UK Centre for Ecology & Hydrology

Updated quantification of the impact of future land use scenarios to 2050 and beyond- Final report

Issue Number 1

Date 07/12/2020

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Title Updated quantification of the impact of future land use scenarios to 2050 and beyond

Client Committee on Climate Change

UKCEH reference 07610/Final report for CCC

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Date 07/12/2020

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1 Executive Summary

1.1 Objectives

- This technical report examines how ambitious land-based mitigation measures could reduce greenhouse gas (GHG) emissions from the UK's land by 2050 and increase production of timber and biomass fuel.
- Mitigation measures at different levels of ambition were combined into six scenarios: Business as Usual, Headwinds, Widespread Engagement, Widespread Innovation, Tailwinds and Balanced Net Zero Pathway. These scenarios have been developed in line with the Committee on Climate Change (CCC) scenario approach for the 6th Carbon Budget advice, which will allow the CCC to consider alternative pathways for reducing emissions in the agriculture and land use sectors to 2050.

1.2 Mitigation measures

- The land-based mitigation options examined were: afforestation and improved management of existing forests, increased planting of biomass energy crops, restoration of degraded peatlands and sustainable management of cropland on peat; and increased areas of agroforestry and hedgerows.
- 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 the six scenarios, 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. 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 tree-based mitigation options.
- Afforestation and peatland restoration mitigation options were associated with the biggest emissions reductions compared with business-as-usual.
- Existing forests produced the greatest proportion of timber and fuel in the 2020s and 2030s, but biomass energy crops produce more fuel in the 2040s under the higher ambition scenarios.

1.3 Scenarios

- The CCC modelled the land 'spared' by agriculture-based mitigation measures in the six scenarios which could then be used for land-based mitigation options. This ensured that the total area of land remained stable. The highest demand was for rough grazing land, followed by permanent grassland, cropland and temporary grassland. Land requirements to meet housing and infrastructure needs for forecast population growth were also included in the analysis.
- The Business as Usual scenario was the least ambitious with only small amounts of afforestation and peatland restoration, reflected in the very small emissions savings by 2050.

- All other scenarios achieved net zero GHG emissions in the 2030s, with the Widespread Innovation and Tailwinds scenarios reaching this target the soonest and achieving the largest emission savings by 2050. The Balanced Net Zero Pathway scenario achieved net zero GHG emissions in 2036 and annual net removals of -19 $MtCO_2e$ by 2050.
- The BAU scenario has insufficient land available to maintain agricultural production at current levels and meet the land requirements for land-based mitigation measures.
- The Balanced Net Zero Pathway scenario had a land requirement of around 2 Mha by 2035 and a requirement of 4 Mha by 2050.
- All non-BAU scenarios produced more timber and fuel than under the BAU scenario, with production increasing rapidly after 2050 (as trees planted since 2020 reached harvestable age). The Balanced Net Zero Pathway scenario produces 4.6 Mt oven-dry timber by 2035 and 4.7 Mt by 2050.
- The Balanced Net Zero Pathway produces 9.4 Mt oven-dry fuel by 2035 (7.5 from existing forests and 1.8 from bioenergy crops) and 14.8 Mt by 2050 (8.4 Mt from existing and new forests and 6.4 Mt from bioenergy).

2 Introduction

The Committee on Climate Change (CCC) is providing its recommendations on the setting of the 6th Carbon Budget (2033-37) in late 2020. This will provide advice on the volume of emissions the UK can emit during the 2033-37 period, and also set the path to the UK's new net-zero emissions target in 2050. As part of this work the CCC wished to revise a set of existing and incorporate new assumptions in the agriculture and land use sector that was used to inform their Net Zero advice in 2019. This work was largely based on consultancy work undertaken by UKCEH and Rothamsted for the CCC in 2018 (Thomson et al. 2018). In this work, six new scenarios have been developed in line with the CCC's scenario approach for the 6th Carbon Budget advice, which will allow the CCC to consider alternative pathways for reducing emissions in the agriculture and land use sectors to 2050.

The CCC have updated the agriculture sector modelling and UKCEH have updated the land-use modelling, as described in this report. A Global Warming Potential of 34 has been used for methane (CH_4) and 298 for nitrous oxide (N_2O), in line with the other preparation work for the 6th Carbon Budget. As in the previous 2018 work, the modelled mitigation measures have not been constrained by technical or financial feasibility.

The six new CCC 6th CB scenarios are fully described in CCC (2020) *The Sixth Carbon Budget - The UK's path to Net Zero:*

- **Business as usual (BAU)**. This will largely be based on the existing BAU from the 2018 CEH/Rothamsted work, and which underpinned the CCC's Net Zero advice.
- **Headwinds**, which is broadly consistent with the Further Ambition scenario (based on the 2018 Multi-functional land use scenario) of the CCC's Net Zero advice.
- **Widespread Engagement**, which implies a higher level of behaviour change (e.g. 50% diet change) to drive emissions reductions.
- **Widespread Innovation**, which relies on the scope for more innovation-based solutions (e.g. lab-grown meat).
- **Tailwinds,** comprising high ambition from behaviour change and technology.
- **Balanced Net Zero Pathway**, which will draw on the above scenarios to derive a separate sixth carbon budget pathway, which is the basis for the CCC's 6th Carbon Budget advice.

The CCC modelled five land release measures (improved crop yields, diet change, waste reduction, grazing intensification and indoor horticulture) and population change to assess the impact on agricultural land area and agricultural GHG emissions (CCC Methodology Report for the 6th Carbon Budget, Ch.7, 2020). The agricultural mitigation measures for each scenario release agricultural land for additional land-based mitigation as well as other uses. These land-based mitigation measures are modelled at different levels of ambition for each scenario, and the balance between the land released ('spared') and the land 'required' is balanced with the total land available in each country of the UK.

The land-based mitigation measure considered are: afforestation and improved management of existing broadleaf forests; increased production of bioenergy crops; restoration and sustainable management of degraded peatlands; and expansion of hedgerows and agroforestry. The land required for settlement expansion with projected population increase is also modelled but does not change between scenarios. The GHG net emissions from settlement expansion, historical land use change (pre-2019) and existing degraded, rewetted or near-natural peatlands are also taken into account in the overall GHG balance for land-based mitigation.

3 Land-based mitigation measures

3.1 Forestry: afforestation and forest management

The Forestry measures comprises 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.

3.1.1 Assumptions

Afforestation occurs on permanent grassland and rough grazing land in proportion to their coverage in each country in the 2019 June agricultural survey (Appendix 1). No afforestation has been modelled as occurring on organic soil (peatlands) or priority habitats.

The forest management and planting assumptions for the CCC 6th CB are summarised below. All assumptions and further details on planting density, species split and open-ground assumptions are given in Table 3.

- Existing forests (planted before 2020) assume an average yield class (YC) of 12 is used for conifer forests, and YC6 for broadleaf forests (as in the 2018 project).
- BAU scenario:
    - Existing forests: no change from current management, where 100% of conifer forests are assumed to be managed, but only 20% of broadleaved forests.
    - Afforestation from 2020: a fixed planting rate of 8.988 kha yr^{-1} is used for 2020-2050, based on the average 5 year planting rate 2014-2018.
    - Conifer afforestation is assumed to be YC14 and broadleaf planting YC6.
- Headwinds scenario:
    - Existing forest: assumes that broadleaf woodland which is currently unmanaged is brought back into production, with 67% actively managed by 2030.
    - Afforestation from 2020: the UK planting rate is ramped up to 30 kha yr^{-1} by 2025 and maintained to 2050.
    - Conifer afforestation is assumed to be YC16, and broadleaf planting YC6.
- Widespread Engagement scenario:
    - Existing forest: assumes that most broadleaf woodland which is currently unmanaged is brought back into production, with 80% actively managed by 2030
    - Afforestation from 2020: the UK planting rate is ramped up to 70 kha yr^{-1} by 2035 and maintained to 2050.
    - Conifer afforestation is assumed to be YC14, and broadleaf planting YC6.
- Widespread Innovation scenario:
    - Existing forest: as for Widespread Engagement.
    - Afforestation from 2020: the UK planting rate is ramped up to 50 kha yr^{-1} by 2030 and maintained to 2050.

- Conifer afforestation 2020-2029 is assumed to be YC16, and broadleaf planting YC6. Conifer afforestation 2030-2050 is assumed to be YC18, and broadleaf planting YC8.
- Tailwinds scenario:
  - Existing forest: as for Widespread Engagement scenario.
  - Afforestation from 2020: as for Widespread Engagement scenario.
- Balanced Net Zero Pathway scenario:
  - Existing forest: as for Widespread Engagement.
  - Afforestation from 2020: the UK planting rate is ramped up to 30 kha yr^{-1} by 2025, changing to 50 kha yr^{-1} in 2035 and maintained to 2050.

3.1.2 Methodology

The forest carbon 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, agroforestry and short rotation forestry (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 1). 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.

