Quantifying the impact of future land use scenarios to 2050 and beyond - Final Report

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Client Ref: IT/KB 0917

Final Report for the Committee on Climate Change

Date 15/11/2018

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Client Committee on Climate Change

Client reference IT/KB 0917

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CEH reference Final Report for CCC

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Date 15/11/2018

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Executive Summary

Objectives

- This project examines how ambitious mitigation measures could reduce greenhouse gas (GHG) emissions from the agriculture and Land Use, Land Use Change and Forestry (LULUCF) sectors by 2050 while at the same time maintaining at least current levels of per capita food production.
- The agriculture and land use sectors need to make considerable progress on GHG emissions reductions in order for the UK to meet its future statutory emissions reductions targets in 2032 and 2050 and to fulfil the ambition of the UNFCCC Paris Agreement to keep global warming below the 1.5 °C threshold.
- Agricultural practices also affect emissions in the Land Use, Land Use Change and Forestry (LULUCF) sector, and both sectors need to be considered together to assess the overall effect of mitigation measures.
- The project considers mitigation measures affecting emissions from agricultural activities, forestry and peatlands at various levels of ambition. The mitigation measures were selected based on technical capability alone, and projected uptake has not been constrained by economic, social or policy factors. These measures are combined into different scenario pathways, which are constrained by the availability of suitable land. The outputs are annual metrics on the area under each land use type; GHG emissions and removals, timber and fuel production, and the volume and value of key crops and animal products. The full outputs have been provided in a MS Excel pivot table to the Committee on Climate Change (CCC) with summary results presented in this report. Emissions were modelled to 2050, and to 2100 for afforestation and forest management.

Mitigation measures

- Three levels of ambition were outlined. Low ambition, also known as Business as Usual, assumed current rates of activity (which were zero for novel measures) were carried forward to 2050/2100, Medium ambition assumed that currently available measures were implemented and the High ambition level assumed increased uptake of Medium ambition measures or the uptake of more radical or novel measures.
- The agricultural mitigation measures were constrained so that per capita UK food production was at least maintained at current levels, ensuring that emissions reductions in UK agriculture were not being achieved simply through displacement by relying on increased imports.
- Agricultural measures focussed on non-CO_2 abatement were: improving nitrogen use efficiency, reducing per capita livestock emissions and manure management. Measures focussed on releasing agricultural land for other land-based mitigation measures were: improved crop breeding, indoor horticulture, food waste reduction, human diet change, and increased livestock stocking densities. Changes to livestock numbers can impact both non-CO_2 emissions abatement and land release.
- Land use mitigation measures were: afforestation and the management of existing forests for fuel and timber; the planting of second generation biomass energy crops; the restoration and rewetting of degraded peatland under agricultural and forest land use; and increased agroforestry and hedgerows.
- Outputs for each ambition level of the mitigation measures were modelled using simplified versions of the calculations used for the National Greenhouse Gas Inventory, BEIS-funded work on peatland emissions and spreadsheet models developed for this project.

- Dietary change was associated with the biggest agricultural emissions reductions, followed by measures that reduce livestock non-CO_2 emissions and crop breeding.
- Afforestation and peatland mitigation measures were associated with the biggest land use emissions reductions compared with business-as-usual.
- Increased management of existing forests made the biggest contribution to timber and fuel production until 2050, and until 2100 in a comparison of the Medium ambition measures, but bioenergy crops produced a higher cumulative contribution to fuel production in the High ambition measure.

Combined land use scenarios

- Five mitigation scenarios were developed that used different combinations of mitigation measure ambitions. The intention of these scenarios is to explore a range of 'what if' land use change/agriculture options that are **technically feasible** between now and 2050, and are **not constrained by economic, social or policy factors**.
    - **Business as Usual (BAU).** Current trends in human diet, land use and management continue to 2050.
    - **High Mitigation Uptake**. Agricultural land is spared as a result of a reduction in food waste, changes in diet away from red meat and dairy products, increased yields and improved agricultural practices: this land, is converted to forestry, energy crops and agro-forestry. Some peatlands which are currently used for agricultural purposes are either permanently rewetted or partly rewetted by raising the water table. Wholly rewetted peatlands are partly restored to semi-natural vegetation.
    - **Technology Push**. There is high uptake of mitigation practices and technological development in agriculture together with high levels of change in diet away from animal products, which are replaced with plant-derived food and other protein sources (e.g. synthetic and cultured meats) as well as large reductions in food waste. The land spared is afforested and used for biomass fuel crops, and there is some peatland restoration. This scenario also includes some multifunctional land use, e.g. agroforestry and re-instatement of hedges around field boundaries.
    - **Multifunctional Land Use.** Reduction in food waste and dietary change away from red meats and dairy products combined with improved agricultural practices allows higher uptake for agroforestry and medium levels of afforestation, along with some increase in the area of biomass fuel crops.
    - **Maximum food production**. Human diet retains current intake of meat and dairy products. Improvements on agricultural practices and yields increase food production per hectare, but land remains in agricultural use rather than being re-purposed.
- It is not necessarily possible to maximise all mitigation options as the UK's land area is finite. Land 'sparing' by technical improvements that increase yields per hectare, or which decouple food production from land use to some extent, can however free up land for other uses.
- Land 'spared' by agricultural mitigation measures was balanced against the land required by the land use mitigation measures, based on the 2016 areas of agricultural land use in the June Agricultural Survey. Land requirements include the ongoing need for land conversion to 'developed' use with forecast population growth. Permanent and rough grazing land are in most demand, cropland only in demand in the higher ambition scenarios and temporary grassland is in relatively low demand (reflecting its smaller extent).
- The Technology Push scenario spares the most land due to high ambition both for dietary change and improved crop yields. The area spared is more than is required for mitigation and could (assuming that the technological innovations incorporated are achievable) be used for additional adaptation (e.g. more protected biodiversity areas) or for additional agricultural production.

- The BAU and Maximum Food Production scenarios have insufficient land available to maintain per capita production at 2016 levels. These two scenarios therefore assume either a) further increases in yields are needed to achieve production on available land, or b) a decrease in per capita production.
- The High Mitigation Uptake and the Multifunctional Land Use scenarios have an approximate balance in the areas of land required and land spared. Any shortfalls could be addressed by shifting mitigation options between agricultural land use categories or reducing the area of mitigation in some countries of the UK and increasing it in others.
- Overall, the GHG emissions from the BAU and Maximum Food Production scenarios increase by 40-41% between 2016 and 2050, whereas the emissions from the other scenarios all show a large reduction: 21% for the Multifunctional Land Use scenario, 61% for Technology Push and 69% for High Mitigation Uptake.
- Fuel and timber production is greatest in the Technology Push and High Mitigation Uptake scenarios.
- Total value of agricultural output increases with time under all scenarios[1]. For those scenarios where there is a decrease in GHG emissions, the value of total agricultural output rises by between 20-45% compared to the 2016 level.
- The agricultural and land use mitigation measures have the potential to enhance ecosystem services and to improve ecosystem resilience to climate change if they are implemented and managed in a sustainable manner.

[1] The value of agricultural products is held constant in real terms.

1 Introduction

1.1 Overview of the context of the project

The UK has national commitments under the Climate Change Act, and international commitments under the UN Framework Convention on Climate Change to reduce net greenhouse gas (GHG) emissions. This mitigation of emissions can be achieved both by reducing emissions from sources and increasing GHG removals by carbon sinks.

The Committee on Climate Change (CCC) wishes to explore how ambitious mitigation measures could reduce GHG emissions from the agriculture and land use sectors while at the same time maintaining at least current per capita levels of food production. Emissions associated with land use and agriculture make up a small but significant proportion of UK greenhouse gas (GHG) emission totals. In 2016, total UK GHG emissions were 468 $MtCO_2e$[2], of which 46.5 $MtCO_2e$ (also includes CO_2 from energy combustion) were from the Agricultural Sector (Brown *et al.* 2018). However, the relative contribution of agriculture to total UK emissions is rising as the rest of the economy decarbonises. The CCC (2018) has shown that if agriculture does not make additional progress on emissions reduction, it could represent one third of total emissions by 2050. If the UK is to meet its statutory emissions reduction targets (80% reduction by 2050 and 57% reduction by 2032), it is essential to explore ways in which agricultural emissions can be reduced.

Agricultural practices and changes in land use also impact emissions reported in the Land Use, Land Use Change and Forestry (LULUCF) sector. Uniquely, the LULUCF sector includes GHG sinks as well as sources, and the UK LULUCF sector has been a net GHG sink since 1990. In 2016, the LULUCF sector provided a net GHG sink of 14.6 $MtCO_2e$. Although net LULUCF emissions and removals are relatively small, the net flux is made up of large individual, but opposing emissions and removals within the sector (Brown *et al.*, 2018). The LULUCF sector inventory currently does not capture the full extent of estimated emissions from organic soils (peatlands), which if included are likely to convert the LULUCF sector from a current net sink into a net source (Evans *et al.*, forthcoming).

Future changes in land use and agriculture in the UK are likely to be affected by a number of factors including market and policy conditions. Market trends will, in turn, be influenced by a combination of factors including change in the UK and global populations; international markets and the trading relationships which are in place between the UK and the rest of the world; lifestyle choices and the availability and price of products. Agricultural and land use policy could drive a variety of scenarios depending on priorities which could include: boosting food production for domestic and export markets; increasing commercial forestry; developing capacity for UK production of biomass fuel feedstocks; carbon sequestration and GHG emissions reduction and adapting to climate change.

1.2 Overview of the objectives of the project

In order to explore pathways for the Agricultural and LULUCF sectors which lead to reductions on GHG emissions, the CCC required a modelling exercise to estimate projected emissions from this sector to 2050 and beyond. It was agreed that the analysis outputs should be simple to use, but transparent enough to show the basis of the projected net emissions, which will be important in understanding where actions might produce conflicting changes in emissions which have to be weighed against each other. The project considers mitigation measures affecting emissions from agricultural activities, forestry and peatlands at various levels of ambition. These measures are combined into different scenario pathways, which are constrained by the availability of suitable land. The outputs are annual

[2] The GHG Inventory sectors are Energy, Industrial Processes, Agriculture, LULUCF (Land Use, Land Use Change and Forestry) and Waste.

metrics on the area under each land use type, GHG emissions and removals, timber and fuel production, and the volume and value of key crops and animal products. In general, emissions were modelled to 2050, but for afforestation and management of forests, emissions were modelled to 2100 because of the longer time periods involved in forestry rotations.

This project has modelled the emissions from the mitigation measures based on methodologies which have been developed by the project team for use in the Agriculture and LULUCF sectors of Greenhouse Gas inventories. The Agricultural and LULUCF inventories assess GHG emissions using methodologies based on internationally agreed guidance (IPCC 2006). These guidelines cover emissions from standard agricultural practices and emissions and removals from land use change and management. The mitigation measures modelled were selected based on technical capability alone, and projected uptake has not been constrained by economic, social or policy factors. The models used are designed to estimate GHG emissions rather than to optimise land use for any particular outcome, and therefore can only be run with defined activity data (primarily areas under different land use and management regimes for LULUCF, and data on crop areas, livestock numbers, manure and fertiliser use for Agricultural emissions).

The measures do not cover all the sinks and sources in the sector inventories as some minor GHG sources have been omitted, for example wildfires. The model used for the Agriculture sector emissions has been simplified to develop implied emission factors per livestock type or cropped land area based on defined production and management parameters. The project did not have access to the Forestry Commission's CARBINE forest carbon stock change model used in the UK GHG inventory, which requires significant staff and computing resources. Instead, the simple CFlow forest carbon model (Dewar 1990; Dewar and Cannell 1992) was used to assess the net emissions and timber/fuel production from afforestation and forest management. The outputs of these simpler tools differ in absolute terms from those developed using the full inventory model, but provide indications of magnitude and change in direction of sufficient robustness for policy assessment based on fewer input requirements. Emissions which fall within the Energy sector, including emissions from on-farm fuel use, emissions from agricultural equipment and transport of products to consumers and emissions from electricity use in food production were not considered within this project. However, novel methods of food production such as use of insect-derived protein, indoor horticulture and synthetic and cultured meat, which are not covered by the current IPCC guidance, were included where research was available.

Resilience indicators such as biodiversity, water and soil quality or water availability/flood risk were not quantitatively modelled but a summary narrative on how these parameters might be affected by the measures is provided. The effect of future climate change was assessed where applicable. This was factored in to forest modelling, including growth rates and yields.

Box 1: Other projection scenarios

There are two instances of other projects that have looked at combined future GHG emissions from the Agriculture and LULUCF sectors: the Balmford model of land use emissions (Lamb *et al*., 2016) and the emissions projections to 2050 produced for the LULUCF sector (Thomson *et al*., 2017).

The Balmford model gives additional modelling of emissions which are reported in the Energy and Industrial Processes Sectors, but does not include outputs of Harvested Wood Products (HWP). The Agricultural/LULUCF model gives a more complete reflection of region variation in agricultural activity, and gives enhanced modelling for carbon stock change in forests, including production of HWP and peatland management. In addition the Agriculture/LULUCF model considers the expansion of Settlements in response to rising population.

Other sources of projected emissions are:

- FAPRI – Defra provide annual forecasts (to 10 years) under a Business as Usual scenario for major agricultural commodities for England, Wales, Scotland and Northern Ireland through the FAPRI-UK model. These provide baseline forecasts for livestock numbers (at a major category scale), areas for major crops, some productivity indicators (e.g. milk yield) and some indication of total nitrogen fertiliser use. FAPRI does not provide forecasts of production methods or farm management practices.
- 5th Carbon Budget (5CB) – Scenarios were developed for 2030 by the CCC based on a range of specific management improvements and other measures relating to soils, crops, livestock and manures. Full details for the scenarios are given in Eroy *et al.* (2015) for soils and crops, livestock and manure management.
- The draft Scottish Climate Change Plan which outlines the proposals and policies (RPP3) for meeting Scotland's annual greenhouse gas emissions targets.

2 Development of the mitigation measures and combined scenarios

The mitigation measures considered for the Agriculture sector were grouped together under Farming practices, Technology development and Diet change. The mitigation measures considered for the LULUCF sector were grouped as Afforestation and Forest Management, Hedgerows and Agroforestry, Bioenergy crops and Peatland emissions mitigation.

Three levels of ambition were outlined. Low ambition, also known as Business as Usual, assumed current rates of activity (which were zero for novel measures) were carried forward to 2050/2100, Medium ambition assumed that currently available measures were implemented and the High ambition level assumed increased uptake of Medium ambition measures or the uptake of more radical or novel measures.

2.1 Description of the different mitigation measures and levels of ambition

A suggested set of mitigation measures were presented at an expert workshop hosted by the CCC on 22nd November 2017. The workshop delegates (Appendix 1) had expertise in agriculture, forestry, agro-forestry, biomass fuels, peatland restoration, and indoor horticulture. They were asked to discuss the mitigation measures and fine-tune the level of ambition for each measure. An outline set of scenarios with different combinations of mitigation measures, which could represent different development pathways for the agriculture and land use sectors, was also presented at the workshop. These scenarios could assess the emissions impact of prioritising GHG mitigation or food production, for example (see section 2.2). The measures and scenarios discussed in the workshop were subsequently refined and agreed by the project team and the CCC. The underlying assumptions and implementation of the mitigation measures are described in Chapter 3.

2.1.1 Agricultural practices and technology

The agricultural mitigation scenarios were constrained such that per capita UK food production was at least maintained at current levels (except for the human dietary change and reducing food waste scenarios), ensuring that emissions reductions in UK agriculture were not being achieved simply through displacement by relying on increased imports. A key requirement of most scenarios was to free up agricultural land for forestry (including agro-forestry), biomass fuel production, and peatland rewetting. With a forecast growing UK human population, these constraints necessitated productivity increases combined with GHG emission intensity reductions.

Mitigation measures based on agricultural practices and technology can be split between those that produce direct emissions abatement, and those that release agricultural land for other land-based mitigation activities:

- Emissions abatement measures were: improving nitrogen use efficiency, reducing per capita livestock emissions and manure management.

- Land release measures were: improved crop breeding, indoor horticulture, food waste reduction and increased livestock stocking densities. Changes to livestock numbers can affect both emissions abatement and land release.

The Low Ambition/BAU measures assume no new policy action, and changes reflect industry trends and a combination of FAPRI forecasts modified where necessary to maintain per capita food production.

The Medium Ambition measures assume realistically feasible uptake of currently-available technologies. In some cases, multiple measures could be applied to the same land, e.g. precision farming and loosening compacted soils, while in other cases measures are mutually exclusive, e.g. low emission slurry application and rapid incorporation of applied manure. The level of uptake of these measures is equal to or in excess of the CCC's estimates for the 5th Carbon Budget. There is a small increase in agroforestry and hedge creation on land which remains in agricultural use.

The High Ambition measures increase in the use of existing mitigations practices and technologies beyond the levels proposed in the Medium Ambition scenario and also include emerging technologies and measures which are not currently viable (e.g. financially, consumer acceptability). These include indoor horticulture, synthetic meat production and production of insect-derived protein. Agroforestry and hedge creation become more widespread on agricultural land. The water table is raised in some areas of cropland and improved grassland on peat in order to reduce emissions.

Nitrogen use efficiency

- Measures include loosening compacted soils, precision farming (variable rate fertiliser application, controlled traffic farming), increased use of organic residues (e.g. digestates), better accounting for nutrients in livestock manures, and increased use of legume crops.
- The Low ambition measure assumes current N fertilizer application rates (average use for the UK in 2016 equates to c. 60 and 145 kg N ha^{-1} across all improved grassland and cropland, respectively) and N use efficiency
- The Medium ambition assumes an overall effect of a 20% improvement in N use efficiency on cropland, and 10% on grassland by 2050.
- The High ambition assumes an overall effect of a 30% improvement in N use efficiency on cropland, and 10% on grassland (more limited potential) by 2050. This includes uptake of fertiliser products incorporating nitrification inhibitors.

Livestock emissions

- Measures include improved ruminant feed digestibility, improvements to animal health and fertility, and genetic improvement to feed conversion ratio.
- The Low ambition measure assumes current livestock management. Nitrogen and Volatile Solids (VS) excretion by dairy cows increases in line with BAU increase in milk yield.
- The Medium ambition assumes an overall effect of a 5% reduction in enteric emission per animal in ruminants, and a 5% reduction in VS and N excretion across all major livestock categories by 2050.
- The High ambition assumes an overall effect of a 10% reduction in enteric emission per animal in ruminants, and a 10% reduction in VS and N excretion across all major livestock categories by 2050. Additional measures include the use of feed additives to reduce enteric fermentation and/or improve N use efficiency and genetic selection of ruminants for inherently low enteric emissions.

Livestock numbers

- In the Low ambition measure livestock numbers increase to maintain per capita food production.
- In the Medium ambition measure ruminant numbers decrease to achieve 20% reduction in red meat and dairy consumption and export. Pig and chicken numbers increase to replace the lost red meat protein and human edible crops increase to replace dairy protein. The effects are lower enteric emissions, N and VS excretion from ruminant livestock, offset to some extent

by increased N and VS excretion by pigs and poultry. There is a reduction in grassland area (and associated fertiliser N use) and net change in arable area (and associated N fertiliser use) through less feed required for ruminants but more required for pigs, poultry and humans.
- In the High ambition, there is a 50% reduction of domestic consumption and export of red meat and dairy by 2050. Pig and chicken numbers and human edible crops are increased as in the Medium ambition, and the remainder of red meat loss and human edible crops is replaced by novel protein (insects, cultured/synthetic meat) sources. This results in lower enteric emissions, N and VS excretion from ruminant livestock, offset to some extent by increased N and VS excretion by pigs and poultry. There is a reduction in grassland area (and associated fertiliser N use) and net change in the arable area (and associated N fertiliser use) through less feed required for ruminants but more required for pigs, poultry, humans and insect production.

Manure management

- The Low ambition continues current manure management practices.
- In the Medium ambition, an increased proportion of livestock manure is treated by anaerobic digestion and manure management improves in livestock housing, manure storage and manure application. By 2030 there is a 20% reduction in the ammonia emission factor for manure spreading emissions and a 20% reduction in the fraction of N leached from manure application. By 2050 10% of all cattle, pig and poultry manure is treated by anaerobic digestion, and there is a 5-10% reduction in ammonia Emission Factors for livestock housing and manure storage.
- In the High ambition, there is increased uptake of anaerobic digestion and improved manure management practices beyond Medium ambition levels, including some additional technologies, e.g. slurry acidification. By 2030 there is a 30% reduction in ammonia emission factors for manure spreading and a 20% reduction in the fraction of N leached from manure application. By 2050 20% of all cattle, pig and poultry manure is treated by anaerobic digestion and there is a 10-20% reduction in ammonia Emission Factors.

Improved crop breeding

- The Low ambition assumes modest yield increases with a linear increase in wheat yield to 8 t/ha by 2050 (scaled proportionately to other crops).
- The Medium ambition assumes improvements through plant breeding and the adoption of genetically modified (GM) crops with improved disease control, although the full impact is counteracted by the effects of climate change. The overall effect is a linear increase in wheat yield to 10 t/ha by 2050 (scaled proportionately to other crops).
- The High ambition assumes the maximum achievable improvements through plant breeding and the adoption of GM crops with improved disease control that are also resilient to climate change. The overall effect is a linear increase in wheat yield to 20 t/ha by 2050 (scaled proportionately to other crops)

Indoor horticulture

- There is no significant indoor horticulture at present (Low ambition).
- In the Medium ambition, there is a move towards high-technology indoor horticulture, with 10% of horticulture moving indoors by 2050.
- In the High ambition, the move towards indoor horticulture is more significant, with 50% moving indoors by 2050.

Food waste reduction

- The Low ambition assumes that food waste remains at current levels.

- In the Medium ambition, food waste at farm gate and post-farm gate including the supply chain and consumer, is reduced to meet the WRAP targets of 20% reduction on current levels by 2025 (www.wrap.org.uk/content/courtauld-commitment-2025) but there is no further reduction by 2050.
- In the High ambition, food waste continues to decrease, achieving 20% reduction on current levels by 2025 and 50% reduction by 2050.

