In CB6 only the values at the end points of the time-period were used, and values in the years between were calculated from using a compound function.

New functionality

- The representation of capital expenditure (capex) has been overhauled to accurately account for the timings of when these expenditures and their renewal costs are incurred (see Appendix C for more details).
- An option to use an S-shaped (logistic) curve as opposed to linear growth when calculating the future uptake see Appendix B for more details).

Universal parameter updates

- Prices (crop, meat and milk, animal feed, nitrogen fertiliser, diesel) have been updated to 2022 values (increased with inflation).
- The projections for the emissions intensity of the grid electricity have been updated to be in line with CB7 assumptions.

2.3. Agricultural activity scenarios

Agricultural activity scenarios, i.e. annual crop and livestock production to 2050, are required as input into the model to calculate the emissions estimates without mitigation. These scenarios play an important role in the abatement potential of the mitigation measures. For example, if there are very few cattle in a scenario in the year 2050, then mitigation measures reducing enteric CH_4 emissions will have a small abatement potential.

Two agricultural activity scenarios were provided by the Climate Change Committee for marginal abatement cost analysis, based on wider changes in the food system and land use, namely Business as Usual (BAU) and the Balanced Pathway (BP). Figure 2.1 shows the projections for grassland, cropland and livestock numbers. The BP scenario is associated with a substantially reduced agricultural land use, the GHG emission and economic effects of this land use change is separately modelled, by the Climate Change Committee, and not included in the current modelling.

Both scenarios assumes 0.5% cumulative annual increase in milk yield until 2032 resulting in a small decrease in the dairy herd, in other areas the BAU scenario assumes the continuation of current land use and livestock production patterns. The BP scenario further assumes crop yield improvement (UK average wheat yield reach 10 t/ha by 2050 and the yield of other crops increases with the same proportion) as well as substantial changes in the food system. In this scenario red and white meat consumption decrease by 40% and 30%, respectively by 2050, and dairy product consumption is reduced by 20% by 2035 (then constant to 2050). 50% of food waste (baseline year 2007) is eliminated by 2030 and another 10% by 2050. Grazing livestock production moves away from the uplands: stocking rates on lowland grasslands increase by 3.8% by 2035 and by 10% by 2050. Finally, 10% of horticultural crops will be produced in indoor systems by 2050.

The scenarios assume that certain aspects of agricultural productivity (milk and crop yields) are going to improve in the period between 2024-2050. As some mitigation measures are also partially, or fully, generate GHG savings via productivity increase, including all mitigation measures in those scenarios would result in double counting the productivity improvements and thus overestimating the mitigation potential. For this reason we excluded the following mitigation measures from the BAU and BP scenario runs: ‘Improved health, dairy’, ‘Asparagopsis, dairy’ and ‘Asparagopsis, beef’. Additionally, we also excluded ‘Improved drainage’ from the BP scenario (Table 2.2).

2.4. Mitigation measures

The GHG abatement potential and cost of numerous agricultural mitigation measures have been estimated in the past years in the UK and in countries with comparable agricultural environment. The 114 mitigation measures extracted from nine of the most relevant publications are presented in Appendix D. This list was used to select 26 measures for the current study: those with a relatively high total

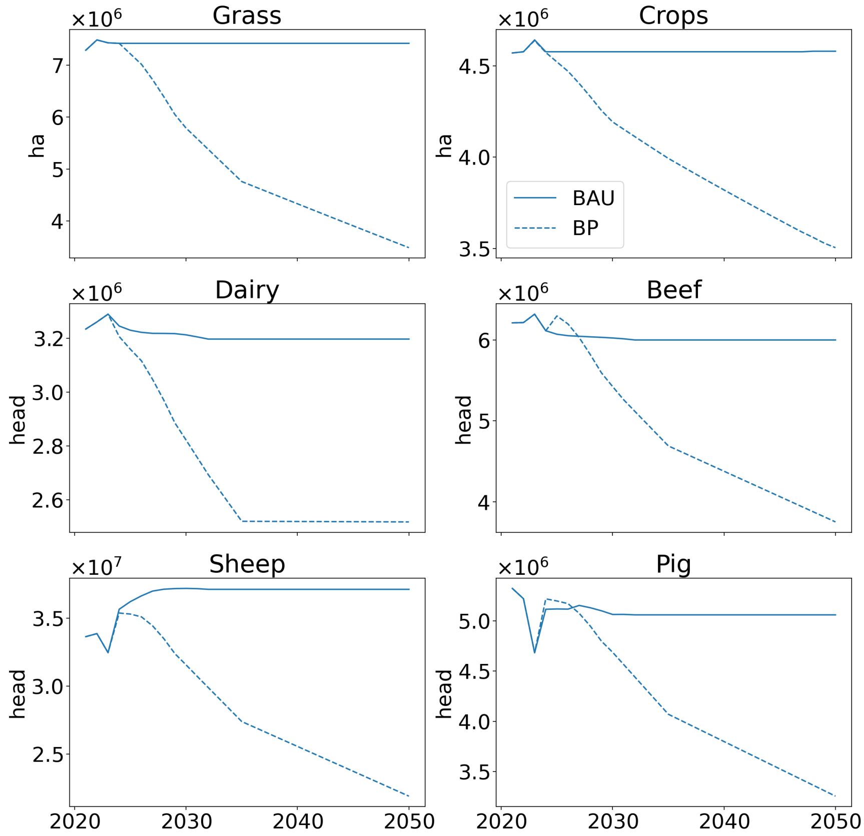

Figure 2.1: Projected livestock numbers and crop/grass areas for the business as usual (BAU) and balanced pathway (BP) scenarios. The category crop includes all crop types that are not improved permanent grass or improved temporary grass. Unfertilised permanent grassland (rough grazing) is not included

abatement potential in the UK, low probability of negative co-effects and strong evidence on GHG mitigation efficacy (Table 2.2). Most of the measures which require a (partial) change in land use have been excluded (except anaerobic digestion which has limited uptake) at the request of the Climate Change Committee, as they were part of a parallel work informing CB7. The livestock measures are represented separately for the main livestock categories (dairy, beef, sheep, pigs), thus in total the modelling included 40 measures.

The majority of the measures were already assessed for CB6 (Eory et al. 2020). Ten measures analysed in the CB6 MACC calculations were not included in the current study, as they were found to have low abatement potential in the UK or weak evidence on the system-wide GHG effects (‘Biostimulants’, ‘Crop health’, ‘Integrating grass leys in rotation’, ‘Analyse manure prior to application’, ‘Take stock off from wet ground’, ‘Higher sugar content grasses’, ‘High starch diet for dairy cows’, ‘Covering slurry with permeable plastic cover’, ‘Gene modified cattle for reducing enteric methane emissions’, ‘Higher uptake of current genetic improvement practices’).

Measures which are above the social cost of carbon are excluded from the final analysis. However, measures which are eventually below the social cost of carbon (as social cost increases and/or measure is more effective) are included but the Start Year (Table 2.2) is changed to the year when they become feasible in terms of the carbon price.

Ten measures were added to the assessment since CB6: ‘Reduced soil compaction, ‘Urease inhibitors’, ‘Improved nutrition, beef’, ‘Improved nutrition, sheep’, ‘Faster finishing, beef’, ‘Current breeding goal, sheep’, ‘Triticale’, ‘Improved health, pigs’, ‘Asparagopsis dairy’ and ‘Asparagopsis beef’. Although their assumptions are presented in Appendix D, upon consultation with the CCC both Asparagopsis measures were excluded from the analysis due to uncertainty around their technology readiness level and effects on production and emissions. The assumptions on the GHG mitigation efficacy, costs, applicability and current uptake of all the measures are presented in Appendix D.

2.5. Assumptions on future uptake

The evolution of the future uptake of the measures is described by 6 parameters: ‘applicability’, ‘current uptake’, ‘start year’, ‘potential uptake’, ‘years until potential uptake’ and an indicator controlling the nature of the uptake curve (linear or S-curve) (Table 2.2).

Applicability is the proportion of agricultural units where the measure is applicable. In some cases, particularly anaerobic digestion (AD) of animal manure, this value is artificially limited to avoid large land-use change within the mitigated scenario (AD also requires crops as feedstock and thus applying AD to a large proportion of animals will require a lot of crop products being used as AD feed stock). All uptake values are expressed as a proportion of applicable units.

Current uptake reflects the proportion of agricultural units that currently have the measure applied. The effect of current uptake on emissions is included in the non-mitigated scenario. The potential uptake is exogenous to the model (values provided by the Climate Change Committee) and represents an uptake level in the future. This uptake level is achieved over a certain period of time (‘years until potential uptake’). In any given year, the difference between the future uptake and the current uptake is the additional uptake; the additional uptake relates to the emission reduction effect calculated in the model.

Measures already commonly known by farmers have a start year of 2025, measures which are rarely used but commercially available start in 2027 or 2028, while measures requiring research and development start in 2035. For most measures it is assumed a 10 year time period is required to reach maximum uptake, though for measures with high current uptake it is 5 years and for those with longer establishment time (due to constraints in either physical or market infrastructure) it is 15 years.

The logistic growth option is a new addition to the model since CB6 and has been added at the request of the Climate Change Committee to capture the urgency in which some measure may need to be taken up in the future. In general, measures which can be applied now (start year: 2025) have a linear uptake and measures which have a longer lead in time have logistic growth (see more detail in Appendix C).

Table 2.2: Uptake assumptions of mitigation measures used in analysis. Measures which are labelled with a * are excluded from the BP to avoid possible double counting and those labelled with ** are excluded from both scenarios

Measure ID	Short measure name	Max uptake of applicable	Start year	Years until max uptake	Uptake function
	Crop/grass/soil measures				
1*	Reduced soil compaction	0.75	2025	10	L
2*	Optimal soil pH	0.75	2025	10	L
3	Cover crops	0.75	2025	10	L
4	Grass BNF	0.75	2025	10	L
7	Variable rate N	0.6	2025	10	L
8	Urease inhibitors	0.6	2027	10	S
9	Nitrification inhibitors	0.6	2027	10	S
49*	Improved drainage	0.5	2025	15	L
50	Reducing N excess	0.75	2025	5	L
51	Improved crop NUE	0.5	2040	10	S
59	Triticale	0.5	2025	15	L
	Livestock measures				
52	Precision feeding, dairy	0.75	2027	10	S
18	Improved nutrition, beef	0.6	2025	10	L
19	Improved nutrition, sheep	0.6	2025	10	L
20	Nitrate, dairy	0.6	2027	10	S
21	Nitrate, beef	0.5	2027	10	S
22	Nitrate, sheep	0.5	2027	10	S
26	3NOP, dairy	0.5	2027	10	S
27	3NOP, beef	0.5	2028	10	S
53**	Asparagopsis, dairy	0.5	2035	10	S
54**	Asparagopsis, beef	0.5	2035	10	S
29	Faster finishing beef	0.5	2025	10	L
33	Improved health, beef	0.6	2025	10	L

34	Improved health, sheep	0.6	2025	10	L
61	Improved health, pigs	0.5	2025	10	L
36	Genomic breeding, dairy	0.6	2025	10	L
37	Genomic breeding, beef	0.5	2025	10	L
38	Lower emission breeding, dairy	0.6	2035	10	S
39	Lower emission breeding, beef	0.5	2035	10	S
40	Current breeding goal, sheep	0.6	2025	10	L
43	Slurry acidification, dairy	0.5	2027	10	S
44	Slurry acidification, beef	0.5	2027	10	S
45	Slurry acidification, pigs	0.5	2027	10	S
46	Impermeable slurry cover, dairy	0.75	2025	10	L
47	Impermeable slurry cover, beef	0.75	2025	10	L
48	Impermeable slurry cover, pigs	0.75	2025	10	L
55	Increased milking frequency	0.6	2025	10	L
56	Biogas flaring, dairy	0.5	2027	10	S
57	Biogas flaring, beef	0.5	2027	10	S
58	Biogas flaring, pigs	0.5	2027	10	S
13	AD, cattle	0.6	2027	10	S
14	AD, pig	0.6	2027	10	S

3

Results

3.1. Total abatement and costs

According to the SRUC MACC model, without applying mitigation measures, agricultural GHG emissions in the UK (excluding emissions from poultry, goats, horses, deer and emissions from non-mobile machinery) are projected to be 40.9 Mt CO_2e in 2025 and 2050 in the BAU agricultural production scenario and 27.8 Mt CO_2e with the BP scenario in 2050, Figure 3.1e[1]. Future GHG emissions in the BP scenario are lower due to three assumptions in this land-use scenario: Dietary shift, reduced food waste and increased productivity. The shift in human diets towards less carbon intensive food items result in reduced livestock production and reduction in grass and cereal production, while the increased productivity reduces on-farm emissions related to input use (such as N_2O emissions from N fertiliser applications and from feed produced for livestock). By farmers applying the mitigation measures (see uptake rate assumptions in Table 2.2, only those under social cost of carbon), the annual GHG emissions would be 34.5 Mt CO_2e and 23.8 Mt CO_2e with the BAU and BP scenarios, respectively, by 2050, Figure 3.1e.

In percentage terms 15.7% and 14.3% of the GHG emissions can be mitigated by 2050 in the BAU and BP scenarios, respectively, by applying mitigation measures Figure 3.2e. Emission and mitigation trends follow similar patterns across the four countries of the UK, with slightly higher mitigation achievable in Northern Ireland (18.9% and 18.3% by 2050 in the BAU and BP scenarios, respectively, Figure 3.2b). The mitigation potential reaches its maximum level after about 10 years from 2025, in line with the assumptions of full policy implementation, which is 10 years for the majority of the measures. The slight temporary drop in the mitigation in England, Wales and Scotland is due to the abatement cost of slurry management measures changing as a result for changing embedded emissions in the grid electricity (affecting anaerobic digestion) and the increase in the social cost of carbon allowing more measures to be included in certain years.

[1] Note, the CCC calculate emissions using a different methodology resulting in slightly different baseline projections in the 7^{th} carbon budget report.