Table 1: Main parameters used in CFlow for this project in the United Kingdom (Dewar & Cannell 1992) *

	Sitka spruce			Sycamore/Ash/Birch		Poplar	Poplar
Afforestation/ Forest management	**Afforestation/ Forest management**			**Afforestation/ Forest management/ Silvo-pastoral planting**	**Afforestation/ Forest management**	**Short rotation forestry**	**Silvoarable planting**
	YC14	**YC16**	**YC18**	**YC6**	**YC8**	**YC12**	**YC12**
Rotation (years)	57	55	53	44	42	26	35
Year of first thinning	18	17	16	15	15	N/A	N/A
Stemwood density (t m^{-3})	0.35	0.34	0.33	0.49	0.49	0.36	0.36
Maximum carbon in foliage (t ha^{-1})	6.3	7.2	8.1	1.7	1.8	1.8	1.8
Maximum carbon in fine roots (t ha^{-1})	2.7	2.7	2.3	2.7	2.7	1.8	1.8
Fraction of wood in branches	0.09	0.09	0.09	0.18	0.18	0.08	0.08
Fraction of wood in woody roots	0.19	0.19	0.19	0.16	0.16	0.15	0.15
Maximum foliage litterfall (t ha^{-1} a^{-1})	1.3	1.4	1.6	1.7	1.8	2	2
Maximum fine root litter loss (t ha^{-1} a^{-1})	2.7	2.7	2.3	2.7	2.7	1.8	1.8
Dead foliage decay rate (a^{-1})	1	1	1	3	3	3	3
Dead wood decay rate (a^{-1})	0.06	0.06	0.06	0.04	0.04	0.08	0.08
Dead fine root decay rate (a^{-1})	1.5	1.5	1.5	1.5	1.5	2	2

* The soil organic carbon decay rate was 0.03 a^{-1} and the fraction of litter lost to soil organic matter was 0.5 for all species

Forest growth is estimated using Forestry Commission Yield Tables (Edwards and Christie 1981), assuming restocking after harvesting. Sitka spruce 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. Sycamore/ash/birch yield classes have been used to represent all broadleaf (hardwood) forestry in the UK. Poplar is used for silvo-arable and short rotation forestry planting.

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[1] (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. Due to the greater range of species and management represented in CARBINE in with different thinning and harvesting regimes and different biomass expansion factors, there are differences between the outputs of the models. Despite the differences, the CFlow model results provide indications of magnitude and change in direction of sufficient robustness for policy assessment based on fewer input requirements. For the outputs of this project, a correction has been applied so that the initial values for 2018 match those published in the 1990-2018 national GHG Inventory (Brown et al. 2019).

Calculations were produced separately for emissions associated with existing forest (planted between 1500 and 2016) and emissions associated with projected forest planting (from 2020 to 2100) to allow the effect of afforestation to be separated from the effect of change in the management of existing forests.

Conifer plantations were assumed to be felled and replanted at the age of Maximum Annual Increment (MAI) at 53-57 years after planting. They were also managed by thinning of trees (reducing tree density) at regular intervals (every five years after the initial thinning) to improve the timber quality and growth of the remaining trees. Broadleaved plantations were assumed to be felled and replanted at 44 years (MAI) with thinning management. This was based on the planting of trees similar to sycamore, ash or birch being planted; other broadleaves such as oak or beech have much longer management rotations (>80 years) but were not included in the modelling. Some additional model runs were also performed with no thinning and no felling before 2100 to assess the impact of implementing more ‘natural’ management. Poplar for agroforestry and short rotation forestry was not thinned as it is planted at lower densities.

The CFlow model calculates the loss of carbon when wood products (thinnings and main harvest) is removed from the forest and the net carbon pool of these products (the balance between the addition of new products and the carbon losses from decay of existing products). It is possible to specify a single decay lifetime for the removed timber, but this does not take account of the possible different fates of the removed wood products (fuel, paper, panelboard or sawnwood) and their different potential lifetimes. The decay lifetime was set to one million years in CFlow so that we could separate wood product accumulation and decay. The fate of wood products from afforestation, forest management, agroforestry and short rotation forestry was dealt with separately. Wood products from conifer afforestation and existing forests was

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

assumed to enter the Harvested Wood Products pool, and wood products from all other sources were assumed to be burnt for fuel.

3.1.3 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 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.,* 2019 for details). All existing 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 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.

The proportion of conifer and broadleaf planting varied by scenario, with a higher proportion of broadleaf planting in the Widespread Engagement and Balanced Net Zero Pathway scenarios (see Table 3). There was also a range of assumptions on the amount of open ground (10-20%) incorporated into afforestation. This area was additional to the planted area, so that the land requirement for afforestation is higher than the area of trees alone.

3.2 Bioenergy crops- *Miscanthus*, Short Rotation Coppice and Short Rotation Forestry

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).

3.2.1 Assumptions

Yield increases due to improved management, breeding and climate change were assumed for *Miscanthus* and SRC. 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[2] (Pogson *et al.,* 2016). Although

[2] 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-

these crops are planted in the UK, 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.

Miscanthus was assumed to be planted on cropland only, SRC was split equally between cropland and temporary grassland and SRF was split between permanent, temporary and rough grassland in proportion to their coverage in each country in the 2019 June agricultural survey.

Innovative agronomy and improved plant breeding including genetic modification (GM) increases the yield of SRC and *Miscanthus* from 12 t/ha to between 15 -20 t/ha oven-dry material by 2050.

3.2.2 Methodology

The calculations for *Miscanthus* and SRC were compiled in MS Excel models, while the SRF calculations were done in the CFlow model (see Forestry methodology section).

For *Miscanthus*, it was assumed that the maximum above-ground biomass stock (Defra 2019) was achieved in the 3rd year after planting and continued at that rate, and the growth rate in the first two years was 50% of the maximum above-ground biomass stock, i.e. 2.75 tC/ha/year. Harvesting started in the 3rd year after planting and harvested all available above-ground biomass on an annual basis. Below-ground biomass was assumed to accumulate over the first two years after planting but remained constant after that (no additional gains or losses) (Dohleman *et al*. 2012, Maleski *et al.* 2019). It was estimated by multiplying the above-ground biomass by the root: shoot ratio (IPCC 2006, vol. 4, table 4.4). A carbon content of 44% was assumed (Maleski *et al.* 2019). The cumulative soil carbon increase from *Miscanthus* planted on cropland was calculated from the values published in Richards et al. (2017).

Miscanthus in the UK has a production yield of 10-15 oven-dried tonnes (odt)/ha/year (Defra 2019). For the scenarios, the average yield was ramped from 12 odt/ha to 15 odt/ha by 2050 for the Headwinds, Widespread Engagement and Balanced Net Zero Pathway scenarios, and from 12 odt/ha to 20 odt/ha for the Widespread Innovation and Tailwinds scenarios.

For SRC, it was assumed that the average above-ground biomass growth per year was the same as production (12 odt/ha in 2020 but increasing to 2050), using a carbon content of 50%. Harvesting started in the 3rd year after planting and harvested all available above-ground biomass on a three year cycle. Below-ground biomass was assumed to accumulate over the first three years after planting but remained constant after that (no additional gains or losses). It was estimated by multiplying the above-ground biomass by the root: shoot ratio of 0.46 (IPCC 2006, vol. 4, table 4.4). The cumulative soil carbon increase from SRC planted on cropland or temporary grassland was calculated from the values published in Richards et al. (2017).

SRC in the UK has a production yield of 8-15 odt/ha/year (Defra 2019). For the scenarios, the average yield was ramped from 12 odt/ha to 15 odt/ha by 2050 for the Headwinds and Balanced Net Zero Pathway scenarios, and from 12 odt/ha to 20

emphasized as the measurement dataset is still small and industry best practices in establishing plantations are not yet widely applied.

odt/ha for the Widespread Innovation and Tailwinds scenarios. SRC was not included in the Widespread Engagement scenario.

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

3.2.3 Activity data

The annual planting rates of *Miscanthus* were ramped over 2022-2030 to 10,000 ha yr^{-1} for the Headwinds, Balanced Net Zero Pathway and Widespread Engagement scenarios, and to 20,000 ha yr^{-1} for the Widespread Innovation and Tailwinds scenarios.

The annual planting rates of SRC were ramped over 2022-2030 to 9,306 ha yr^{-1} for the Headwinds and Balanced Net Zero Pathway scenarios, and to 19,000 ha yr^{-1} for the Widespread Innovation and Tailwinds scenarios.

The annual planting rates of SRF were ramped over 2025-2030 to 10,833 ha yr^{-1} for the Headwinds and Balanced Net Zero Pathway scenarios, and to 21,667 ha yr^{-1} for the Widespread Innovation and Tailwinds scenarios.

No planting of biomass energy crops was assumed for the BAU scenario, and no planting of SRC or SRF in the Widespread Engagement scenario.

3.3 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 silvo-pastoral or silvo-arable systems. Silvo-pastoral systems integrate low density woodland with livestock grazing, and silvo-arable systems, in the UK context, integrate narrow strips of economically valuable woodland with arable cropping (alley cropping or shelter belts).

3.3.1 Assumptions

In the BAU scenario agroforestry remains at its current (very low) level and hedgerows remain at their current extent until 2050.