Increased livestock stocking densities

- In the Low ambition there is a small increase in current stocking densities, based on the increase in livestock numbers required to maintain per capita food production. Stocking densities imply higher numbers of livestock per unit of land area, but there is no assumption that the number or time spent by livestock indoors increases.
- In the Medium ambition there is a refocus from extensive to more intensive grazing, particularly for sheep, in upland areas. This has the effect of reducing livestock in upland areas by redistributing them to other grazing areas, with an overall increase of 10% in the stocking rate on the remaining upland grassland.
- In the High ambition, there is an increase in stocking density across all grassland, with an additional 10% increase in the stocking density of the reduced area of upland grassland, and a 10% increase in stocking density on improved grassland.

2.1.2 Forestry

The Forestry measures cover afforestation of previously unforested land and the management of existing forests for fuel and timber. These measures do not include Short Rotation Forestry or agroforestry, which are included under other measures.

The Low Ambition/BAU measures assume that current rates of planting and felling (based on the average rate for 2014-2016, see Table 12 in section 3.2) are continued. It assumes that there is no change from current management, where 100% of conifer forests are assumed to be managed, but only 20% of broadleaved forests. It assumes that the conifer forests will continue to produce the current mix of harvested wood products (paper, panel board and sawn wood, with some fuel) and that all broadleaved harvested wood products will be used for fuel.

The Medium Ambition measures increase afforestation to the 5th Carbon Budget maximum levels, with 31 kha planted annually across the UK to 2100.. New planting avoids deep peat and areas of landscape sensitivity. Although some planting may occur on cropland and intensive grassland, this will be limited to small areas of shelter belt, and most commercial planting is likely to be mainly on extensive grassland used for rough grazing and improved pasture. Broadleaf woodland which is currently unmanaged is brought back into production, with 67% actively managed by 2030 for biomass fuel and timber. Thinnings from both conifer and broadleaf forest are assumed to be used for fuel. Production of long-lived harvested wood products (sawn board) for construction increases. Overall yields increase linearly to 10% above current levels by 2050 as a result of improved management, planting the right species in the right location, and climate change (CO_2 fertilisation effect).

The High Ambition measures increase afforestation beyond the 5th Carbon Budget maximum levels to rates exceeding those in the 1970s, when there was also rapid forest expansion (50 kha annually across the UK to 2100New planting avoids deep peat, but landscape sensitivity is not a barrier. Commercial afforestation occurs on improved grassland and cropland as well as extensive grassland used for rough grazing capable of supporting trees. Most broadleaf woodland which is currently unmanaged is brought back into production, with 80% actively managed by 2030 for biomass fuel and timber. The areas of forest producing constructional timber increases beyond the Medium ambition levels. Overall yields increase linearly to 20% above current levels by 2050 as a result of improved management, planting the right species in the right location, breeding and climate change.

2.1.3 Bioenergy Crops

The Bioenergy Crop measures cover the planting of second generation biomass energy crops such as *Miscanthus*, short rotation coppice (SRC) and Short Rotation Forestry (SRF), and assumed yield increases due to improved management, breeding and climate change. These crops are grown for the heat and energy markets, mostly on an industrial basis. The formulation of these measures was informed by the team working on the ELUM project[3] (Pogson *et al.,* 2016).

The Low Ambition/BAU measures continue current rates of biomass energy crop planting (which are very close to zero) planting and no change in management.

The High ambition assumes an increase the area of biomass energy crops (SRC willow, Short Rotation Forest and *Miscanthus*) towards the ETI 1,400 kha target by 2050. This area was capped at 1,200 kha for this project, as there was insufficient land available when this measure was combined with other high ambition measures (see section 3.3 for details). The split between *Miscanthus* and SRC/SRF was determined by the availability of cropland: it was assumed that *Miscanthus* crops would be planted on existing cropland (including land currently used for 1st generation biomass energy crops) and tree-based energy crops (SRC/SRF) would be planted on grassland. Innovative agronomy and improved plant breeding including genetic modification (GM) increases the yield of SRC and Miscanthus from 10 t/ha to 20 t/ha oven-dry material by 2050.

The Medium ambition assumes an increase in the area of biomass fuel crops (SRC willow and *Miscanthus*) to 2050 to 7000kha, which is half of the Energy Technology Institute 1,400 kha target (ADAS 2016). Planting is on a mix of crop land (*Miscanthus*) and grassland (SRC/SRF). There is an increase in the area of short rotation forest (planted on grassland) managed for biofuel production from 2030. Good agronomy and plant breeding increases the yield of SRC and Miscanthus from 10 t/ha to 15 t/ha oven-dry material by 2050.

2.1.4 Peatland

The Peatland measures cover the restoration and rewetting of degraded peatland under agricultural and forest land use. By 2050 mitigation on these areas will abate GHG emissions rather than increase GHG removals due to the long-time profile required to sequester carbon following restoration, and relatively slow rate of peat formation in natural systems. The areas and emission factors used for calculating emissions from peatlands are taken from Evans *et al.*, (forthcoming). This was a BEIS-funded project (referred to as the Wetlands Supplement project) to improve activity data and emission factors for organic soils in the UK with a view to future reporting under the UNFCCC's Kyoto Protocol. The work has not yet been implemented in the UK's national GHG inventory. Currently only emissions from peat extraction sites and carbon losses from drained forest, cropland and improved grassland are included in the LULUCF inventory. These currently total 1.6 MtCO2e. If fully implemented, GHG emissions from a much larger area of organic soils and additional GHG sources will be included in the inventory, which will likely convert the current LULUCF net GHG sink into a net GHG source. The Wetlands Supplement project included five emissions scenarios for future peatland management in the UK to 2050. These have been adapted for use in this project.

The Low Ambition measures are based on the Wetland Supplement Central scenario (Evans *et al.,* forthcoming), which only includes peatland restoration for which there is current policies and funding in place. Industrial peat extraction sites are restored at planned dates where known (England only) or

[3] http://www.elum.ac.uk/. The information provided to this project by the ELUM team was that the initial carbon stock of a given land use was a better guide for where to plant SRC or *Miscanthus*, with locations with a higher initial soil carbon stock (generally grassland but not always) being more likely to lose carbon. The team noted that potential losses of soil organic carbon from grasslands are likely over-emphasized as the measurement dataset is still small and industry best practices in establishing plantations are not yet widely applied.

remain at 2014 levels. Only Scotland has policies/funding in place for peatland restoration (Scottish Government 2018): the target areas are 50 kha of upland peatlands and forest restored by 2020 and 250 kha restored by 2030 (representing 40% of the currently degraded peatland area). No restoration of peatland is assumed in other administrations of the UK.

The Medium ambition measures are based on the Wetland Supplement Low Emission scenario (Evans *et al.,* forthcoming), where policy aspirations[4] for peatland restoration in each administration of the UK are projected forward beyond 2021. This assumes that by 2050 and across all administrations:

- restoration of 25% of the area of degraded intensively managed lowland peat which are currently cropland or improved grassland to semi-natural habitat;
- restoration of 50% of the area of degraded upland peat which is currently heather moorland, extensive grassland or modified bog;
- restoration of 25% of forest (conifer) on peat with less than Yield Class 8;
- cessation of all peat extraction with 100% restoration to semi natural habitats by 2050.

The High ambition measures are based on the Wetland Supplement Stretch scenario (Evans *et al.,* forthcoming), which exceeds current policy aspirations for peatland restoration. This assumes that by 2050 and across all administrations:

- restoration of 50% of the area of degraded intensively managed lowland peat which are currently cropland or improved grassland to semi-natural habitat;
- restoration of 75 % of the area of degraded upland peat which is currently heather moorland, extensive grassland or modified bog;
- restoration of 50 % of forest on peat with less than Yield Class 8;
- cessation of all peat extraction with 100% restoration to semi natural habitats by 2030.

In addition, under the High ambition there is more abatement of emissions from intensively managed lowland peats by raising the water table on a seasonal or permanent basis on the remaining areas used for crop production or improved grassland (i.e. unrestored intensively managed lowland peatlands). This is intended to represent the abatement of emissions by halving the water table depth (and thus halving emissions) while still maintaining some agricultural production.

2.1.5 Hedgerows and agroforestry

Mitigation measures based on increased agroforestry and hedgerows aim to increase carbon sequestration by increasing the amount of permanent vegetation on agricultural land whilst maintaining agricultural production. Agroforestry in this context means silvopastoral or silvoarable systems. Silvopastoral systems integrate low density woodland with livestock grazing, and silvoarable systems, in the UK context, integrate narrow strips of economically valuable woodland with arable cropping.

In the Low ambition measure, agroforestry remains at its current (very low) level and hedgerows remain at their current extent until 2050.

In the Medium ambition there is an increase of land used for agroforestry so that 5% of cropland is converted to silvoarable systems and 5% of permanent grassland is converted to silvopastoral systems by 2050. The length of hedges in the UK is restored to 1984 levels (an increase of 30%) by 2050, and 10% of this hedge length is managed for biomass fuel.

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[4] Defra £10M peat restoration fund https://www.gov.uk/government/news/10m-fund-to-restore-peatland-opens-for-applications; Scotland's National Peatland Plan https://www.nature.scot/sites/default/files/2017-07/A1697542%20-%20150730%20-%20peatland_plan.pdf; Welsh Government Sustainable Management Scheme projects

In the High ambition there are higher levels of agroforestry so that 10% of cropland is converted to silvoarable systems and 10% of permanent grassland is converted to silvopastoral systems by 2050. The length of hedges in the UK is restored to 10% above 1984 levels by 2050 and 30% of this hedge length is managed for biomass fuel.

2.1.6 Human dietary change

Human dietary change mitigation measures include the food waste reduction measures (section 2.1.1) and dietary change measures (affecting livestock numbers).

The Low Ambition/BAU measures assume no change from current food consumption patterns (per capita consumption is maintained).

The Medium ambition measures require a moderate shift in human diet away from red meat and dairy by 2050 (20% reduction in consumption) to alternative existing protein sources with lower emissions intensities such as legumes, mycoprotein and poultry.

The High ambition measures require a large shift in human diet away from red meat and dairy by 2050 (50% reduction in consumption) in a diet which includes novel protein sources such as insect-derived protein and synthetic meat and milk, as well as existing alternatives. The impact of these measures is reflected in a reduction in livestock numbers and land required for grazing and fodder production.

2.2 Scenario description

Five mitigation scenarios were developed in the November 2017 workshop that used different combinations of mitigation measure ambitions. The intention of these scenarios is to explore a range of 'what if' land use change/agriculture options that are **technically feasible** between now and 2050, and are **not constrained by economic, social or policy factors**. The only constraints assumed are that land for settlement growth and maintaining current levels of UK food production per capita are met first, and protected land areas (e.g. national parks) are not converted.

- **Business as Usual (BAU).** Current trends in human diet, land use and management continue to 2050.
- **High Mitigation Uptake**. Agricultural land is spared as a result of reduction in food waste and change in diet away from red meat and dairy products, increased crop yields and improved agricultural practices. The spared land is converted to forestry and energy crops to produce timber and fuel crops. Half of lowland peatlands which are currently used for agricultural purposes are wholly rewetted, and there is the option to party rewet the remaining unrestored area of agricultural land still in production by raising the water table. Wholly rewetted peatlands are partly restored to semi-natural vegetation.
- **Technology Push**. This scenario entails high uptake of mitigation practices and technological development in agriculture together with high levels of change in diet away from animal products, which are replaced with plant-derived food and other protein sources (e.g. synthetic and cultured meats) as well as large reductions in food waste. The land spared is afforested and used for biomass fuel crops, and there is some peatland restoration.
- **Multifunctional Land Use.** Reduction in food waste and dietary change away from red meats and dairy products combined with improved agricultural practices allows widespread uptake for agroforestry and medium levels of afforestation, along with some increase in the area of biomass fuel crops.
- **Maximum Food Production**. Human diet retains current intake of meat and dairy products. Improvements in agricultural practices and yields increase food production per hectare, but land remains in agricultural use and is not released for alternative uses.

The combination of measure ambitions for each scenario are given in Table 1. There are also assumptions common to all scenarios:

- **The area of developed land is assumed to increase** as it does in the LULUCF inventory projections (Thomson *et al.,* 2017), where house building (and pro-rata increase in other urban development) increases at a rate that will accommodate the increase in population. The developed land, or 'Settlement', category in the LULUCF sector includes buildings but also recreational areas, infrastructure, quarries and military land. It assumes that the area of brownfield development and density of dwellings will remain constant until 2050. Although there may be potential for additional carbon storage on these areas, e.g. in woodlands, these areas would not be managed for food/timber/fuel production
- For all scenarios (except 'Max food production'), **UK consumption per capita in calories is maintained** at 2016 levels, based on the UK human population growth forecast[5], as is UK production as a proportion of UK consumption for each crop or livestock product[6]. To derive required production levels for future years, it was assumed that exports remained at 2016 absolute levels (unless there was excess production e.g. under the 'Max food production' scenario) and imports increased pro-rata with population growth.

Table 1: The level of ambition, by measure, for the scenarios

	BAU	High Mitigation Uptake	Technology Push	Multi-functional Land Use	Maximum Food Production
Agricultural farming practices	Low	High	High	Medium	Medium
Agriculture technology development	Low	Medium	High	Medium	Medium/ High
Hedges and agro-forestry	Low	High	Low	High	Low
Afforestation and forest management	Low	High	High	Medium	Low
Bioenergy crops	Low	High	High	Medium	Low
Peatlands emissions mitigation	Low	High	Medium	Medium	Low
Diet change	Low	Medium	High	Medium	Low
Food output per capita	BAU	Low	Low	Low	High

5 https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationprojections/bulletins/nationalpopulationprojections/2015-10-29

6 https://www.gov.uk/government/statistics/agriculture-in-the-united-kingdom-2016

3 Mitigation measures

3.1 Agriculture

The UK GHG emission inventory for the agriculture sector now uses the smart inventory model (the culmination of the Defra GHG Platform projects AC0114, AC0115 and AC0116) with detailed sectoral, spatial and temporal resolution. As such, the model requires many parameters and input data and has long run times. To run the relatively simple, high level scenarios for this project, a simplified spreadsheet version of the smart inventory model was therefore created. This operated at Devolved Administration level, with less individual sector detail than the smart inventory model, but retained the relationships between key inputs (e.g. fertiliser use, N excretion by different livestock types) and emission estimates.

The individual measures considered for Agriculture are described in more detail below together with the impacts on emissions, activity data and production when compared with the business as usual scenario. It is important to note that including a combination of measures in a given scenario will not necessarily result in the sum of the individual effects, as there will often be interactions between measures. For example, combining lower livestock emissions with human dietary change will result in a lower overall reduction in emissions than the sum of the measures assessed individually, because the lower livestock emissions will only be applied to a lower total number of livestock as a result of reducing ruminant numbers through human dietary change. This has been accounted for in the scenarios described in Section 2.3 and the results presented in Section 4. In addition, for the combined agriculture and land use scenarios, land use requirements for other purposes also had to be included and total grassland and cropping areas may differ from those presented for the individual measure assessments. If other measure combinations are to be run, these considerations need to be taken into account.

For the Business as Usual scenario, UK agricultural production per capita output was maintained. This required an assumed increase in productivity (as per FAPRI for cereal and milk yields), livestock numbers and cropping area, which was associated with an increase in estimated GHG emissions to 2050 (

Table 2). Subsequent assessments of individual measures were against this Business as Usual baseline.

Table 2: Business as Usual estimates for GHG emissions, activity data and production of selected outputs for UK agriculture for 2016, 2030 and 2050.

	units	2016	2030	2050
Emissions				
Enteric emissions	Mt CO_2e	21.94	23.49	25.02
Methane manure management	Mt CO_2e	4.32	4.63	4.94
Nitrous oxide manure management	Mt CO_2e	2.89	3.09	3.29
Nitrous oxide soils	Mt CO_2e	11.26	11.78	12.30
Liming and urea use	Mt CO_2e	1.29	1.31	1.33
Total CO_2e	Mt CO_2e	41.70	44.29	46.88
Activity data				
Cattle	'000s	9886	10435	10900
Sheep	'000s	34663	37719	40945
Pigs	'000s	4866	5295	5747
Poultry	'000s	172607	187822	203890
Total grassland	'000 ha	12255	12255	12255
Total arable land	'000 ha	4662	4999	5340
Fertiliser use	kt N	1090	1139	1188
Production				
Milk	million litres	14522	15753	17053
Beef and veal	kt	913	993	1078
Mutton and lamb	kt	300	326	354
Pigmeat	kt	887	965	1048
Poultrymeat	kt	1792	1950	2117
Wheat	kt DM	14383	15526	16732

The **improved N use efficiency** measure was assumed to include precision (variable rate) fertiliser application, which can reduce requirement by 5%, and controlled traffic farming on cropland which can reduce use by 10-15% (Balafoutis *et al.*, 2017). Also assumed are increased utilisation of organic residues from e.g. anaerobic digestion of food wastes, crops and livestock manures, replacing manufactured fertiliser N, improved accounting for the utilisation of the N content of livestock manures with associated reduction in fertiliser N use, and an increased use of legumes:

- For the Medium scenario, these were assumed to give a 20% improvement in N use efficiency on cropland and 10% improvement on grassland by 2050.

- For the High scenario, increased implementation of the same measures was assumed, and also uptake of fertiliser products incorporating urease and nitrification inhibitors. Use of urease inhibitors with urea fertiliser can significantly reduce ammonia emissions (by 70% on average in a UK study, Defra NT2605), and give crop yield benefits equivalent to the fertiliser N saving through the reduction in ammonia emissions. Nitrification inhibitors can give a 30-70% reduction in direct N_2O emissions from fertilisers (e.g. Misselbrook *et al.*, 2014), although this is associated with a much lower (if any) increases in crop yield or N uptake, cited as 5% on average in a meta-study by Abalos et al. (2014). This increased implementation of improved practices and uptake of novel fertiliser products was assumed to give a 30% improvement in N use efficiency on cropland but still only a 10% improvement on grassland (where opportunity for implementation was assumed to be more limited as fertiliser N use on grassland has decreased markedly over the past 20 years) by 2050.

Improved N use efficiency measure was associated with only very modest reductions in emissions, with an estimated 7% (Medium scenario, 2030) and 23% (High scenario, 2050) reduction in fertiliser N use giving only 0.8 and 2.6% reduction in total GHG emissions from UK agriculture, respectively (Table 3). This should not perhaps be too surprising as GHG emissions from fertiliser use account for <10% of total emissions from UK agriculture. For this measure it was assumed there were no impacts on production; the same level of production was achieved with lower fertiliser N input.

Table 3: Impacts of N use efficiency measures on GHG emissions and activity data of selected outputs for UK agriculture for 2030 and 2050.

	units	2030			2050		
		BAU	Medium	High	BAU	Medium	High
Emissions							
Nitrous oxide soils	Mt CO_2e	11.78	11.46	11.34	12.30	11.49	11.18
Liming and urea use	Mt CO_2e	1.31	1.28	1.27	1.33	1.26	1.23
Total CO_2e	Mt CO_2e	44.29	43.95	43.82	46.88	46.00	45.66
Activity data							
Fertiliser use	kt N	1139	1062	1033	1188	992	915

The **lower livestock emissions** measure was associated with lower enteric emissions for ruminant animals (cattle and sheep) and lower N and volatile solids (VS, the source of methane emissions from manure management) excretion by all livestock. For ruminants, there is limited potential to decrease enteric emissions through improved feed digestibility (particularly where grazed grass reperesents a major proportion of the animal diet), improvements to animal health and fertility (fewer replacement animals required for breeding herds), genetic improvements to feed conversion ratios and hence lower N excretion (e.g. Hristov *et al.*, 2016):

- Implementation of these practices in the Medium scenario was assumed to give 5% reduction in enteric methane emission per ruminant animal and 5% reduction in N and VS excretion for all livestock types.

- Under the High scenario, these measures were combined with the use of feed additives and genetic selection for inherently low enteric methane ruminants (without compromising productivity or other desired traits), giving 10% reduction in enteric methane emission per ruminant animal and 10% reduction in N and VS excretion for all livestock types.

Enteric methane emissions account for approximately 50% of total UK agriculture GHG, so although the scenario reductions are relatively conservative on a per animal basis, they are associated with emission reductions of between 1.8 (Medium scenario, 2030) and 8.8% (High scenario, 2050) (

Table 4). There were no changes to activity data or production associated with this measure, although in reality we might assume some productivity gains with lower enteric emissions.

Table 4: Impacts of lower livestock emissions measures on GHG emissions and activity data of selected outputs for UK agriculture for 2030 and 2050.

	units	2030			2050		
		BAU	Medium	High	BAU	Medium	High
Emissions							
Enteric emissions	Mt CO_2e	23.49	22.89	22.31	25.02	23.50	22.00
Methane manure management	Mt CO_2e	4.63	4.54	4.44	4.94	4.69	4.45
Nitrous oxide manure management	Mt CO_2e	3.09	3.03	2.97	3.29	3.14	2.98
Nitrous oxide soils	Mt CO_2e	11.78	11.72	11.67	12.30	12.15	12.01
Total CO_2e	Mt CO_2e	44.29	43.49	42.70	46.88	44.81	42.77

The **manure management** measures included treatment of livestock manure by anaerobic digestion, ammonia emission reduction measures (thereby lower indirect N_2O emissions) for livestock housing (floor design, air scrubbers) and manure storage (covers) and the use of low ammonia emission slurry application equipment and rapid incorporation of manures to tilled land (e.g. Bittman *et al.*, 2014). In addition, implementation of nutrient management plans and a move of manure spreading away from late summer/autumn to reduce nitrate leaching (and indirect N_2O emissions):

- For the Medium scenario, 10% of all cattle, pig and poultry manure was assumed to be treated by anaerobic digestion by 2050, implied ammonia emission factors for manure management for cattle were reduced by 10% and for pig and poultry by 5%, implied ammonia emission factors for manure spreading reduced by 20% and the fraction of manure leached reduced by 20%.

- For the High scenario, 20% of all cattle, pig and poultry manure was assumed to be treated by anaerobic digestion by 2050, implied ammonia emission factors for manure management for cattle were reduced by 20% and for pig and poultry by 10%, implied ammonia emission factors for manure spreading reduced by 30% and the fraction of manure leached reduced by 20%.

There were no impacts of the manure management measures on activity data or production output. Impacts on GHG emissions from UK agriculture varied between 0.6 (Medium scenario, 2030) and 2.1% (High scenario, 2050) (Table 5).