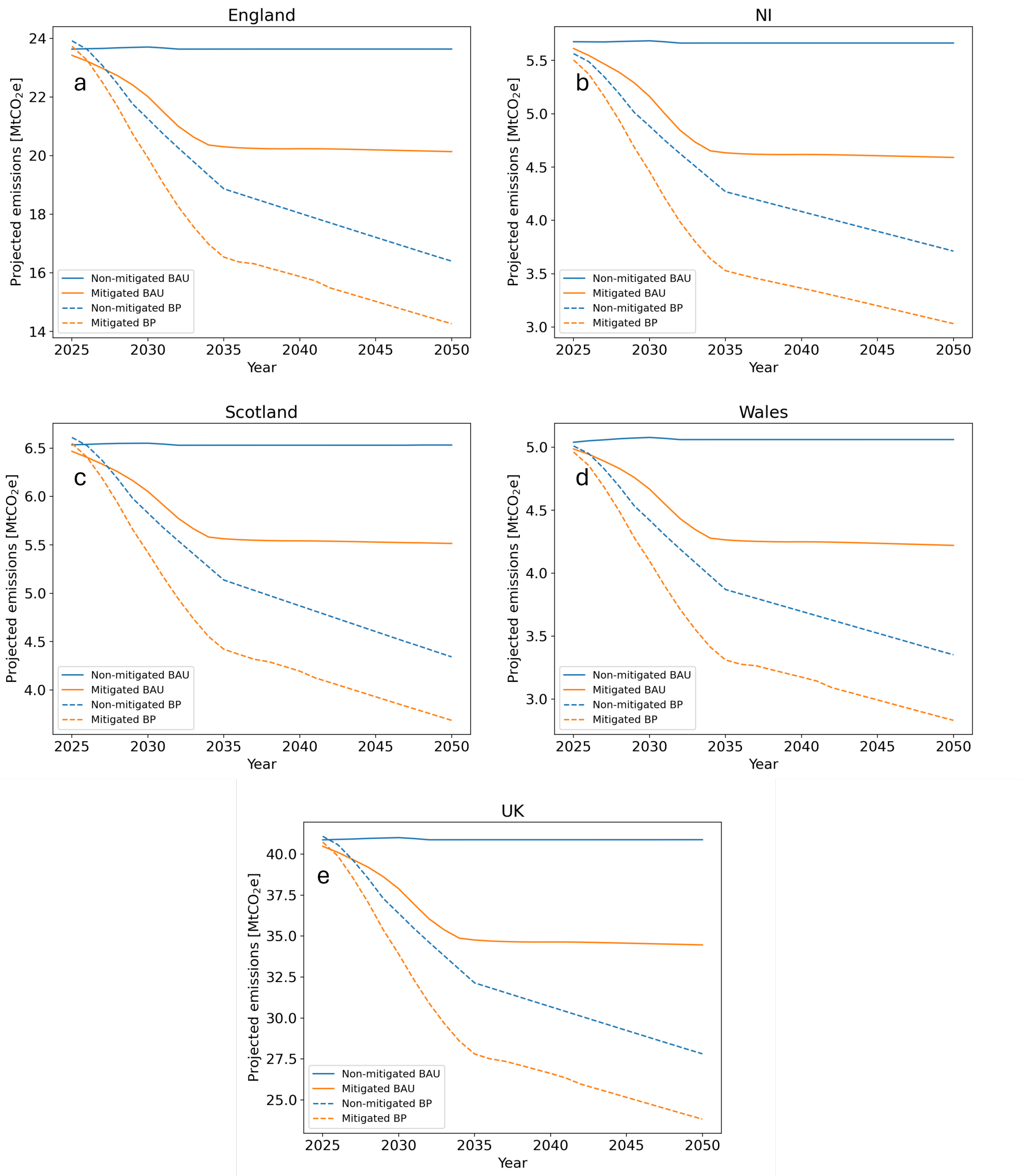

Figure 3.1: Projected absolute emissions for the Business as usual (BAU) and Balanced Pathway (BP) land use scenarios in the mitigated and non-mitigated scenarios in a) England, b) Northern Ireland, c) Scotland, d) Wales and e) the UK. Only mitigation measures which were below the Carbon price were included in this analysis.

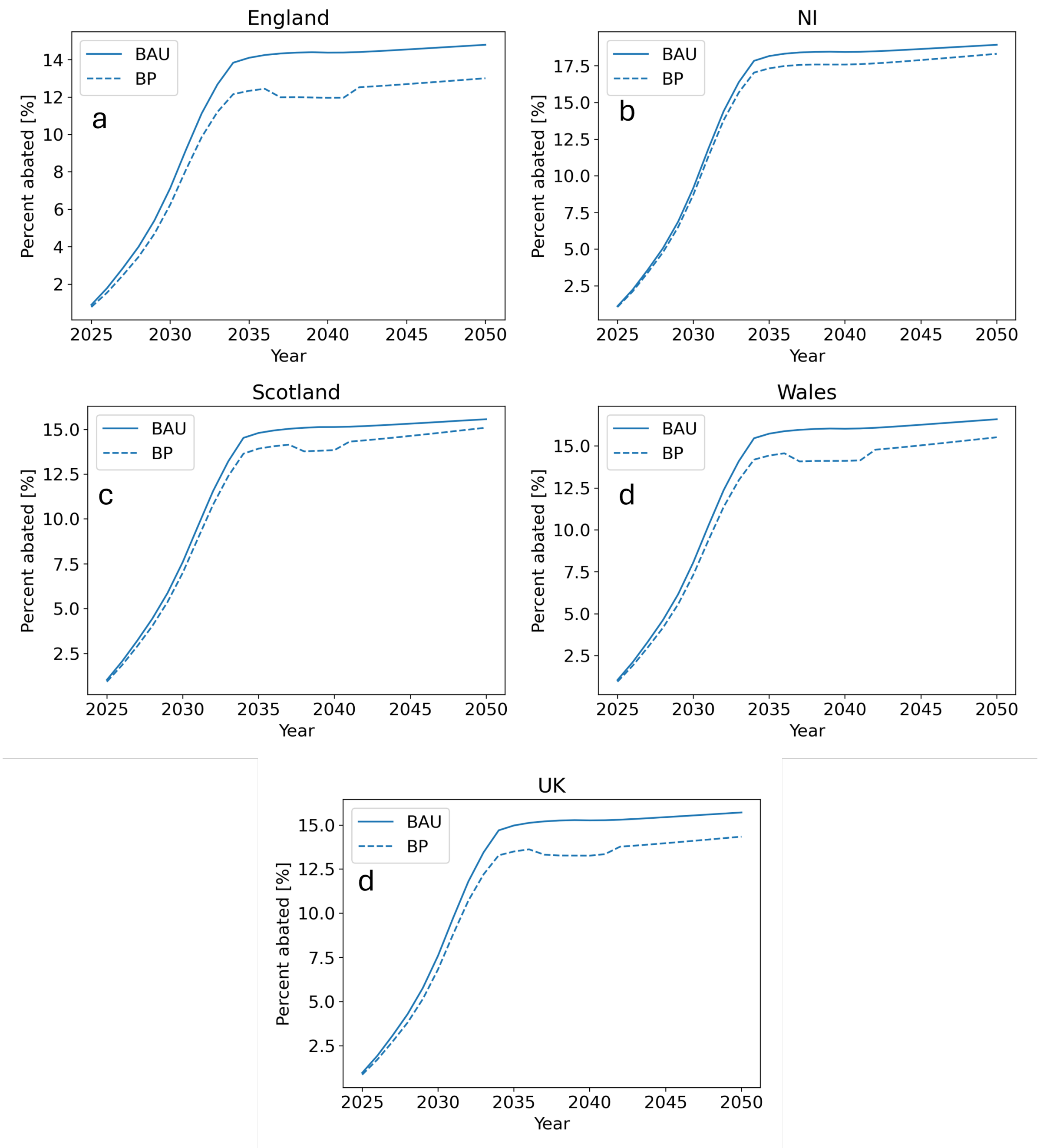

Figure 3.2: Projected total percent abatement potential for the Business as usual (BAU) and Balanced Pathway (BP) land use scenarios in a) England, b) Northern Ireland, c) Scotland, d) Wales and e) the UK. Only mitigation measures which were below the Carbon price were included in this analysis.

Mitigation measures where the annual abatement cost is above the social cost of carbon are excluded, in line with overall CCC methodology. This resulted the exclusion of 8 mitigation measures in the initial years (until the social cost of carbon is high enough), namely ‘Urease inhibitors’, ‘Nitrification inhibitors’, ‘AD, cattle’, ‘Improved nutrition, beef’, ‘Improved nutrition, sheep’, ‘Improved crop NUE’, ‘Nitrate, beef’ and ‘Improved health, pig’.

The results are similar to those reported in the agricultural mitigation assessment supporting the 6th carbon budget. All seven agricultural production scenarios in that report assumed some level of dietary shift and production efficiency improvements, and the mitigation potential was estimated to be 4-5.5 Mt CO_2e in 2035, dropping to 2.5-4.5 Mt CO_2e in 2050 (Eory et al. 2020).

The total annual cost of the mitigation is -512 M£ and -35.6 M£ in 2050 in the UK in the BAU and BP scenarios respectively. However, this requires large capital investment: the annual capital expenditure varies between 317 and 563 M£ for the BAU scenario and 51 and 232 M£ in the BP scenario (Figure 3.3). Capital expenditure varies yearly as it is a composite of capital expenditures of the various mitigation measures, with different lifetimes and thus investment periods. The operational expenditure reaches -869 and -137 M£ in the UK by 2050 for the BAU and BP scenarios, respectively (Figure 3.4), following the pattern of mitigation measure uptake. The large difference in capital, operational and total expenditure between the scenarios is due to the exclusion of measures, which would increase crop yield, from the BP scenario (Table 2.2), such as ‘Reduced soil compaction’ and ‘Optimal soil pH’, which have large investment costs but come with a large efficiency saving.

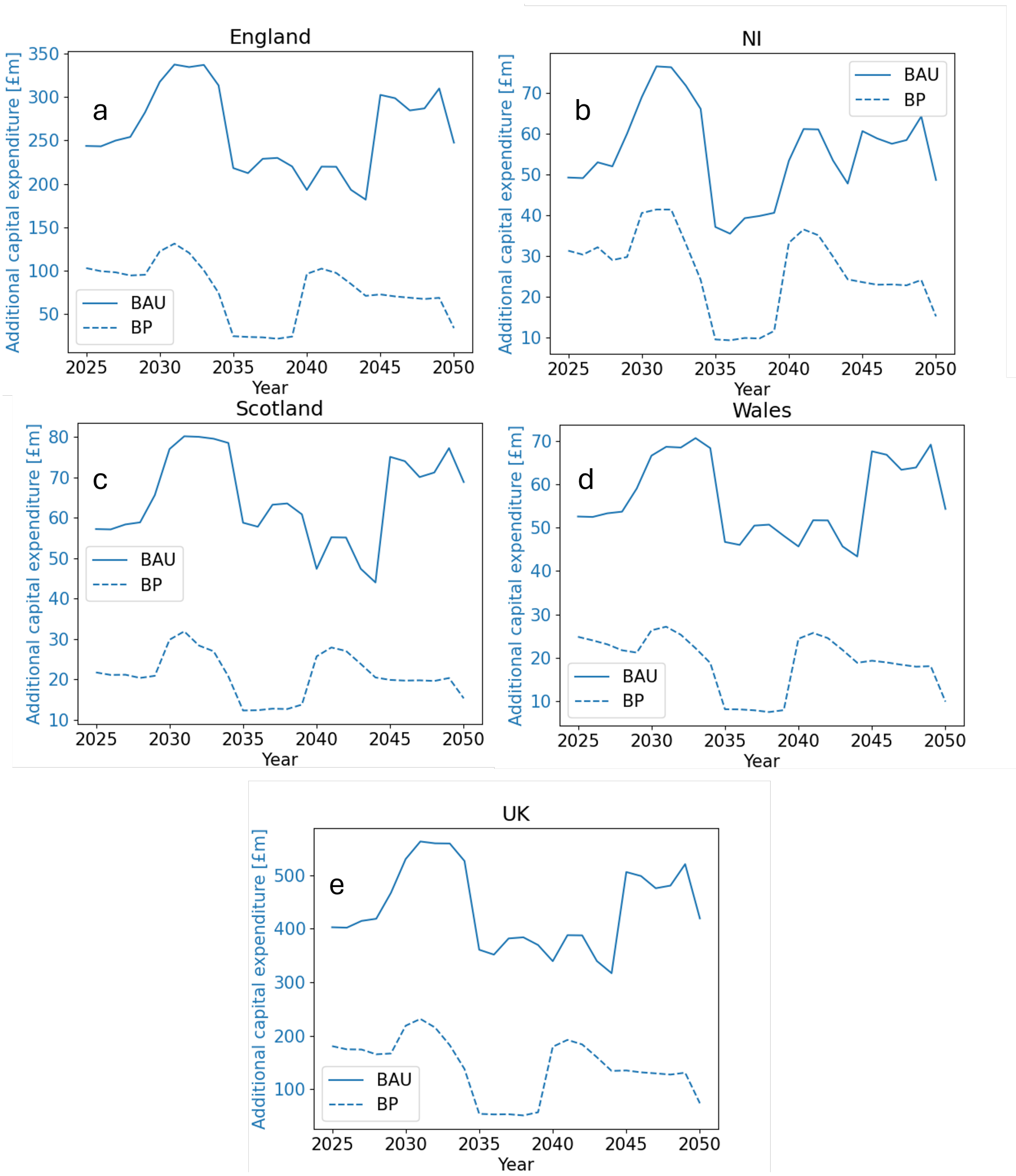

Figure 3.3: Projected total additional CAPEX (capital expenditure) in each year to achieve abatement potential shown in Figure 3.2 for the Business as usual (BAU) and Balanced Pathway (BP) land use scenarios in a) England, b) Northern Ireland, c) Scotland, d) Wales and e) the UK. Only mitigation measures which were below the carbon price were included in this analysis.

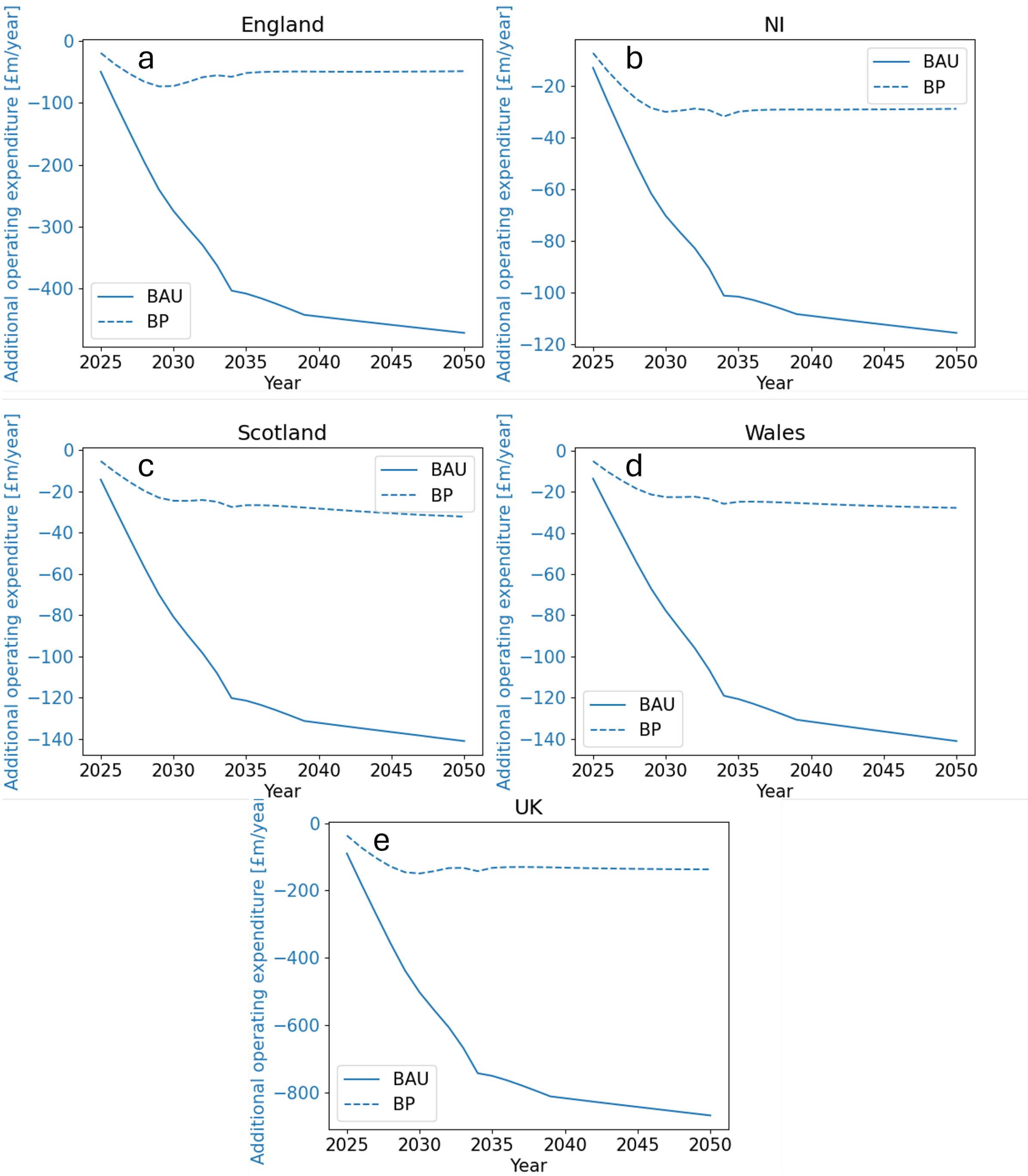

Figure 3.4: Projected total additional OPEX (operating expenditure) in each year to achieve abatement potential shown in Figure 3.2 for the Business as usual (BAU) and Balanced Pathway (BP) land use scenarios in a) England, b) Northern Ireland, c) Scotland, d) Wales and e) the UK. Only mitigation measures which were below the carbon price were included in this analysis. A negative OPEX means a net saving.