In the other scenarios, there is an increase in agroforestry so that between 5% and 15% of agricultural land is converted to silvo-arable or silvo-pastoral systems (Table 3). Agroforestry systems have low densities of tree planting, so only a small percentage of the converted area is actually lost to agriculture (14% of the converted grassland area and 6.7% of the converted arable area). Tree planting of poplar yield class 12 (no thinning) was assumed for silvo-arable systems, with a 2m-wide strip for each tree row, 8m between trees in a row and 30m between each row. This spacing achieved a compromise between the maintenance of crop productivity (which can be reduced by tree shading) (Chirko et al. 1996) and carbon sequestration. Planting of sycamore/ash/birch yield class 6 was assumed for silvo-pastoral systems, with a planting density of 400 trees/ha. The effect of shading by trees on arable yields was not taken into account in the agriculture production estimates.

The increase in hedgerows used the assumptions from the 2018 project: under the Headwinds and Widespread Innovation scenarios the length of hedges is restored to 1984 levels (an increase of 30%) by 2050, with 10% of this hedge length managed for biomass fuel; under the Widespread Engagement, Tailwinds and Balanced Net Zero Pathway scenarios, the length of hedges is restored to 10% above 1984 levels by 2050 (increase of 40%) and 30% of this hedge length is managed for biomass fuel.

3.3.2 Methodology

Carbon stock changes in agroforestry were estimates using the CFlow model. Agroforestry systems have low densities of tree planting, so only a small percentage of the converted area is actually lost to agriculture (14% of the converted grassland area and 6.7% of the converted arable area). Tree planting of poplar yield class 12 (no thinning) was assumed for silvo-arable systems, with a 2m-wide strip for each tree row, 8m between trees in a row and 30m between each row. This spacing achieved a compromise between the maintenance of crop productivity (which can be reduced by tree shading) (Chirko et al. 1996) and carbon sequestration. Planting of sycamore/ash/birch yield class 6 was assumed for silvo-pastoral systems, with a planting density of 400 trees/ha. The effect of shading by trees on arable yields was not taken into account in the agriculture production estimates.

Hedgerow carbon stock changes were modelled in MS Excel (see the 2018 report). 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.

3.3.3 Activity data

There are currently negligible amounts of agroforestry in the UK, so a baseline of zero was assumed and subsequent planting rates from Table 3.

Current hedgerow lengths (managed and unmanaged) are taken from the GB and Northern Ireland Countryside Surveys 2007. There are 62.2 kha of managed hedges in the UK in 2016, and 58.2 kha of unmanaged hedges. There is no change in the length of lines of trees and scrub (with or without fences).

3.4 Peatland restoration and sustainable management of peatlands

The peatland restoration measures cover the restoration, rewetting and sustainable management of degraded peatlands currently under agricultural and forest land use. Degraded peatlands no longer function like natural peatlands because of drainage and grazing or burning management, resulting in net GHG emissions to the atmosphere rather than net removals. 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 majority of emissions from organic soils (peatlands) are not currently included in the UK's national GHG inventory, but their inclusion is planned for the

1990-2019 or the 1990-2020 inventory to be published in 2021 and 2022 respectively (see Brown *et al*. 2018).

3.4.1 Assumptions

The areas and emission factors used for calculating emissions from peatland restoration are taken from Evans *et al*., (2017). 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 same areas and activity data will be used for the forthcoming GHG inventory reporting of emissions from organic soils.

Emission factors for CO_2, CH_4 and N_2O are given by Evans et al. (2017) for pristine ("near-natural"), degraded and rewetted peatlands under different land use types. The current scientific evidence is that rewetted peatlands have higher emission factors than near-natural peatlands, although the eventual goal of restoration should be a return to near-natural conditions and net carbon sequestration. At present, the time period for transition between the degraded and rewetted state, and between rewetted and near-natural states, is unknown (no estimate is provided by the IPCC methodology for example). Therefore, it has been assumed that there is an immediate transition between the degraded and rewetted emission factors, but no transition from rewetted to near-natural state before 2050.

The restorable peatland land-use types modelled for this project were: upland grassland, lowland grassland (intensive and extensive grassland), lowland cropland, peat extraction sites, and forest on peat. Net emissions from near-natural peatlands and peatlands rewetted before 2020 were also calculated.

Lowland cropland on peat soils has high agricultural value, so emissions from sustainable management of this land use type, as well as from full restoration, were estimated. These sustainable management options depend on raising the water table (either permanently or seasonally) closer to the ground surface than under current management, while still maintaining the land use as cropland. Restoration of cropland was either full restoration to a near-natural state or restoration of the water table and usage of the land for paludiculture crops.

In England there are large areas of peat soils, particularly in East Anglia, known as 'wasted' peats. These peatlands have been so degraded over time that they now typically have a depth of <40 cm but still have high soil organic carbon content. There is currently a lack of scientific evidence as to whether these wasted peats behave differently, i.e. have different emission factors, from deep peats. Expert judgement (Evans pers. comm) considers that emissions from wasted peats should be lower than those from deep peats, which would substantially reduce the BAU emissions across large parts of the drained cropland area, and also reduce the net benefit from the management options. There is an in-progress BEIS-funded Lowland Peat Research project to address this data gap. For the scenario modelling, wasted peats are assumed to have the same emission factor as deep peats under the same land use.

For the BAU scenario, peatland restoration is assumed to only occur where there are current policies and funding in place. 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, apart from some peat extraction sites in England where there are known dates for restoration before 2050.

For upland grassland on peat 100% restoration is assumed by 2045 (Widespread Engagement, Widespread Innovation, Tailwinds and Balanced Net Zero Pathway) or by 2050 for Headwinds.

For lowland grassland, 50% restoration is assumed by 2050 (Widespread Engagement, Widespread Innovation, Tailwinds and Balanced Net Zero Pathway) or 25% by 2050 for Headwinds. The proportion of restoration on lowland intensive and extensive grassland varies across the scenarios (see Table 3).

For cropland, there was 50% restoration of the total area by 2050 for Headwinds, and 75% restoration by 2050 for Widespread Engagement, Widespread Innovation, Tailwinds and Balanced Net Zero Pathway. Restoration to near-natural condition was applied to 10%-25% of the area, paludiculture restoration to 10%-25%, and water level management to 30%-50% of the area (Table 3).

For extraction sites, 100% restoration by 2035 is assumed for all non-BAU scenarios. For forest on peat, 100% restoration on forest on sites with forest <YC8 is assumed for all non-BAU scenarios. With higher forest yield classes, the net carbon balance between carbon losses from deforestation and carbon gains from peat restoration can be equivocal, so only the restoration of low-yield forest sites is considered here.

3.4.2 Methodology and activity data

GHG emissions from peatland (unrestored, restored and near-natural) are calculated in a spreadsheet (MS Excel) model using the areas and emission factors from Evans *et al*. (2017).

Emissions from cropland under sustainable management were derived from unpublished data by Professor Chris Evans. It is assumed that emissions are proportional to water table depth (WTD). The mean WTD for cropland under business-as-usual conditions is estimated at 106 cm. Cropland management with a continuously raised water table is assumed to have a mean year-round WTD of 40 cm: this level coincides with the Indonesian government's regulatory target and would still allow agricultural production. Cropland management with a dynamic water table is calculated from the seasonal pattern in Table 2 (mean WTD of 50cm), assuming temporary deep drainage in summer and near-inundation in winter and are based on expert judgement.

Table 2: Monthly water table depth of cropland peat soils.

Month	WTD
1	10
2	10
3	10
4	40
5	60
6	80
7	100
8	100
9	80
10	60

11	40
12	10
Mean	50

The calculation of dynamic water table emissions does not factor in seasonal variation in CO_2/CH_4 emissions: these would potentially lead to higher overall emissions but the detailed analysis required to parameterise this was beyond the scope of this project.

Restoration of cropland to paludiculture usage is assumed to require a mean WTD of 10 cm. Restoration to near-natural peatland condition is assumed to create a mean WTD of 5 cm, which is optimal for net CO_2+CH_4 emissions (this is very close to the original emission factor for near-natural fen in Evans et al. 2017).

CH_4 emissions from ditches are assumed to be constant for all cropland management options other than restoration to near natural, as all other options (including paludiculture) require a functional ditch network. N_2O emissions are scaled linearly between cropland and near-natural EFs (Evans *et al*. 2017) as a function of WTD (assuming a linear N_2O vs WTD relationship as in Couwenberg *et al*., 2011).

3.5 Other land use change – settlement and historic 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 (future conversion to settlement is assumed to occur on pasture and rough grazing grassland only). We assume that the projected rate of settlement expansion will be in line with the projected increase in the number of households[3]. Data on historical development patterns[4] and the density of residential development are used to calculate further land requirements. It was assumed that 24% of all future settlement expansion was due to residential development (an increase from the current proportion of 17% in 2017/18). Soil and biomass carbon stock changes due to settlement expansion are estimated using the GHGI LUC model assuming change from grassland (see Brown *et al.,* 2019 Annex 3.6 for further details of this model).

Other LUC emissions arise from continuing soil carbon emissions/removals from LUC that occurred before 2019 (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-2019 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.

[3] https://www.gov.uk/government/statistical-data-sets/live-tables-on-household-projections Table 401
[4] https://www.gov.uk/government/statistical-data-sets/live-tables-on-land-use-change-statistics using the change from non-developed "Agriculture", "Forest, open land and water" and "Vacant non-previously developed" to other developed categories and the "Outdoor recreation", "Residential garden" and "Undeveloped land" categories.