Table 5: Impacts of manure management measures on GHG emissions for UK agriculture for 2030 and 2050.

	units	2030			2050		
		BAU	Medium	High	BAU	Medium	High
Emissions							
Methane manure management	Mt CO_2e	4.63	4.48	4.33	4.94	4.54	4.15
Nitrous oxide manure management	Mt CO_2e	3.09	3.08	3.08	3.29	3.27	3.25
Nitrous oxide soils	Mt CO_2e	11.78	11.66	11.64	12.30	12.17	12.13
Total CO_2e	Mt CO_2e	44.29	44.03	43.84	46.88	46.33	45.88

The **improved crop breeding** measure was defined by average yield targets for wheat by 2050 of 10 and 20 t ha^{-1} under the Medium and High scenarios, respectively. Yields for other crop types were assumed to also increase by proportionally the same amount as wheat, although this may be an ambitious scenario as funding for crop development has largely focussed on major crops including wheat, with less emphasis on other UK crop types. Wheat yields have increased in the UK from approximately 4 to 8 t ha^{-1} over the period 1970 to 2016 (AHDB, http://cereals-blog.ahdb.org.uk/moving-on-up-end-of-the-wheat-yield-plateau/), but yield increases have plateaued in recent years. The 20 t ha^{-1} average wheat yield target under the High scenario is therefore particularly ambitious and would require significant scientific advances in crop breeding, but a major Research Council project exists to do just that (BBSRC Designing Future Wheat https://www.rothamsted.ac.uk/projects/designing-future-wheat-dfw).

The High scenario results in substantial sparing of arable land (by 60% by 2050 compared with BAU) and fertiliser use (by 39% by 2050 compared with BAU) to maintain per capita productivity. Impacts on GHG emissions from UK agriculture varied between 1.1 (Medium scenario, 2030) and 7.1% (High scenario, 2050) (Table 6).

Table 6: Impacts of crop breeding measures on GHG emissions and activity data of selected outputs for UK agriculture for 2030 and 2050.

	units	2030			2050		
		BAU	Medium	High	BAU	Medium	High
Emissions							
Nitrous oxide soils	Mt CO_2e	11.78	11.31	9.88	12.30	11.24	9.12
Total CO_2e	Mt CO_2e	44.29	43.80	42.29	46.88	45.76	43.53
Activity data							
Total arable land	'000 ha	4999	4529	3081	5340	4272	2136
Fertiliser use	kt N	1139	1071	862	1188	1034	725

Moving horticulture production indoors into controlled environmental production units with precision light, temperature, water and nutrient supply would release arable land for other purposes and potentially reduce fertiliser N use. Horticultural crops were assumed to be those in the June Agricultural Survey (JAS) classified as: 'vegetables', 'other horticultural crops', 'soft fruit', 'top fruit' and 'wine grapes'. The Medium and High scenarios assumed a move of 20 and 50%, respectively, of current horticultural land area to indoor production. No displacement of agricultural land was assumed for the increase in indoor production. Although a very intensive sector, horticulture represents a very small fraction of the total agricultural cropped land area, fertiliser N use and GHG emissions from UK agriculture, therefore impacts of this measure were small with a reduction in fertiliser N use of 1.0% and reduction in total GHG emission from UK agriculture by 0.2% for the High scenario by 2050 compared with BAU (Table 7). There would be some increased energy use associated with moving production systems indoors, but these could be assumed to be from renewable energy over the considered time period.

Table 7: Impacts of moving horticultural production indoors on GHG emissions and activity data of selected outputs for UK agriculture for 2030 and 2050.

	units	2030			2050		
		BAU	Medium	High	BAU	Medium	High
Emissions							
Nitrous oxide soils	Mt CO_2e	11.78	11.77	11.74	12.30	12.28	12.21
Liming and urea use	Mt CO_2e	1.31	1.31	1.31	1.33	1.33	1.32

Total CO_2e	Mt CO_2e	44.29	44.29	44.26	46.88	46.86	46.79
Activity data							
Total arable land	'000 ha	4999	4992	4965	5340	5324	5257
Fertiliser use	kt N	1139	1138	1134	1188	1186	1176

Increasing grazing intensity was achieved through reducing the grassland area available while keeping grazing livestock numbers at BAU levels. The assumption was made that upland (rough grazing) is used by mostly by sheep and beef (80% of rough grazing was associated with sheep and 20% with beef cattle). Grazing livestock density was derived by dividing approximate total livestock units (assuming cattle, weighted across all types, = 1 LU, and sheep, across all types, = 0.1 LU) by total grassland area (rough grazing, temporary and permanent improved grassland):

- Under the Medium scenario, the area of rough grazing was then reduced to achieve an overall stocking rate increase of 10% on rough grazing by 2050.

- Under the High scenario, further to the Medium scenario the stocking rate on improved grassland only (permanent and temporary) was increased by a further 10% by 2050. Livestock numbers (and production) were assumed to remain the same, but under the High scenario N application rate to improved grassland was increased by 10% to account for higher production requirement per unit of land.

This scenario did not result in any direct reductions in GHG emissions from agriculture – indeed, under the High scenario there is a small increase in emissions due to the increased fertiliser use on lowland grassland (Table 8). Rather, the impact is to spare grassland area, with approximately 9% of total grassland area released by 2050 under the High scenario (Table 8) which could then be used e.g. for afforestation.

Table 8: Impacts of increasing grazing intensity on GHG emissions and activity data of selected outputs for UK agriculture for 2030 and 2050.

	units	2030			2050		
		BAU	Medium	High	BAU	Medium	High
Emissions							
Nitrous oxide soils	Mt CO_2e	11.78	11.78	11.86	12.30	12.30	12.50
Total CO_2e	Mt CO_2e	44.29	44.29	44.38	46.88	46.88	47.09
Activity data							
Total grassland area	'000 ha	12255	11770	11764	12255	11141	11134
Fertiliser use	kt N	1139	1139	1156	1188	1188	1229

The **food waste reduction** measures were based on:

- Under the Medium scenario, the WRAP targets, with a 20% reduction by 2025 (with no further reduction to 2050).

- Under the High Scenario a further reduction to 50% total reduction by 2050. under the High scenario.

Current quantity of food waste was derived from WRAP statistics (http://www.wrap.org.uk/food-waste-reduction) as 10 million tonnes per year post-farm gate. From WRAP (2012), vegetable and fruit were identified as the food types with highest amounts wasted, followed by bread and then meat/fish. Considering the quantities of these food types that are home produced and the relative ratios of food waste, we derived broad estimates for the required reduction in UK production as 12, 3.5 and 1.5% of horticultural area, milling wheat area and meat/milk production to achieve the 2025 target and 29, 8.9 and 3.7%, respectively, for the 2050 target. For meat production, livestock numbers (beef, sheep, pigs and poultry) were reduced pro-rata to meet these targets. Area reductions for total horticultural land for each DA were applied in proportion to the total horticultural produce reduction for the UK. Area of grassland and arable land associated with total livestock production were reduced proportionally in each DA assuming the same reduction across all livestock product types.

The impacts of reductions in food waste were a requirement for significantly less production and land area and animals required for production (Table 9), resulting in total emission reductions for UK agriculture of between 1.7 (Medium scenario, 2030) and 4.1% (High scenario, 2050) compared with BAU.

Table 9: Impacts of reducing food waste on GHG emissions, activity data and production of selected outputs for UK agriculture for 2030 and 2050.

	units	2030			2050		
		BAU	Medium	High	BAU	Medium	High
Emissions							
Enteric CH_4	Mt CO_2e	23.49	23.14	23.04	25.02	24.66	24.10
CH_4 manure management	Mt CO_2e	4.63	4.56	4.54	4.94	4.86	4.75
N_2O manure management	Mt CO_2e	3.09	3.05	3.03	3.29	3.24	3.17
N_2O soils	Mt CO_2e	11.78	11.51	11.44	12.30	12.03	11.63
Liming and urea use	Mt CO_2e	1.31	1.30	1.29	1.33	1.32	1.30
Total CO_2e	Mt CO_2e	44.29	43.56	43.34	46.88	46.11	44.96
Activity data							
Cattle	'000s	10435	10279	10232	10900	10737	10492
Sheep	'000s	37719	37153	36984	40945	40332	39411
Pigs	'000s	5295	5215	5191	5747	5661	5532
Poultry	'000s	187822	185007	184163	203890	200834	196250
Total grassland	'000 ha	12255	12071	12016	12255	12071	11796
Total arable land	'000 ha	4999	4807	4749	5340	5147	4858
Fertiliser use	kt N	1139	1105	1095	1188	1154	1103
Production							
Milk	million litres	15753	15517	15446	17053	16797	16414
Beef and veal	kt	993	979	974	1078	1062	1038
Mutton and lamb	kt	326	321	320	354	349	341
Pigmeat	kt	965	951	946	1048	1032	1009
Poultrymeat	kt	1950	1921	1912	2117	2085	2037
Wheat	kt DM	15526	14930	14751	16732	16127	15223

For the **human dietary change** measure:

- The Medium scenario was defined as a 20% reduction in red meat and dairy consumption, to be replaced by pork, chicken and human-edible crops. The production of beef, lamb and milk was reduced by 20% (by 2050) from BAU. All grassland areas were reduced in proportion with the reduction in total cattle and sheep numbers – i.e. by 20% by 2050 (note, this is a very simplistic view which assumes no change in the structure of these sectors – i.e. the same proportion reared in uplands/lowlands as under BAU). Total arable area is changed by the net difference in reduction due to less ruminant cereal-based feed required and the increase due to more pig and poultry cereal feed and human-edible crops; cropping area requirements for animal feed were taken from Audsley *et al.* (2010; Table 9 – assume for year 2008 and express per livestock number to populate for future years). Relative replacement values of red meat with white meat were taken from Audsley *et al.* (2010; Table 4). Dairy produce was replaced with 'human-edible crops' based on an approximate replacement of protein content (assumed as 3% for milk and 13% for human-edible crops with crop yield of 7.5 t/ha). There were no assumptions made regarding total calorific content of the diet or essential trace elements.

- The High scenario reduced red meat and dairy consumption by 50%, with 20% being replaced by pork, chicken and human-edible crops as for the Medium scenario and the remaining 30% being replaced (on a protein basis) by novel protein products such as synthetic meat and insects. There was an assumption of a 93% reduction in land area required when converting from beef or sheep meat to insect-derived protein (Alexander *et al.*, 2018; Figure 1**Error! Reference source not found.**). No accounting of differences in GHG emissions due to energy requirement in housing and processing of insects compared with red meat products were made, but figures from Smetana *et al.* (2015) would suggest an overall reduction in these areas too.

The human dietary change measures resulted in the greatest reduction in GHG emissions from UK agriculture, by 37% under the High scenario by 2050 compared with BAU (Table 10). This measure has the greatest impact on cattle numbers in particular, which are the major source of GHG emissions from UK agriculture.

Table 10: Impacts of human dietary change on GHG emissions, activity data and production of selected outputs for UK agriculture for 2030 and 2050.

	units	2030			2050		
		BAU	Medium	High	BAU	Medium	High
Emissions							
Enteric CH_4	Mt CO_2e	23.49	21.64	18.86	25.02	20.23	13.01
CH_4 manure management	Mt CO_2e	4.63	4.36	3.89	4.94	4.23	3.03
N_2O manure management	Mt CO_2e	3.09	2.94	2.66	3.29	2.90	2.19
N_2O soils	Mt CO_2e	11.78	11.42	10.86	12.30	11.37	9.89
Liming and urea use	Mt CO_2e	1.31	1.30	1.28	1.33	1.30	1.26
Total CO_2e	Mt CO_2e	44.29	41.66	37.56	46.88	40.03	29.39
Activity data							
Cattle	'000s	10435	9586	8312	10900	8742	5504
Sheep	'000s	37719	34612	29953	40945	32756	20473
Pigs	'000s	5295	5505	5505	5747	6303	6303
Poultry	'000s	187822	196566	196566	203890	226942	226942
Total grassland	'000 ha	12255	11204	9627	12255	9484	5326
Total arable land	'000 ha	4999	5017	5037	5340	5388	5441
Fertiliser use	kt N	1139	1099	1038	1188	1083	923
Production							
Milk	million litres	15753	14502	12625	17053	13754	8806
Beef and veal	kt	993	912	789	1078	863	539
Mutton and lamb	kt	326	299	259	354	283	177
Pigmeat	kt	965	1006	1006	1048	1155	1155
Poultrymeat	kt	1950	2040	2040	2117	2354	2354
Wheat	kt DM	15526	15572	15613	16732	16855	16964

As discussed above, the impacts of the measures are not necessarily additive if more than one are combined. Figure 1 shows the impact of sequential implementation of the measures under the Medium and High scenarios, in the order that the measures have been described in this section. Under sequential implementation, the High scenario results in an emission reduction of 25.5 Mt CO_2e compared with BAU whereas simple addition of each individual measure equates to a 28.9 Mt CO_2e reduction.

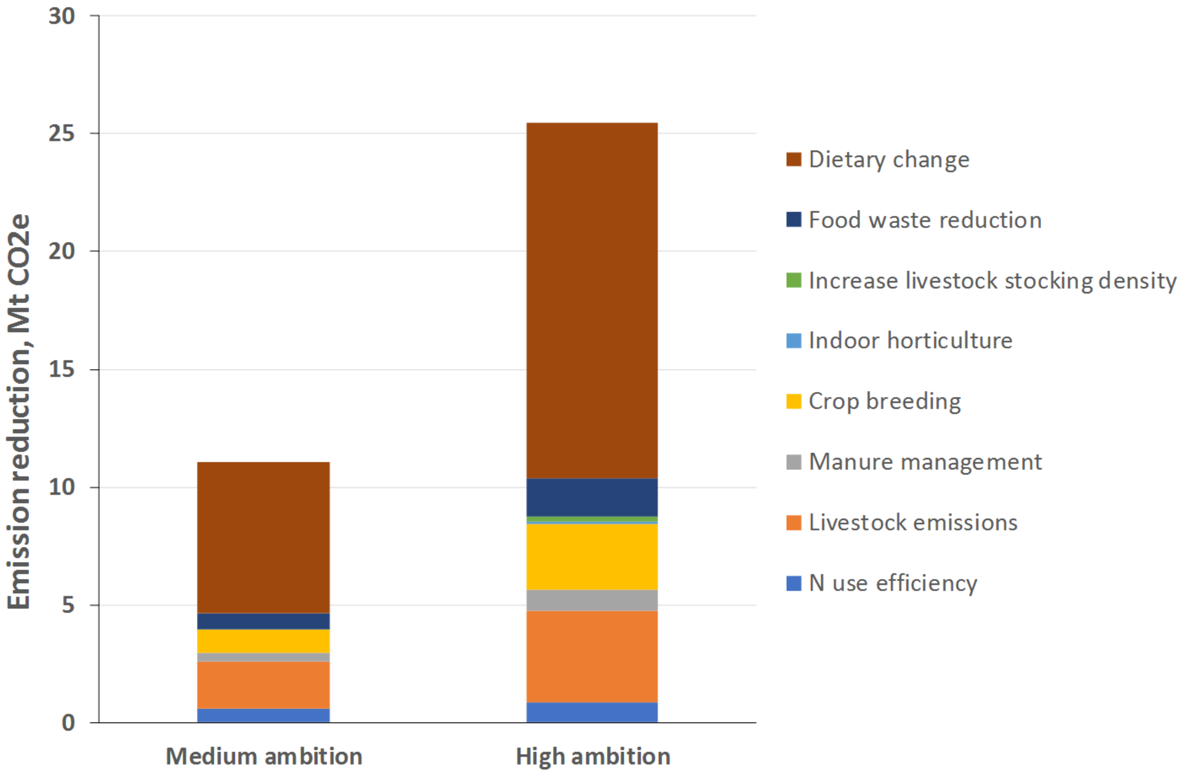

Figure 1: Annual emission reduction in 2050 compared with BAU (BAU emission from Agriculture= 45.7 Mt CO_2e)

3.2 Forestry

The C-Flow model

The Excel-based forestry model, CFlow, has been used to assess the net change in forest carbon stocks, and hence the CO_2 emissions and removals associated with afforestation. (Dewar and Cannell 1992; Cannell and Dewar 1995; Milne *et al.*, 1998). CFlow requires input data on the areas of new forest planted annually and the growth rates and harvesting patterns of these forests. The model is parameterised with expansion factors to estimate the volume of different tree components (stem, foliage, branches and roots) and the decomposition rates of litter, soil carbon and harvested wood products (Table 11). A positive net carbon stock change removes carbon from the atmosphere whereas a negative net carbon stock change releases carbon back into the atmosphere. CFlow models carbon inputs to the soils from trees and takes into account continuing carbon losses from soil disturbance on both mineral and organic soils.

Forest growth is estimated using Forestry Commission Yield Tables (Edwards and Christie 1981), assuming restocking after harvesting. Yield Class 12 m^3 ha^{-1} a^{-1} Sitka spruce (*Picea sitchensis*) has been used to represent all coniferous (softwood) forestry. Sitka spruce is the commonest species in UK forests being about 50% by area of total conifer forest coverage. Yield Class 6 m^3 ha^{-1} a^{-1} Beech (*Fagus sylvatica*) has been used to represent all broadleaf (hardwood) forestry. Beech was selected to represent all broadleaves as it has characteristics intermediate between fast growing species e.g. birch, and very slow growing species e.g. oak

Although CFlow was used to calculate afforestation carbon stock changes for the LULUCF GHG Inventory in the past, since the 1990-2012 submission the CARBINE model has been used for this purpose[7] (Forestry Research) (Matthews *et al.,* 2014). CARBINE is a much more complex model, and is able to take account of a wider range of tree species and management types. A comparison of model results from the two models for 1990-2016 showed that both models predicted similar carbon stock changes in living biomass, harvested wood products, litter and soil in 1990 but there was an increasing divergence in predicted living biomass carbon stock change towards 2016. It is difficult to unpick the exact reasons for this, as publicly available documentation on CARBINE is limited (see chapter 5 in Morison et al. 2012), but it is thought to be due to the greater range of species and management represented in CARBINE in with different thinning and harvesting regimes and different biomass expansion factors. Predicted harvested wood product carbon stock changes are very similar between the two models between 1990 and 2016. Although there are differences in the results from the two models, the CFlow model results provide indications of magnitude and change in direction of sufficient robustness for policy assessment based on fewer input requirements.

Irrespective of species assumptions, the variation in net emissions from 1990 to the present is determined by the afforestation rate in earlier decades and the effect this has on the age structure in the present forest estate, and hence the average growth rate.

Table 11: Main parameters used in CFlow for this project in the United Kingdom (Dewar & Cannell 1992)

	Sitka spruce	*Beech*	*Poplar*	*Poplar*	*Sycamore*
	Afforestation/ Forest management	*Afforestation/ Forest management/ Silvoarable planting*	*Short rotation forestry*	*Silvoarable planting*	*Silvo-pastoral planting*
	YC12	**YC6**	**YC12**	**YC12**	**YC6**
Rotation (years)	59	92	26	35	44
Initial spacing (m)	2	1.2			
Year of first thinning	25	30	NA	NA	20
Stemwood density (t m^{-3})	0.36	0.55	0.36	0.36	0.49
Maximum carbon in foliage (t ha^{-1})	5.4	1.8	1.8	1.8	1.7
Maximum carbon in fine roots (t ha^{-1})	2.7	2.7	1.8	1.8	2.7
Fraction of wood in branches	0.09	0.18	0.08	0.08	0.18
Fraction of wood in woody roots	0.19	0.16	0.15	0.15	0.16
Maximum foliage litterfall (t ha^{-1} a^{-1})	1.1	2	2	2	1.7
Maximum fine root litter loss (t ha^{-1} a^{-1})	2.7	2.7	1.8	1.8	2.7

[7] https://www.forestresearch.gov.uk/research/forestry-and-climate-change-mitigation/carbon-accounting/forest-carbon-dynamics-the-carbine-carbon-accounting-model/

	Sitka spruce	*Beech*	*Poplar*	*Poplar*	*Sycamore*
	Afforestation/ Forest management	*Afforestation/ Forest management/ Silvoarable planting*	*Short rotation forestry*	*Silvoarable planting*	*Silvo-pastoral planting*
	YC12	**YC6**	**YC12**	**YC12**	**YC6**
Dead foliage decay rate (a^{-1})	1	3	3	3	3
Dead wood decay rate (a^{-1})	0.06	0.04	0.08	0.08	0.04
Dead fine root decay rate (a^{-1})	1.5	1.5	2	2	1.5
Soil organic carbon decay rate (a^{-1})	0.03	0.03	0.03	0.03	0.03
Fraction of litter lost to soil organic matter	0.5	0.5	0.5	0.5	0.5
Lifetime of timber products	59	92	1	35	44
Fuel product lifetime	1	1	1	1	1

For this project, CFlow has been set up to separately model forests which are managed for timber production, forests which are managed for fuel production and forests which are "unmanaged" (no thinning or felling). Thinnings[8] from all types of forestry are assumed to be used for fuel (this does not include the dead biomass such as foliage and twigs that remain behind in the forest and area added to the litter carbon pool). All coniferous forest is considered to be actively managed for either timber or fuel, but some broadleaf forest is not actively managed (for example woodland of high conservation or recreation value), and therefore does not yield timber or wood fuel products. CFlow makes a simple assumption that the lifetime of timber products is equal to the rotation length of the tree species producing the timber, i.e. products from conifers (softwood) have shorter lifetimes than products from broadleaved trees (hardwoods). This is different to the 'half-life' (exponential decay) approach now used in the GHG Inventory but makes little material difference to the predicted emissions/removals from timber. Timber products decompose following an exponential curve and release CO_2 back to the atmosphere. All fuel HWP is assumed to be burnt (with CO_2 release to the atmosphere) within the year of harvesting.

In addition, coniferous forest is split between forest planted on mineral soils, and forest on organic (peat) soils, as the soil-related emissions of GHGs differ for these soil types. Broadleaved forest is assumed to only occur on mineral soils for the purposes of this project.

Calculations were produced separately for emissions associated with existing forest (planted between 1500 and 2016) and emissions associated with projected forest planting (from 2017 to 2100) to allow the effect of afforestation to be separated from the effect of change in the management of existing forests.