3.2. Mitigation measures

Marginal abatement cost curves (MACC) for both scenarios, up to the social cost of carbon, for 2035 and 2050 are presented on Figures 3.5 and 3.6 respectively. These figures show the abatement cost (y-axis) and abatement potential (x-axis) of each measure individually, based on estimated average values for the UK. On individual farms the values are expected to vary substantially and results should only be interpreted at the national (England, Scotland, Wales and Northern Ireland) level. The sum of the values on the x-axis represents the total abatement potential, i.e. 6.1 and 6.4 Mt CO_2e and in 2035 and 2050, respectively, for the BAU scenario; and 4.3 and 4.0 Mt CO_2e and in 2035 and 2050, respectively, for the BP scenario. These results include the interactions between measures so that if two measures interact, the measure further right on the x-axis in the MACC curve has the reduction applied. Therefore, these plots should *not* be used to assess the effectiveness of an individual measure being applied in isolation.

In both scenarios in 2050, the measure ‘Grass BNF’ has the highest abatement potential (and ranked highest), however, the efficiency measure ‘Faster finishing beef’ is ranked second for the BAU scenario while ‘Increased milking frequency’ is second in the BP scenario due to the differing amounts of beef and dairy cattle in the scenarios (Figure 3.6).

Approximately half the abatement potential in both scenarios are offered by measures where the abatement cost is below the social cost of carbon but is still positive, and the other half by measures which are estimated to provide savings (like the ones above and ‘Genomic breeding, dairy’, ‘Genomic breeding, beef’, ‘Improved health, sheep’, ‘Optimal soil pH’, ‘Improved drainage’). These profitable measures (with the exception of ‘AD pig’) all improve farm efficiency by increasing yield or reducing input costs (fertiliser, animal feed, etc), though many need initial investment. Overall, the implementation of all measures below the social cost of carbon is estimated to generate net profit. However, to achieve this net profit, large investment (up to £0.5 billion yearly) is required (Figure 3.3).

All but one manure management measures (‘Biogas flaring’, ‘Impermeable slurry cover’, ‘Slurry acidification’) have positive abatement cost (above the x-axis on Figure 3.6), nevertheless, they offer a large abatement potential. AD pig is the only manure management measure which has negative abatement cost, however, this is highly dependent on the uncertain future prices of co-digestate feed stock and electricity, as well as on the average emissions of electricity generation. Similarly, CH_4 reducing feed additives (‘Nitrate’ and ‘3NOP’) have a high abatement potential but their abatement cost is positive.

Certain measures have very low abatement cost and low abatement potential (i.e. thin and deep on Figure 3.6, such as ‘Reduced soil compaction’, ‘Lower emission breeding goal, dairy’, ‘Reducing N excess’); this can happen for two reasons. First, the measure can be primarily an efficiency saving practice, and the GHG abatement is only secondary, therefore the cost is very negative, but the abatement is small, causing abatement cost to be very negative. The measure ‘Triticale’ is an example for this. Second, they could be ‘out-ranked‘ by other measures: if measures ranked above them (further left on the MACC) target emissions with the same mechanism, the abatement potential of the measure in question is reduced, and the abatement cost becomes more negative. For example, ‘Lower emission breeding goal, dairy’ gets out-ranked by ‘Genomic breeding, dairy’ (Figure 3.6a), and as they are mutually exclusive, the abatement potential of ‘Lower emission breeding goal, dairy’ is drastically reduced. Still, this measure applied individually would be effective, only with less financial savings.

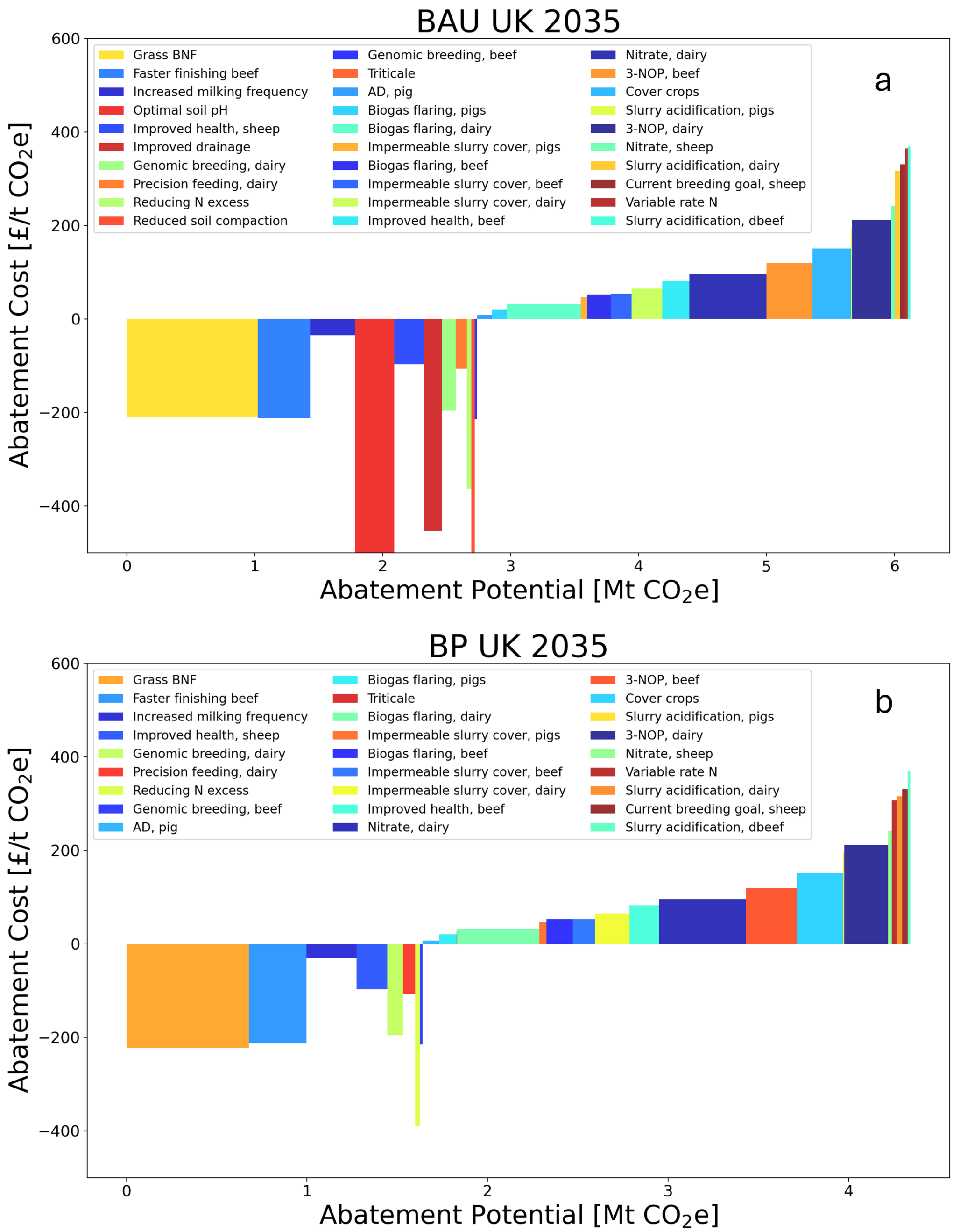

Figure 3.5: Marginal abatement cost curves (MACC) for the entire UK in the a) Business as Usual (BAU) and b) Balanced Pathway (BP) land use scenarios in 2035 considering potential interactions between the measures. Note the different x-axis scales. The measures appear ranked within the legend. The y-axis is restricted between -400 and 600 £/tCO_2e.

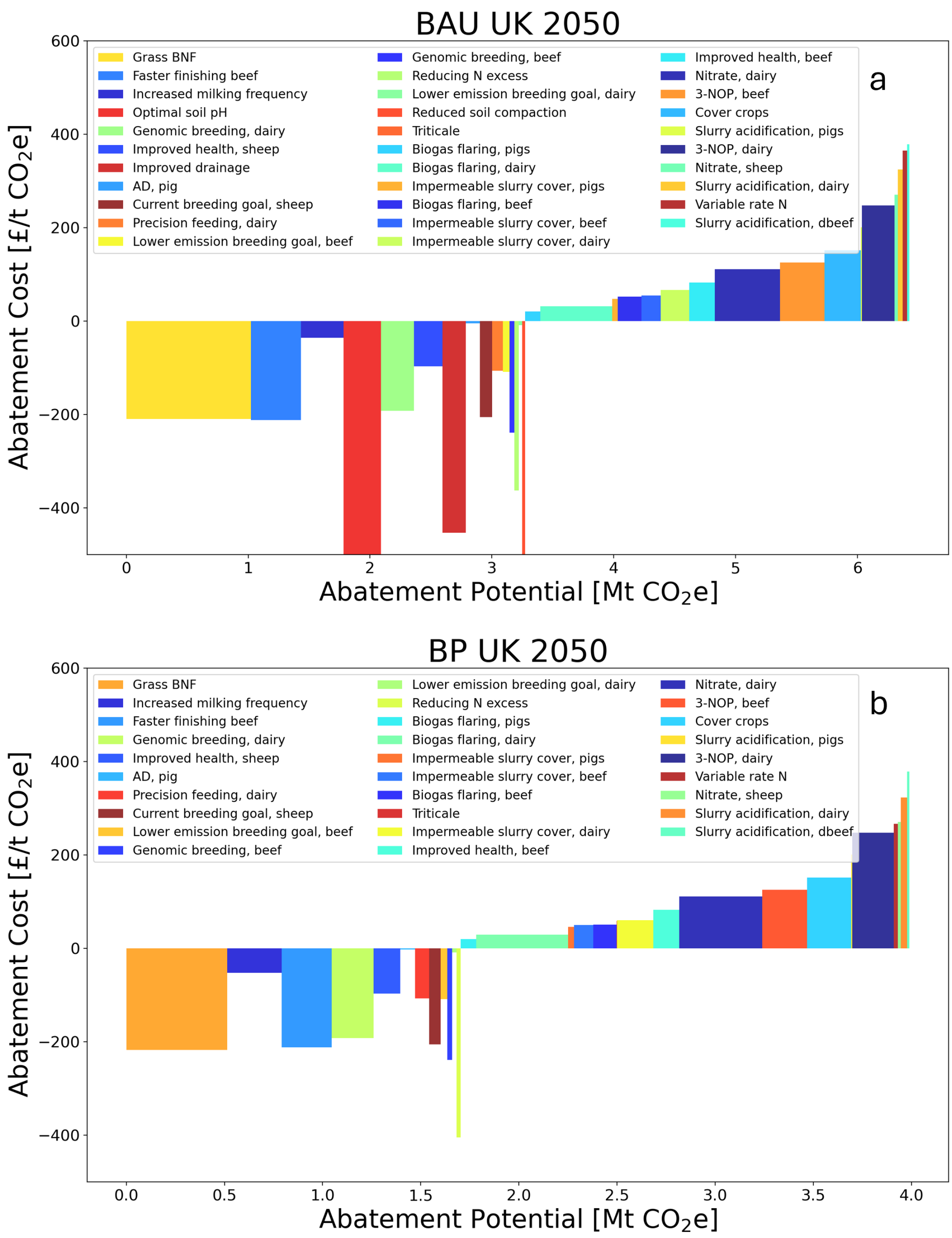

Figure 3.6: Marginal abatement cost curves (MACC) for the entire UK in the a) Business as Usual (BAU) and b) Balanced Pathway (BP) land use scenarios in 2050 considering potential interactions between the measures. Note the different x-axis scales. The measures appear ranked within the legend. The y-axis is restricted between -400 and 600 £/tCO_2e.

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A

Additional Operating Cost Calculation

In CB6 additional operational cost was calculated as average cost per applied unit multiplied by number of applied units which resulted in a slight miss calculation of cost when the mitigation measure altered the yield and thus number of units. Now additional operational cost is calculated as the difference in operational costs between the non-mitigated scenario and the scenario when a proportion of units has the measure applied. Here we describe the differences between the methodology for calculating the additional operating cost of a mitigation measure using a mitigation measure on cattle as an example as this is the most complicated.

Let c be the annual cost per head of the mitigation, F_0 and F_{MM} be the feed cost per head of the non-mitigated and mitigated animals respectively, $let N_0$ and N_{MM} be the value of nitrogen (N) excreted per head by the non-mitigated and mitigated animals respectively (this is to account for the value of the N in the manure which can be changed if the number of animals change), n be the total number of animals in the system, Y the yield per head of the non-mitigated animals, y be the percent change in yield due to applying the mitigation measure, p be the percent of animals where the mitigation measure is applied and v the value of the product per unit. In the mitigated scenario, the number of animals where the mitigation measure has been applied is $\hat{n}_{MM} = \frac{p}{100}n$ and the number of animals where the mitigation is not applied is $n_0 = \frac{1-p}{100}n$. Since the mitigation measure increases the yield of the animals by y% we need less animals where the measure is applied to produce the same amount of food, denoted by $n_{MM} = \frac{\hat{n}_{MM}}{1+\frac{y}{100}}$ which accounts for this fact.

Since only a partial accounting of the farm accounts is considered, we introduce and ‘auxiliary cost’ which can account for efficiency savings due to increased yields. This auxiliary cost is defined by assuming that any additional income that would have come from the increased production of the surplus animals ($\hat{n}_{MM} - n_{MM}$) results in a saving when the animal numbers are reduced resulting in the equation for auxiliary cost per head:

$$a_{MM} = (1 + \frac{y}{100})Yv - Yv = \frac{y}{100}Yv,$$

if this value is negative, it saves cost. When no yield-effecting mitigation measure has been applied ($y = 0$) the value is 0.