3.6 Assumptions for each scenario

The assumptions (Table 3) for each mitigation measure/scenario combination were devised by the CCC, with an iterative process of refinement driven by the balance of land spared vs. required and policy drivers.

Table 3: Assumptions by measure

Measure	Measure component	BAU	Headwinds	Widespread Engagement	Widespread Innovation	Balanced Net Zero Pathway	Tailwinds
Afforestation	Planting rate target	Average of past 5 years (2014-2018)	30,000 ha yr^{-1} from 2025	70,000 yr^{-1} from 2035	50,000 ha yr^{-1} from 2030	30,000 ha yr^{-1} from 2025, 50,000 ha yr^{-1} from 2035	70,000 ha yr^{-1} from 2035
Afforestation	Planting trajectory		Ramp 2020-2025 then constant rate	Ramp 2020-2035 then constant rate	Ramp 2020-2030 then constant rate	Ramp 2020-2025 then constant rate 2025-34, constant rate from 2035	Ramp 2020-2035 then constant rate
Afforestation	Planting density	2,000 trees ha^{-1} (BL) 3,000 trees ha^{-1} (CON)	2,000 trees ha^{-1} (BL) 3,000 trees ha^{-1} (CON)	1,200-1,800 trees ha^{-1} (BL) 2,500 trees ha^{-1} (CON)	2,000 trees ha^{-1} (BL) 3,000 trees ha^{-1} (CON)	2,000 trees ha^{-1} (BL) 3,000 trees ha^{-1} (CON)	1,200-2,000 trees ha^{-1} (BL) 3,000 trees ha^{-1} (CON)
Afforestation	Planting split (BL:CON)	Average of past 5 years ENG 89:11 SCOT 45:55 WALES 59:41 NI 66:34	ENG 65:35 SCOT 35:65 WALES 50:50 NI 55:45	ENG 80:20 SCOT 50:50 WALES 80:20 NI 80:20	ENG 40:60 SCOT 25:75 WALES 40:60 NI 40:60	ENG 80:20 SCOT 50:50 WALES 80:20 NI 80:20	71% planted using Widespread Innovation assumptions, 29% planted using Widespread Engagement assumptions
Afforestation	Yield class/species	Conifer YC14 Broadleaf YC6	Conifer YC16 Broadleaf YC6	Conifer YC14 Broadleaf YC6	2019-2029: Conifer YC16 Broadleaf YC6 2030-2100	Conifer YC16 Broadleaf YC6	2019-2029: Conifer YC16 Broadleaf YC6 2030-2100

Measure	Measure component	BAU	Headwinds	Widespread Engagement	Widespread Innovation	Balanced Net Zero Pathway	Tailwinds
					Conifer YC18 Broadleaf YC8		Conifer YC18 Broadleaf YC8
Afforestation	Open ground margin to conform with UK Forest Standard	10% open space	15% open space	20% open space	15% open space	15% open space	71% has 15% open space, 29% has 20% open space
Management of existing forests		No change in current management (100% management of conifer forests, 20% management of broadleaf forests.	Unmanaged broadleaf forest brought back into production, 67% actively managed by 2030.	Unmanaged broadleaf forest brought back into production, 80% actively managed by 2030.	As for Widespread Engagement.	As for Widespread Engagement.	As for Widespread Engagement.
Biomass Energy Crops	*Miscanthus*	N/A	Ramp planting 2022-2030 to 10,000 ha yr^{-1} (245,000 ha by 2050) Production increase from 12 to 15 t ODM ha^{-1} by 2050	Ramp planting 2022-2030 to 10,000 ha yr^{-1} (245,000 ha by 2050) Production increase from 12 to 15 t ODM ha^{-1} by 2050	Ramp planting 2022-2030 to 20,000 ha yr^{-1} (470,000 ha by 2050) Production increase from 12 to 20 t ODM ha^{-1} by 2050	Ramp planting 2022-2030 to 10,000 ha yr^{-1} (245,000 ha by 2050) Production increase from 12 to 15 t ODM ha^{-1} by 2050	Ramp planting 2022-2030 to 20,000 ha yr^{-1} (470,000 ha by 2050) Production increase from 12 to 20 t ODM ha^{-1} by 2050
Biomass Energy Crops	Short rotation coppice	N/A	Ramp planting 2022-2030 to 9,306 ha yr^{-1} (218,000 ha by 2050)	N/A	Ramp planting 2022-2030 to 19,000 ha yr^{-1} (436,000 ha by 2050)	Ramp planting 2022-2030 to 9,306 ha yr^{-1} (218,000 ha by 2050)	Ramp planting 2022-2030 to 19,000 ha yr^{-1} (436,000 ha by 2050)

Measure	Measure component	BAU	Headwinds	Widespread Engagement	Widespread Innovation	Balanced Net Zero Pathway	Tailwinds
			Production increase from 12 to 15 t ODM ha^{-1} by 2050		Production increase from 12 to 20 t ODM ha^{-1} by 2050	Production increase from 12 to 15 t ODM ha^{-1} by 2050	Production increase from 12 to 20 t ODM ha^{-1} by 2050
Biomass Energy Crops	Short rotation forestry	N/A	Ramp planting 2025-2030 to 10,833 ha yr^{-1} (255,000 ha by 2050)	N/A	Ramp planting 2025-2030 to 21,667 ha yr^{-1} (509,000 ha by 2050)	Ramp planting 2025-2030 to 10,833 ha yr^{-1} (255,000 ha by 2050)	Ramp planting 2025-2030 to 21,667 ha yr^{-1} (509,000 ha by 2050)
Agroforestry	Silvo-pastoral	N/A	5% of permanent and rough grassland converted (14% of area lost to tree planting)	15% of permanent and rough grassland converted (14% of area lost to tree planting)	10% of permanent and rough grassland converted (14% of area lost to tree planting)	10% of permanent and rough grassland converted (14% of area lost to tree planting)	15% of permanent and rough grassland converted (14% of area lost to tree planting)
Agroforestry	Silvo-arable	N/A	5% of arable and temporary grassland converted (6.7% of area lost to tree planting)	10% of arable and 15% of temporary grassland converted (6.7% of area lost to tree planting)	10% of arable and temporary grassland converted (6.7% of area lost to tree planting)	10% of arable and temporary grassland converted (6.7% of area lost to tree planting)	10% of arable and 15% of temporary grassland converted (6.7% of area lost to tree planting)
Peatland restoration – upland	Grassland	155,000 ha restoration 2020-2030 in Scotland only	100% restoration by 2050	100% restoration by 2045	100% restoration by 2045	100% restoration by 2045	100% restoration by 2045
Peatland restoration and sustainable	Cropland	N/A	**50% restoration and**	**75% restoration and**	**75% restoration and**	**75% restoration and**	**75% restoration and**

Measure	Measure component	BAU	Headwinds	Widespread Engagement	Widespread Innovation	Balanced Net Zero Pathway	Tailwinds
management – lowland			**management by 2050** 10% Full restoration to Paludiculture use 10% Full restoration to near-natural condition	**management by 2050** 15% Full restoration to Paludiculture use 25% Full restoration to near-natural condition	**management by 2050** 25% Full restoration to Paludiculture use	**management by 2050** 15% Full restoration to Paludiculture use 25% Full restoration to near-natural condition	**management by 2050** 15% Full restoration to Paludiculture use 25% Full restoration to near-natural condition
Sustainable management options-cropland		N/A	30% converted to Dynamic Water Level Management	20% converted to Dynamic Water Level Management 15% converted to Continuous Raised Water Level	50% converted to Continuous Raised Water Level	20% converted to Dynamic Water Level Management 15% converted to Continuous Raised Water Level	20% converted to Dynamic Water Level Management 15% converted to Continuous Raised Water Level
Peatland restoration – lowland	Grassland		Restoration of 25% lowland grassland by 2050	Restoration of 50% lowland grassland by 2050	Restoration of 50% all lowland grassland by 2050	Restoration of 50% lowland grassland by 2050	Restoration of 50% lowland grassland by 2050
	Extensive grassland	*5,000 ha restoration 2020-2030 in Scotland only*	*50% restoration by 2050 (19,900 ha)*	*Zero restoration*	*50% restoration by 2050 (19,900 ha)*	*Zero restoration*	*Zero restoration*
	Intensive grassland	*N/A*	*22% restored (33,700 ha)*	*61% (107,200 ha) restored by 2050*	*50% restoration by 2050 (87,250 ha)*	*61% (107,200 ha) restored by 2050*	*61% (107,200 ha) restored by 2050*

Measure	Measure component	BAU	Headwinds	Widespread Engagement	Widespread Innovation	Balanced Net Zero Pathway	Tailwinds
Peatland restoration – lowland	Extraction sites	Planned restoration of sites in England	100% restoration by 2035	100% restoration by 2035	100% restoration by 2035	100% restoration by 2035	100% restoration by 2035
Peatland restoration – lowland	Forest on peat	60,000 ha restoration 2020-2030 in Scotland only	100% restoration of sites <YC8	100% restoration of sites <YC8	100% restoration of sites <YC8	100% restoration of sites <YC8	100% restoration of sites <YC8
Hedgerow management and creation		N/A	30% increase in length over 2018 levels, 10% managed for biomass fuel	40% increase in length over 2018 levels, 30% managed for biomass fuel	30% increase in length over 2018 levels, 10% managed for biomass fuel	40% increase in length over 2018 levels, 30% managed for biomass fuel	40% increase in length over 2018 levels, 30% managed for biomass fuel

4 Tree and energy crop mitigation per hectare

Model runs were undertaken for a single hectare of planting of the bioenergy crop and forest types (**Error! Reference source not found.** and **Error! Reference source not found.**) and are a useful comparison of the carbon sequestration impact of different energy crop and tree-based mitigation measures. Bioenergy crops were modelled to 2050, and forest types to 2100.