Activity data

The UK's forestry definition, used for international and domestic reporting, is a minimum area of 0.1 hectares; a minimum width of 20 metres; a tree crown cover of at least 20 %; and a minimum height

[8] In forestry, thinning is the selective removal of trees, primarily undertaken to improve the growth rate of health of the remaining trees and thinnings are the removed material.

of 2 metres, or the potential to achieve it. This definition includes felled areas awaiting restocking and integral open spaces up to 0.5 hectare.

The afforestation data for existing forests comes from national planting statistics from 1921 in Great Britain (Forestry Commission) and from 1900 in Northern Ireland (Northern Ireland Forest Service). The national statistics do not include areas of woodland between 0.1 and 0.5 ha (0.7 Mha, Forestry Commission 2017c) but these areas have been added to the afforestation dataset provided by Forest Research. An assessment of the approximate age of initial planting of older forests and small woodland areas based on the National Forest Inventory has produced a time series of forest planting back to 1500 that is used in the LULUCF GHG inventory (see Annex 3.4.1 of the National Inventory Report, Brown *et al.,* 2018 for details). All pre-2016 broadleaf planting is assumed to be on mineral soils. Conifer planting on organic soils only occurs after 1900. The increased planting rates in the mid to late twentieth century (Figure 2) have had a pronounced effect on overall forest carbon stock change, particularly as large areas of conifer plantation reach felling age and the carbon losses (into timber products or fuel) outweigh the carbon gains from more recently planted forests.

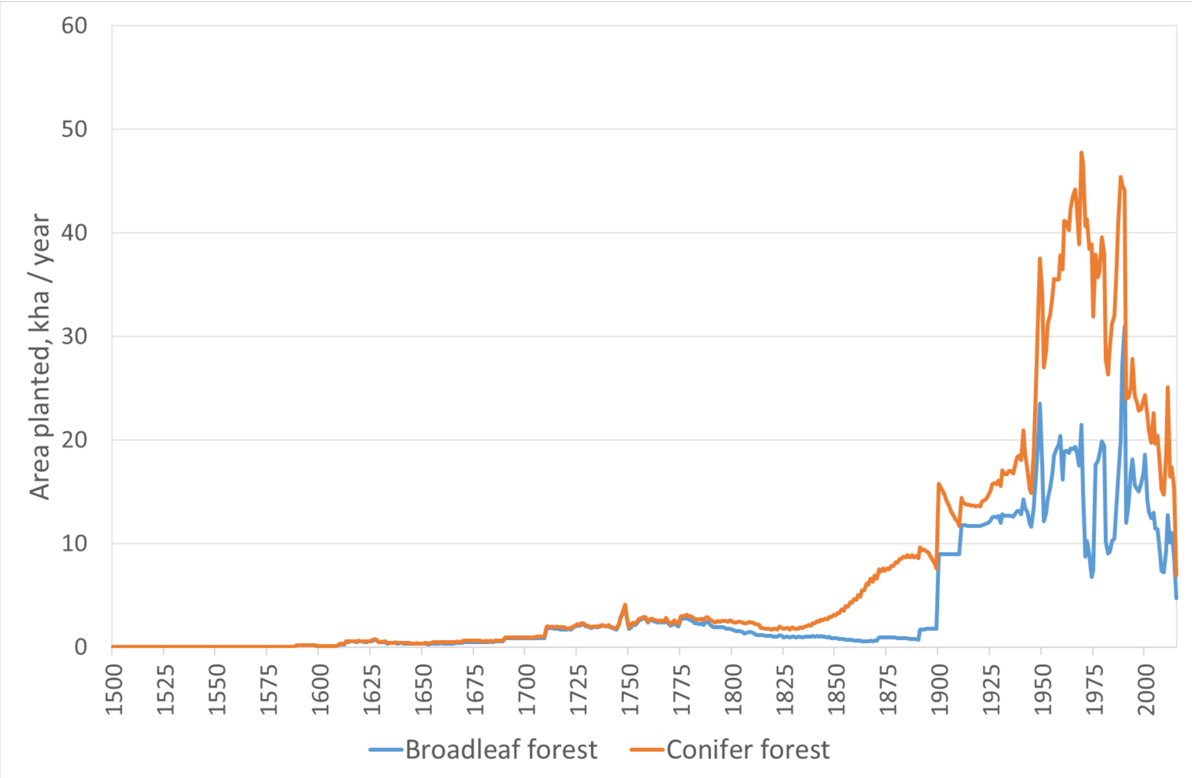

Figure 2: Forest planting in the UK 1500-2016

The afforestation areas for projected forest planting are from the three levels of ambition (section 2.1.2, Table 11):

- The Low ambition measure is based on current rates of forest planting (the average rate of 2014-2016 planting), with 60% of new planting being broadleaf across the UK although this varies considerably between countries (England has broadleaf as 97% of all new planting, Scotland 53%, Wales 43% and Northern Ireland 94%).

- The Medium ambition measure assumes increased afforestation rates of 31 kha/yr across the UK split between conifer: broadleaf using the proportions used in the LULUCF GHG inventory projections (Thomson *et al.,* 2017): 30:70 in England); 60:40 in Scotland; 11:89 in Wales; and 7:93 in Northern Ireland.

- The High ambition measure assumes afforestation rates return to the high levels of the 1970s at 50 kha/yr, with a lower rate of broadleaf afforestation (40%) as this level of land use change would probably need commercial investment with conifers being more productive. Planting rates for the Medium and High ambition measures are ramped up to target levels between 2016 and 2023 at 50% of target rates, then planting continues at the target rate until 2100.

The projected rates of afforestation give an increase in the forest cover of the UK from 15%[9] in 2016 to 18% (Low), 25% (medium) or 32% (High) by 2100. Afforestation will occur on permanent grassland and rough grazing land (not peatlands or priority habitats). It is assumed that there is no new planting on organic soils (these soils have organic horizon depth > 40 cm in England and Wales, > 50 cm in Scotland and Northern Ireland, in accordance with national peat definitions).

Table 12: Areas of projected UK afforestation under the 3 ambition levels

Ambition		Low	Medium	High
England	Area planted kha a^{-1}	1.5	10.0	16.0
Scotland	Area planted kha a^{-1}	7.0	15.0	24.0
Wales	Area planted kha a^{-1}	0.5	5.0	8.0
Northern Ireland	Area planted kha a^{-1}	0.2	1.0	2.0
UK in 2050	Conifer area, kha	1785	2046	2576
	Broadleaf area, kha	2117	2489	2538
	Total forest area, kha	3902	4535	5114
UK in 2100	Conifer area, kha	1967	2677	4076
	Broadleaf area, kha	2394	3408	3538
	Total forest area, kha	4361	6085	7614

There are also three levels of forest management ambition:

- Low: maintaining current management rates (100% conifer forest is managed, 20% of broadleaf forest is managed)
- Medium: 67% of broadleaf woodland is brought into active management by 2030 and yields increase by 10% above current levels by 2050 as a result of improved management, breeding and climate change.
- High: 80% of broadleaf woodland is brought into active management by 2030. Overall yields increase linearly to 20% above current levels by 2050 as a result of improved management, breeding and climate change.

These management ambitions are applied to existing forests by combining model runs for current management (Low ambition for managed and unmanaged woodland) and runs for higher ambition management levels using weighting to achieve a smooth transition between 2016 and 2030.

[9] As this includes woodlands between 0.1 and 0.5 ha the coverage is greater than the 13% value published by the Forestry Commission.

Carbon stock changes in wood, litter and soil

Total carbon emissions arising from UK forests show considerable variation between 2016 and 2100, as a result of historic afforestation and management (Figure 3). The annual variation is a function of the planting series with single tree species/management regime, where an increase in the conifer planting rate is reflected in a reduction in the net sink due to harvesting of those trees 59 years later. In the GHG inventory projections to 2050 (Thomson *et al*. 2017) the annual variation is smoothed by the use of a wider range of species and management regimes with different thinning and harvesting patterns. The differences between the ambition levels (

Table 13) come from the post-2016 forest planting: changes to the management of existing broadleaf forests have little impact. For all ambition levels, the existing forest is forecast to be a net emissions source in 2100, but this is offset by the increasing sink in the post-2016 planted forests.

In terms of the management, forests managed for timber make an increasing contribution across the three ambition levels (Figure 4). Forest managed for fuel make a greater contribution to the net sink in the Medium ambition than in the High ambition. The sink contribution of the unmanaged forest decreases across the three ambition levels, as more broadleaved forest is brought into active management.

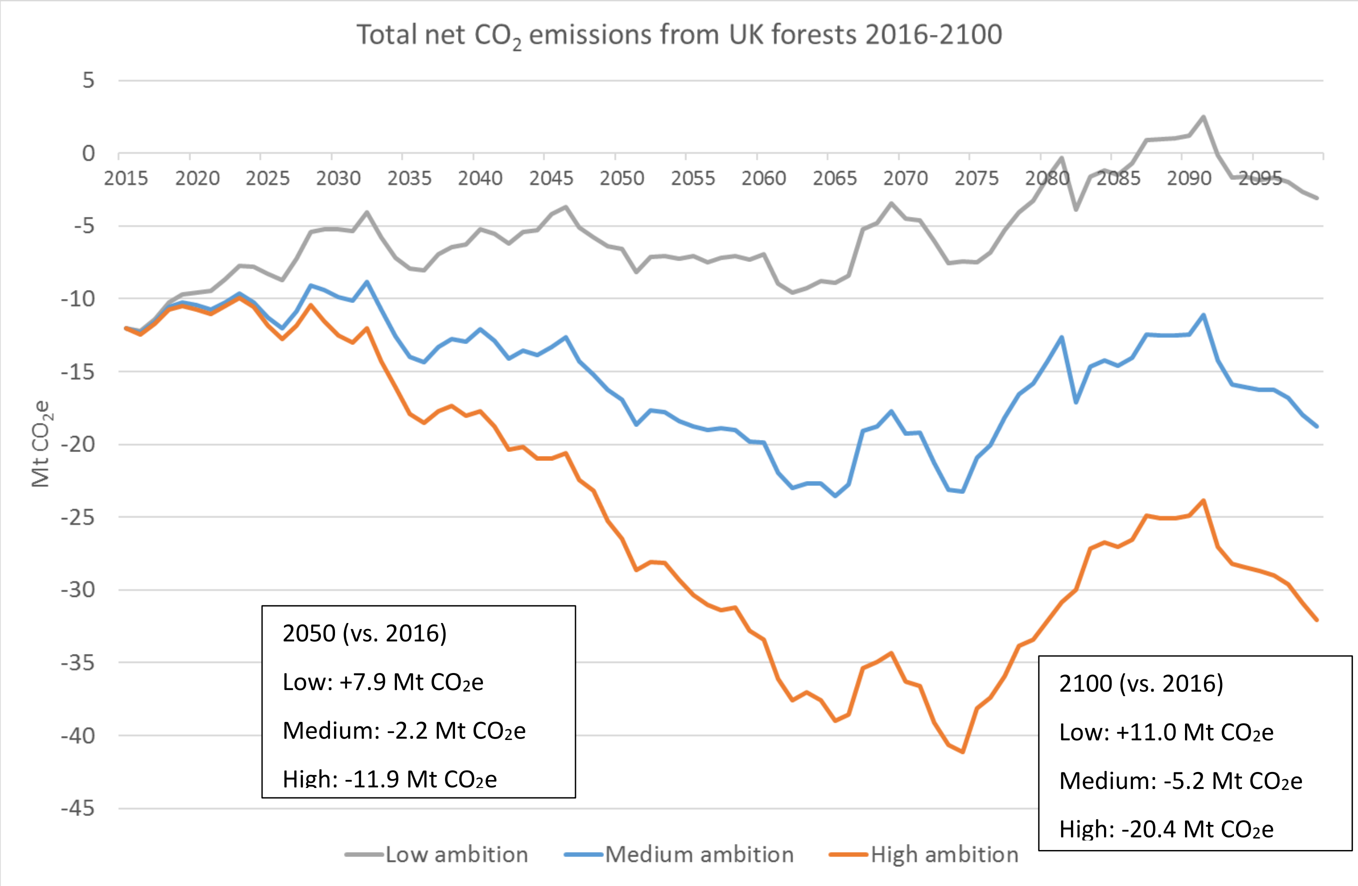

Figure 3: Time series of forest carbon emissions for the three ambition levels

Table 13: Net emissions from UK forests, Mt CO_2 (does not include harvested wood products)

		Low ambition				Medium ambition				High ambition			
	2016	2030	2050	2080	2100	2030	2050	2080	2100	2030	2050	2080	2100
All forest	*-13.7*	-8.2	-5.8	-4.4	-2.7	-12.6	-15.9	-19.1	-18.9	-15.2	-25.6	-38.1	-34.1
Existing forest	*-13.7*	-7.1	-2.6	0.7	3.0	-8.4	-3.4	0.7	3.1	-9.9	-4.4	-0.4	2.8
Post 2016 forest	*0.0*	-1.0	-3.2	-5.1	-5.6	-4.2	-12.5	-19.9	-21.9	-5.3	-21.2	-37.7	-36.9
Forest managed for HWP	*-6.9*	-3.3	-2.4	-1.9	-0.7	-6.4	-8.5	-10.0	-8.5	-11.3	-19.8	-30.0	-25.8
Forest managed for fuel	*-2.0*	-0.9	-1.0	-0.4	-0.5	-3.8	-5.0	-6.0	-7.0	-2.5	-4.1	-5.7	-5.6
Natural broadleaved forest	*-4.8*	-3.9	-2.3	-2.1	-1.4	-2.3	-2.4	-3.1	-3.4	-1.3	-1.7	-2.4	-2.8

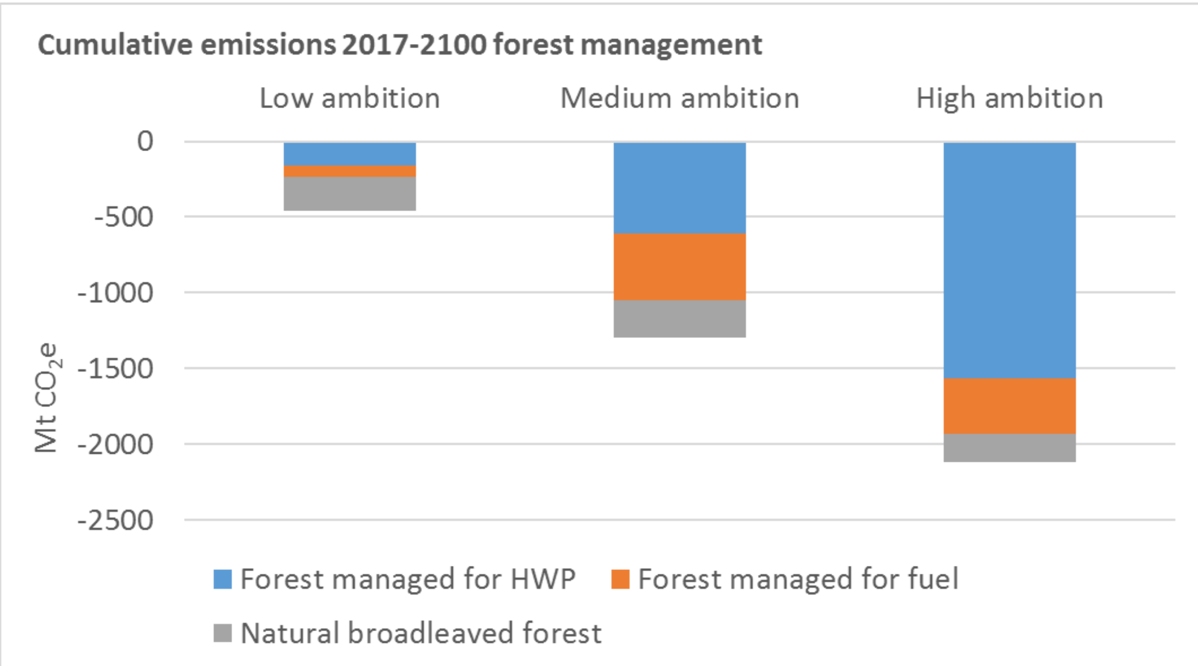

Figure 4: The contribution of different forest management to overall forest emissions

Harvested wood products

Thinnings from all managed forests are used for fuel, and are assumed to oxidise and return to the atmosphere within the year of harvest. The net carbon stock change from timber products (which are assumed to decompose over time) are shown in

Table 14. More complex modelling of the HWP decay, with different lifetimes for different HWP products, was outside the scope of this project.

Table 14: Carbon stock change in biomass, soils and timber, assuming decomposition, Mt CO_2e

			Low ambition				Medium ambition				High ambition			
		2016	2030	2050	2080	2100	2030	2050	2080	2100	2030	2050	2080	2100
Existing forest	Biomass and soil	*-12.1*	-4.2	-3.2	1.2	2.4	-5.2	-3.8	1.7	2.4	-6.3	-4.1	1.3	2.1
	HWP pool*	*-1.6*	-2.9	0.6	-0.5	0.6	-3.2	0.4	-1.0	0.7	-3.6	-0.3	-1.8	0.7
Post 2016 forest	Biomass and soil	*0.0*	-1.0	-3.2	-4.5	-5.4	-4.2	-12.5	-17.6	-21.1	-5.3	-21.2	-34.7	-34.1
	HWP pool*	*0.0*	0.0	0.0	-0.6	-0.2	0.0	0.0	-2.3	-0.8	0.0	0.0	-3.0	-2.8

* Does not include fuel wood, as these products do not enter the HWP pool

To model timber and fuel output using CFlow, the model was adjusted so that effectively there is no HWP decay, so that the annual carbon stock change was only due to new HWP input without decomposition losses. HWP carbon is converted to dry weight timber using the IPCC default 0.5 carbon fraction.

Wood production varies across the time series, depending on the historical planting and management patterns (Figure 5**Error! Reference source not found.**):

- The Low ambition measure is based on the current mix of harvested wood products, where 33% of harvested broadleaf and 85% of harvested conifer is used for timber products and the remainder is used for fuel (Table 15).
- In the Medium ambition measure 35% of harvested broadleaf forest and 85% of harvested conifer is used for timber products and the remainder is used for fuel.
- In the High ambition measure 75% of harvested broadleaf and 85% of harvested conifer is used for timber products and the remainder is used for fuel. The increased proportion of broadleaf timber is anticipated to be directed towards novel timber products such as glulam[10], but there is insufficient information to examine this in detail (such products still require relatively high quality timber, but trees that have not been actively managed for timber production throughout their life cycle may not produce timber of sufficient quality).

These values represent the maximum potential production: in reality, particularly for fuel production, not all of this potential may be realised.

[10] Glued laminated timber, also called glulam, is a type of structural engineered wood product that is manufactured by bonding together individual laminations of solid timber. This produces members of rectangular cross-section that are larger and longer than may be obtained simply by sawing a normal log.

Table 15 Timber and fuel production from UK forests, Mt oven-dried product

			Low ambition				Medium ambition				High ambition			
		2016	2030	2050	2080	2100	2030	2050	2080	2100	2030	2050	2080	2100
Timber production	Existing forests	*2.7*	4.2	2.8	3.3	3.0	4.9	3.5	4.3	3.7	5.8	4.7	5.7	4.9
	New forests	*0.0*	0.0	0.0	0.4	0.4	0.0	0.0	1.6	1.6	0.0	0.0	4.2	4.2
Fuel production	Existing forests	*5.4*	5.4	5.9	6.4	5.9	7.0	7.7	8.4	7.5	7.4	7.9	8.3	7.5
	New forests	*0.0*	0.0	0.2	0.6	0.6	0.0	0.5	2.6	3.1	0.0	1.2	6.2	7.3

Figure 5: Wood production from UK forests 2017-2100, Mt oven-dried material

3.3 Bioenergy crops

Activity data

Three types of bioenergy crop are considered: *Miscanthus* grass, short rotation coppice (SRC) and short rotation forestry (SRF). Although these crops have been planted before 2016, the areas captured by the annual agricultural survey are very small and highly uncertain, so have been assumed to be zero for the purposes of these projections.

Under the three measures:

- The Low ambition assumes no additional bioenergy crop planting
- The High ambition scenario assumes an area of 1200 kha will be planted by 2050 (Table 16). This is based on the ETI target of 1400 kha, but when this level was initially applied in the High Mitigation- Wood & Bioenergy scenario there was insufficient land available to achieve all the scenario objectives. This was rectified by adjusting the target area for the High ambition bioenergy crops to 1200 kha.
- The Medium ambition scenario assumed an area of 700 kha of bioenergy crops will be planted by 2050.

Planting of SRF is assumed to start in 2030. There is no new planting of bioenergy crops after 2050, but existing areas remain under bioenergy crops (with replanting as necessary) and their yields are modelled to 2100.

Table 16: Areas of projected bioenergy crops by 2050 under the three ambition levels

Measure	*Miscanthus*, kha	SRC, kha	SRF, kha	Total bioenergy crop area, kha
Low ambition	0	0	0	0
Medium ambition	245.0	227.5	227.5	700
High ambition	420.0	390.0	390.0	1200

CEH have studied cropland and grassland transitions to bioenergy crops, principally *Miscanthus* and SRC. The lower risk scenario in terms of changes to soil organic carbon (SOC) is to plant bioenergy crops on existing cropland as opposed to grassland, as cropland generally has a lower initial SOC stock than grassland. For this project *Miscanthus* is assumed to be only planted on existing cropland. SRC and SRF are planted on permanent and temporary grassland and on rough grazing land (see section 2.1.3). The total target UK area is divided between countries in proportion to the areas of the agricultural land types in 2016 in each country (see Appendix 1). The annual area increment 2017-2023 was half the rate 2024-2050.

Emission model

Emissions are calculated for the change in biomass and soil carbon stocks (Table 17). The change in soil carbon stocks as a result of land use change from grassland to cropland is calculated for SRC using the LUC model, and using CFlow for SRF. This may over-estimate the amount of soil disturbance and carbon stock loss under conversion to SRC as there would probably not be full tillage for planting SRC. It also does not take account of litter inputs to the soil from SRC. It was not possible to develop new parameters for SRC to allow modelling with CFlow within the resources of the project, and this is an area that would benefit from a more detailed modelling approach. Although conversion of existing cropland to *Miscanthus* involves transitioning from an annual cropping and tillage system into a “low management intensity” perennial crop measured data has shown no significant change in SOC (Rowe et al. 2015) , although modelling the transition does suggest a small increase in SOC over time when projected to 2050 (Richards *et al*. 2016). For this project it is assumed that there is no change in the soil carbon stock under *Miscanthus*.