In previous carbon budget delivery plans (CB<=6) the additional operating cost of a measure was calculated by first calculating the difference in operational cost per head between the mitigated and non-mitigated units which can be represented by the formula:

$$\Delta cph_{MM} = c + (N_0 - N_{MM}) + (F_{MM} - F_0) - \frac{y}{100}Yv + a_{MM},$$

where Δ refers to the fact that this a difference in cost per head and the income from selling the produce is seen as a negative cost. Note the order of subtraction for the value of N in the manure is reversed since less N being produced by the mitigated animals should result in a positive cost. The total additional operating expenditure in CB6 was then calculated as

$$TC_{CB6} = \Delta cph_{MM} \times n_{MM}.$$

This approach can result in a slight error in cost when the mitigation measure has a yield change causing a change in animal numbers because it does not account for the total number of animals in the system. We now calculated the total additional operating cost as the total additional operating cost in the mitigated scenario minus that in the non-mitigated scenario. The cost per head for the mitigated animals is

$$cph_{MM} = c - N_{MM} + F_{MM}(1 + \frac{y}{100})Yv + a_{MM},$$

while for the non-mitigated animals it is

$$cph_0 = -N_0 + F_0 - Yv + a_0.$$

We then calculate the net cost in the non-mitigated scenario as $NC_0 = cph_0 n$ and in the mitigated scenario as $NC_{MM} = cph_0 n_0 + cph_{MM} n_{MM}$ resulting in the following formula for the additional operating expenditure in the mitigated scenario

$$TC_{CB7} = NC_{MM} - NC_0 = cph_0 n_0 + cph_{MM} n_{MM} - cph_0 n.$$

We can see the difference between the two approaches by subtracting TC_{CB6} from TC_{CB7}:

$$TC_{CB7} - TC_{CB6} = N_0(n - n_0 - n_{MM}) + F_0(-n + n_0 - n_{MM}) + Yv(n - n_0 + n_{MM}),$$

and we see that they are only guaranteed to produce the same result when $n = n_0 + n_{MM}$ i.e. when there is no yield change for the mitigated animals.

B

Logistic Uptake Evolution

Here we describe the equations used for linear and logistic uptake evolution in terms of the parameters in Table 2.2. The logistic uptake evolution is a new option added since CB6. Let $0 \leq M \leq 1$ be the potential uptake proportion of the mitigation measure, t_s be the year the mitigation measure starts, T be years until potential uptake and let $0 \leq B \leq 1$ be the current uptake proportion. t and t_s are indexes from the starting year of the simulation, so if the year the mitigation measure starts is 2024 and the simulation starts in 2016 then $t_s = 7$. If a mitigation measure is assigned linear uptake growth (L) then a piece-wise linear function is used giving a Z-shaped function:

$$U_Z(t) = \begin{cases} B & t \leq t_s \\ \frac{M-B}{T}t - \frac{M-B}{T}t_s & t_s \leq t \leq t_s + T \\ M & t > t_s + T. \end{cases}$$

Typically, a logistic equation is defined by the formula

$$f(t) = \frac{M}{1 - e^{-k(t-t_0)}},$$

where M is the potential uptake, t_0 is the value of t where $f(t)$ is $M/2$ and k is the logistic growth rate. We re-factored the logistic equation so that the same parameters as the linear equation can be used and force the logistic equation to start in the start year and reach the potential uptake in the desired period (T years) resulting in the equation giving an S shaped function:

$$U_S(T) = \begin{cases} B & t \leq t_s \\ \frac{M-B}{1+\exp(\frac{-2ln(\frac{1}{1-\epsilon})}{T}(t-t_s-\frac{T}{2}))} & else, \end{cases}$$

where ϵ is a free parameter which controls how close U_S is to M at time T i.e. $U_S(T) = M - \epsilon M$. By default, ϵ is set to 0.01 for all mitigation measures which have a logistic uptake evolution. This equation is discontinuous at $t = t_s$.

C

Capex and Renewal Costs

Agricultural mitigation measures can have an upfront cost (capex) which is incurred when the mitigation measure is taken up. For example, a mitigation measure may require the purchase of a new attachment for a tractor. The tractor attachment can have a live span of t^* years and needs replacing and thus the capex charge is incurred t^* years later when the farmer buys the replacement tractor attachment. Additionally, over the time span of the simulation, the number of agricultural units (i.e. hectares of land under cultivations or individual animals) are changing due to land use change or increases in yield causing fewer units being required to produce the same quantity of produce. Additionally, uptake of the mitigation measure typically scales up in time e.g. n units take up the mitigation measure in 2024, then another n in 2025, similarly, the renewal costs will happen t^* years later. However, due to a possible decrease in total agricultural units, some of these mitigated units maybe decommissioned and do not require a renewal cost. In this appendix, we detail how capex and renewal costs are included in the Agricultural MACC while accounting for changing units.

Let $TN(t)$ be the total number of units (e.g. hectares) at time t which can increase or decrease, and let $0 \leq p(t) \leq 1$ be the proportion of units where the mitigation has been applied at time t, typically this is always increasing then reaches a maximum i.e. $p'(t) \geq 0$.

Then the proportion of units where the mitigation measure has been applied is $A(t) = p(t)TN(t)$ where it is unclear if the derivate, $A'(t) = p'(t)TN(t) + p(t)T'(t)$, is positive or negative. Let $C > 0$ be the Capex cost when one unit has the mitigation measure applied which has a lifetime of t^* years, when the cost is incurred again. We want to find a formula for the total capex cost function in time denoted $TC(t)$. We will first start with simple cases then include more detail to get to the final equation to capture all the detail. We will use a continuous description then discretize to get an equation relevant at a yearly time resolution. The equation will be able to handle non-linear total-unit functions and proportion of uptake functions in time.

No renewal costs

In this case the capex cost function is proportional to the rate at which $A(t)$ changes:

$$TC(t) = CA'(t).$$

This equation is only valid when $A'(t) \geq$ so we don't get negative costs. If we relaxed this assumption, we can use the following equation:

$$TC(t) = \max(CA'(t), 0),$$

to be sure we don't get negative costs when uptake decreases. Note, negative costs would imply that as farmers stop applying the mitigation measure, they can sell their tractor attachment for the price they purchased it. However, since this is a national model, there would be no demand.

Renewal costs but $TN(t)$ is constant

Then there is also renewal costs every integer multiple of t^* years proportional to the capex cost t^* years previous:

$$\begin{aligned} TC(t) &= CA'(t) + CA'(t - t^*) + CA'(t - 2t^*) + ... \\ TC(t) &= \sum_{k=0}^{N} CA'(t - kt^*). \end{aligned}$$

We require TN to be constant in this case to ensure that historically mitigated units do not get decommissioned and we are not charging the renewal costs unnecessarily.

TN monotonically decreasing but A monotonically increasing

In this case we account for when previously mitigated units are decommissioned. We assume that units that are out of commission are disturbed evenly amongst mitigated and non-mitigated units so the renewal cost can be scaled down by the ratio $\frac{TN(t)}{TN(t-kt^*)}$:

$$\begin{aligned} TC(t) &= CA'(t) + CA'(t - t^*)\frac{TN(t)}{TN(t - t^*)} + CA'(t - 2t^*)\frac{TN(t)}{TN(t - 2t^*)} + ... \\ TC(t) &= \sum_{k=0}^{N} CA'(t - kt^*)\frac{TN(t)}{TN(t - kt^*)}. \end{aligned}$$

We require $TN'(t) \leq 0$ so that $\frac{TN(t)}{TN(t-kt^*}$ ≤ 1 thus we do not charge a renewal cost for new units. We can relax this assumption and use the following equation

$$TC(t) = \sum_{k=0}^{N} CA'(t - kt^*) \min(1, \frac{TN(t)}{TN(t - kt^*)}).$$

Final Equation

We can remove all the restrictions on the growth of A and TN and use the following equation:

$$TC(t) = \sum_{k=0}^{N} C \max(0, A'(t - kt^*)) \min(1, \frac{TN(t)}{TN(t - kt^*)}).$$

Discretizing

We use a backward difference with a step size of one year to discretize the derivative (i.e. the previous years uptake of the measure is used to define A' in the current year), resulting in the final equation used in the MACC model. Let $t_0, t_1, t_2, ..., t_M$ be the first of January in year $0, ..., M$:

$$TC(t) = \sum_{k=0}^{N} C \max(0, A(t - kt^*) - A(t - kt^* - 1)) \min(1, \frac{TN(t)}{TN(t - kt^*)}),$$

choose integer N so that $N \geq \frac{M}{t^*}$ to capture all renewal costs.

D

Mitigation Measures

This appendix briefly summarises each measure and details how each mitigation measure is parameterised in the MACC model. Each measure has an associated table which lists the parameters, e.g. for MM1 Loosing compacted soils and preventing soil compaction it is Table D.1. When a ‘Unit’ is allocated as ‘Change’ this means the parameter is changed proportionally compared to the non-mitigated values.

D.1. Reduced soil compaction (MM1)

Soil compaction increases N_2O emissions from both croplands and grasslands (Pulido-Moncada et al. 2022). Compaction occurs as a result of physical impact from animal trampling and agricultural machinery. While the first type of compaction mainly affects the upper layer of the soil, machinery can cause compaction to 90 cm depth (Berisso et al. 2012). Field measurements showed that the N_2O emissions from compacted croplands can be 1.4-9.9 higher than from non compacted soils, and in the case of grasslands compacted soils can emit 1.2-7.4 times more N_2O than non compacted areas (Pulido-Moncada et al. 2022). This emission difference can be especially high at fertilisation events (ibid.). Besides increasing N_2O emissions, compaction also causes a reduction in yield (Zhang et al. 2024). Though best practice is to prevent soil compaction (e.g. by lowering tractor tyre pressure, avoiding machinery and livestock on fields in wet periods), once it is present, it can be alleviated by subsoiling and ploughing, depending on the extent of compaction.

Consistent information on the prevalence and extent of soil compaction in the UK is lacking (Eory et al. 2023; Eory et al. 2015). Though the latest Farm Practices Survey where soil compaction was included (2018, Current Farming Topics) showed an approximately 25% drop in farmers reporting soil compaction problem, compared to 2012 (Defra 2013; Defra 2019), we used our previous, conservative estimate of 20% compaction both on croplands and grasslands.

Reducing soil compaction was not included in the CB6 report (Eory et al. 2020), though its mitigation was quantified in the 5th Carbon Budget (Eory et al. 2015). In a report to Scottish Government, those assumptions were updated (Eory et al. 2023). For the current analysis we used the assumptions from this latest report, adding the GHG emissions arising from the diesel use and updating the cost assumptions.

For the diesel use and cost assumption we relied on the approximation that in half of the cases topsoil cultivation is enough while in the other half subsoiling is necessary. The diesel use was estimated with the average of subsoiling and heavy cultivation (20 l ha^{-1}) (SAC 2023). The subsoiling cost was estimated as the sum of contractor and diesel cost (£67 ha^{-1} and £24 ha^{-1}, respectively) (SAC 2023). The topsoiling contractor cost was estimated as £36.5 ha^{-1} (adjusted for inflation from Newell-Price et al. 2011) and the related diesel cost was approximated with heavy cultivation diesel cost (£24 ha^{-1}) (SAC 2023). Table D.1 shows all assumptions used for 'Reduced soil compaction' in the MACC model.

Table D.1: Assumptions for modelling reducing soil compaction

Parameter	Unit type	Unit	Value	Source
Crop yield	non-grass (but not: miscanthus, willow, fruits and wine grape)	Change	0.02	(Eory et al. 2023)
Crop yield	temporary grassland	Change	0.01	(Eory et al. 2023)
Crop residue N	non-grass (but not: miscanthus, willow, fruits and wine grape)	Change	0.02	(Eory et al. 2023)
Crop residue N	temporary grassland	Change	0.01	(Eory et al. 2023)
EF_1	all	Change	-0.06	(Eory et al. 2023)
Diesel consumption	all	kg CO_2e ha^{-1} y^{-1}	5.04	(SAC 2023)
Current uptake	all	-	0	(Eory et al. 2023)
Applicability	non-grass	-	0.2	(Eory et al. 2023)
Applicability	temporary grassland	-	0.2	(Eory et al. 2023)
Applicability	permanent grassland, miscanthus, willow, fruits and wine grape	-	0	(Eory et al. 2023)
Cultivation cost	all	£ ha^{-1}	74.62	(SAC 2023)
Lifetime of cultivation	all	year	10	(Eory et al. 2023)

D.2. Optimal soil pH (MM2)

Plant productivity depends on the acidity (pH) of the soil; most crops prefer the soil to be in the range of pH5.5 – pH6.5, depending on the crop and the soil type (AHDB 2024b). Beyond this range the nutrient availability is reduced, and thus crop growth is limited (ibid.). Furthermore, soil acidity is an important factor in determining the extent of N_2O emissions, more acidic soils have higher N_2O losses (Goulding 2016; Wang et al. 2018; Zhu et al. 2019). The default IPCC soil N_2O emission factor of 1% happens at soil pH 6.76, according to a global meta-analysis (Wang et al. 2018). Finally, soil pH also impacts the soil C content, though this relationship is context specific (Holland et al. 2018). In general, alkaline soils can have higher C concentrations than acidic soils (Fornara et al. 2011; Goulding 2016; Kemmitt et al. 2006) though in soils with high organic C content (peaty soils) liming can increase decomposition rate and thus CO_2 loss (Biasi et al. 2008).

The extent of arable and grassland areas in the UK where the pH is suboptimal is difficult to estimate, direct statistical information is not available. From reviewing relevant data, the CGSI project concluded that around 9% of arable and 22% or grassland could be untested and too acidic (Barnes et al. 2022), giving a conservative estimate for the applicability of the measure.

Soil pH was included in the CB6 report (Eory et al. 2020). In a report to Scottish Government those assumptions were revisited and some of them were changed (Eory et al. 2023). For the current analysis we used the assumptions from this latest report, with two further changes: adjusting the costs with inflation and updating the CO_2 emissions from liming, as the previous assumptions included pre-farm-gate emissions.

Table D.2: Assumptions for modelling improving soil pH

Parameter	Unit type	Unit	Value	Source
Crop yield		Change	6.22%	(Eory et al. 2020)
Crop residue N	non-grass	Change	6.22%	(Eory et al. 2020)
EF_1		Change	-3%	(Eory et al. 2023)
Carbon sequestration		t CO_2e ha^{-1} y^{-1}	0.3	(Eory et al. 2023)
CO_2 emissions from liming		t CO_2e ha^{-1} y^{-1}	0.11	1 t ha^{-1} limestone in every 4 years, C content 12% (IIPCC 2006)
Current uptake		-	0	(Eory et al. 2020)
Applicability	non-grass		0.09	(Eory et al. 2023)
Applicability	improved grass		0.22	(Eory et al. 2023)
Lime cost		£ ha^{-1}	156.7	(Eory et al. 2023)
Spreading cost		£ ha^{-1}	10.2	(Eory et al. 2023)
Spreading cost lifetime		Year	4	(Eory et al. 2023)
Soil analysis cost		£ ha^{-1}	24.2	(Eory et al. 2023)
Soil analysis cost lifetime		Year	4	(Eory et al. 2023)

D.3. Cover crops (MM3)

Cover crops are non-cash crops which replace bare fallow in the winter period in years when a spring crop is sown in the rotation, integrated into the main crop rotation (Poeplau et al. 2015). They are typically grown to maintain soil cover during fallow periods which limits soil erosion, holds residual N in the soil-plant and increases soil carbon content. They provide two-fold benefits in terms of net GHG emissions: reducing N leaching in the winter periods and increasing the soil carbon content.