Conifer plantations were managed by thinning management and harvesting at the MAI (see Forestry section) followed by replanting. Broadleaf plantations were allowed to continue growing to 2100 rather than being felled at the MAI. The broadleaf "Managed" and "Not Managed" lines illustrate the impact of thinning management on overall broadleaf forest carbon sequestration, with non-thinned broadleaf sequestering carbon at a lower rate but still greater accumulation than conifer plantations by 2100.

Production yields of 15 odt ha^{-1} yr^{-1} were assumed for both *Miscanthus* and SRC. The "*Miscanthus*-15 years" and "*Miscanthus*-20 years" lines represent different life-cycles before replanting but make little difference to sequestration. It was assumed that all below-ground biomass was lost when the crop was dug up and replanted, and that there was an 18% loss of the accumulated soil carbon at replanting (based on the IPCC 2019 Refinement, Vol. 4, Chapter 5, Table 5.5 using the value for temporary set-aside).

Figure 1: Cumulative carbon sequestration to 2050 from different crop and forest types for 1 ha of planting

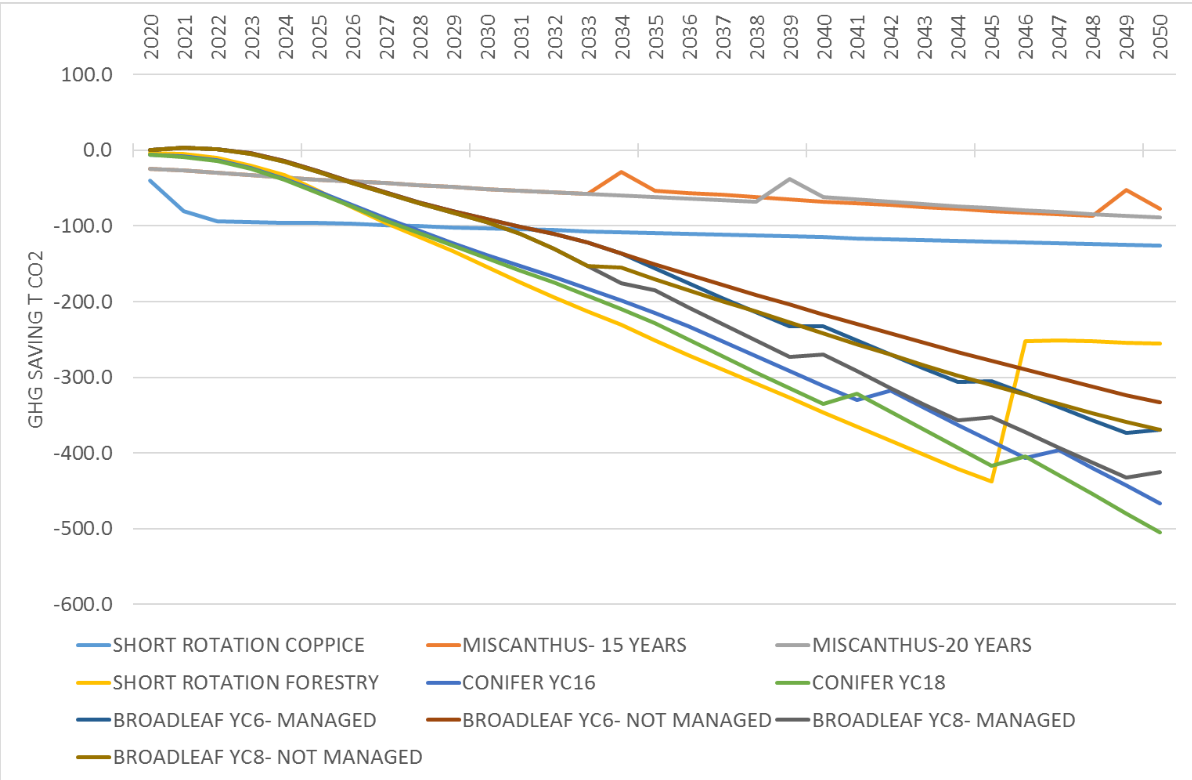
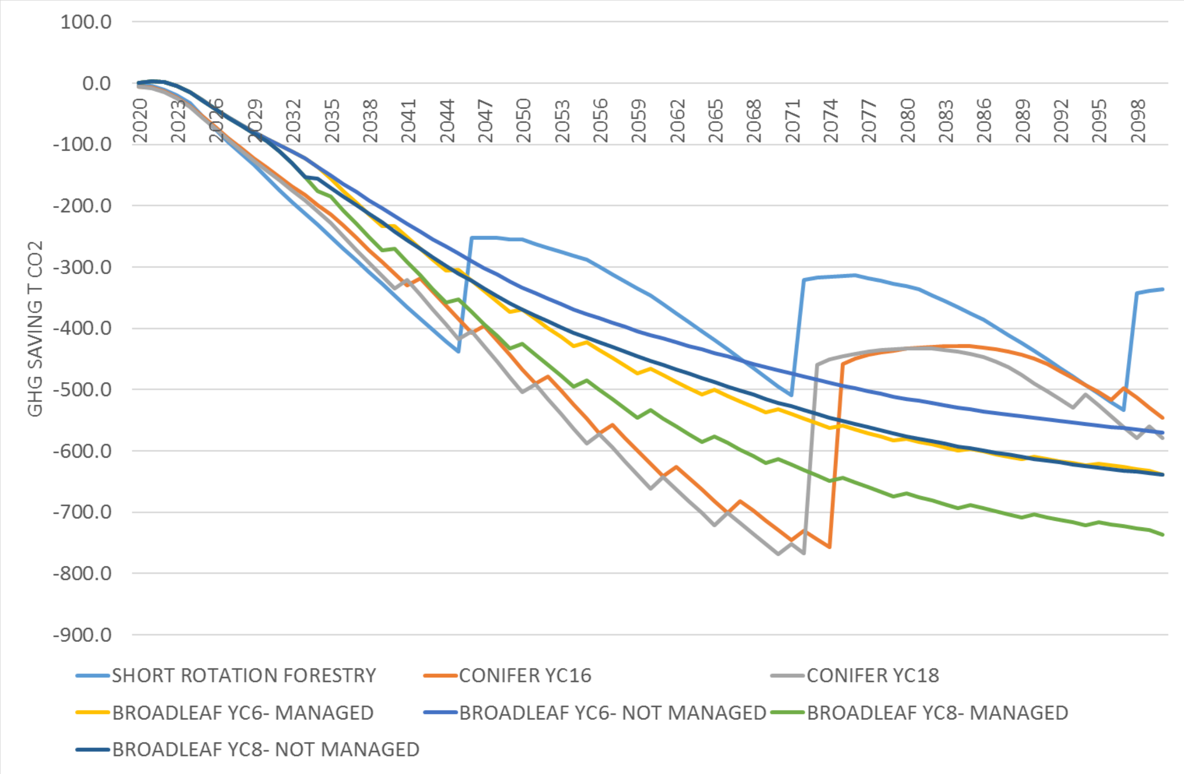


Figure 2: Cumulative saving to 2100 by different forest types for 1 ha of planting



5 Results

5.1 Land required for mitigation

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 released (or 'spared') by agricultural mitigation measures. 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 total area of each land type and mitigation measure is shown in Table a-f. The area of agricultural land types (cropland, rough grazing and permanent/temporary grassland) is the land required to maintain current levels of food production per capita. The "residue" area is the balance remaining after agricultural land 'sparing' and mitigation/settlement growth requirements have been taken into account. If the residue balance is negative, the residue area may be used for purposes such as additional mitigation, 'rewilding' or additional agricultural production. If the residue balance is positive (as in the BAU scenario) then additional agricultural land will be needed to maintain current levels of food production per capita.