Miscanthus

The average standing biomass carbon used in the modelling is 9.97 t C/ha (uncertainty 2.48 t C/ha) for both above- and below-ground biomass (Moxley *et al.,* 2014). Planted *Miscanthus* is not harvested for the first two years. The production yield was 12.5 tonnes oven-dried product/ha (Defra 2017), equivalent to 6.25 t C/ha. In the Medium ambition measure this was assumed to increase to 15 t/ha by 2050 due to good agronomy and plant breeding, and to 20 t/ha in the High ambition measure, due to innovative agronomy and improved breeding including genetic modification, as decided by the stakeholder workshop.

Table 17: Net emissions from bioenergy crops, biomass and soils (Mt CO_2)

Carbon stock change		Medium ambition		High ambition	
	2016	2030	2050	2030	2050
Miscanthus	0	-0.3	-0.3	-0.5	-0.5
Short rotation coppice	0	0.7	2.6	1.2	4.5
Short rotation biomass	0	-0.0	-0.8	-0.1	-6.4
Total	0	0.4	1.5	0.6	-2.5

Table 18: Bioenergy fuel production, Mt oven-dried product

	Medium ambition	High ambition

	2016	2030	2050	2080	2100	2030	2050	2080	2100
Miscanthus	0	0.9	3.4	3.7	3.7	1.8	7.8	8.4	8.4
SRC	0	0.8	3.2	3.4	3.4	1.6	7.3	7.8	7.8
SRF	0	0.0	0.0	0.0[1]	1.1	0.0	0.0	0.0[1]	1.8
Total	0	1.8	6.6	7.1	8.1	3.5	15.1	16.2	18.0

[1] SRF starts producing fuel from 2056 but there is a gap in production 2077-2081 because of the rotation length.

Short rotation coppice

SRC can be a range of broadleaf species but the biomass carbon stock used in the modelling was based on UK SRC willow with an average standing biomass (above and below-ground) of 4.36 tC/ha (uncertainty 2.9 t C/ha) (Moxley *et al.,* 2014). This assumed a uniform age distribution and the average standing biomass was half the annual yield obtained from field measurement. The production yield was 11.8 tonnes oven-dried product/ha/yr (Defra 2017), equivalent to 5.9 t C/ha. In the Medium ambition scenario this was assumed to increase to 15 t/ha by 2050 due to good agronomy and plant breeding, and to 20 t/ha in the High ambition measure, due to innovative agronomy and improved breeding including genetic modification, as decided by the stakeholder workshop.

Short rotation forestry

Poplar yield class 12 with a 26 year rotation and no thinning is assumed to be planted as SRF in all countries (see Table 11 for the CFlow parameters). Poplar is the best yielding species for SRF and was also used in the ELUM work.

Fuel production

Fuel production is based on average yields per hectare for *Miscanthus* and SRC and harvested wood production as modelled by CFlow for SRF (Table 18).

3.4 Peatland restoration and rewetting

Activity data

The activity data, emission factors and peatland mitigation measures are based on those produced for the BEIS Wetland Supplement project (Evans *et al.,* forthcoming). The peat condition categories considered are Forest, Cropland (exclusively located in lowland areas),, Unimproved Grassland, Improved Grassland, Rewetted Bog/Fen, Near-natural Bog/ Fen, and Peat Extraction sites. Unimproved Grassland is the combined area of the Eroded Modified Bog, Grass Dominated Modified Bog and Extensive Grassland categories and can be drained or undrained. Cropland and Improved Grassland are both drained and intensively managed. Peat extraction can be for industrial or domestic use. Peat condition categories can be on deep peat or wasted peat (England only).

Activity data for the peatland mitigation measures are given in Table 19:

- The Low ambition measure is based on the Wetlands Supplement project ‘Central Emission’ scenario. There is little peatland restoration, except in Scotland where 50 kha of degraded peat on unimproved grassland is restored by 2020, and 250 kha by 2030, based on current government commitments (although similar ambitions have been expressed in England and Wales, these currently lack specific area targets so could not be incorporated in this scenario). Restoration in Scotland is phased in with the rewetting rates for 2017 being 50% of the rate between 2018 and 2030. Industrial peat extraction sites in England are restored at the current planned dates.

- The Medium ambition measure is based on the Wetlands Supplement project ‘Low Emission’ scenario. Peatland rewetting occurs on 25% of the area of intensively managed lowland peat (Cropland and Improved Grassland) and peatland restoration occurs on 50% of the area of degraded Unimproved Grassland and on 25% of the area of forest on peat (deforestation) with less than Yield Class 8 by 2050. Rewetting is phased in, with the rewetting rates between 2016 and 2023 at 50% of the rate in subsequent years.

- The High ambition measure is based on the Wetlands Supplement project 'Stretch Emission' scenario. Peatland rewetting occurs on 50% of the area of intensively managed lowland peat (Cropland and Improved Grassland) and peatland restoration occurs on 75% of the area of degraded Unimproved Grassland and on 50% of the area of forest on peat (deforestation) with less than Yield Class 8 by 2050. Rewetting/restoration is phased in, with the rewetting rates between 2016 and 2023 at 50% of the rate in subsequent years.
- Under the High ambition, the effect of partial rewetting of unrestored intensively managed lowland peats is reported separately, where water tables are raised to half the current depth for all intensively managed lowland peats that have not been fully restored by 2050, following a linear trajectory based on results from the Defra Lowland Peat project (Chris Evans, pers. comm.). All peatland extraction sites are restored by 2050.

Soil emissions from forests on peat are modelled within CFlow and are included in the Afforestation emissions. The timber and fuel yield from the deforested trees is calculated separately, based on the average carbon stock of the forest planted on organic soils.

Table 19: Areas of peatland condition classes restored by 2050 under the three ambition levels

	Cropland, kha	Unimproved grassland, kha	Improved grassland, kha	Rewetted, kha	Near natural, kha	Peat extraction, kha
2016	191.9	1245.3	185.8	95.8	638.9	144.4
Low ambition	191.9	1062.0	185.8	347.9	638.9	143.9
Medium ambition	143.9	622.7	139.3	970.0	638.9	8.4
High ambition	96.0	311.3	92.9	1405.2	638.9	0.0

Table 20: Net emissions from peatland condition classes, Mt CO_2e

		Low ambition		Medium ambition		High ambition		High ambition with partial rewetting	
	2016	2030	2050	2030	2050	2030	2050	2030	2050
Cropland	*7.5*	7.5	7.5	6.8	5.6	6.2	3.7	5.2	2.2
Unimproved grassland	*4.1*	3.5	3.5	3.4	2.1	3.0	1.0	3.0	1.0
Improved grassland	*5.6*	5.6	5.6	5.1	4.2	4.6	2.8	3.7	1.4
Rewetted	*0.2*	0.5	0.5	1.0	2.2	1.8	3.1	1.8	3.1
Near natural	*0.0*	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Peat extraction	*1.2*	1.2	1.2	0.7	0.1	0.0	0.0	0.0	0.0
Total	***18.5***	**18.1**	**18.1**	**17.0**	**14.1**	**15.6**	**10.7**	**13.7**	**7.8**

Emission model

Emissions due to the peatlands mitigation measures are shown in Table 20. Emission factors and 2016 areas for each peat category come from Evans *et al.* (forthcoming) using a UK-specific Tier 2 approach, which is based on empirical data, except for forest on peat, where soil carbon is modelled using CFlow. Methane and N_2O emissions from peatlands are included in the emissions estimates.

Emissions from the removal of forest from peatland area estimated by dividing the cumulative carbon stock change between 1900 (no afforestation of organic soils before this date) and the year of deforestation by the area of that forest type (conifer on organic soil managed either for timber of fuel) in a given year.

The tree biomass carbon stock removed due to deforestation is assumed to be split between timber products and fuel wood using the same ratios as for afforested land. Carbon in litter lost to deforestation is assumed to oxidise instantaneously and return immediately to the atmosphere.

Restoration of afforested peatland

We were advised by forestry experts that only areas of low yielding forest on peatland would be removed for peatland restoration, as it was felt that the carbon (and presumably the timber sales income) lost from deforestation of higher yielding trees would outweigh the gains from peatland restoration in this context. This is consistent with current practices in England and Scotland, but there may also be higher yielding forests removed on sites with exceptional biodiversity value.

The area of low-yielding forest (under Yield class 8) for Great Britain was calculated by overlaying the Forestry Commission sub-compartment database with the peat extent maps produced in the Wetlands Supplement project (giving the extent of publicly-owned low-yielding forest on peat), and scaling this to include privately-owned forest by assuming that it is in the same proportion as publicly-owned forest. Northern Ireland is not covered by the sub-compartment database, so the area of planted post-1980 was used, as in the Wetlands Supplement Stretch projection scenario. The areas used for each ambition measure are shown in Table 21. The higher area of deforestation under the Low ambition measure is driven by the Scottish policy to restore 250kha of upland and forested peatland by 2030, which presumes a higher proportion of restoration of forested peatlands than in the other ambition measures.

Table 21: Area of deforestation on peat under the three ambition levels, kha

Area of forest on peat	237.3
Area of forest <YC8 on peat	84.3
Area of peat deforested- Low ambition	68.3
Area of peat deforested- Medium ambition	21.1
Area of peat deforested- High ambition	42.2

Fuel production

It is assumed that any harvested material produced from deforestation is transferred to timber or fuel (

Table 22). In the original definition of mitigation measures, it was assumed that rewetted intensively managed lowland peat could be used for SRC; however, the CCC committee members subsequently commented that SRC would not be the first choice of crop cover for rewetted peat and it has not been modelled. Reed canary grass for bioenergy has also been suggested as a viable option for rewetted intensively managed lowland areas, and other wetland species such as common reed and bulrush, as well as alder, may have potential as bioenergy crops. There would be 94 kha available by 2050 under the Medium ambition and 189 kha under the High ambition.

Table 22: Timber production from deforestation on peat, Mt oven dried material

		Low ambition				Medium ambition				High ambition			
	2016	2030	2050	2080	2100	2030	2050	2080	2100	2030	2050	2080	2100
Timber production	0	0.83	0	0	0	0.01	0.01	0	0	0.13	0.12	0	0
Fuel production	0	0.15	0	0	0	0.00	0.00	0	0	0.02	0.02	0	0

3.5 Hedgerows and agroforestry

The measures in this activity are increased hedgerow planting and management, and increased planting of trees on agricultural land for boundaries, shelter and wood production.

Activity data: hedgerows

Current hedgerow lengths (managed and unmanaged) are taken from the GB and Northern Ireland Countryside Surveys 2007. Total hedgerow areas are calculated from hedgerow lengths using an average width of 1.5 metres. There are 62.2 kha of managed hedges in the UK in 2016, and 58.2 kha of unmanaged hedges:

- In the Low ambition measure there is no increase in hedgerow length after 2016.
- In the Medium ambition measure hedgerows are assumed to increase back to the level recorded in the 1984 Countryside Survey (an increase of 30% from current levels) by 2050 with 10% of hedges being brought into management for fuel.
- In the High ambition measure hedge length increases to 10% above the level recorded in the 1984 Countryside Survey in GB and 10% above the 1991 level for Northern Ireland (Cooper and McCann 2002), with 30% of hedges being brought into management for fuel.

Activity data: agroforestry

Silvoarable and silvopastoral systems are considered under agroforestry.

UK silvoarable agriculture is uncommon but is usually based on an alley cropping design with arable crops in the alleys. Shelter-belt planting also comes under this definition. 10% of the arable area in each country is assumed to be converted to silvoarable systems by 2050 (

Table 23), planting poplar Yield Class 12 in England and Wales (poplar is commonly used in silvoarable systems in France), and Beech Yield Class 6 in Scotland and Northern Ireland, as poplar is unlikely to be successful here (Reisner *et al.,* 2007). The poplar yield table is set up for no thinning and wide planting (8 m by 8 m) (Table 11), working out at 188 trees/ha, which is similar to some of the UK agroforestry experiments that used a 10 m by 6.5 m spacing (160 trees/ha), and appropriate for alley-run style agroforestry (Burgess 2017). A 10 m spacing between tree rows, leaves an 8m cropping alley between rows, so for each hectare converted to silvoarable, 0.82 ha of croppable area is retained. The beech planted area is adjusted to be 8.5% of the agroforestry area, again based on the initial planting densities.

Silvopastoral agriculture in the UK is based on the establishment of farm woodland on existing pastures to provide shelter for animals and other environmental benefits (soil stabilisation, flood mitigation). 10% of the permanent grassland area in each country (taking account of other land use change) is assumed to be converted to silvopastoral systems by 2050 (

Table 23). A sycamore/birch/ash (SAB) Yield Class 6 (Table 11), representative of medium to fast growing broadleaved species, is used with a tree planting density of 400 trees/ha, as this seems to be widely used in current UK experiments/grants (e.g. the FC grant for small woods on sheep pastures in Scotland). Carbon stock changes are modelled by CFlow with the planting density adjusted from the initial planting rate of 2918 trees/ha (adjusted so that the planted area in CFlow is 14% of the 10% area (400/2918)). The planted area is assumed to increase at a constant rate between 2017 and 2050 and there is no managed thinning.

Table 23: Area of hedges and agroforestry by 2050 under the three ambition levels

Measure	Hedgerow area in 2050, kha	Silvoarable area in 2050, kha (wooded area)	Silvopastoral area in 2050, kha (wooded area)
Low ambition	120.4	0.0	0.0
Medium ambition	168.2	165.2 (146)	251.5 (35.2)
High ambition	181.3	330.3 (2925)	503.0 (70.4)

Emission modelling: Hedgerows

All hedge creation is on grassland (assigned pro-rata to permanent and temporary grassland in each country). Hedges are assumed to be 1.5 m wide and with biomass stock densities derived in the BEIS Biomass Extension project (Moxley *et al.,* 2014). Hedge creation follows a linear trajectory with no phase-in period. There is assumed to be no change in SOC stock due to hedge creation. There is no change in the length of lines of trees and scrub (with or without fences).

Hedges managed for wood fuel are coppiced to near ground level on a 15 year cycle. They have a higher density of Above Ground Biomass (mean value of 52.68 t C/ha rather than the median of 26.14 t C/ha from Moxley *et al.,* 2014) as they are allowed to grow higher and 60% of this biomass is converted into wood fuel at the end of each coppicing cycle.

Emission modelling: agroforestry

The carbon stock changes in the tree component of the silvoarable and silvopastoral systems are modelled with C-Flow (Table 24). Alley cropping in silvoarable systems is likely to reduce arable crop yields as the trees reach maturity (Burgess 2017) but this is highly dependent on the spacing and growth rates of trees and has not been considered in this report.

Table 24: Net emissions from carbon stock change in hedges and agroforestry, Mt CO_2

		Medium ambition		High ambition	
	2016	2030	2050	2030	2050
Hedges	0.0	-0.2	-0.2	-0.3	-0.3
Silvoarable	0.0	-0.7	-2.2	-1.8	-4.8
Silvopastoral	0.0	-0.1	-0.3	-0.3	-0.8
Total	**0.0**	**-1.0**	**-2.7**	**-2.4**	**-5.9**

The difference between the silvoarable and the silvopastoral sink is due to: arable land being planted with more productive tree species in England, which produce higher biomass carbon stock increments (and more additions to litter and soil stocks); and conversion of grassland reduces the soil carbon stock in the early years after planting, whereas conversion of arable land delivers larger and quicker soil carbon improvements. These differences offset the greater areas and tree planting density in silvopastoral systems than in silvoarable systems.

Fuel production

The amount of fuel produced from management of hedgerows and agroforestry systems is shown in Table 25.

Table 25: Multi-functional land use fuel production, Mt oven-dried product

	Medium ambition					High ambition			
	2016	2030	2050	2080	2100	2030	2050	2080	2100
Hedgerows	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1
Silvoarable	0.0	0.0	0.0	0.6	0.6	0.0	0.0	1.2	1.2
Silvopastoral	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0[1]
Total	**0.0**	**0.0**	**0.0**	**0.7**	**0.6**	**0.1**	**0.1**	**1.4**	**1.3**

[1] Silvopastoral starts producing fuel from 2061 but there is a gap in production 2095-2100 because of the rotation length.

3.6 Other land use change

The increase in settlement area (land needed for buildings, infrastructure and non-agricultural green space such as sports pitches) is fixed for all scenarios (conversion to settlement occurs on the improved pasture and rough grazing grassland only). Settlement area increases as for the Central projection for the LULUCF inventory projections (Thomson *et al.,* 2017). Conversion to Settlement assumes that the rate of house building is sufficient to meet the projected increase in the number of households (DCLG 2016). These household projections use the 2011 national population census updated to 2014 and trends in population demography and household formation to project household numbers to 2037-2039. The estimated area (Table 26) converted from undeveloped to residential use is multiplied by a ratio (1:0.17) to take account of conversion to non-residential development in the total area of development on non-previously developed land. There is assumed to be no conversion of Settlement to other land uses post-2016. Soil and biomass carbon stock changes due to LUC are estimated using the LUC model Matlab scripts using a single average value (not Monte Carlo) (see Brown *et al.,* 2018 Annex 3.6 for further details of this model).

Other LUC emissions arise from continuing soil carbon emissions/removals from LUC that occurred before 2016 (as it can take many decades for soil carbon stocks to reach equilibrium after a land use change). These have been modelled using the LUC model and reported for conversion to settlement areas and net conversion to agricultural land (conversion to cropland and conversion to grassland). The pre-2016 agricultural LUC flux moves from a source to a sink over time as the rapidly-occurring net loss of soil carbon from conversion to cropland is offset by the slower increase in soil carbon from conversion to grassland.

Table 26: Area of conversion to settlement and associated emissions for the UK

	2016	2017	2030	2050
Cumulative area, kha		26.4	448.6	1028.6
Annual emissions, Mt CO_2e		0.4	5.2	7.6
Pre-2016 LUC to settlement, Mt CO_2e	5.8	5.4	2.8	1.0
Pre-2016 agricultural LUC, Mt CO_2e	0.3	0.0	-2.9	-4.7

3.7 Comparison of mitigation measures

The emissions associated with the land use mitigation measures under Medium and High ambition against the baseline of the Low ambition emissions are compared in Figure 6. The equivalent for the agriculture mitigation measures is in **Error! Reference source not found.**Figure 1. The measures are ot additive because it may not be possible to implement all measures at the same level of ambition simultaneously due to competition for land. This is explored further in the combined scenarios in Chapter 4.

It can be seen that the forests planted after 2016 make the greatest contribution to reduced emissions/increased removals of GHGs, followed by peatland mitigation measures. The bioenergy crops measures actually slightly increase GHG emissions compared to the Low ambition level of zero emissions, because the carbon losses associated with soil disturbance on conversion to bioenergy crops counterbalances the gains from biomass growth. This does not take account of the bioenergy fuel production, which can be used to replace fossil fuels at a significantly lower level of GHG emission.

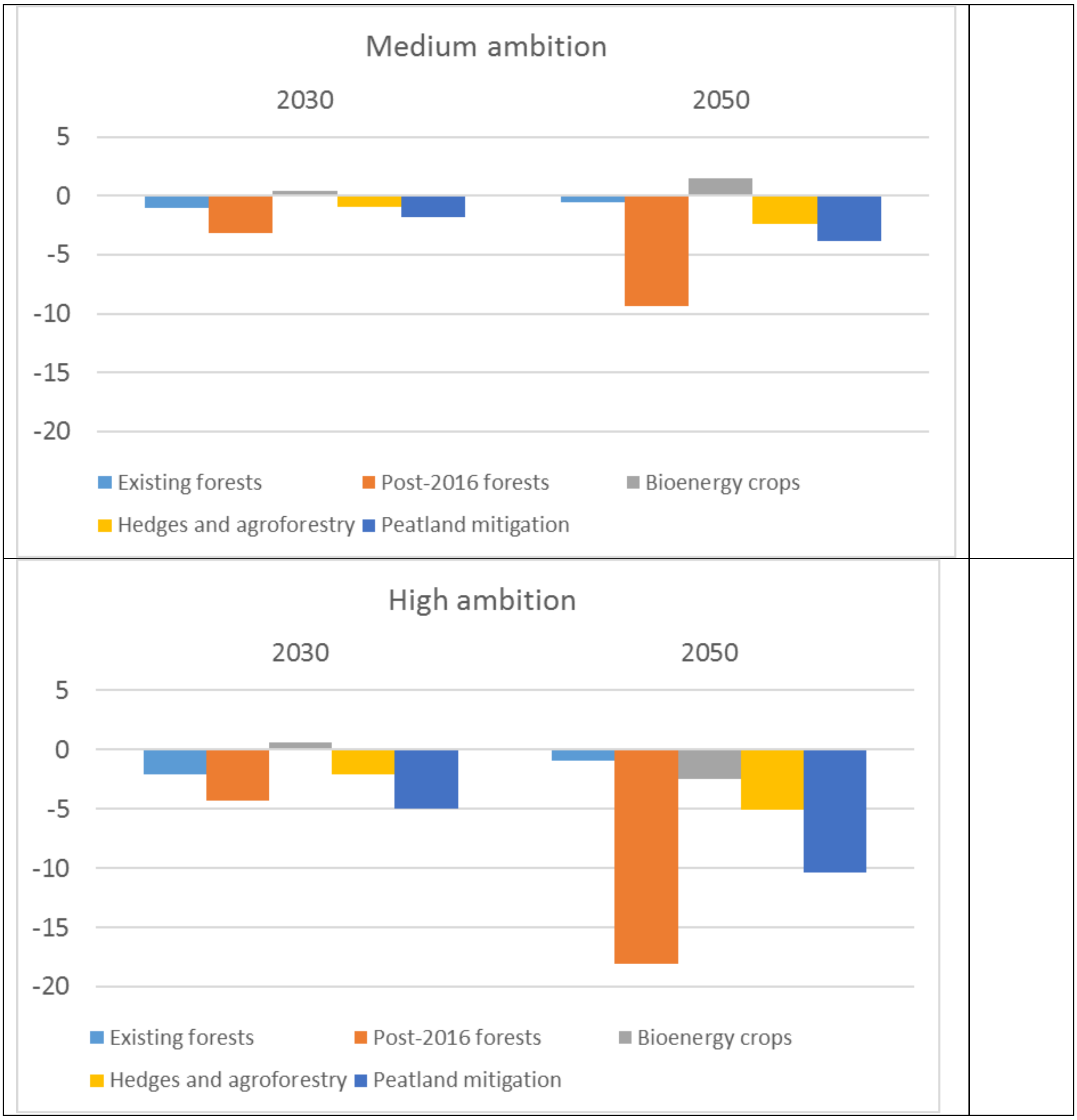

Figure 6: Comparison of the Medium and High ambition land use mitigation measures against the Low ambition baseline, Mt CO_2e

A comparison of the average emissions per unit of area (Table 27) shows that the newly planted forests (post-2016) make the most contribution to emissions reductions per unit area. Management of existing forests makes a relatively small contribution, as overall these forests already have relatively stable carbon stocks.