In the CB6 report the carbon sequestration effect was assumed to be 1.06 t CO_2e ha^{-1} y^{-1}, based on the cover crop modelling carried out in CGtSI project (Barnes et al. 2022). To avoid the complexity of relying on a sub-model, in this work we use a published average the value found by a global meta-analysis; which is 1.17 t CO_2e ha^{-1} y^{-1} (0.32 t C ha^{-1} y^{-1}) for the first 40 years and 0 afterwards (Poeplau et al. 2015). The 40-year cut-off period reflects the saturation of the carbon sequestration. The effect on N losses (leaching factor) remained the same.

The CB6 project found no statistics about the current uptake of catch/cover crops and assumed that they are used on 30% of the area where they are applicable. Since then we identified relevant, though slightly outdated Eurostat statistics, showing (2016 UK data from the UK), showing that approximately 3% of land was under cover or intermediate crop and 54% under non-winter crop in 2016 (Eurostat n.d.) i.e. uptake in 2016 was around 6% of the applicable area. (Eurostat n.d.) Table D.3 provides a summary of the how the measure is implemented in the model.

Table D.3: Assumptions for modelling cover crops

Parameter	Unit type	Unit	Value	Source
Carbon sequestration		t CO_2e ha^{-1} y^{-1}	1.17	New
Frac leach		Change	-45%	(Eory et al. 2020)
Current uptake	Non-grass non-winter crops	-	0.06	New
Applicability	winter crops, grass, all fruits, willow, miscanthus, maize, linseed, pulses, other fodder crops	-	0	(Eory et al. 2020)
Applicability	Potatoes and root crops	-	0.368	(Eory et al. 2020)
Applicability	Oats non-winter	-	0.173	(Eory et al. 2020)
Applicability	Wheat non-winter	-	0.012	(Eory et al. 2020)
Applicability	OSR non-winter	-	0.003	(Eory et al. 2020)
Applicability	All other crops	-	0.234	(Eory et al. 2020)
Combined Cost	All applicable crops	£ ha^{-1}y^{-1}	180.7	(Eory et al. 2020)

D.4. Biological nitrogen fixation in grassland (MM4)

N_2O emissions arising from the use of synthetic N fertilisers can be reduced by relying more on biologically fixed N in crop production. Biological N fixation occurs in N fixing crops (legumes) which form symbiotic relationships with bacteria (Rhizobia) in the soil that allow them to transform atmospheric N_2 to reactive N compounds, and use this in place of N provided by synthetic fertilisers. Besides the fixed N supporting the growth of the legume crop (e.g. clover), part of these N compounds also become available to the grass plants, reducing their need for synthetic N. This effect becomes substantial at clover content of around 20%-30% in the sward (Lüscher et al. 2014). The effect is robust and persistent across legume species and climatic regions, as shown by a series of experiments in Europe over three years, where savings of over 300 kg N ha^{-1} were achieved without compromising the yield (Lüscher et al. 2014). Evidence suggests that the biological fixation itself does not lead to significant emissions; the IPCC 2006 recommendations (IPCC 2006) removed legumes as a source of direct N_2O emissions (Lüscher et al. 2014). Another effect of clover in the swards on GHG emissions is that the proportion of N leached into the ground (and eventually to ground and surface water) can increase if the clover content is too high (Lüscher et al. 2014).

Since CB6 (Eory et al. 2020) we have updated the additional cost of grass seed containing clover and the re-seeding times, Table D.4. We have also included the effect of reduced fuel use due to reduced fertiliser spreading as well as the increases fuel use due to drilling permanent grass with clover and any associated costs/saving, Table D.4.

Table D.4: Assumptions for modelling grass-legume mix

Parameter	Unit type	Unit	Value	Source
Synthetic N fertilisation rate	All improved grass	kg N ha^{-1} y^{-1}	0	(Eory et al. 2020)
CO_2 emissions from fuel use	Temporary improved grass	kg CO_2e ha^{-1} y^{-1}	-4.03%	(SAC 2023)
CO_2 emissions from fuel use	Permanent improved grass	kg CO_2e ha^{-1} y^{-1}	9.63	(SAC 2023)
Current uptake	All improved grass	-	0.26	(Eory et al. 2020)
Applicability	All improved grass	-	1	(Eory et al. 2020)
Applicability	All other crops	-	0	(Eory et al. 2020)
Additional seed cost	All improved grass	£ ha^{-1}	6.05	(Eory et al. 2023)
Additional seed cost lifetime	Temporary improved grass	y	2	(Eory et al. 2023)
Additional seed cost lifetime	Permanent improved grass	y	5	(Eory et al. 2023)
Reduced fertiliser spreading cost	All improved grass	£ ha^{-1} y^{-1}	-13.43	(SAC 2023)
Drilling cost	Permanent improved grass	£ ha^{-1}	77.9	(Eory et al. 2020)
Drilling cost lifetime	Permanent improved grass	y	5	(Eory et al. 2020)

D.5. Variable rate nitrogen application (MM7)

Variable rate N technology (VRNT) is an example precision farming where N doses are varied within a field to account for the N requirement of the crop at the location within in a field. It has the potential to reduce GHG emission intensity by reducing the N fertiliser application rate and/or by increasing the yield (Denora et al. 2023). Evidence on the yield, N use, and especially GHG effects of VRNT has been sporadically reported in the past, with evidence from across a range of countries, crops, precision farming technology solutions, fertilisation levels, making it hard to compare N savings and yield effects . Most evidence suggest that VRNT can reduce fertiliser use by 5 to 40% depending on crop and initial fertiliser dose with no impact on yield (Argento et al. 2021; Denora et al. 2023; Jovarauskas et al. 2021; Vizzari et al. 2019). However, some evidence suggests grain protein can be reduced due to the reduced N availability (Vizzari et al. 2019). Variable rate N application was included in the CB6 analysis (Eory et al. 2020) and those assumptions were updated in this report. Advice from farm consultants about current experiences suggested that in practice the N rate is reduced, rather than the yield increasing. Based on the reported experimental results, the N reduction was modelled as 10%, a conservative value representing cautious N reductions so not to affect the grain protein content. Technically the measure is applicable on all cropland and grassland, however, the within-field variability is not large enough everywhere to apply this measure. We assumed that the measure is applicable on 80% of the land area. Current uptake is estimated from the 2019 Farm Practices Survey (Defra, 2020), which found that in England 42% of cereal and cropping and 11% of grazing livestock farms use various precision farming technologies. Costs were modelled as annual costs, as precision farming services are increasingly available from contractors. The premium on Variable rate spreading compared to uniform spreading is £4.46 ha^{-1}) (NAAC 2024) and the cost of drone mapping (£7 ha^{-1}) (*pers. comm.* with Steve Frost, SAS Land Services).

Table D.5: Assumptions for modelling variable rate nitrogen application

Parameter	Unit type	Unit	Value	Source
Synthetic N fertilisation rate		Change	-10%	new
Current uptake	Non-grass crops	-	0.42	new
Current uptake	Improved grass	-	0.11	new
Applicability	All crops	-	0.8	new
Cost difference between variable rate and uniform		£ ha^{-1} y^{-1}	4.46	new
Cost of drone vegetation mapping		£ ha^{-1} y^{-1}	7	new

D.6. Urease inhibitors (MM8)

N fertilisers containing urea have high NH_3 emissions upon application as soil bacteria containing urease enzyme start to break down the urea (Sigurdarson et al. 2018). This high NH_3 volatilisation results in indirect N_2O emissions and considerable losses in plant-available N. Urease inhibitors are chemical substances which suppress the rate of urea hydrolysis and thus reduce NH_3 losses, keeping more N in the soil (Modolo et al. 2018). Urease inhibitors' efficacy has been demonstrated globally in numerous studies, though the effectiveness depends on a range of factors, including inhibitor application timing, product type, fertiliser type, application rate and application method, soil N content, crop type and water management (Fan et al. 2022). A global meta-analysis showed that urea's NH_3 volatilisation is reduced by 52% with N-(n-butyl) thiophosphoric triamide (NBTI), a commonly available urease inhibitor (e.g. AgrotainTM) (Silva et al. 2017), while a similar study found that urease inhibitors overall result around 50% reduction in NH_3 volatilisation and a concurrent 5% yield increase (Fan et al. 2022). At the same time, by keeping more N available in the soil, urease inhibitors can, in certain circumstances, increase direct soil N_2O emissions, though the reduction in indirect N_2O emissions in most cases more than offsets this effect (ibid.).

The CB6 analysis has not considered urease inhibitors as a stand-alone measure (Eory et al. 2020). In a report to Scottish Government, the measure was assessed, using a simplified method of assuming that urea's EF_1 is reduced by 27% (Eory et al. 2023). For the current analysis we used the assumptions from this latest report. Table D.6 shows the assumptions used for modelling in CB7.

Table D.6: Assumptions for modelling urease inhibitors

Parameter	Unit type	Unit	Value	Source
EF_1 of urea	All crops receiving urea	Change	-27%	(Eory et al. 2023)
Applicability	All crops receiving urea	-	1	(Eory et al. 2023)
Current uptake	All crops receiving urea	-	0	(Eory et al. 2023)
Fertiliser cost increase	All crops receiving urea	£ kg N^{-1}	0.12	(Eory et al. 2023)

D.7. Nitrification inhibitors (MM9)

N fertilisers, of synthetic and organic origin, are the main source of N_2O emissions. These emissions occur due to chemical processes in the soil, which transform ammonium compounds through to nitrate compounds (nitrification) and the denitrification of nitrate leading N_2O release. Nitrification inhibitors reduce the rate of nitrification by inhibiting the bacterial enzyme activity, and thus reduce N_2O emissions (Akiyama et al. 2010; Ruser et al. 2015). Just like in the case of urease inhibitors, nitrification inhibitors' effectiveness depends on environmental and management factors, like nitrification inhibitor product type, fertilisation rate, crop type (grass or other), precipitation (Fan et al. 2022). The same study showed that N_2O emissions are reduced by around 50% on average across inhibitor types, and yield increased with the application of certain nitrification inhibitors by 4-6%, though other products did not have a significant effect on yield. Similarly, some products increased NH_3 volatilisation while others did not (ibid.). Experiments in the UK with the product dicyandiamide (DCD) showed that, across six sites, the mean reduction in N_2O emissions from ammonium nitrate fertiliser was 39%, while from urea fertiliser it was 69%; while NH_3 emissions were not affected (Misselbrook et al. 2014). Another UK study on grasslands, across five sites, found that DCD reduced N_2O emissions from ammonium nitrate by 19% and from urea by 85% (L.M. Cardenas et al. 2019). In four of five sites the yield was not affected significantly.

The CB6 analysis has included nitrification inhibitors (Eory et al. 2020). The GHG abatement assumptions were updated in a report to Scottish Government (Eory et al. 2023). For the current analysis we used the assumptions from this latest report. Table D.7 shows the assumptions used for modelling in CB7.

Table D.7: Assumptions for modelling nitrification inhibitors

Parameter	Unit type	Unit	Value	Source
EF_1 of urea	All crops receiving urea	Change	-60%	(Eory et al. 2023)
EF_1 of ammonium nitrate	All crops receiving ammonium nitrate	Change	-30%	(Eory et al. 2023)
Applicability	All crops receiving urea	-	1	(Eory et al. 2023)
Applicability	All crops receiving ammonium nitrate	-	1	(Eory et al. 2023)
Current uptake	All crops receiving urea or ammonium nitrate	-	0	(Eory et al. 2023)
Fertiliser cost increase	All crops receiving urea or ammonium nitrate	£ kg N^{-1}	0.12	(Eory et al. 2023)

D.8. Improved drainage on mineral soils (MM49)

Well drained mineral soils support higher yields and lower N_2O emissions than waterlogged soils. Waterlogging increases nitrification and denitrification processes which convert ammonium compounds into N_2O, and also enhances the risk of compaction and structural damage (Krol et al. 2016; Lilly et al. 2012). Drainage installation and maintenance is a long-term investment, and not practiced everywhere across the UK.

This mitigation measure was assessed in the CB6 report (Eory et al. 2020), the same assumptions were used in this current work, see Table D.8.

Table D.8: Assumptions for modelling improved drainage on mineral soils

Parameter	Unit type	Unit	Value	Source
EF_1	All crops	Change	-64%	(Eory et al. 2020))
Crop yield	All crops	Change	11%	(Eory et al. 2020)
Applicability	Non-grass crops	-	0.08	(Eory et al. 2020)
Applicability	Grass	-	0.1	(Eory et al. 2020)
Current uptake	All crops	-	0	(Eory et al. 2020)
Drainage improvement cost	All crops	£ ha^{-1}	5,285	(Eory et al. 2020)

D.9. Reducing excess nitrogen fertilisation (MM50)

Crop yield is a function of N availability: additional (synthetic or organic) N sources substantially increase the yield until the point which is close to the yield potential of the crop (or lower, if other limitations, for example limited water availability, exist). The economically optimal N fertilisation rate also depends on the fertiliser and future crop prices (AHDB 2019), However, due to the uncertainty in the growing conditions, it is not possible to predict exactly the most optimal application rate. Though the use of nutrient management tools and precision farming technologies help with N planning, not all farmers use them. Furthermore, farmers might leave a margin of error and apply N slightly in excess in order to achieve higher yields if the growing conditions turn out to be more favourable. With a wider uptake nutrient planning, the excess N application could be reduced.

This mitigation measure was assessed in the CB6 report Eory et al. 2020, the same assumptions were used in this current work and are shown in Table D.9

Table D.9: Assumptions for modelling reducing N excess

Parameter	Unit type	Unit	Value	Source
N fertilisation rate	All crops	Change	-10%	(Eory et al. 2020)
Applicability	All crops	-	0.27	(Eory et al. 2020)
Current uptake	All crops	-	0	(Eory et al. 2020)
Nutrient management plan cost	All crops	£ ha^{-1}	9.6	(Eory et al. 2020)
Nutrient management plan lifetime	All crops	y	5	(Eory et al. 2020)
Nutrient management plan update cost	All crops	£ ha^{-1} y^{-1}	2	(Eory et al. 2020)

D.10. Crop varieties with improved nitrogen use efficiency (MM51)

Crop breeding has can have an impact on N_2O emissions through developing varieties with better nitrogen use efficiency (NUE) (Bingham et al. 2012). Crop varieties can perform very differently with regarding NUE, as demonstrated in European wheat varieties (Barraclough et al. 2010), and historically NUE has been, though slowly, increasing (Riedesel et al. 2022). We assumed that further improvement is possible for the main cereal and oil crops, that is, wheat, barley and oilseed rape, and the improvement will manifest as a reduction in fertilisation rate – in line with our overall assumption in the modelling about constraining total production. The effect is modelled as an annually increasing, cumulative N reduction effect.