Table 4: Annual UK area (kha) of land use and activity by scenario

a) BAU

BAU		**2020**	**2030**	**2035**	**2040**	**2050**
Cropland	Required area	4797	4968	5036	5100	5219
	Residue area	83	254	322	387	505
Permanent grassland	Required area	6264	6482	6571	6655	6809
	Residue area	68	410	559	701	968
Temporary grassland	Required area	1204	1245	1262	1278	1307
	Residue area	12	68	91	113	155
Rough grazing	Required area	5205	5294	5330	5364	5427
	Residue area	45	383	469	551	707
Forest	Total area	3545	3586	3631	3676	3766
	New planting	9	99	144	189	279
Settlement	Total area	1807	1960	2031	2098	2226
Peatland restoration	Total area	20	215	215	215	215
	Upland grassland	15	160	160	160	160
	Lowland grassland	0	0	0	0	0
	Extraction areas	0	0	0	0	1
	Forested peat	5	54	54	54	54
Remains as cropland	Dynamic water table management	0	0	0	0	0
Remains as cropland	Raised water level continuously	0	0	0	0	0
	Lowland cropland converted to paludiculture	0	0	0	0	0
	Full restoration of lowland cropland	0	0	0	0	0
Bioenergy crops	Total area	0	0	0	0	0
	Miscanthus	0	0	0	0	0
	SRC	0	0	0	0	0
	SRF	0	0	0	0	0
Hedgerows	Total area	0	0	0	0	0
Agroforestry	Total area	0	0	0	0	0
	Silvoarable	0	0	0	0	0
	Silvopastoral	0	0	0	0	0

b) Headwinds

Headwinds		**2020**	**2030**	**2035**	**2040**	**2050**
Cropland	Required area	4797	4366	4197	4037	3707
	Residue area	83	-280	-366	-444	-608
Permanent grassland	Required area	6264	5770	5592	5406	4935
	Residue area	74	-103	-97	-104	-217
Temporary grassland	Required area	1204	1110	1077	1042	953
	Residue area	11	-39	-32	-28	-39
Rough grazing	Required area	5205	4616	4318	4024	3421
	Residue area	33	30	67	107	168
Forest	Total area	3558	3844	4003	4163	4481
	New planting	18	331	504	676	1021
Settlement	Total area	1807	1960	2031	2098	2226
Peatland restoration	Total area	13	545	830	1073	1558
	Upland grassland	0	373	578	783	1193
	Lowland grassland	0	18	27	36	54
	Extraction areas	8	93	136	136	136
	Forested peat	3	29	42	55	82
Remains as cropland	Dynamic water table management	0	6	10	13	19
Remains as cropland	Raised water level continuously	0	6	10	13	19
	Lowland cropland converted to paludiculture	0	6	10	13	19
	Full restoration of lowland cropland	0	6	10	13	19
Bioenergy crops	Total area	0	105	256	406	708
	Miscanthus	0	35	85	135	235
	SRC	0	32	79	125	218
	SRF	0	38	92	146	255
Hedgerows	Total area	0	14	21	28	42
Agroforestry	Total area	0	28	46	64	100
	Silvoarable	0	6	9	13	20
	Silvopastoral	0	22	37	51	79

c) Widespread Engagement

Widespread Engagement		2020	2030	2035	2040	2050
Cropland	Required area	4797	4277	4064	3858	3443
	Residue area	83	-368	-512	-649	-927
Permanent grassland	Required area	6264	4741	4229	3707	2398
	Residue area	74	-1069	-1303	-1528	-2245
Temporary grassland	Required area	1204	916	819	721	474
	Residue area	12	-249	-332	-418	-640
Rough grazing	Required area	5205	4343	4009	3674	2903
	Residue area	34	-111	29	190	163
Forest	Total area	3559	3931	4289	4696	5510
	New planting	19	418	790	1210	2050
Settlement	Total area	1807	1960	2031	2098	2226
Peatland restoration	Total area	126	758	1073	1346	1672
	Upland	450	697	945	1193	450
	Lowland grassland	0	36	54	71	107
	Extraction areas	8	93	136	136	136
	Forested peat	3	29	42	55	82
Remains as cropland	Dynamic water table management	1	13	19	25	37
Remains as cropland	Raised water level continuously	1	10	14	19	28
	Lowland paludiculture	0	10	14	19	29
	Full restoration of lowland cropland	0	16	24	32	48
Bioenergy crops	Total area	0	35	85	135	235
	Miscanthus	0	35	85	135	235
	SRC	0	0	0	0	0
	SRF	0	0	0	0	0
Hedgerows	Total area	0	19	28	37	56
Agroforestry	Total area	0	79	130	181	283
	Silvoarable	0	13	21	29	45
	Silvopastoral	0	67	110	153	238

d) Widespread Innovation

Widespread Innovation		2020	2030	2035	2040	2050
Cropland	Required area	4797	3996	3666	3361	2773
	Residue area	83	-594	-763	-907	-1172
Permanent grassland	Required area	6264	4581	3949	3309	1803
	Residue area	74	-1202	-1544	-1898	-2833
Temporary grassland	Required area	1204	886	766	645	361
	Residue area	12	-246	-295	-347	-493
Rough grazing	Required area	5205	4202	3768	3337	2401
	Residue area	33	-252	-227	-201	-472
Forest	Total area	3558	3913	4187	4462	5010
	New planting	18	400	688	975	1550
Settlement	Total area	1807	1960	2031	2098	2226
Peatland restoration	Total area	14	658	1003	1305	1661
	Upland	0	451	699	948	1197
	Lowland grassland	0	36	54	71	107
	Extraction areas	8	93	136	136	136
	Forested peat	3	29	42	55	82
Remains as cropland	Dynamic water table management	0	0	0	0	0
Remains as cropland	Raised water level continuously	3	33	48	63	93
	Lowland paludiculture	0	16	24	32	48
	Full restoration of lowland cropland	0	0	0	0	0
Bioenergy crops	Total area	0	202	505	809	1415
	Miscanthus	0	70	170	270	470
	SRC	0	56	151	246	436
	SRF	0	76	184	293	509
Hedgerows	Total area	0	14	21	28	42
Agroforestry	Total area	0	56	92	128	200
	Silvoarable	0	11	18	26	41
	Silvopastoral	0	45	73	102	159

e) Balanced Net Zero Pathway

Balanced Net Zero Pathway		2020	2030	2035	2040	2050
Cropland	Required area	4797	4312	4158	4020	3770
	Residue area	83	-316	-378	-424	-490
Permanent grassland	Required area	6264	4738	4544	4342	3782
	Residue area	74	-1101	-1093	-1096	-1262
Temporary grassland	Required area	1204	915	879	841	735
	Residue area	12	-231	-226	-224	-249
Rough grazing	Required area	5205	4201	3890	3585	2933
	Residue area	33	-297	-224	-147	-284
Forest	Total area	3558	3844	4026	4301	4849
	New planting	18	331	527	814	1389
Settlement	Total area	1807	1960	2031	2098	2226
Peatland restoration	Total area	13	656	1001	1303	1659
	Upland	0	450	697	945	1193
	Lowland grassland	0	36	54	71	107
	Extraction areas	8	93	136	136	136
	Forested peat	3	29	42	55	82
Remains as cropland	Dynamic water table management	1	13	19	25	37
Remains as cropland	Raised water level continuously	1	10	14	19	28
	Lowland paludiculture	0	10	14	19	29
	Full restoration of lowland cropland	0	16	24	32	48
Bioenergy crops	Total area	0	105	256	406	708
	Miscanthus	0	35	85	135	235
	SRC	0	32	79	125	218
	SRF	0	38	92	146	255
Hedgerows	Total area	0	19	28	37	56
Agroforestry	Total area	0	56	92	128	200
	Silvoarable	0	11	18	26	41
	Silvopastoral	0	45	73	102	159

f)Tailwinds scenario

Tailwinds		**2020**	**2030**	**2035**	**2040**	**2050**
Cropland	Required area	4797	3996	3660	3349	2753
	Residue area	83	-585	-754	-899	-1163
Permanent grassland	Required area	6264	4581	3941	3296	1753
	Residue area	74	-1186	-1526	-1875	-2828
Temporary grassland	Required area	1204	886	765	643	351
	Residue area	12	-244	-294	-345	-496
Rough grazing	Required area	5205	4202	3759	3320	2359
	Residue area	33	-243	-221	-197	-482
Forest	Total area	3558	3918	4266	4660	5449
	New planting	19	405	766	1174	1989
Settlement	Total area	1807	1960	2031	2098	2226
Peatland restoration	Total area	13	656	1001	1303	1659
	Upland	0	450	697	945	1193
	Lowland grassland	0	36	54	71	107
	Extraction areas	8	93	136	136	136
	Forested peat	3	29	42	55	82
Remains as cropland	Dynamic water table management	1	13	19	25	37
Remains as cropland	Raised water level continuously	1	10	14	19	28
	Lowland paludiculture	0	10	14	19	29
	Full restoration of lowland cropland	0	16	24	32	48
Bioenergy crops	Total area	0	202	505	809	1415
	Miscanthus	0	70	170	270	470
	SRC	0	56	151	246	436
	SRF	0	76	184	293	509
Hedgerows	Total area	0	19	28	37	56
Agroforestry	Total area	0	79	130	181	283
	Silvoarable	0	13	21	29	45
	Silvopastoral	0	67	110	153	238

5.2 Land-based scenario greenhouse gas emissions

The pathways of the different land-based mitigation scenarios are shown in Table 4 and Figure 3. Under BAU the emissions stay fairly constant at 11-13 MtCO_2e from 2018 to 2050, but they reduce over time to below net zero GHG emissions under all other scenarios. This is driven by the near halving of emissions from degraded peatlands, and three times as much carbon sequestration by forests by 2050 compared with that in the BAU scenario. The carbon sequestration by forests under all non-BAU scenarios is between two and three times greater by 2050 than it would be if current levels of new forest planting were maintained.

Net emissions reach zero in 2034 for Widespread Innovation and Tailwinds, 2036 for Balanced Net Zero Pathway, 2037 for Widespread Engagement, and 2040 for Headwinds.