Table 27: Average emissions per unit area for each land use mitigation measure, t CO_2e/ha

	Low ambition		Medium ambition		High ambition	
	2017-2050 average emissions, t CO_2e /ha	2017-2100 average emissions, t CO_2e /ha	2017-2050 average emissions, t CO_2e /ha	2017-2100 average emissions, t CO_2e /ha	2017-2050 average emissions, t CO_2e /ha	2017-2100 average emissions, t CO_2e /ha
Existing forests	-1.9	-0.8	-2.2	-0.9	-2.4	-1.2
Post-2016 forests	-7.9	-8.6	-11.6	-11.3	-9.9	-11.4
Bioenergy crops	-	-	1.0	-	-0.6	-
Hedges and agroforestry	0.0	-	-3.5	-	-4.8	-
Peatland mitigation	5.3	-	6.6	-	5.9*	-

* Without partial rewetting. Average emissions would be 5.1 t CO2e /ha with partial rewetting.

Table 28 shows the fuel produced under the different measures and ambition levels. Forests produce the most fuel, as should be expected, but bioenergy crops produce an increasing amount by 2100. Existing forests produce the most timber (Table 29): although post-2016 forests start to produce more timber by 2100 most of their harvesting output will occur after 2100.

Table 28: Cumulative fuel production, Mt oven-dry weight

	2017-2050			2017-2100		
	Low ambition	Medium ambition	High ambition	Low ambition	Medium ambition	High ambition
Forests	190.2	236.4	253.0	519.7	736.6	902.6
Hedges and agroforestry	0.0	1.1	3.3	0.0	33.8	70.4
Bioenergy crops	0.0	93.9	201.9	0.0	490.1	1083.4
Deforestation of peat	1.5	0.1	0.7	1.5	0.1	0.7

Table 29: Cumulative timber production, Mt oven-dry weight

	2017-2050			2017-2100		
	Low ambition	Medium ambition	High ambition	Low ambition	Medium ambition	High ambition
Existing forests	115.0	134.2	161.1	273.7	333.7	421.1
Post-2016 forests	0.0	0.0	0.0	10.5	40.2	104.4
Deforestation of peat	8.6	0.4	3.9	8.6	0.4	3.9

3.8 Co-benefits and barriers to implementation

3.8.1 Afforestation and forest management measures

UK woodlands provide a wide range of ecosystem services (Chapter 8, UK National Ecosystem Assessment 2011), including provisioning, regulating, cultural and supporting services:

- Provisioning services
  - 1.1 Trees for timber, wood chips and pulp.
  - 1.2 Timber as an alternative for other building materials with high embodied GHGs (steel and concrete).
  - 1.3 Harvested products as biofuel or wood fuel.
  - 1.4 Wooded catchments provide important water supplies for major urban areas.

2 Regulating services
  - 2.1 Woodlands can reduce climate stress by protecting soils, animals and humans from extremes of temperature, winds and UV light.
  - 2.2 Trees, woodlands soils and timber products can all sequester carbon, thus mitigating GHG emissions to the atmosphere.
  - 2.3 Tree cover can offer protection from soil erosion and moderate precipitation runoff, delaying and reducing flood events.
  - 2.4 Sustainably managed woodlands can moderate water quality, soil quality and noise pollution and capture air pollutants, reducing exposure for humans, animals and crops.
  - 2.5 Woodlands provide habitats for diverse wild pollinator communities.

3 Cultural and supporting services
  - 3.1 UK forests provide habitat for a wide range of flora and fauna.
  - 3.2 Woodlands provide many opportunities for recreation and outdoor pursuits and increase the diversity of landscape character in the UK.
  - 3.3 Woodlands facilitate soil formation and other essential biogeochemical processes such as nutrient cycling, water cycling and oxygen production.

Afforestation and forest management mitigation measures can enhance the ecosystem services provided by UK forests, if undertaken following the principles of sustainable forest management (Forestry Commission 2002; Forestry Commission 2017a). The Medium and High ambition mitigation measures would increase the provisioning services of timber and bio/wood fuel production of UK forests, lessening the UK's reliance on imports. The UK currently imports 82% of the wood products it uses (Forestry Statistics, Forestry Commission 2017b), from a range of EU and non-EU countries. UK production accounts for 36% of the UK sawnwood market, 49% of the UK wood panel market, 41% of the UK paper and paperboard market and only 5% of the wood pellet market. It is not possible to estimate the proportional increase that could come from implementing Medium or Higher ambition mitigation measures, as national timber production statistics are expressed in green tonnes or cubic metres, whereas CFlow calculates HWP production in terms of carbon, which has been converted into megatonnes of oven-dry material. There is no simple conversion between the units, as much depends on the moisture content and type of wood product. Comparison of HWP production from the higher ambition measures against the BAU level shows an increase in production of 25% (Medium) and 68% (High) in 2050 and 59% (Medium) and 168% (High) in 2100.

A potential barrier to the implementation of higher ambition measures for afforestation is the requirement for a very large increase in planting rates. Current rates have fallen from an average of 35 kha/yr in the 1980s to 15 kha/yr between 2010 and 2016. The high rates of afforestation during the 20th century mean that the areas most suitable for afforestation have already been planted. The remaining land area is either less suitable (e.g. due to high elevation or thin soils) for planting (and less economic) or in competition for other land uses (e.g. due to high agricultural productivity or protected status). Afforestation also takes decades to implement and timber and fuel outputs from the newly planted forests will be small until late in the time period of study (after 2075), with most harvest outputs occurring after 2100.

Other issues may lessen the effect of forest management mitigation measures. One ambition is to bring more of the broadleaved forest area into active management for production; however, as these existing forests have not been recently managed for this purpose they are not likely produce high quality timber (e.g. for construction) for some decades. There may also be risks in the removal of too high a proportion of thinnings from forest for wood fuel, as this may degrade litter inputs and soil quality over the long term. At present, it is generally not economic to remove small diameter thinnings from the forest and they are left to decompose on site. Questions have been raised about the overall impact of the use of woody biomass for heat and power on the global climate (Brack 2017) with a recommendation that any financial/regulatory support should be limited to products (sawmill residues and post-consumer waste) that reduce carbon emissions over the short term. A widespread increase in active management (as well as an increase in forest area) would also require an increase in the skilled labour force.

3.8.2 Bioenergy crops

Although the main purpose of biomass energy crops is the production of fuel (and climate regulation through the replacement of fossil fuels), they also reduce soil GHG fluxes (McAlmont *et al.,* 2017; Whitaker *et al.,* 2018) and there are positive impacts on other ecosystem services. A synthesis of the impact of land use change to biomass energy crops (Holland *et al.,* 2015) suggested positive effects on water quality, soil quality, pollination, disease and pest control and hazard regulation for crops planted on arable and grassland, but negative effects on water availability on cropland. McAlmont *et al.* (2017) found similar positive impacts for Miscanthus in the UK. Whitaker et al (2018) reviewed the existing evidence which suggests that the GHG balance of perennial bioenergy crops will often be favourable, particularly where crops are grown in soils with low carbon stocks and conservative nutrient application (particularly nitrogen). Holland *et al.* (2015) state that the intensity of production and the length of the management cycle are the key factors, and that most benefits would be realised by the conversion of arable land, rather than grassland, although the conversion of marginal land would have the benefit of bringing under-utilised areas into agricultural production. However, conversion of such marginal areas might negatively affect livestock production, and should be avoided on areas of high biodiversity value. Other potential benefits for biodiversity of conversion to biomass energy crops include increasing spatial heterogeneity and refuge areas for farmland species (Rowe *et al.,* 2015; Petrovan *et al.,* 2017), as these crops are not harvested on an annual basis.

In some regions of the UK, higher yielding species (eucalyptus) for SRF could be grown, particularly and more extensively as the climate warms (assuming sufficient water), which could have higher wood density and volume production but shorter rotation lengths than poplar. This would give very different dynamics and, potentially much higher biomass production. However, weather extremes would probably limit the viability of these higher yielding species.

A potential barrier to implementation is the apparent lack of enthusiasm of British farmers for biomass energy crops. Bioenergy crops for biomass fuel currently occupy only a very small area of the cropland area in the UK (<1%). Despite subsidy schemes and other incentives, there has been virtually no increase in the area of Miscanthus or SRC grown in England since 2009 (Defra 2017). There would need to be high and rapid implementation in order to achieve the projected crop areas under the Medium and High ambition measures. However, these measures can be rapidly implemented, and the impact on both fuel production and GHG mitigation would be evident in the short term (< 5 years).

A point to consider for both this and the afforestation measure, is how and where the fuels would be used and whether additional infrastructure would be needed to transport fuel stocks to centralised locations, as has been done with the Scottish Government's Strategic Timber Transport Scheme[11].

3.8.3 Hedges and agroforestry

There is evidence that hedgerows in the British landscape provide regulatory services by improving water quality, reducing flood risk, reducing soil losses through water and wind erosion, improving crop pollination by providing pollinator habitat and climate change mitigation through the storage and accumulation of carbon above and below ground (Wolton *et al.,* 2014). Many plant species within hedgerows can be collected for wild foods and hedges have the potential to be cropped for wood fuel, replacing fossil fuels. They also enhance biodiversity on farmland through the provision of habitat for wildlife and contribute to the cultural landscape of the UK (UK National Ecosystem Assessment 2011).

Silvopastoral and silvoarable agroforestry in the UK can provide shelter and shade for livestock and crops, improve nutrient cycling, improve air quality through pollutant capture, provide habitat for pollinators and other wildlife and improve water retention (Jose 2009; Smith 2010). Depending on the crops, silvoarable agroforestry can also increase total yields and profitability: in this study, we have only modelled dual cropping with timber trees but using fruit or nut trees as the tree crop may be more profitable[12]. Replacing the modelled timber crops with faster-growing species such as willow SRC or birch would also give a faster impact on both carbon stock accumulation and wood fuel production. Silvoarable systems also require fewer nitrogen inputs, both because the area of crop is reduced and because the greater litter input and more extensive root systems fix nitrogen in the soil.

There is also potential for silvopastoral agroforestry to act as riparian buffer strips. Riparian buffer strips have interactions with terrestrial and aquatic environments, and are often characterised by high primary productivity and plant and animal biodiversity. They provide benefits for water quality downstream i.e. via uptake and assimilation of nutrients from groundwater and surface water, promote stream bank stability and erosion control, forage and habitat for wildlife and space for flood water storage resulting in improved flood defence downstream (Naiman and Decamps 1997; Sabater et al., 2003; Wharton and Gilvear 2007).

Potential barriers to implementation of increased hedgerows and agroforestry include the policy framework: currently agroforestry falls in the gap between forestry, environmental stewardship and agriculture and funding options are unclear[8]. Other barriers are a lack of knowledge and practical guidance and the limitations on long-term business planning and capital investment imposed by short-term tenancies. While a return to 1984 levels of hedgerows under the Medium ambition scenario sounds feasible many arable agricultural practices are adapted to large fields and the use of large machinery and it would be challenging to reintroduce field boundaries and consequently smaller fields. However, alley cropping has been successfully applied in other European countries and an initial focus on planting shelter belts along existing field boundaries might also be a successful approach.

3.8.4 Peatland restoration and rewetting

The UK's peatlands occupy around 3.0 million hectares (Evans *et al.,* forthcoming) and provide a range of ecosystem services including provisioning, regulating and cultural services (Chapter 5, UK National Ecosystem Assessment 2011).

- Provisioning services

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[11] https://scotland.forestry.gov.uk/news-releases/funding-for-projects-around-scotland-that-take-timber-lorries-off-fragile-public-roads

[12] https://www.soilassociation.org/media/15756/agroforestry-in-england_soilassociation_june18.pdf

  - Intensively managed lowland peat areas are some of the most productive agricultural soils in the UK, particularly for intensive arable cropping in Eastern England.
  - Although they are generally classed as poor quality agricultural land, upland peatland areas are used for extensive livestock grazing and game shooting (deer and gamebirds).
  - Peat extraction for horticultural use and for fuel still occurs on peatland sites, although there are government commitments to phasing out peat extraction in England, and extraction has ceased in Wales.
  - Upland peat areas are a significant source of water supply for the UK.
- Regulating services
  - Climate regulation in the form of carbon storage and the potential for increased carbon accumulation.
  - More sustainable management of peatlands can mitigate flood risks by increasing vegetation 'roughness' and thereby slowing water flow across the peat surface
  - Pollution mitigation: water from the uplands can dilute downstream pollutants.
- Cultural services
  - UK peatlands provide habitat for a wide range of flora and fauna, including important bird breeding areas and migratory stopovers.
  - Peatlands provide opportunities for recreation and outdoor pursuits.
  - Peatlands can act as an archive of environmental and cultural history.

Possible trade-offs in increasing the area of restored peatlands include:

- Raising water levels can reduce carbon losses and increase biodiversity but can increase methane emissions (this is taken into account in the emission modelling).
- More habitat for insect pests and disease vectors with an increase in wetland area.
- The restoration of upland peat would likely require a reduction or removal of grazing, reducing livestock production in those areas, although the filling of drainage ditches may also reduce stock losses.
- Rewetting of intensively managed lowland peatland under intensive agricultural use is likely to affect the types of crops that can be grown (Evans *et al.,* 2017) and may reduce agricultural production in those areas. However, the rate of carbon loss from these intensively farmed peat soils is such that the 'lifetime' of these areas may be less than 100 years, with obvious consequences for future agricultural production.
- The technical constraints of rewetting intensively managed lowland peat would mean that both complete and partial rewetting could only be applied at a landscape scale because of hydrological connectivity across drainage board areas. Some intensively managed lowland peat areas are currently drained in winter to provide flood water storage, as protection for urban areas, therefore either permanent or seasonal re-wetting of these areas would have to be implemented with carefully to ensure that low-lying settlements in the vicinity are not put at risk of flooding. The availability of water in low-rainfall regions (such as East Anglia) could also act as a constraint, particularly if water levels are dynamically managed through the year. Permanently raised water levels may be more practicable to maintain, particularly at the scale of whole drainage board units, as this would largely just require the cessation of pumping..

4 Combined land use scenarios

The CCC wished to explore a range of 'what if' land use change/agriculture scenarios by combining mitigation options at different levels of ambition. These scenarios are intended to be technically feasible between now and 2050, but are not constrained by economic, social or policy factors. It is not the intention to recommend one particular scenario to plan for, but to identify trade-offs between different land uses, no-regrets options and to understand the impact of different choices. The overall aim is to support decision making across the whole of the land use sector.

The original project specification was that protected areas were excluded from the area available for land mitigation. The area of protected land in the UK in 2017 was 6.8 Mha[13] , representing 27% of the UK land area. However, given the majority of these areas are in some kind of anthropogenic use (and not all areas have been designated for their habitat status), it should be possible to apply mitigation options to these areas in a sensitive manner without damaging their protected status, e.g. peatland restoration, planting of native broadleaved woodland. As a result, we have not explicitly excluded protected areas.

4.1 Land requirements and land sparing

Projecting the effect of agricultural and land use mitigation measures into the future is dependent upon the amount of land required for land mitigation measures and the amount of land that can be freed up (or 'spared'). It is not necessarily possible to maximise all mitigation options as the UK's land area is finite. Land 'sparing' by technical improvements that increase yields per hectare, or which decouple food production from land use to some extent, can however free up land for other uses.

The land requirements and the land spared for each scenario were calculated in parallel and then compared. The categories of land spared/required are those used in the annual agricultural survey (Defra 2017), using a baseline of 2016 values (Appendix 1). Some land use categories, such as permanent grassland, are in higher demand than others, depending on the combination of measures in each scenario. Land requirements also include the ongoing requirement for land conversion to 'developed' use with forecast population growth. This is all assumed to be on grassland on a pro-rata basis for each country of the UK.

A comparison of the land requirements for each scenario (Figure 7) shows that the Maximum Food Production and BAU scenarios are identical in terms of their relatively low land requirements, and that the remaining scenarios have much higher land requirements, reflecting the higher ambition of the mitigation measures. Permanent and rough grazing land are in most demand, cropland only in demand in the higher ambition scenarios and temporary grassland is in relatively low demand (reflecting its smaller extent).

[13] Biodiversity Indicators 2018 c.1. Protected areas http://jncc.defra.gov.uk/page-4241

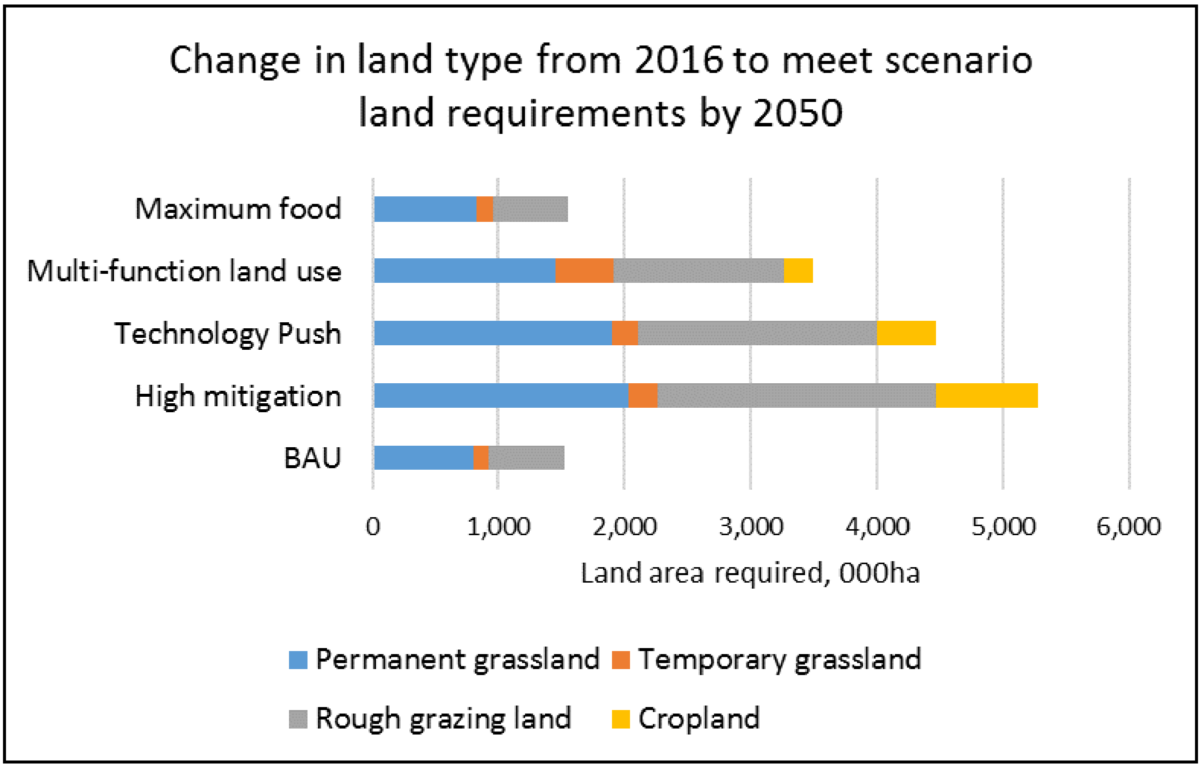


Figure 7: Land requirements by 2050 across the five scenarios

Figure 8 and Table 30 show the land spared by agricultural mitigation measures across the five scenarios at the UK level. The Technology Push scenario spares the most land, particularly permanent grassland and cropland, largely due to dietary change and improved crop yields. The area spared is more than is required for mitigation and could (assuming that the technological innovations incorporated are achievable) be used for additional adaptation (e.g. more protected biodiversity areas) or for additional agricultural production.

The BAU and Maximum Food Production scenarios actually have insufficient land available to maintain per capita production at 2016 levels, even with the assumed BAU crop production and milk yield increases. These two scenarios therefore assume either a) further increases in yields are needed to achieve production on available land, or b) a decrease in per capita production.

The amounts of land spared and required are approximately balanced in both the High Mitigation Uptake and the Multifunctional Land Use scenarios, although the High Mitigation Uptake scenario has a small shortfall in the amount of rough grazing land required and the Multifunctional Land Use scenario has a small shortfall in cropland. Some land use types are also under more pressure in some countries: for example rough grazing land is in high demand in Scotland for afforestation and peatland mitigation, and there is also a shortfall of permanent grassland in England in the High Mitigation Uptake scenarios. In cases of small shortfalls, the amount of land spared versus that required could be balanced by shifting mitigation options between agricultural land use categories (e.g. from permanent to temporary grassland) or reducing the area of mitigation in some countries and increasing it in others. Where the gap between the land spared and the land required is greater, as in the case of the first iteration of the High Mitigation uptake scenario, the target area of mitigation, and hence the land required, had to be reduced. Thus land required for bioenergy crops was reduced from 1.4 Mha by 2050 to 1.2 Mha.