This mitigation measure was assessed in the CB6 report (Eory et al. 2020), the same assumptions were used in this current work, Table D.10

Table D.10: Assumptions for modelling improved crop nitrogen use efficiency

Parameter	Unit type	Unit	Value	Source
Annual change in N fertilisation rate	Wheat, barely, oilseed rape	Change	0%	(Eory et al. 2020)
Applicability	Wheat, barely, oilseed rape	-	1	(Eory et al. 2020)
Applicability	Other crops	-	0	(Eory et al. 2020)
Current uptake	All crops	-	0	(Eory et al. 2020)
Seed cost increase	Wheat	£ ha^{-1} y^{-1}	9.3	(Eory et al. 2020)
Seed cost increase	Winter barely	£ ha^{-1} y^{-1}	9	(Eory et al. 2020)

D.11. Replacing second wheat with Triticale (MM59)

Triticale is a wheat and rye cross that became commercially available in the mid twentieth century and has been used primarily as feed for livestock (McGoverin et al. 2011), as it has a lower grain protein content than wheat (Roques et al. 2017). Triticale is a minor crop, with low global production levels; the UK provided 0. 3% of global production in 2022 (United Nations (FAO) 2023).

Triticale has higher NUE than wheat, especially comparing triticale with the second wheat in the rotation: it produces higher yield at the same N fertilisation rates (Roques et al. 2017Clarke et al. 2016). Thus, replacing some of the wheat production with triticale could reduce N_2O emissions in the UK. Based on UK experimental results, we assumed that the increase in grain and straw yield would be 7% (Roques et al. 2017).

Triticale was cultivated on only 10.7 thousand ha in the UK in 2022, compared to the 1.8 million ha wheat production area (United Nations (FAO) 2023). An important barrier to increased production is likely to be the lack of mature market; therefore, assuming this barrier is maintained, we limited the applicability to future triticale area to twice of the current area, that is, an additional 0.6% of wheat area, to account for the limited demand. Furthermore, we restricted the applicability of the measure to replacing second wheat, which is 33% of the total wheat area in the UK (Magazine 2016).

Growing triticale instead of second wheat impacts the gross margin by changes in selling prices, yield and input costs. According to FAOSTAT data, triticale has a 6-11% lower price than wheat (United Nations (FAO) 2023); we assumed a price difference of 8% relative to wheat. Furthermore, input costs are estimated to be £19 ha^{-1} less than that of wheat (Clarke et al. 2016), or £24.89 ha^{-1} at 2024 values (changes in costs of non-N fertilisers, fungicides, plant growth regulators). That values used for modelling Triticale can be seen in Table D.11

Table D.11: Assumptions for modelling replacing second wheat with Triticale

Parameter	Unit type	Unit	Value	Source
Triticale yield, modelled as wheat yield		Change	7%	Based on (Clarke et al. 2016)
Additional straw yield		t DM ha^{-1} y^{-1}	0.36	Based on (Clarke et al. 2016)
Applicability	Wheat	-	0.03	Limited uptake due to low demand
Current uptake		-	0	Any current uptake is included as 'Minor_Cereals'
Triticale price relative to wheat		Change	-8%	Based on (United Nations (FAO) 2023)
Other variable cost changes		£ ha^{-1} y^{-1}	-24.89	Based on (Clarke et al. 2016)

D.12. Precision feeding, dairy (MM52)

Precision feeding, similarly to precision farming of crops, is based on the concept of individually tailoring nutritional requirements to the animals' needs. This individual-based approach increases the feed conversion ratio of the animals, reducing both the GHG emissions related to feed production and also the direct enteric and manure related GHG emissions and N excretion from the animals (Fischer et al. 2020; Morey et al. 2023).

Implementing precision feeding requires precision farming tools, i.e. performance data (e.g. milk yield, weight), decision software and automated feed mixer. It is an investment intensive technology and most suited to animals which are mainly non-grazing. This mitigation measure was assessed in the CB6 report (Eory et al. 2020), the same assumptions were used in this current work, see Table D.12

Table D.12: Assumptions for modelling precision feeding, dairy

Parameter	Unit type	Unit	Value	Source
Gross energy coefficient (representing feed efficiency)	Dairy	Change	-2%	(Eory et al. 2020)
Applicability	Dairy	-	0.5	(Eory et al. 2020)
Current uptake	Dairy	-	0	(Eory et al. 2020)
Annualised total cost	Dairy	£ $head^{-1}$ y^{-1}	8.2	(Eory et al. 2020)

D.13. Nitrate feed additive, dairy, beef and sheep (MM20, MM21, MM22)

Ruminants' digestion, particularly the enteric fermentation process in the rumen, is the largest source of direct GHG emissions from cattle and sheep production. In this complex microbial process, the generated hydrogen reacts with CO_2 and the resulting CH_4 is emitted as a by-product. Multiple ways exist to modify the processes, one is to add chemicals which react with the hydrogen, thus reducing the amount of CH_4 generated (Zijderveld et al. 2010; Zijderveld et al. 2011). The nitrate needs to be mixed into the feed homogenously, as the dose needs to be tightly controlled to avoid nitrate poisoning.

The measures nitrate additive for dairy and beef have been evaluated in CB6 (Eory et al. 2020), but the assumptions have been updated for this report. A review focusing on the UK highlighted the difference in effectiveness between dairy and beef animals and quantified the efficacy based on relevant experimental results as -18% for dairy and -5.1% for beef animals (Duthie et al. 2021). The same study also found that the weight gain and yield was increasing with the nitrate additive, with 3.1% for both cattle types and the cost of administering the measure was estimated to be £92 per animal annually (ibid.). There is still no reliable information on uptake of the measure in the UK.

The measure nitrate additive for sheep was not evaluated in CB6 (Eory et al. 2020); it was added as a new measure in this report. Experimental evidence is scarcer for sheep than for cattle, thus the assumption on the GHG effect was based on a UK study (Nolan et al. 2010), and the cost was assumed to be proportional to that of cattle, based on the weight of the animals. Additionally, since sheep are rarely housed, the applicability is very low.

In all cases the applicability of the measure was restricted to the time animals spend housed, and for cattle older than 12 months and sheep older than 6 months. We assumed that the measure would not be applicable on organic farms, see Table D.13 for full set of assumptions.

Table D.13: Assumptions for modelling nitrate feed additive for dairy, beef and sheep

Parameter	Unit type	Unit	Value	Source
Y_M	Dairy	Change	-18%	(Duthie et al. 2021)
Y_M	Beef	Change	-5%	(Duthie et al. 2021)
Y_M	Sheep	Change	-23%	(Nolan et al. 2010)
Gross energy coefficient (representing feed efficiency)	Dairy, beef	Change	-3.10%	(Duthie et al. 2021)
Applicability	Dairy and beef, animals older than 12 months, housed, not organic	-	1	(Duthie et al. 2021)
Applicability	Dairy and beef, other animals	-	0	(Duthie et al. 2021)
Applicability	Sheep, animals older than 6 months, housed, not organic	-	1	-
Applicability	Sheep, other animals	-	0	-
Current uptake	Dairy, beef	-	0	(Duthie et al. 2021)
Current uptake	Sheep	-	0	-
Cost	Dairy, beef	£ $head^{-1}$ y^{-1}	92	(Duthie et al. 2021)
Cost	Sheep	£ $head^{-1}$ y^{-1}	9.2	Assumption based on weight ratio with cattle

D.14. Improved nutrition, beef and sheep (MM18, MM19)

Forage quality has significant impact on both the productivity and the GHG emission intensity of ruminant livestock (Hristov et al. 2013). Feed with higher digestibility tends to increase the dry matter intake and thus growth rate (Davis et al. 2014; Steen et al. 2002), resulting in lower GHG emissions for the same production volume.

Improved beef and sheep nutrition were not included in the CB6 report (Eory et al. 2020), though its mitigation was quantified in the 5th Carbon Budget (Eory et al. 2015). In a report to Scottish Government, those assumptions were checked and found to be still appropriate (Eory et al. 2023). For the current analysis we used these same assumptions, regarding mitigation effect, uptake, applicability and costs. The current uptake assumptions were compared to the latest edition of Defra's Farm Practices Survey, which found that in 2023 39% of cattle and sheep farmers use nutritional advice always or most of the time, another 16% some of the time and yet another 16% rarely (Defra 2024). Assumptions used in modelling can be seen in Table D.14.

Table D.14: Assumptions for modelling improved beef and sheep nutrition

Parameter	Livestock type	Unit	Value	Source
Roughage digestible energy content	Beef	Percentage point change	+2%	(Eory et al. 2015)
Concentrate digestible energy content	Beef	Percentage point change	+2%	(Eory et al. 2015)
Live weight	Beef	Change	+2%	(Eory et al. 2015)
Applicability	Beef	-	1	(Eory et al. 2015)
Current uptake	Beef	-	0.6	(Eory et al. 2015)
Cost of nutritional advice and twice-yearly forage analysis	Beef	£ $head^{-1}$ y^{-1}	2.13	(Eory et al. 2015)
Enteric CH_4 emissions	Sheep	Change	-4%	(Eory et al. 2015)
Live weight	Sheep	Change	+2%	(Eory et al. 2015)
Applicability	Sheep	-	1	(Eory et al. 2015)
Current uptake	Sheep	-	0.6	(Eory et al. 2015)
Cost of nutritional advice and twice-yearly forage analysis	Sheep	£ $head^{-1}$ y^{-1}	2.13	(Eory et al. 2015)

D.15. Asparagopsis feed additive, dairy and beef (MM53, MM54)

Certain red seaweed species, in the *Asparagopsis* genus (Glasson et al. 2022) can alter the enteric fermentation process and reduce CH_4 emissions. The main active ingredient, bromoform $CHBr_3$, reduces the CH_4 generation capacity of two enzymes (coenzyme M methyltransferase and methyl-coenzyme M reductase) and contributes to increased H_2 production and a change in the volatile fatty acid composition (*ibid*).

As growing evidence suggests that this feed additive is very effective in reducing enteric fermentation, it has been included as a new measure in this report. However, given the early stages of product development, compared to other feed additives, finally it was excluded from both scnarios.

A UK review of feed additives, based on relevant experimental results, assessed the efficacy and the effects of *Asparagopsis* on feed efficiency and yield/growth (Duthie et al. 2021). The reduction in CH_4 was found to be 24.7% for dairy and 20% for beef animals; their performance was slightly reduced (-3. 8% milk yield and -1% total growth), while the feed efficiency also changed (decreased for dairy cows but improved for other dairy animals and beef cattle (*ibid.*)).

The cost of administering the measure was estimated to be £48 per animal annually (*ibid*). As products are not commercially available, uptake in the UK was assumed to be zero.

For both dairy and beef, the applicability of the measure was restricted to the time animals spend housed, and for animals older than 12 months. We assumed that the measure would not be applicable on organic farms.

D.16. Breeding using genomic tools, dairy and beef (MM36, MM37)

Many production and fitness traits have been shown to have a genetic component and have scope to be improved 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. 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. 2016). 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 CH_4 emissions from the dairy industry could be reduced by 10-15%.

Genetic improvement in the national herd can be enhanced by using genomic tools. This entails farmers collecting performance information on the individual animals and genetic testing, and feeding back these information to breeding goal development (genomic tools) and also incorporating enteric CH_4 emission in the breeding goal.

This mitigation measure was assessed in the CB6 report Eory et al. 2020, the same assumptions were used in this current work and are shown in Table D.15. Since the agricultural activity scenarios used in CB7 already assume an increase in milk yield, we reduce this measure's effect on milk yield to avoid double counting.

Table D.15: Assumptions for modelling genomics breeding of dairy and beef

Parameter	Unit type	Unit	Value	Source
Milk yield	Dairy	Annual growth	+0.9%/year	(Eory et al. 2020)
Milk yield	Dairy in BAU/BP	Annual growth.	+0.3%/year	Avoid double counting
Milk protein	Dairy	Annual growth	+0.9%/year	(Eory et al. 2020)
Applicability	Dairy cows	-	0.9	(Eory et al. 2020)
Applicability	Beef	-	0.2	(Eory et al. 2020)
Fertility	Dairy	Annual growth	+0.3%/year	(Eory et al. 2020)
Live-weight	Beef	Annual growth	+0.25%/year	(Eory et al. 2020)
Growth rate	Beef	Annual growth	+0.25%/year	(Eory et al. 2020)
Genomics tools recurring cost	Dairy	£m per 5 years	0.25	(Eory et al. 2020)
Genomics tools testing cost	Dairy	£ head^{-1} y^{-1}	0.048	(Eory et al. 2020)
Genomics tools recurring cost	Beef	£m per 5 years	0.25	(Eory et al. 2020)
Genomics tools testing cost	Beef	£ head^{-1} y^{-1}	0.048	(Eory et al. 2020)

D.17. Including lower emissions in the breeding goals, dairy and beef (MM38, MM39)

Literature suggests that the genetics of mammals have an influence on the micro-organisms present in the gut (Hegarty et al. 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 could reduce CH_4 emissions from cattle, though might limit the productivity and fitness improvements to some extent.

This mitigation measure was assessed in the CB6 report Eory et al. 2020, the same assumptions were used in this current work and are shown in Table D.16. Since the agricultural activity scenarios used in CB7 already assume an increase in milk yield, we reduce this measure's effect on milk yield to avoid double counting.

Table D.16: Assumptions for modelling lower emission breeding goal fo dairy and beef

Parameter	Unit type	Unit	Value	Source
Milk yield	Dairy	Annual growth	+0.75%/year	(Eory et al. 2020)
Milk yield	Dairy in BAU/BP	Annual growth.	+0.15%/year	Avoid double counting
Milk protein	Dairy	Annual growth	+0.75%/year	(Eory et al. 2020)
Y_M	Dairy	Annual growth	-0.15%/year	(Eory et al. 2020)
Live-weight	Beef	Annual growth	+0.25%/year	(Eory et al. 2020)
Growth rate	Beef	Annual growth	+0.25%/year	(Eory et al. 2020)
Y_M	Beef	Annual growth	-0.15%/year	(Eory et al. 2020)
Applicability	Dairy Cows	-	0.9	(Eory et al. 2020)
Applicability	Beef	-	0.2	(Eory et al. 2020)
Genomics tools recurring cost	Dairy	£m / 5 years	0.6	-
Genomics tools testing cost	Dairy	£ head^{-1} y^{-1}	0.048	(Eory et al. 2020)
Genomics tools recurring cost	Beef	£m / 5 years	0.25	-
Genomics tools testing cost	Beef	£ head^{-1} y^{-1}	0.048	(Eory et al. 2020)

D.18. Higher uptake of current breeding goal, sheep (MM40)

The increased uptake of current breeding goals in sheep has not been included in the MACC model until now so more detail is given for this measure. As with breeding measures in cattle [!!!][not really true?], much of the benefit of this measures comes from changes in the heard structure which is not captured within the MACC model. Therefore, the effect of this mitigation measure was calculated by Michael MacLeod with the Global Livestock Environmental Assessment Model (GLEAM, MJ MacLeod et al. 2018) model before being implemented within the MACC model.