The contribution of different activities to the land-based mitigation totals are illustrated inFigure 4 a-f, showing the reducing emissions from degraded peatland as restoration progresses, and the increasing GHG removals by other mitigation measures, especially afforestation and bioenergy.

The contribution of the different peatland restoration options to the overall peatland emissions are shown in Figure 5 a-f. In the BAU scenario, emissions from lowland agriculture on peat (cropland and grassland), forested peat and upland grassland make up the majority of the GHG emissions. In the mitigation scenarios, the emissions from cropland, lowland and upland grassland and extraction sites all decrease. The emissions from forested peat reduce by a comparatively small amount as only a small area with <YC8 is restored (18% of the total forested peat). Also note that rewetted peatland will continue to produce GHG emissions.

Table 4: Combined GHG emissions (Mt CO_2e) from land-based mitigation activities.

a) BAU

Category	2018	2030	2035	2040	2050
Forestry	-18	-13	-12	-11	-11
Agricultural LUC	-1	-3	-4	-4	-5
Bioenergy	0	0	0	0	0
Hedges and Agroforestry	0	0	0	0	0
Peatland mitigation	24	24	24	24	24
Urban Expansion	7	6	6	6	6
Total	13	14	13	13	11

b) Headwinds

Category	2018	2030	2035	2040	2050
Forestry	-18	-15	-17	-18	-23
Agricultural LUC	-1	-3	-4	-4	-5
Bioenergy	0	-1	-2	-4	-6
Hedges and Agroforestry	0	0	-1	-1	-1
Peatland mitigation	24	22	20	19	17
Urban Expansion	7	6	6	6	6
Total	13	9	4	-1	-12

c) Widespread Engagement

Category	2018	2030	2035	2040	2050
Forestry	-18	-16	-18	-20	-31
Agricultural LUC	-1	-3	-4	-4	-5
Bioenergy	0	0	0	-1	-1
Hedges and Agroforestry	0	-1	-1	-2	-4
Peatland mitigation	24	20	18	17	14
Urban Expansion	7	6	6	6	6
Total	13	7	2	-4	-19

d) Widespread Innovation

Category	2018	2030	2035	2040	2050
Forestry	-18	-17	-19	-22	-32
Agricultural LUC	-1	-3	-4	-4	-5
Bioenergy	0	-2	-5	-9	-16
Hedges and Agroforestry	0	-1	-1	-2	-3
Peatland mitigation	24	20	19	17	15
Urban Expansion	7	6	6	6	6
Total	13	5	-4	-12	-33

e) Balanced Net Zero Pathway

Category	2018	2030	2035	2040	2050
Forestry	-18	-16	-17	-18	-26
Agricultural LUC	-1	-3	-4	-4	-5
Bioenergy	0	-1	-2	-4	-6
Hedges and Agroforestry	0	-1	-1	-2	-3
Peatland mitigation	24	20	18	17	14
Urban Expansion	7	6	6	6	6
Total	13	6	1	-4	-19

f) Tailwinds

Category	2018	2030	2035	2040	2050
Forestry	-18	-16	-19	-23	-36
Agricultural LUC	-1	-3	-4	-4	-5
Bioenergy	0	-2	-5	-9	-16
Hedges and Agroforestry	0	-1	-1	-2	-4
Peatland mitigation	24	20	18	17	14
Urban Expansion	7	6	6	6	6
Total	13	5	-4	-14	-38

Figure 3: Total GHG emissions 2020-2050 for land-based mitigation under all scenarios

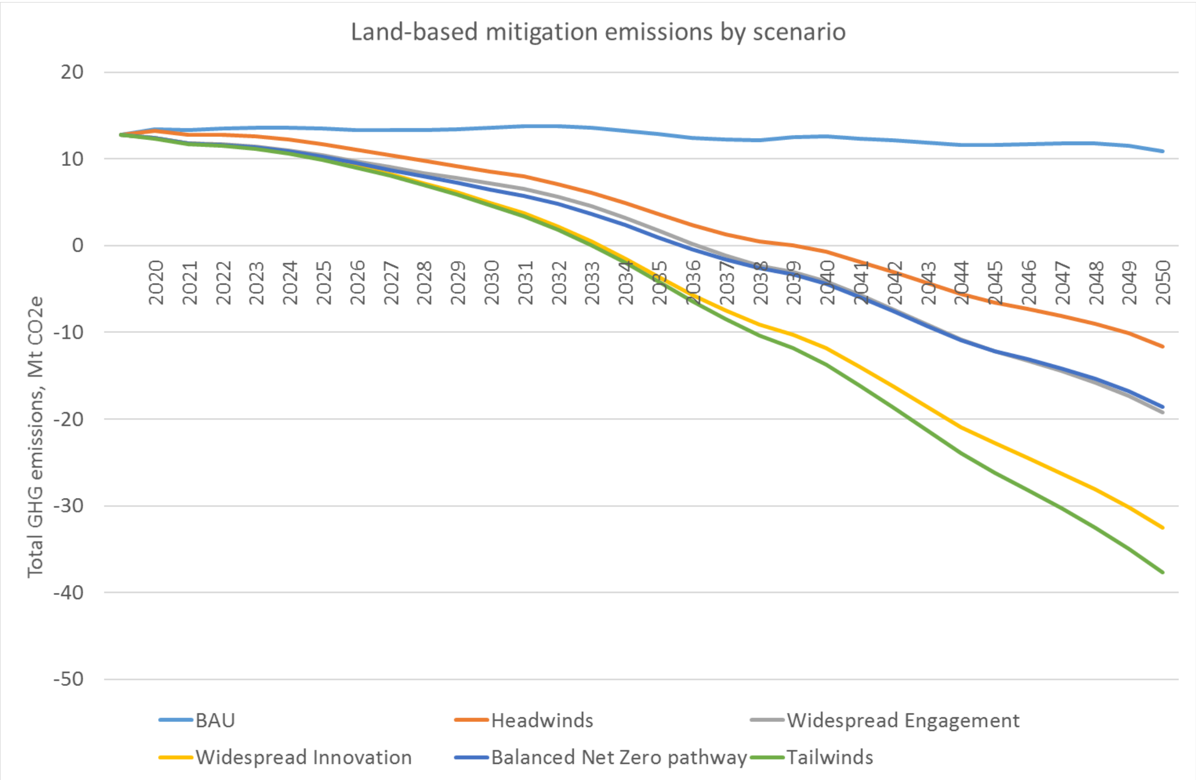
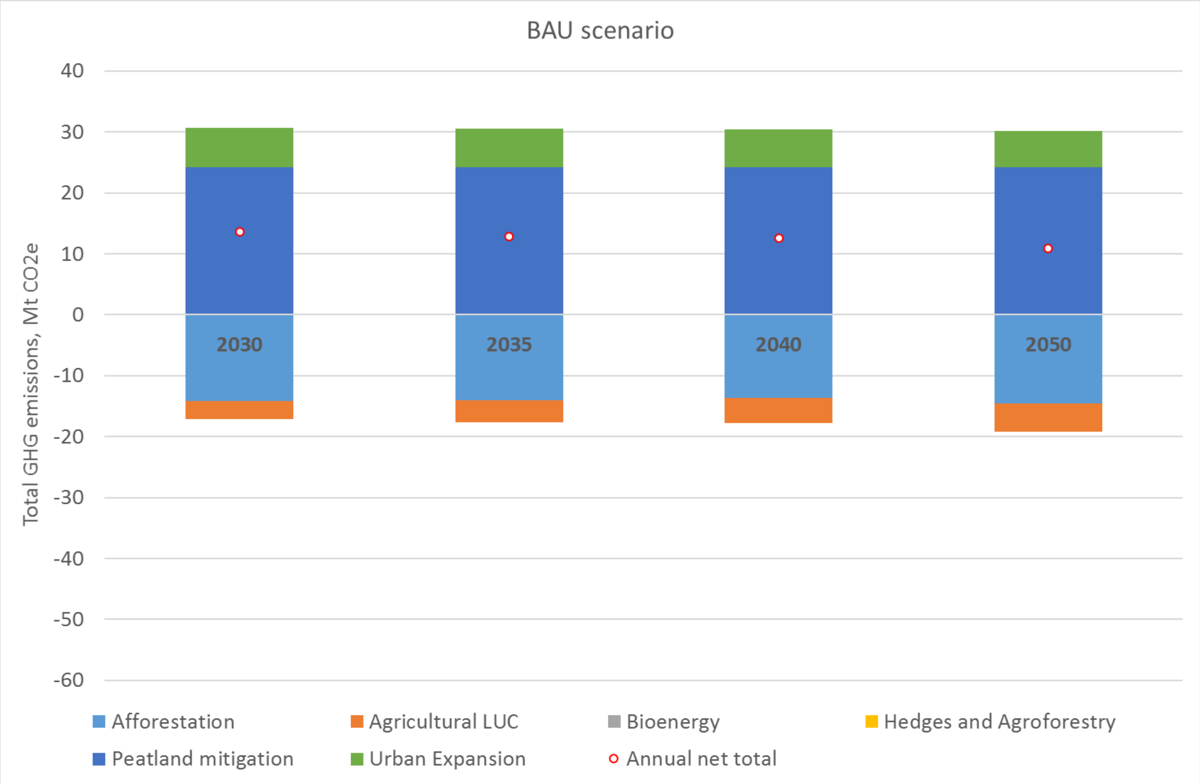
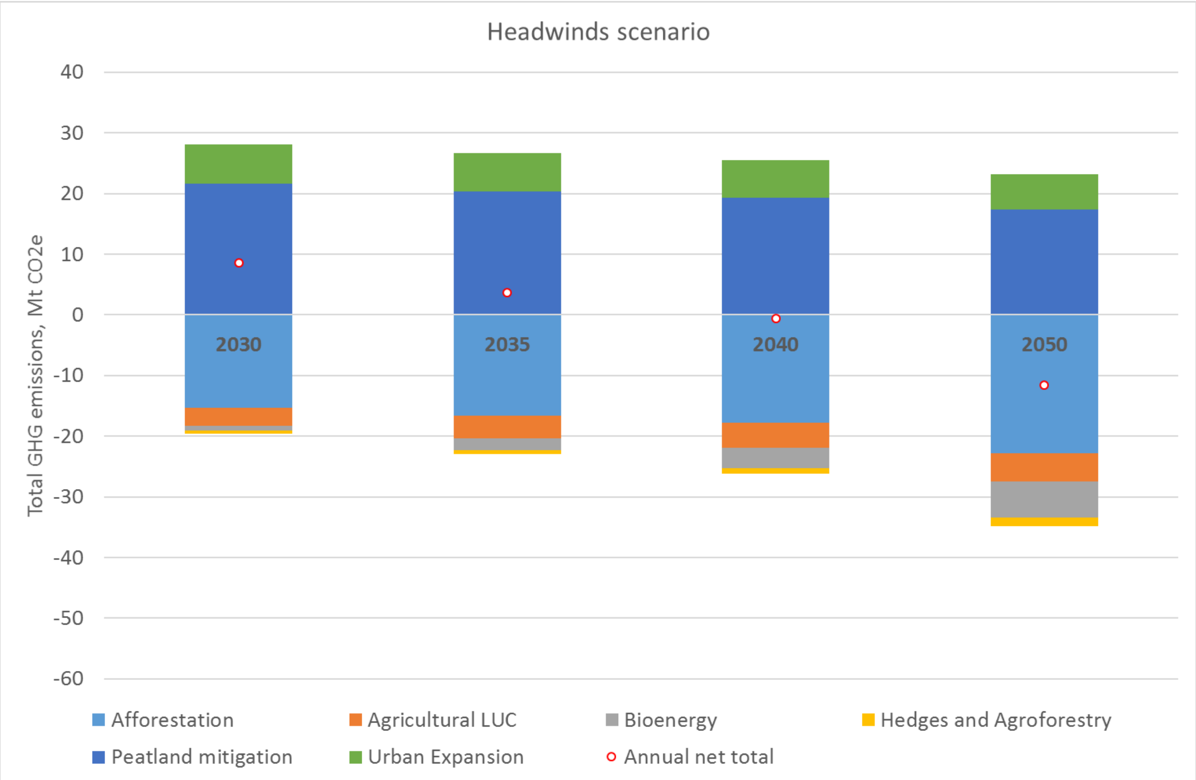