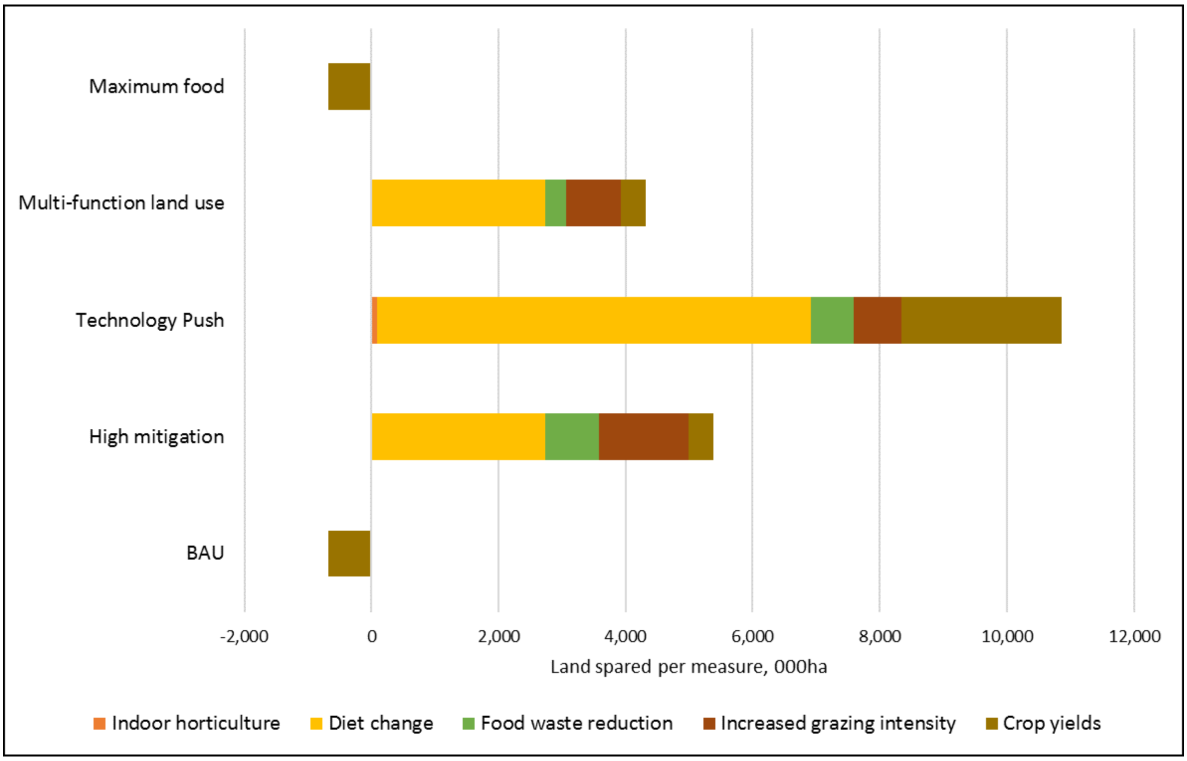


Figure 8: Area of land spared by 2050 across the five scenarios

Table 30: Areas of agricultural land use categories spared across the five scenarios

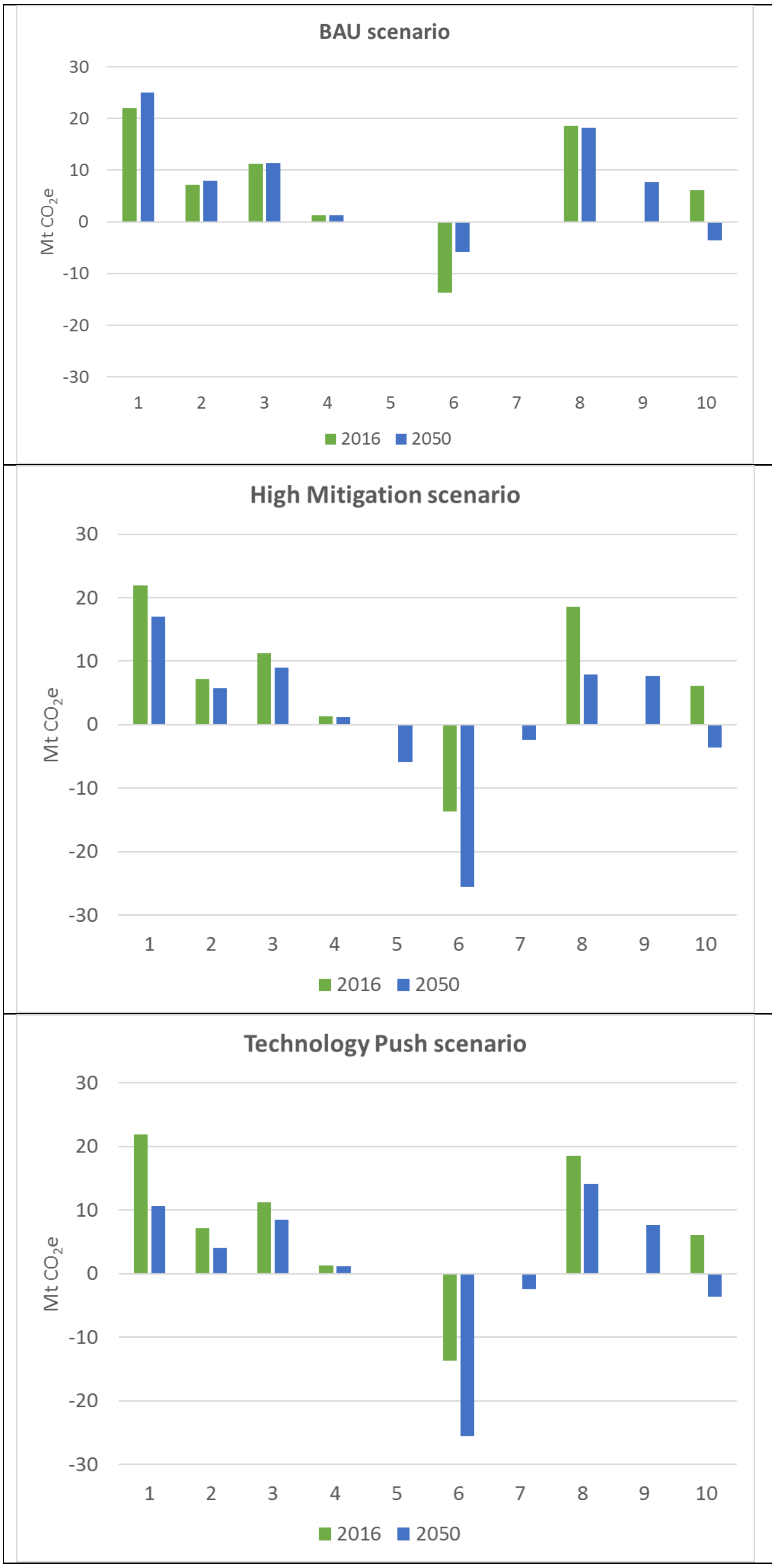
	2050 gap in spared vs. requirements		Permanent grassland		Temporary grassland		Rough grazing		Cropland	
BAU/ Maximum Food production	-2,231	*-13%*	-821	*-13%*	-134	*-12%*	-598	*-12%*	-678	*-15%*
High Mitigation Uptake	108	*+0.6%*	255	*4%*	191	*17%*	-370	*-7%*	32	*1%*
Technology Push	6,363	*+38%*	2,497	*41%*	608	*53%*	745	*15%*	2,513	*54%*
Multi-functional land use	524	*+3%*	184	*3%*	123	*11%*	249	*11%*	-33	*-1%*

4.2 Combined scenario greenhouse gas emissions

Figure 9**Error! Reference source not found.** compares GHG emissions from the scenarios in 2016 and 2050:

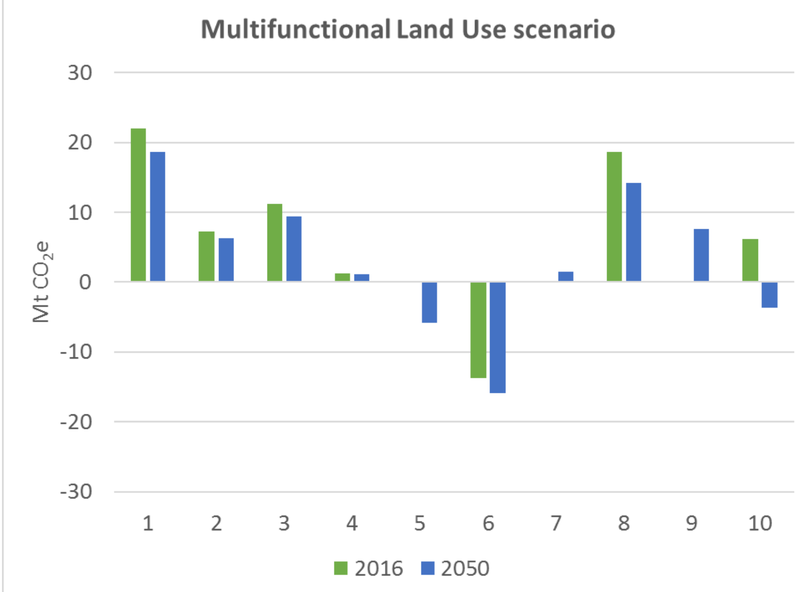
- Emissions from enteric fermentation and manure management increase between 2016 and 2050 in the BAU and Maximum Food scenarios but fall in scenarios with higher ambition mitigation.
- Emissions from agricultural soils and from peatlands fall in the more ambitious scenarios, and removals due to land-based mitigation measures all increase.

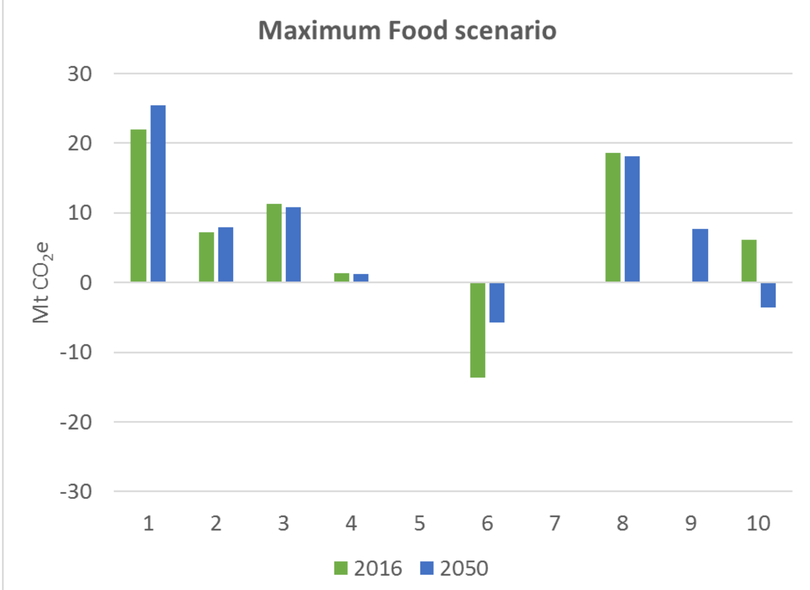
- There is an increase in the land use change emissions between the BAU/Maximum Food scenarios and the higher ambition scenarios: this is due to soil emissions when there is conversion from grassland to cropland for bioenergy, as emissions from conversion to developed land are the same in both scenarios.
- Overall, (excluding ongoing emissions from historic land use change) the GHG emissions from the BAU and Maximum Food Production scenarios increase by 40-41% between 2016 and 2050, whereas the emissions from the other scenarios all show a large reduction: 21% for the Multifunctional Land Use scenario, 61% for Technology Push and 69% for High Mitigation Uptake.



1 = Enteric Fermentation;
2 = Manure management;
3 = Soils;
4 = Liming and urea;
5 = Hedges and agroforestry;
6 = Afforestation and forest management;
7 = Bioenergy crops and HWP;
8 = Peatlands mitigation;
9 = Land use change
10 = Ongoing emissions from pre-2016 land use change.

Figure 9: Net GHG emissions in the combined scenarios scenario





1 = Enteric Fermentation;
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5 = Hedges and agroforestry;
6 = Afforestation and forest management;
7 = Bioenergy crops and HWP;
8 = Peatlands mitigation;
9 = Land use change
10 = Ongoing emissions from pre-2016 land use change

Figure 9 continued: Net GHG emissions in the combined scenarios scenario

The relative contribution of the agricultural mitigation measures and the land-based mitigation measures (excluding urban expansion and on-going emissions from pre-2016 LUC which total 4.0 Mt CO_2e in 2050) can be seen in Table 31.

Table 31: GHG emissions under the scenarios in 2050, Mt CO_2e

Scenario	Agriculture emissions	Land-use mitigation	Total GHG emissions
High mitigation uptake	32.9	-26.1	14.4
Technology Push	24.4	-13.9	18.1
Multifunctional Land Use	35.5	-6.1	37.1
BAU	45.7	12.4	65.7
Maximum Food Production	45.3	12.4	65.3
2016	41.7	4.9	46.6

4.3 Fuel and HWP production

Fuel production in 2050 and 2100 is shown in Figure 10**Error! Reference source not found.** and Figure 11**Error! Reference source not found.**. As in the GHG emissions, fuel production is identical in both 2050 and 2100 for the BAU and Maximum Food Production scenarios, with the majority of fuel coming from existing forests. In the other scenarios Miscanthus and short rotation coppice are both making a large contribution to total fuel production in 2050 but the contributions from other mitigation measures are small. By 2100, post-2016 forests are making a greater contribution to overall fuel production and both silvoarable agroforestry and short rotation forestry are making a more noticeable contribution to fuel production.

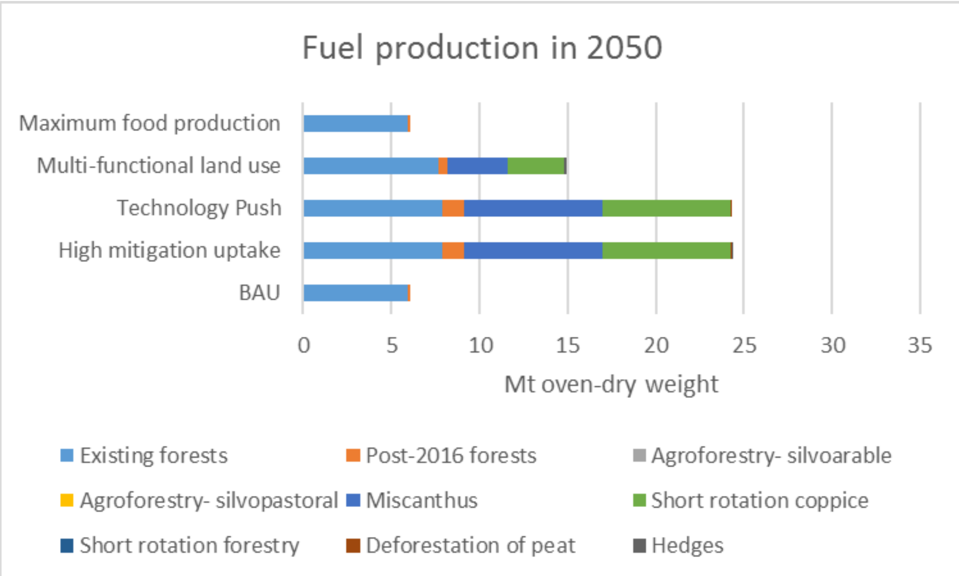

Figure 10: Fuel production by scenario in 2050

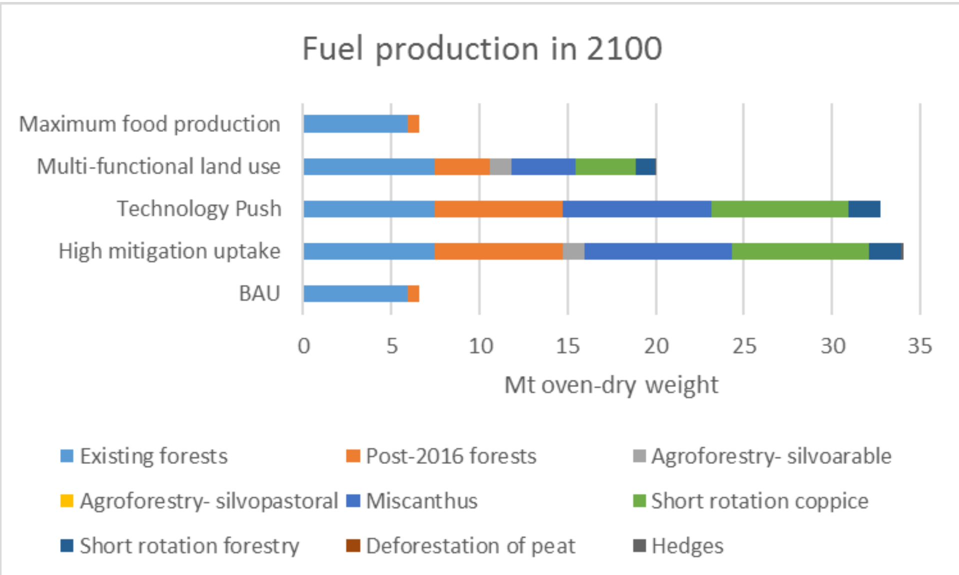

Figure 11: Fuel production by scenario in 2100

For HWP production, there is no difference between the High Mitigation Uptake and Technology Push scenarios as they have the high ambition afforestation measure (Table 32). Applying the high ambition mitigation measure results in nearly twice as much cumulative HWP production by 2100 compared with the low ambition measure.

Table 32: HWP production in the scenarios, Mt oven-dry material

Scenario	Production in 2050	Cumulative production 2017-2050	Production in 2100	Cumulative production 2017-2100
BAU/Max Food	2.8	115.0	3.4	284.2
High Mitigation Uptake	4.7	161.1	9.1	525.4
Technology Push	4.7	161.5	9.1	525.4
Multifunctional Land Use	3.5	134.2	5.4	373.9

4.4 Agricultural production

The changes in livestock numbers by 2050 in the different scenarios shown in Figure 12**Error! Reference source not found.** is reflected by changes in meat and milk production (Figure 13**Error! Reference source not found.** and Figure 14**Error! Reference source not found.**). Red meat and milk production reduce in the more ambitious scenarios but increase in the BAU and Maximum Food Production scenarios. Pork and poultry production increase in all scenarios. The changes in crop production (showing wheat as a proxy for all arable and horticultural crops) are shown in Figure 15**Error! Reference source not found.**, where the Technology Push scenario shows much greater increases than the other scenarios.