There have been a number of recent studies quantifying the potential effect of sheep breeding on GHG emissions. Farrell et al. (2022) modelled two scenarios: (a) high where ‘dams within the top 20% of animals for the replacement index were assumed to be bred with terminal sires within the top 20% of animals on the terminal index’ and a (b) low scenario where the ‘bottom 20% of animals for the replacement index were assumed to be bred with terminal sires within the bottom 20% of animals for the terminal index’. The difference in performance between the two scenarios was determined from the Irish national sheep production database. In brief, the high flock has 10% more lambs scanned per ewe, 9% lower lamb mortality and 7% higher lamb growth rates than the low flock. They found that the ‘high’ flock had 4% lower emissions intensity (EI) than the average flock, mostly due to the fact that lambs were sold at a younger age from the high flock. Morgan-Davies et al. (2021) found that using performance recording for genetic merit reduced emissions intensity by 9 to 18%, increased economic performance by £6/ewe but required an additional 10% in labour costs for Scottish flocks. Rowe et al. (2021) found that by including enteric CH_4 as a selection index they could lower enteric CH_4 by 7.5% over 20 years in New Zealand.

To model the effect of increased uptake of breeding goals in GLEAM the following assumptions were used. Scenario (A) Breeding for improved productivity. Based on Farrell et al. (2022), we assume that the average flock performance could be improved by half the difference between the low and high flock, i.e. that lambs scanned increase by 5%, lamb mortality decreases by 4.5% and Live-weight gain (LWG) increases by 3.5%.

Although not included in the MACC modelling, we also describe parameters for a scenario (B) Breeding for lower enteric CH_4 where Ym can (conservatively) be reduced by 5% by 2050 based on Rowe et al. (2021). [!!!][???]

Table D.18 shows the results from GLEAM modelling of the baseline and scenario A and B.

For the MACC modelling assumptions we assume it takes 25 years to achieve the percent differences resulting in the changes seen in Table D.17. The increase in growth rate and live weight is to capture the extra meat production.

Table D.17: Assumptions for modelling higher uptake of current breeding goal, sheep

Parameter	Unit type	Unit	Value	Source
Applicability	Sheep	-	0.9	-
Current uptake	Sheep	-	0	-
Enteric CH_4 emissions	Sheep	Annual growth	4×10^{-4} /year	Table D.18
Manure CH_4 emissions	Sheep	Annual growth	4×10^{-4} /year	Table D.18
N excretion	Sheep	Annual growth	4×10^{-4} /year	Table D.18
Live weight	Sheep	Annual growth	2×10^{-3} /year	Table D.18
Growth rate	Sheep	Annual growth	2×10^{-3} /year	Table D.18
Cost per ram	Ram	£ head^{-1} y^{-1}	75	Morgan-Davies et al. 2021
Cost per ewe	Ewe	£ head^{-1} y^{-1}	2	Morgan-Davies et al. 2021

Table D.18: Sheep breeding results from GLEAM showing the baseline, breeding for increased productivity (A), breeding for lower CH_4 (B), and both combined.

Scenario	Unit	Baseline	Genetic Improvement			Difference v Base		
			A. Productivity	**B. Enteric CH4**	**A & B**	**A**	**B**	**A & B**
System		Sheep	Sheep	Sheep	Sheep			
#Adult Female (AF)	head	15,624,233	15,624,233	15,624,233	15,624,233	**0%**	**0%**	**0%**
Age at slaughter	months							
Meat production	ktLW	877	924	877	924	**5%**	**0%**	**5%**
Meat production	ktCW							
Milk production	ktMILK							
Enteric CH_4	ktCO_2e	5780	5866	5491	5573	**1%**	**-5%**	**-4%**
Manure CH_4	ktCO_2e	117	119	117	119	**1%**	**0%**	**1%**
Feed N_2O	ktCO_2e	2852	2895	2852	2895	**2%**	**0%**	**2%**
Manure N_2O	ktCO_2e	158	160	158	160	**1%**	**0%**	**1%**
CO_2 (feed energy)	ktCO_2e	1121	1139	1121	1139	**2%**	**0%**	**2%**
CO_2 (on-farm energy)	ktCO_2e	0	0	0	0			
Total	ktCO_2e	10028	10178	9739	9885	**2%**	**-3%**	**-1%**
EI	kgCO_2e/ kgLW	11.4	11.0	11.1	10.7	**-4%**	**-3%**	**-6%**
EI - enteric CH_4 only	kgCO_2e/ kgLW	6.6	6.4	6.3	6.0	**-4%**	**-5%**	**-9%**
AF productivity	kg CW per AF	56.1	59.1	56.1	59.1	**5%**	**0%**	**5%**
GHG per AF	kgCO_2e/AF/year	642	651	623	633	**2%**	**-3%**	**-1%**

D.19. Slurry acidification, dairy, beef and pigs (MM43, MM44, MM45)

Slurry acidification is achieved by adding strong acids (e.g. sulphuric acid or hydrogen chloride) to the slurry to achieve a pH of 4.5-6.8 depending on the slurry type and the acid used (Fangueiro et al. 2015). There are three main types of technology relating to the stage at which the acid is added to the slurry: in-house, in the storage tank, or before field application. Here we focus on acidification in the storage tank.

According to a review by Fangueiro et al. (2015), reductions of 67-87% of manure CH_4 emissions were achieved using H_2SO_4, and 90%, 40-65% and 17-75% reduction was observed with lactic acid [!!!], hydrochloric acid and nitric acid, respectively. NH_3 emissions also decreased by 50-88% with sulphuric acid and 27-98% with other acids – therefore indirect N_2O emissions must have decreased as well. On the other hand, N_2O emissions after manure spreading can increase by 23% as more N is retained in the slurry (Fangueiro et al. 2015), this increase is deducted from the GHG mitigation.

This mitigation measure was assessed in the CB6 report (Eory et al. 2020). Lacking more up-to-date reviews on the mitigation effect, the CB6 assumptions were used for CH_4 and NH_3 reduction. The cost assumptions are based on Eory et al. (2023). The latest assumptions were used in the current work, see Table D.19.

Table D.19: Assumptions for modelling slurry acidification for dairy, beef and pigs

Parameter	Unit type	Unit	Value	Source
Slurry CH_4 conversion factor	Dairy, Beef Pig	Change	-75%	(Eory et al. 2020)
Slurry NH_3 volatilisation factor	Dairy, Beef Pig	Change	-70%	(Eory et al. 2020)
Applicability	Slurry tanks	-	1	(Eory et al. 2020)
Costs	Dairy	£/head/year	32.74	(Eory et al. 2023)
Costs	Beef	£/head/year	18.34	(Eory et al. 2023)
Costs	Pigs	£/head/year	2.62	(Eory et al. 2023)

D.20. Impermeable slurry cover, dairy, beef and pigs (MM46, MM47, MM48)

Animal excreta stored in liquid systems is an important source of NH_3 and CH_4 emissions, as during the storage the N 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 (Sven G Sommer et al. 2000). Several factors affect the rate of NH_3, CH_4 and N_2O emissions, including manure composition and physical variables (most importantly temperature, rainfall, airflow) (Monteny et al. 2006; Sven Gjedde Sommer et al. 2004). These factors can be to some extent modified by management choices and technologies, like reducing the airflow over the manure by covering the store.

Various technologies exist to cover stored liquid livestock excreta (VanderZaag et al. 2015).Rigid covers include wooden or concrete lids while floating covers can be made of organic (e.g. straw, vegetable oil), inorganic (expanded clay) or synthetic materials. Cattle slurry, if not agitated, can develop a natural crust (Chadwick et al. 2011). This mitigation measure is about floating plastic covers which are impermeable for gaseous material, as these types of covers can reduce CH_4 emissions substantially besides mitigating NH_3 emissions.

Covering slurry stores can substantially reduce NH_3 emissions (Hou et al. 2015; VanderZaag et al. 2015). With reduced NH_3 emissions indirect N_2O emissions also reduce. The presence of a slurry cover increases the slurry's N content and fertiliser value, but also potential subsequent NH_3 and N_2O losses when the slurry is applied to the soil, unless low NH_3-emission spreading techniques are implemented, both features are captured during modelling.

Rodhe et al. (2012) found that an impermeable floating cover could reduce the CH_4 conversion factor of pig slurry by 47%, direct N_2O emissions by 100% and NH_3 emissions by 80%. In a review, VanderZaag et al. (2015) found that impermeable floating covers could reduce NH_3 emissions by 80%.

This mitigation measure was assessed in the CB6 report (Eory et al. 2020) and the costs have since been updated. The latest assumptions used in the current work can be seen Table D.20.

Table D.20: Assumptions for modelling impermeable slurry cover for dairy, beef and pigs

Parameter	Unit type	Unit	Value	Source
Slurry CH_4 conversion factor	Dairy, Beef Pig	Change	-47%	(Eory et al. 2020)
Slurry NH_3 volatilisation factor	Dairy, Beef Pig	Change	-80%	(Eory et al. 2020)
Slurry EF_3	Dairy, Beef Pig	Change	-100%	(Eory et al. 2020)
Applicability	Slurry/Lagoons	-	1	(Eory et al. 2020)
Installation costs	Dairy, Beef, Pig	£ m^{-3} manure	10.28	(Eory et al. 2020)
Installation cost lifetime	Dairy, Beef, Pig	year	10	(Eory et al. 2020)
Maintenance Costs	Dairy, Beef, Pig	proportion of installation costs	0.02	(Eory et al. 2020)

D.21. Increased milking frequency with robotic milking (MM55)

The use of robotic milking parlours allows cows to choose when they want to be milked which typically increases milking frequency from twice a day to three times per day. Increased milking frequency removes milk from the udder thereby stimulating further milk production. Milking three times a day is known to increase milk yield and N use efficiency by reducing energy and N requirements. These effects increase efficiency which subsequently reduce N_2O emissions related to N loses (Moorby et al. 2007). Results from the literature show that switching to robotic milking from milking twice a day can increase milk yield by 8-15% (Salfer 2017; Moorby et al. 2007; Sitkowska et al. 2015).

Increased milking frequency was considered in CB6 (Eory et al. 2020) and in the CGtSI project (Barnes et al. 2022). Here we use these previous parameters with costs updated, Table (D.21)

Table D.21: Assumptions for modelling increased milking frequency

Parameter	Unit type	Unit	Value	Source
Applicability	Dairy	-	1	(Eory et al. 2020)
Milk yield	Dairy	Change	+10%	(Eory et al. 2020)
Milking system cost	Dairy	£/head	1250	(Eory et al. 2020)
Milking system lifetime	Dairy	year	15	(Eory et al. 2020)

D.22. Biogas flaring, dairy, beef and pigs (MM56, MM57, MM58)

Biogas flaring is a liquid manure storage technology, whereby the CH_4 generated during storage is collected and burnt, converting it to less potent GHG CO_2 (Pellerin et al. 2013). Liquid slurry systems, due to the mostly anaerobic environment in the liquid, are important sources of CH_4 emissions. Part of the organic material in the excreta is converted to CH_4 by bacteria in anaerobic respiration process. Along with the substantial amount of NH_3 and odour, the CH_4 escapes to the atmosphere from traditionally stored slurry. These emissions can be reduced in various ways, including covering the stores. If an airtight, impermeable cover is used the gases can be collected. One option is to purify the gas and sell the CH_4 i.e. anaerobic digestion, while a technologically simpler solution is flaring the gas. This measure is different from anaerobic digestion not only in the use of the biogas (i.e. no heat and energy capture), but also in the way that the bacterial processes are not managed (e.g. no additional feedstock is used and the temperature is not controlled) and the gas is not used for electricity or heat generation. As with slurry covers, NH_3 emissions are substantially reduced, leaving more N available in the manure, potentially leading to increased emissions from manure spreading, unless slurry spreading technologies which have low NH_3 emissions are used.

As no study was found which reported on GHG emissions from biogas flaring systems, information on the GHG effects of impermeable covers was used i.e. Table D.20, complemented with assumption on the flaring efficiency for captured CH_4.

This measure was considered in CB6 (Eory et al. 2020) and in the CGtSI project (Barnes et al. 2022). Here we use these previous parameters with updated costs, Table (D.22).

Table D.22: Assumptions for modelling biogas flaring for dairy, beef and pigs

Parameter	Unit type	Unit	Value	Source
Slurry CH_4 conversion factor	Dairy, Beef Pig	Change	-94.7%	(Eory et al. 2020)
Slurry NH_3 volatilisation factor	Dairy, Beef Pig	Change	-80%	(Eory et al. 2020)
Slurry EF_3	Dairy, Beef Pig	Change	-100%	(Eory et al. 2020)
Applicability	Slurry/Lagoons	-	1	(Eory et al. 2020)
Installation costs	Dairy, Beef, Pig	£ m^{-3} manure	17.3	(Eory et al. 2020)
Installation cost lifetime	Dairy, Beef, Pig	year	10	(Eory et al. 2020)
Maintenance Costs	Dairy, Beef, Pig	proportion of installation costs	0.02	(Eory et al. 2020)

D.23. Anaerobic digestion of manure, cattle and pig (MM13, MM14)

During the storage of livestock excreta GHGs are formed and released, from liquid systems mainly CH_4, while from solid systems predominantly N_2O (Chadwick et al. 2011). Anaerobic Digestion (AD) of excreta in a closed system utilises microbial processes, which convert much of the organic carbon into biogas (a mixture of CH_4 and CO_2). This biogas is captured and utilised as an electricity and/or heat source. Therefore, AD can reduce GHG emissions by limiting N_2O and CH_4 during manure storage *and* by producing electricity and heat which avoids emissions. The N, phosphorous and the remaining organic material forms in the digestate, can also be used as a fertiliser. 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. 2015). A further negative side effect is the increased land use (with related GHG emissions and water and air pollution) if the additional feedstock in the digester is not a material which could not be used at a higher level in the biomaterial value pyramid, e.g. as food or animal feed (Bacenetti et al. 2016). Furthermore, NH_3 emissions during landspreading could also be higher unless low emission spreading is employed as most of the N is in the form of ammonical N (Kupper et al. 2020), though acidification of digestate would prevent these NH_3 emissions (Finzi et al. 2019).

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

During modelling, the change in N_2O and CH_4 emissions due to change in manure management mode is handled by the MACC model described in chapter 2 and parameters are presented by Table D.23. However, the avoided emissions due to energy generation and costs/income are handled by a separate model which we describe here, and parameters can be seen in Table D.24.

Table D.23: Anaerobic Digestion cattle and pig

Parameter	Unit type	Unit	Value	Source
Managed manure proportion not AD	Dairy/Beef/Pig	Change	-78%	We assume not all of an animals manure is managed AD when the measure is applied
Managed manure proportion AD	Dairy/Beef/Pig	Change	+78%	Not all manure is managed AD
Applicability	Dairy/Beef/Pig	proportion of animals	0.2	limited to avoid land-use change
Current uptake	Dairy/Beef/Pig	proportion of animals	0.05	Biogas-info

Anaerobic digestion model

The MACC model handles the reduced emissions from changing manure management method to AD and assigns a given proportion of manure from a proportion of animals to AD, Table D.23. The anaerobic digestion model then calculates the cost, energy generation and avoided emissions from this manure by calculating:

1. How much external crop feed stock is needed (and its cost) along with the manure and the total CH_4 available from the manure and crop.
2. How much CH_4 would leak (5% of total).
3. How much energy is required to run the digester
4. Net energy produced (produced minus required) subdivided into heat and electricity.
5. The capital cost of building n 500kW plants to process the volume of assigned manure
6. The operating cost of running n 500kW AD plant processing the volume of assigned manure including the cost of the additional substrate as feed stock to the and the transport of manure to the AD plant.
7. The amount of electricity and heat generated from the CH_4 and how much emissions they avoid.