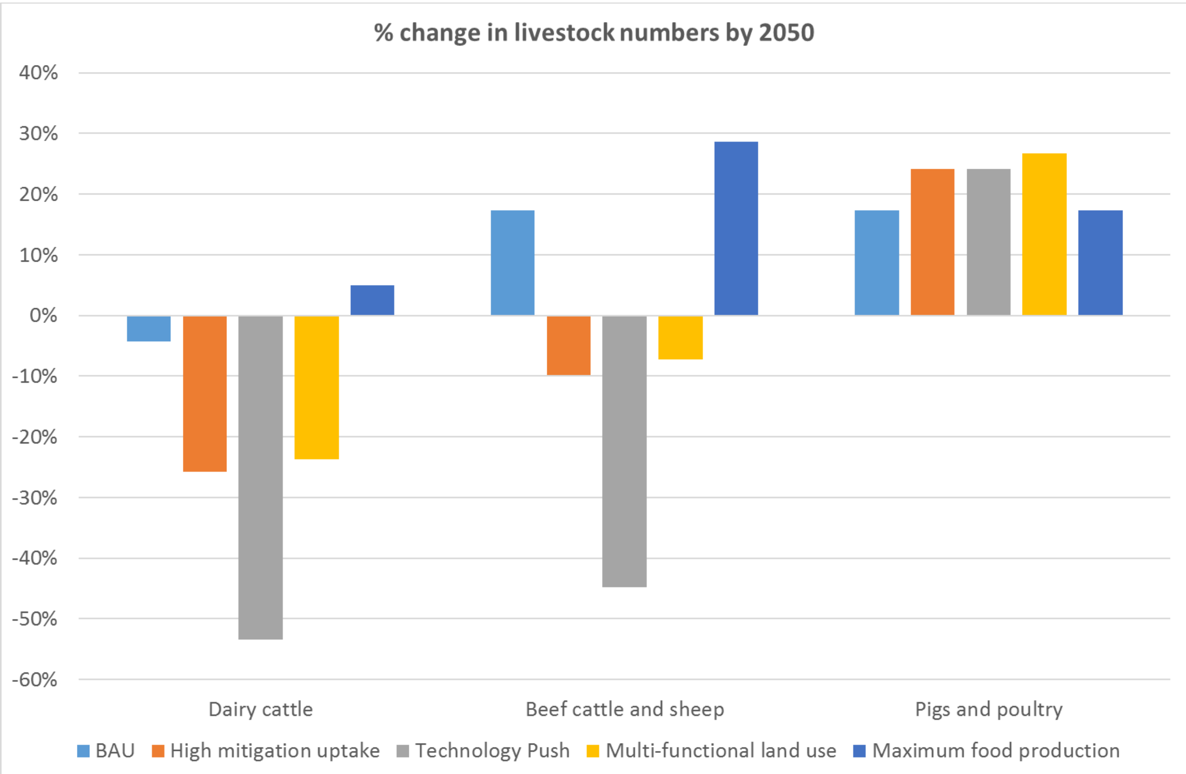

Figure 12: Change in livestock numbers by 2050 in the scenarios

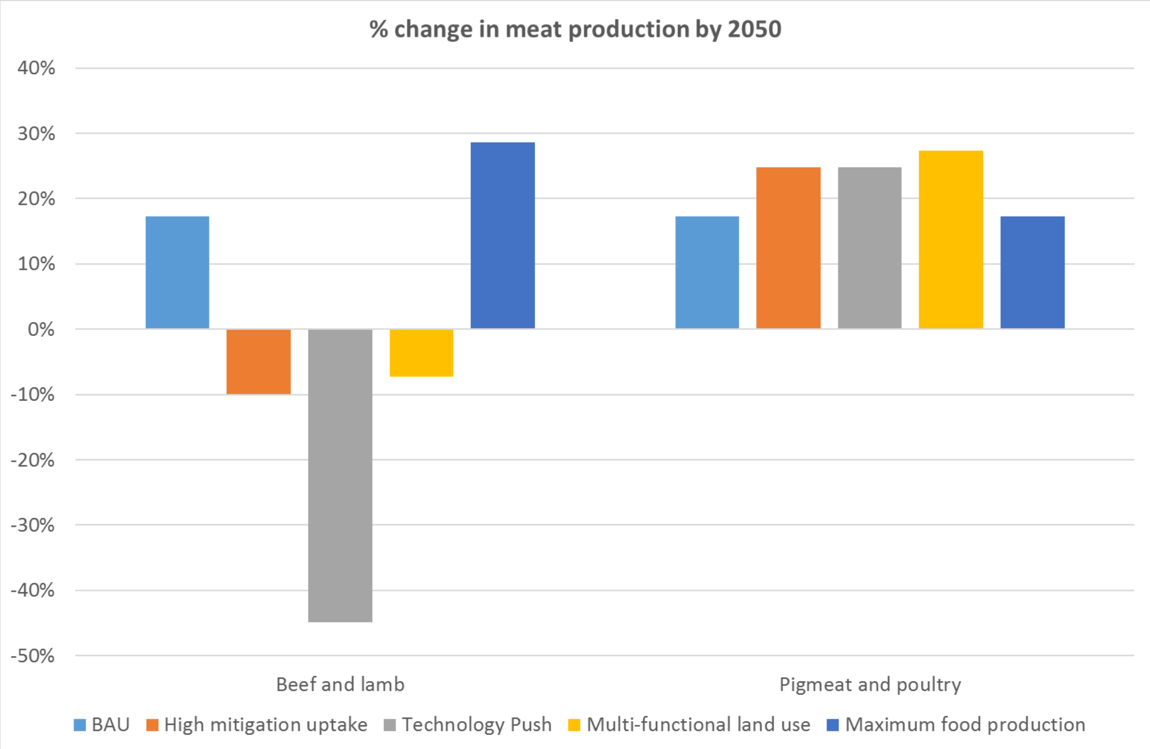

Figure 13: Change in meat production by 2050 in the scenarios

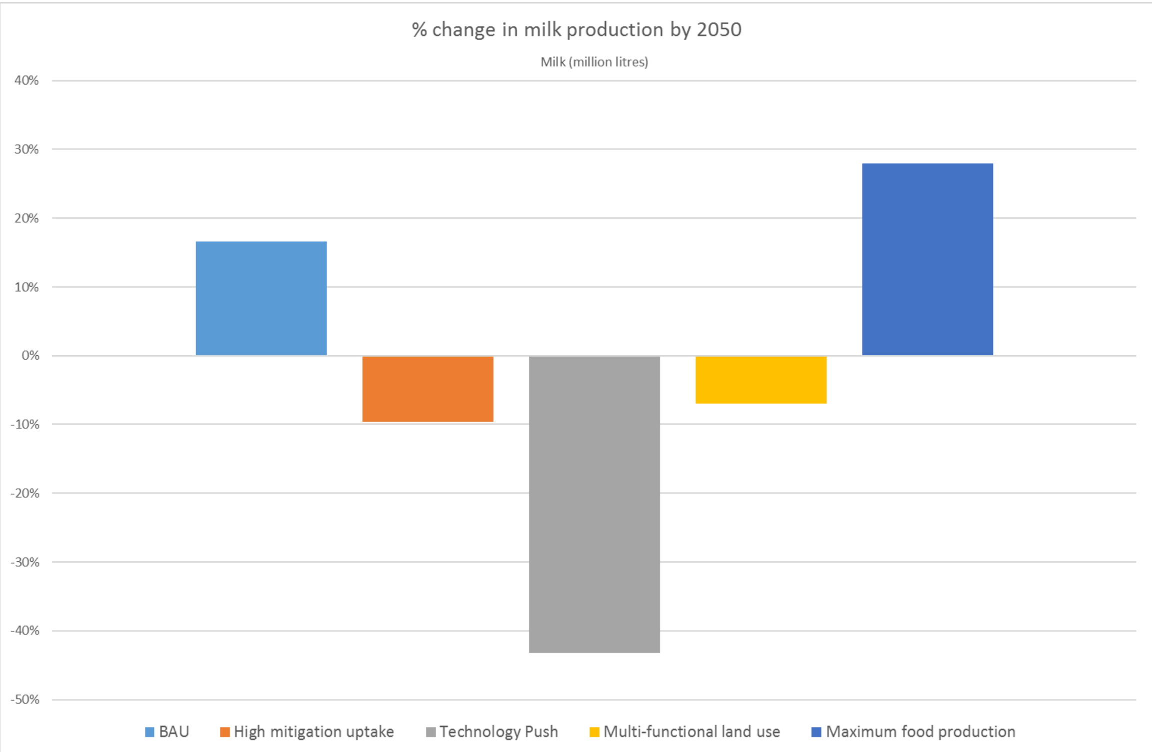

Figure 14: Change in milk production by 2050 in the scenarios

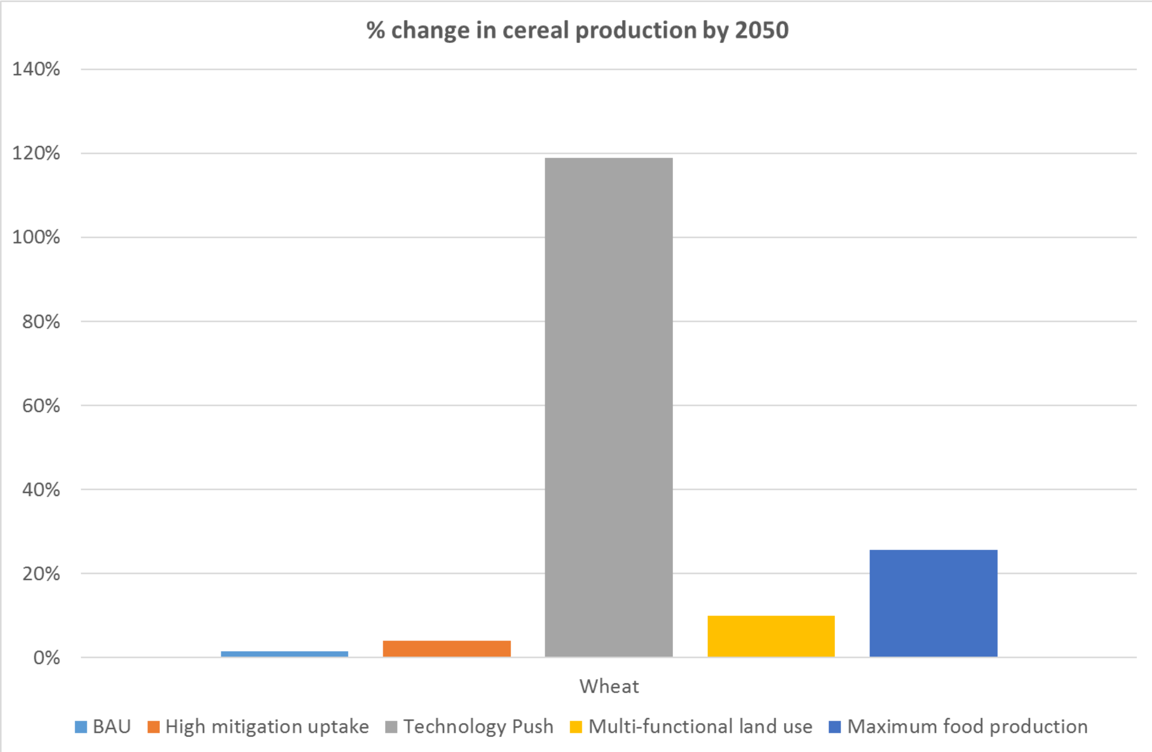

Figure 15: Change in cereal production by 2050 (also proxy for other arable and horticultural products)

5 Adaptation to climate change

The UK Climate Change Risk Assessment Synthesis Report (ASC 2017) introduced an overview of climate change risks and opportunities in different regions of the UK.Winter and summer temperatures are projected to be warmer by 1-4°C in all parts of the UK, with the greatest increases to be seen in eastern and southern England. Annual precipitation is not projected to change by more than ±5%, but winter precipitation will increase (+ 5-35%) and summer precipitation will reduce (+5 to -40%) (Synthesis report Figure SR.6).

The impact on agricultural production will vary across the UK: warmer, drier summer conditions may have a more negative impact on production in the south and east than in the north and west, where production may benefit (Morison and Matthews 2016). The benefits of warmer temperatures and longer growing seasons and increased CO_2 concentrations will be outweighed by reductions in water availability in future decades. More extreme weather events, such as droughts and storms, may reduce yields on a regional basis and increased flooding may lead to substantial losses of crop production in low-lying agricultural areas. Different crops will also respond to the changes in climate in different ways: a longer growing season may increase the productivity of root crops but earlier maturation may reduce cereal yields. Heat stress in livestock may also reduce their productivity.

As well as their direct impact on climate change through the reduction in GHG emissions and increase in carbon sinks, the mitigation measures outlined in this report may also counteract some of the negative aspects of climate change. The adaptation of new technologies in arable and livestock agriculture will reduce soil damage and soil erosion and improve water quality. Mitigation measures such as increasing the area of agroforestry and hedgerows will increase the provision of shade and shelter for livestock, and provide additional habitat for pollinators and pest predators. Measures that promote perennial plant cover (agroforestry and hedgerows, bioenergy crops and afforestation) can have beneficial effects on water retention and mitigate flooding (at certain scales) and reduce erosion of soil by water and wind.

The effects of climate change on the UK's forests are complex and regionally variable. Heat stress and water shortages are likely to impair forest growth in the south and east of England, but warmer growing conditions may enhance productivity in forests in the west and north (Morison *et al.,* 2012). It is highly likely that existing forests will be increasingly vulnerable to pest and disease outbreaks, as warmer conditions favour the survival of pests and disease vectors over winter, and these outbreaks are most likely to affect overall productivity than the direct change in climate. The Forestry Commission is already adapting to use new species to maintain yields and increase resilience to climate stress. The incidence of storms is also predicted to increase over the 21st century, but forest stand losses are very localised and not expected to have a significant effect at the national level. The forestry sector in the UK has adapted its management to windy conditions in order to minimise losses through site selection, thinning regime and harvesting age.

Both the agriculture, land management and forestry sectors are already adapting to climate change by introducing new species, varieties and management practices, but the planning, adoption and evaluation of management changes will be a continuous process as the future unfolds and brings previous unconsidered impacts and opportunities.

6 Conclusions

This project has developed and modelled agricultural and land use mitigation measures at three levels of ambition to assess their impact on GHG emissions, land availability and food, fuel and timber production. Both the agriculture and the land use sectors need to be considered together to realistically assess the availability of suitable land and assess the overall impact of mitigation measures. The measures have been combined into five scenarios to investigate possible land use futures in the UK. This emissions analysis stops at the UK's land use sector boundary and does not consider net changes in emissions from savings in energy or from the substitution of products with high embodied GHG emissions (e.g. timber substituted for steel or concrete).

The agricultural mitigation measure with the greatest emissions reduction was dietary change, as this reduced livestock numbers and livestock fodder requirements, thereby reducing livestock emissions and nitrogen usage. Measures improving crop yields and reducing livestock emissions also had a substantial impact.

Afforestation has the greatest potential for enhancing carbon sinks but is reliant on a massive and rapid increase in tree planting rates to achieve this. Peatland mitigation measures have a substantial impact in reducing emissions but peatland area will continue to be a GHG source, and their full extent is not currently reflected in the LULUCF sector GHG inventory. Hedges and agroforestry measures are the third in size in terms of average emissions reductions per unit area, but their area of coverage is comparatively small. While bioenergy crops do not contribute substantial emissions reductions compared to the other land use mitigation measures the modelling approach was relatively simple and did not include N_2O effects. Under the more ambitious measures, bioenergy crops produce substantial amounts of fuel, approaching or overtaking the contribution from forests by 2100. The GHG benefits of agroforestry and bioenergy crops also included the reduced use of nitrogen as arable land is reduced, as these crops/systems require less nitrogen due to increased litter falls and more extensive root systems.

Of the combined scenarios, the Technology Push scenario had the greatest agricultural emission reduction potential and the second greatest land use emissions reduction potential, principally, and spared the greatest area of land for other uses. The High Mitigation Uptake scenario had the greatest emissions reduction potential overall, but also the greatest land requirements. In its first iteration there was insufficient suitable land available to implement this scenario, illustrating the importance of considering the whole land management sector. Under the BAU and Maximum Food Production scenarios there was insufficient land to maintain food production at 2016 levels with the forecast growth in population and requirement for additional settlement and infrastructure development on agricultural land.

The co-benefits and adaptation impacts of the mitigation measures have been considered at a high level, and it is evident that the implementation of these measures has the potential to increase the resilience of the UK's land management sector and counter-balance some of the negative impacts of climate change.

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[2] *https://www.gov.uk/government/statistics/agriculture-in-the-united-kingdom-2016*

8 Appendices

1. Workshop attendees

Name	Area of expertise	Organisation
Mark Broadmeadow	Forestry	Forestry Commission
Judith Stuart	Peatland and soils	Defra
Adrian Williams	Agriculture	Cranfield University
William Macalpine	SRC willow	Rothamsted Research
Sarah Wynn	ETI land use work	ADAS
Caroline Harrison	Forestry & timber	Confor
John Clifton-Brown	Miscanthus	Aberystwyth University
Julian Franklin	Indoor farming	Rothamsted Research
Ian Brown	CCRA assumptions	Dundee
Beccy Wilebore	Quantitative ecologist	Oxford
Joe Morris	CCC land use champion	ex-Cranfield
Martin Lukac	Agroforestry	Reading University

2. Agricultural land use in 2016

Appendix table 1: All land, areas in kha

Land Use type	Forest (conifer)	Forest (broadleaf)	Permanent grassland	Temporary grassland	Rough grazing (including common land)	Cropland	Settlement	Peatlands (near natural, rewetted and peat extraction sites)
England	354	1265	3282	628	802	3991	1432	151
Northern Ireland	67	17	653	148	173	47	61	130
Scotland	1085	447	1118	210	3580	536	180	565
Wales	155	199	1066	158	437	88	107	33
UK	1661	1928	6118	1144	4993	4662	1780	879

Appendix table 2: Area on peat soils, kha

<table>
<tr><th>Land Use type</th><th>Forest (conifer)</th><th>Forest (broadleaf)</th><th>Permanent grassland</th><th>Temporary grassland</th><th>Rough grazing (including common land)</th><th>Cropland</th><th>Settlement</th><th>Peatlands (near natural, rewetted and peat extraction sites)</th></tr>
<tr><td>England</td><td>17</td><td rowspan="5">Assumed zero</td><td>73</td><td rowspan="5">Included with permanent grassland</td><td>209</td><td>182</td><td rowspan="5">Assumed zero</td><td>151</td></tr>
<tr><td>Northern Ireland</td><td>33</td><td>33</td><td>45</td><td>3</td><td>130</td></tr>
<tr><td>Scotland</td><td>180</td><td>104</td><td>918</td><td>7</td><td>565</td></tr>
<tr><td>Wales</td><td>8</td><td>13</td><td>35</td><td>0</td><td>33</td></tr>
<tr><td>UK</td><td>237</td><td>223</td><td>1207</td><td>192</td><td>879</td></tr>
</table>

Appendix table 3 Comparison of land use classifications

LULUCF Land Use (IPCC categories)	LUC Matrices	Agricultural Census category	Wetland Supplement project category
Forest	Woods		Forest
Cropland	Farm (Arable)	Cropland	Cropland
Grassland	Farm (Pasture)	Permanent Grassland	Intensive Grassland
		Temporary Grassland	
	Natural	Rough Grazing	Eroded Modified Bog
			Heather Dominated Modified Bog
			Grass Dominated Modified Bog
			Extensive Grassland
Wetland			Peat Extraction Sites Rewetted Bog and Fen Near natural bog and fen.
Settlement	Urban		
Other Land	Other		

3. England: Summary

Land sparing vs. land requirements by scenario

Percentage and area difference (kha)	2050 gap in spared vs. requirements		Permanent grassland		Temporary grassland		Rough grazing		Cropland	
BAU/ Maximum Food production	-1542	-18%	-678	-21%	-122	-19%	-166	-21%	-576	-14%
High Mitigation Uptake	110	1%	-58	-2%	64	10%	98	12%	6	0%
Technology Push	4075	47%	1255	38%	315	50%	301	38%	2204	55%
Multi-functional land use	95	1%	-85	-3%	32	5%	194	24%	-46	-1%

GHG emissions by scenario

		Low ambition				Medium ambition				High ambition			
Emissions Mt CO_2e	2016	2030	2050	2080	2100	2030	2050	2080	2100	2030	2050	2080	2100
Afforestation and forest management	**-3.5**	**-1.6**	**-1.3**	**-0.4**	**-0.1**	**-3.1**	**-4.9**	**-5.9**	**-6.1**	**-4.7**	**-8.3**	**-11.9**	**-10.9**
Bioenergy crops	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**-0.2**	**-1.3**	**-1.0**	**0.2**	**-0.4**	**-3.3**	**-2.4**	**0.4**
Hedgerows and agroforestry	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**-0.9**	**-2.4**	**-0.5**	**-0.3**	**-2.1**	**-5.3**	**-0.6**	**-0.4**
Peatland restoration	**10.1**	**10.1**	**10.1**	**0.0**	**0.0**	**9.4**	**8.0**	**0.0**	**0.0**	**8.7**	**6.0**	**0.0**	**0.0**
Urban expansion	**2.8**	**5.4**	**6.6**			**5.4**	**6.6**			**5.4**	**6.6**		
Agricultural LUC	**-0.9**	**-1.4**	**-1.1**			**-1.4**	**-1.1**			**-1.4**	**-1.1**		

4. Scotland: Summary

Land sparing vs. land requirements by scenario

Percentage and area difference (kha)	2050 gap in spared vs. requirements		Permanent grassland		Temporary grassland		Rough grazing		Cropland	
BAU/ Maximum Food production	-577	-11%	-73	-7%	-3	-2%	-416	-12%	-85	-16%
High Mitigation Uptake	-598	-11%	-10	-1%	31	15%	-648	-18%	29	5%
Technology Push	563	10%	165	15%	64	30%	66	2%	267	50%
Multi-functional land use	-221	4%	-64	-6%	9	4%	-188	-5%	21	4%

GHG emissions by scenario

		Low ambition				Medium ambition				High ambition			
Emissions Mt CO_2e	2016	2030	2050	2080	2100	2030	2050	2080	2100	2030	2050	2080	2100
Afforestation and forest management	**-9.3**	**-6.3**	**-3.8**	**-3.9**	**-2.6**	**-7.9**	**-8.0**	**-9.7**	**-8.4**	**-8.3**	**-11.6**	**-17.8**	**-15.5**
Bioenergy crops	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.5**	**2.1**	**0.3**	**-0.1**	**0.8**	**1.7**	**-0.8**	**0.1**
Hedgerows and agroforestry	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**-0.1**	**0.0**	**0.0**	**-0.1**	**-0.2**	**0.0**	**-0.1**
Peatland restoration	**6.1**	**6.2**	**5.7**	**0.0**	**0.0**	**5.5**	**4.3**	**0.0**	**0.0**	**5.0**	**3.3**	**0.0**	**0.0**
Urban expansion	**1.5**	**1.5**	**1.4**			**1.5**	**1.4**			**1.5**	**1.4**		
Agricultural LUC	**1.3**	**-1.1**	**-3.3**			**-1.1**	**-3.3**			**-1.1**	**-3.3**		

5. Wales: Summary

Land sparing vs. land requirements by scenario

Percentage and area difference (kha)	2050 gap in spared vs. requirements		Permanent grassland		Temporary grassland		Rough grazing		Cropland	
BAU/ Maximum Food production	-56	-3%	-30	-3%	-3	-2%	-12	-3%	-11	-13%
High Mitigation Uptake	344	20%	177	17%	52	33%	122	28%	-7	-8%
Technology Push	1072	61%	666	62%	124	79%	270	62%	13	14%
Multi-functional land use	390	22%	189	18%	44	28%	165	38%	-9	-10%

GHG emissions by scenario

	Low ambition					Medium ambition				High ambition			
Emissions Mt CO_2e	2016	2030	2050	2080	2100	2030	2050	2080	2100	2030	2050	2080	2100
Afforestation and forest management	**-0.4**	**-0.3**	**-0.4**	**-0.1**	**0.1**	**-1.5**	**-2.5**	**-2.9**	**-3.7**	**-1.9**	**-4.6**	**-6.7**	**-6.3**
Bioenergy crops	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.1**	**0.4**	**0.1**	**0.0**	**0.1**	**-0.7**	**-0.8**	**0.1**
Hedgerows and agroforestry	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**-0.1**	**-0.1**	**0.0**	**0.0**	**-0.1**	**-0.3**	**0.0**	**-0.1**
Peatland restoration	**0.4**	**0.4**	**0.4**	**0.0**	**0.0**	**0.4**	**0.3**	**0.0**	**0.0**	**0.3**	**0.2**	**0.0**	**0.0**
Urban expansion	**0.6**	**0.5**	**0.3**			**0.5**	**0.3**			**0.5**	**0.3**		
Agricultural LUC	**0.1**	**-0.1**	**-0.1**			**-0.1**	**-0.1**			**-0.1**	**-0.1**		

6. Northern Ireland: Summary

Land sparing vs. land requirements by scenario

Percentage and area difference (kha)	2050 gap in spared vs. requirements		Permanent grassland		Temporary grassland		Rough grazing		Cropland	
BAU/ Maximum Food production	-28	-3%	-16	-3%	-3	-2%	-4	-2%	-6	-12%
High Mitigation Uptake	251	2%	145	22%	44	30%	58	34%	4	8%
Technology Push	683	67%	436	67%	110	74%	108	62%	29	61%
Multi-functional land use	260	25%	143	22%	38	26%	79	45%	0	0%

GHG emissions by scenario

		Low ambition				Medium ambition				High ambition			
Emissions Mt CO_2e	2016	2030	2050	2080	2100	2030	2050	2080	2100	2030	2050	2080	2100
Afforestation and forest management	**-0.5**	**-0.1**	**-0.2**	**0.0**	**0.0**	**-0.2**	**-0.5**	**-0.6**	**-0.7**	**-0.3**	**-1.1**	**-1.7**	**-1.5**
Bioenergy crops	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.1**	**0.4**	**0.1**	**0.0**	**0.1**	**-0.2**	**-0.5**	**0.1**
Hedgerows and agroforestry	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**-0.1**	**0.0**	**0.0**	**0.0**	**-0.1**	**0.0**	**0.0**
Peatland restoration	**1.9**	**1.9**	**1.9**	**0.0**	**0.0**	**1.8**	**1.5**	**0.0**	**0.0**	**1.6**	**1.3**	**0.0**	**0.0**
Urban expansion	**0.9**	**0.7**	**0.4**			**0.7**	**0.4**			**0.7**	**0.4**		
Agricultural LUC	**-0.3**	**-0.4**	**-0.2**			**-0.4**	**-0.2**			**-0.4**	**-0.2**		

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