Emissions

Let $VS^i(t)$ be the kg of volatile solids produced by animal type i passed to AD in year t and let B_0^i [$m^3 CH_4$ kg^{-1} VS] be the potential CH_4 of the manure produced by animal type i. Then the CH_4 available in all the manure in year t, $M_{CH4}(t)$ [$kgCH_4$], is

$$M_{CH4}(t) = \sum_{i=1}^{l} VS^i(t) B_0^i (1 - MCF_{AD} - CCF_{AD}) \times 0.67,$$

where l is the number of animal types, $MCF_{AD} = 0.05$ accounts for the CH_4 loss from the manure gets to the digester, $CCF_{AD} = 0.05$ accounts for the CO_2 loss and the factor 0.67 converts from m^3 to kg of CH_4. Similarly the total amount of volatile solid in the manure is $VS_M(t) = \sum VS^i(t)$. The amount crop volatile solids required as co-digestate is calculated as $VS_C(t) = VS_M(t)/R$ where R is the typical ratio of manure to crop VS in AD (Table D.24). The crop fresh mass, FM_C [kgDM] required is calculated as

$$FM_C(t) = \frac{VS_C(t)}{DM_C \times 0.94},$$

where $DM_C = 0.3$ is dry fresh matter ratio of the crop (Forage maize) and the factor 0.94 is the VS proportion from which the crop cost in year t, $C_C(t)$ [£], can be calculated based on the value of the crop (0.309 [£ kg^{-1}DM]) and the land area demand based on the yield of the crop. The CH_4 available in the crop is calculated as $C_{CH4}(t) = FM_C(t) \times 0.523 \times 0.67$ [$kgCH_4$] where 0.523 is the potential CH_4 in the crop (equivalent to B_0 for manure) and the factor 0.67 converts from m^3 to kg of CH_4.

The total CH_4 produced by AD in year t is then

$$T_{CH4}(t) = (M_{CH4}(t) + C_{CH4}(t))(1 - 0.0005),$$

where 0.0005 is the proportion of CH_4 that leaks from the AD plant which is counted as an emission.

The energy used by AD, E_U [MJ] is a function of the amount of gas (CH_4 and CO_2) produced

$$E_U(t) = \frac{\frac{T_{CH4}(t)}{0.67\times(1-0.0005)}}{1 - C_{prop}} \times E_{req},$$

where $C_{prop} = 0.47$ is the proportion of biogas which is CO_2 and E_{req} [MJ m^{-3}] is energy required by AD to produce the given volume biogas. Similarly the heat used $H_U(t)$ [MJ] by AD is

$$H_U(t) = \frac{\frac{T_{CH4}(t)}{0.67\times(1-0.0005)}}{1 - C_{prop}} \times H_{req},$$

where $H_{req} = 1.64$ [MJ m^{-3}] is the heat required to produce the given volume of biogas.

The energy produced by AD $E_P(t)$ [MJ] is calculated as

$$E_P(t) = T_{CH4}(t) \times \rho \times E_{eff}$$

where ρ [MJ kg^{-1}] is the energy density of CH_4 and $E_{eff} = 0.375$ is the AD plants energy efficiency, Table D.24. Similarly, the heat produced is calculated as

$$E_P(t) = T_{CH4}(t) \times \rho \times H_{eff},$$

where $H_{eff} = 0.43$ is the AD plants heat efficiency. The net heat and net energy is then $H_N(t) = H_P(t) - H_U(t)$ and $E_N(t) = E_P(t) - E_U(t)$ respectively. The avoided emissions from the generated electricity ($AE_E(t)$ [kgCO_2e]) and heat ($AE_H(t)$ [kgCO_2e]) is then calculated as

$$AE_E(t) = E_N(t) \times 0.2778 \times E_{EF}(t),$$
$$AE_H(t) = E_N(t) \times 0.2778 \times H_{EF},$$

where 0.2778 converts from MJ to kWh, $E_{EF}(t)$ [kgCO_2e MJ^{-1}] are the emissions associated with producing electricity in the UK in year t provided by the CCC and $H_{EF} = 0.27$ [kgCO_2e MJ^{-1}] is the (fixed) emissions associated with producing heat. The avoided emissions $AE_E(t)$ and $AE_H(t)$ are counted as abatement for AD.

Costs

AD plants built to process the manure are assumed to be operational $p = 0.8$ proportion of the time, therefore the cumulative power, $P(t)$ [kW], of AD plants required to process the manure is

$$P(t) = \frac{E_P(t) \times 0.2778}{p \times 365 \times 24},$$

where 0.2778 converts energy from MJ to kWh. The number of 500 kW AD plants required to produce $P(t)$ power in year t is calculated as

$$N(t) = \left\lceil \frac{P(t)}{500} \right\rceil,$$

where $\lceil \cdot \rceil$ is the ceiling function. Mistry et al. (2011) provides formulas to calculate the opex and capex as functions of the mass of fresh mass being processed per plant. The crop fresh mass FM_C has already been calculated and the manure fresh mass $FM_M(t)$ is calculated by assuming the kg fresh mass per kg dry mass of cattle manure is 0.09 and pig manure is 0.25 and the kg VS per kg dry mass of cattle manure is 0.8 for cattle and 0.9 for pigs. The total fresh mass being processed is $FM_T(t) = FM_M(t) + FM_C(t)$ and the fresh mass per 500 kW plant is therefore $FM(t) = \frac{FM_T}{N(t)}$. Mistry et al. (2011) provide an equation for capex per plant as

$$CAPEX(t) = \alpha \frac{FM(t)}{1000} + \beta + G,$$

where the parameters α_O and β can be seen in the Table D.24 and are adjusted for inflation. To match other sectors calculation of AD capex within CB7 we include the grid hook up cost G which was not considered in Mistry et al. (2011). The opex per plant is also provided by Mistry et al. (2011) given by

$$OPEX(t) = (1 + \beta_O)\alpha_O \left(\frac{FM(t)}{1000}\right)^{(1+\beta_O)} + \frac{C_C(t)}{N} + \frac{T}{N}$$

where the parameters α_O and β can be seen in the Table D.24 and are adjusted for inflation when implemented. The $C_C(t)$ term accounts for the cost of buying the co-digestate which is not considered in Mistry et al. (2011) and already defined above. T is the cost of transporting the manure and co-digestate to the AD plant which is calculated using the parameters in Table D.24 under 'Manure transport costs'.

The amount of manure being passed to the AD model increases as uptake of the measure increases over time, Table 2.2. During modelling, the capital cost is only incurred in the years when a new plant is required to meet demand for manure being used foe anaerobic digestion. In the BP scenario, where animals numbers decrease and manure being passed to AD is reduced, no renewal cost is incurred on plants that are no longer required due to reduced demand, see Appendix C.

Table D.24: Parameters used in the model for Anaerobic Digestion

Parameter	Value	Unit	Notes	References
CH_4 energy density (ρ)	55	MJ/kg		
AD plant energy efficiency (E_{eff})	0.375	1		Institute 2015
AD plant heat efficiency (H_{eff})	0.43	1		Institute 2015
Manure:Crop VS ratio (R)	0.57	-	How much crop volatile solid as co-digestate to process the manure	(Eory et al. 2020)
Crop potential CH_4	0.52	$m^3 CH_4$ $kg^{-1} VS$	Equivalent B_0 for manure	(Eory et al. 2020)
CO_2 proportion (C_{prop})	0.47	1	What proportion of the biogas is CO_2	

Energy input (E_{req})	0.78	MJ/m^3	How much energy does the plant need to generate a m^3 of CH_4	
Heat input (H_{req})	1.64	MJ/m^3	How much heat does the plant need to generate a m^3 of CH_4	
Proportion on (p)	0.8	1	What proportion of the time is the AD plant operating	
Plant power	500	kW	How much power 1 plant produces	
CH_4 loss factor	0.05	1	CH_4 leakage from plant	Institute 2015
CO_2 loss factor	0.05	1	CO_2 leakage from plant	Institute 2015
Dry matter content crop	0.3	kgDM /kgFW	Dry matter content of feedstock crop	
Cost parameters				
α	79.5		$capitalcost = \alpha \times freshMass + \beta$	In 2011£ Mistry et al. 2011
β	516000		$capitalcost = \alpha \times freshMass + \beta$	In 2011£ Defra Mistry et al. 2011
α_O	218		$operatingcost = \alpha_O \times freshMass^{1-beta_O}$	In 2011£ Mistry et al. 2011
β_O	-0.306		$operatingcost = \alpha_O \times freshMass^{1-beta_O}$	In 2011£ Mistry et al. 2011
grid hook up cost (G)	500000	£	Cost to hook up AD plant to grid	
Potential CH_4 in manure (B_0)	Animal dependent	m^3CH_4/kg volatile solid	CH_4 in manure	

Manure transport costs			
Mass per truck	11	tFW/truck	How much fresh weight a lorry can transport
mile per galloon	9.1	mpg	
lorry running costs	0.14	£/km	
lorry fixed costs	220	£/day	wages etc
lorry day distance	150	km/day	one way
average distance	10	km/day	how far from farm to AD plant one-way

D.24. 3NOP feed additive, dairy and beef (MM26, MM27)

3NOP is a chemical that reduces the excretion of enteric methane by ruminants when added to their rations (or introduced via a bolus). It does so by reducing the rates at which rumen archaea convert the hydrogen in ingested feed into methane. Specifically, 3NOP inhibits methyl-coenzyme M reductase, the final step of CH_4 synthesis by archaea (Duin et al. 2016).

Parameters for both 3NOP measures have been updated specifically for CB7 based on the DEFRA report Duthie et al. 2021 which reviewed the effectiveness, cost and ancillary effects of methane suppressing feed additives. The report also estimates the cost of 3NOP for beef and dairy cattle at £40/year/animal in 2021. All parameters used for modelling can be see in Table D.25.

Table D.25: 3NOP additive, dairy and beef and sheep

Parameter	Unit type	Unit	Value	Source
Y_M	Dairy	Change	-24.7%	(Duthie et al. 2021)
Y_M	Beef	Change	-20%	(Duthie et al. 2021)
Milk yield	Dairy Cattle	Change	-3.8%	(Duthie et al. 2021)
Gross energy coefficient (representing feed efficiency)	Dairy Cows	Change	+1.2%	(Duthie et al. 2021)
Gross energy coefficient (representing feed efficiency)	Other Cattle	Change	-1.0%	(Duthie et al. 2021)
Applicability	Dairy and beef, animals older than 12 months, housed, not organic	-	1	(Duthie et al. 2021)
Applicability	Dairy and beef, other animals	-	0	(Duthie et al. 2021)
Current uptake	Dairy, beef	-	0	(Duthie et al. 2021)
Cost	Dairy, beef	£ head^{-1} y^{-1}	48	(Duthie et al. 2021)

D.25. Improved health, dairy, beef, sheep and pigs (MM32, MM33, MM34, MM61)

The health of the animals on the farm can, in most cases, improved, by a combination of good practice including more attention to biosecurity, herd health planning with advice from veterinarians, early disease detection and timely treatment, along with prevention (e.g. vaccination), where appropriate. A series of studies showed that with improved health status the GHG emission intensity of production reduces (Fox et al. 2018, Chen et al. 2016), mainly due to higher individual outputs (milk yield and growth rates) and lower culling rates.

Improved livestock health is modelled via changing the productivity of the animals. The values underlying the modelling are derived from a more detailed livestock model, the Scottish Agricultural Emissions Model (Michael MacLeod et al. 2018). SEAM was used to estimate the emission intensity difference between current and a higher health status, changing key performance parameters, like growth and death rates at various stages, fertility rate and number of offsprings.

Improved ruminant health mesures were included in the CB6 report (Eory et al. 2020), using assumptions developed for the 5th Carbon Budget (Eory et al. 2015), after a literature review confirmed their validity. For the current analysis we used the same assumptions on the GHG effect, and updated the cost of the measure, using an estimated cost of herd health plans (*pers. comm.* C. Mason); £23.4/year/animal for cattle, and one fifth of this value for sheep. Table D.26 shows all parameters used for modelling improved livestock health.

The effects of improved health on GHG emissions in pigs were modelled for this report. The baseline physical performance was based primarily on InterPIG data (AHDB 2022). The values for high health status were derived from a variety of sources including published key performance indicators (AHDB 2024a), research articles and discussions with pig industry experts during a workshop.

Table D.26: Assumptions for modelling improved health for dairy, beef, sheep and pigs

Parameter	Unit type	Unit	Value	Source
Milk yield	Dairy	Change	0.0638	(Eory et al. 2015)
Current up-take	Dairy	-	0	(Eory et al. 2015)
Applicability	Dairy	-	0.8	(Eory et al. 2015)
Cost	Dairy	£ head^{-1} y^{-1}	23.4	Pers. comm. C. Mason
Live weight	Beef	Change	0.0638	(Eory et al. 2015)
Current up-take	Beef	-	0	(Eory et al. 2015)
Applicability	Beef	-	0.8	(Eory et al. 2015)
Cost	Beef	£ head^{-1} y^{-1}	23.4	Pers. comm. C. Mason
Live weight	Sheep	Change	0.1045	(Eory et al. 2015)
Current up-take	Sheep	-	0	(Eory et al. 2015)
Applicability	Sheep	-	0.8	(Eory et al. 2015)
Cost	Sheep	£ head^{-1} y^{-1}	4.68	Authors' estimate
Live weight	Pigs	Change	0.042	Authors' estimate
Current up-take	Pigs	-	0	Authors' estimate
Applicability	Pigs	-	0.5	Authors' estimate
Cost	Pigs	£ head^{-1} y^{-1}	11.7	Authors' estimate

D.26. Faster finishing beef (MM29)

Faster finishing was suggested as a mitigation measure in Scotland, in the The Suckler Beef Climate Scheme report (Group 2020). 3% of total beef emissions originate from slaughter animals which are older than 24 months (Moxey et al. 2020). The report argues that slaughter age could be reduced to 21 months, with no impact on slaughter weight, and thus the additional 3 months' worth of emissions can be avoided. In practice this can be achieved by a combination of improved feeding and health practices, as well as sending the animals to slaughter once they reached the appropriate weight, rather than later.

This mitigation measure was modelled using the assumptions developed for the latest Scottish MACC (Eory et al. 2023), by reducing the number of animals in the relevant animal categories (7.3%, 7.3% and 7.5% of steers, cereal fed bulls and females for slaughter are over 24 months, respectively pers. comm. A. Moxey). We assumed that the measure has no financial effects on the farm. Table D.27 shows all parameters used for modelling Faster finishing beef.

Table D.27: Assumptions for modelling faster finishing beef

Parameter	Unit type	Unit	Value	Source
Number of animals	Beef Females for Slaughter, Beef Cereal Fed Bull, Beef Steers	Change	-0.075	(Eory et al. 2023)
Number of animals	Beef Heifers for Breeding, Beef Bulls for Breeding, Beef Cows	Change	0	(Eory et al. 2023)
Current uptake	Beef	-	0	(Eory et al. 2023)
Applicability		-	1	(Eory et al. 2023)
Cost		£ head^{-1} y^{-1}	0	(Eory et al. 2023)