Figure 4: GHG emissions reductions from land-based mitigation activities under each scenario

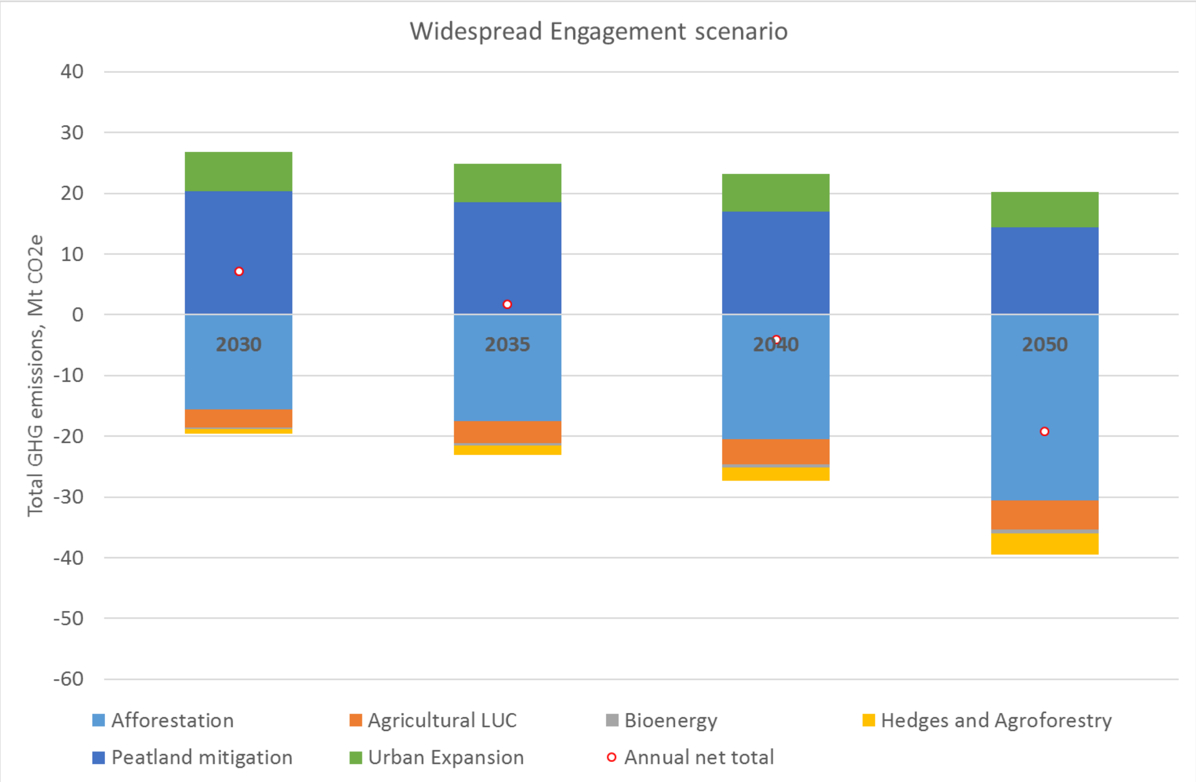
a) BAU



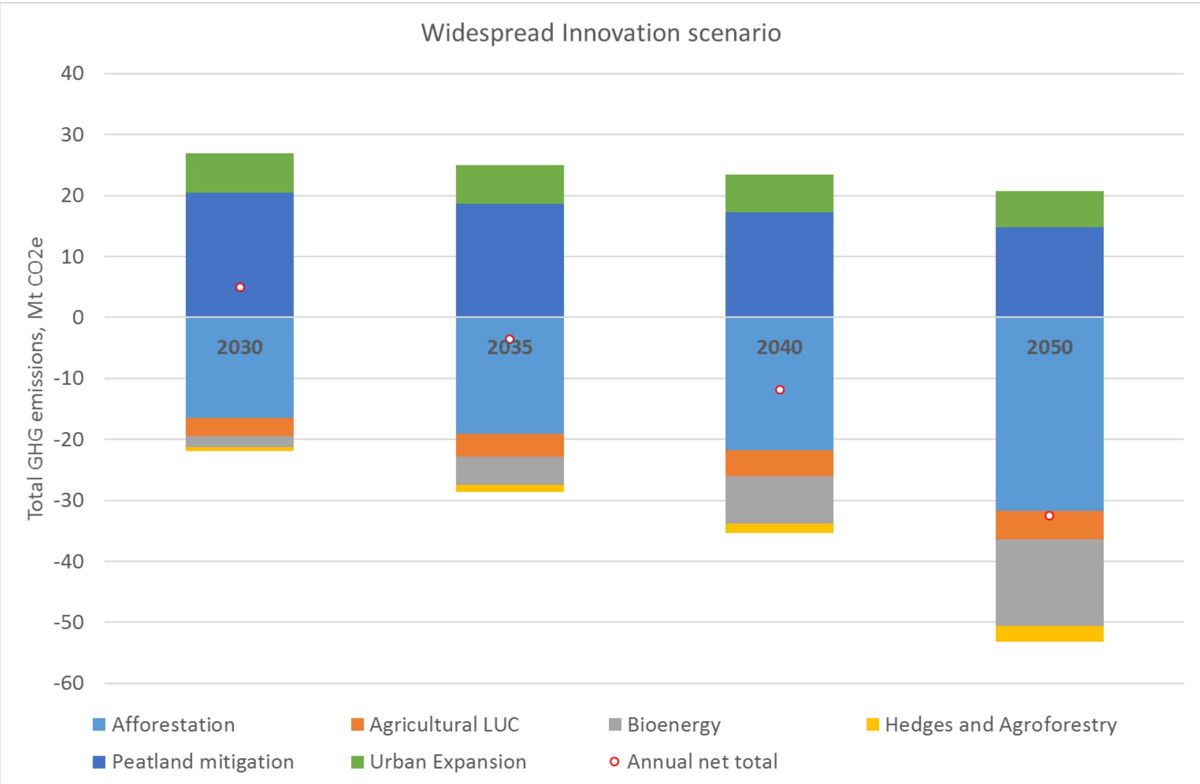
b) Headwinds



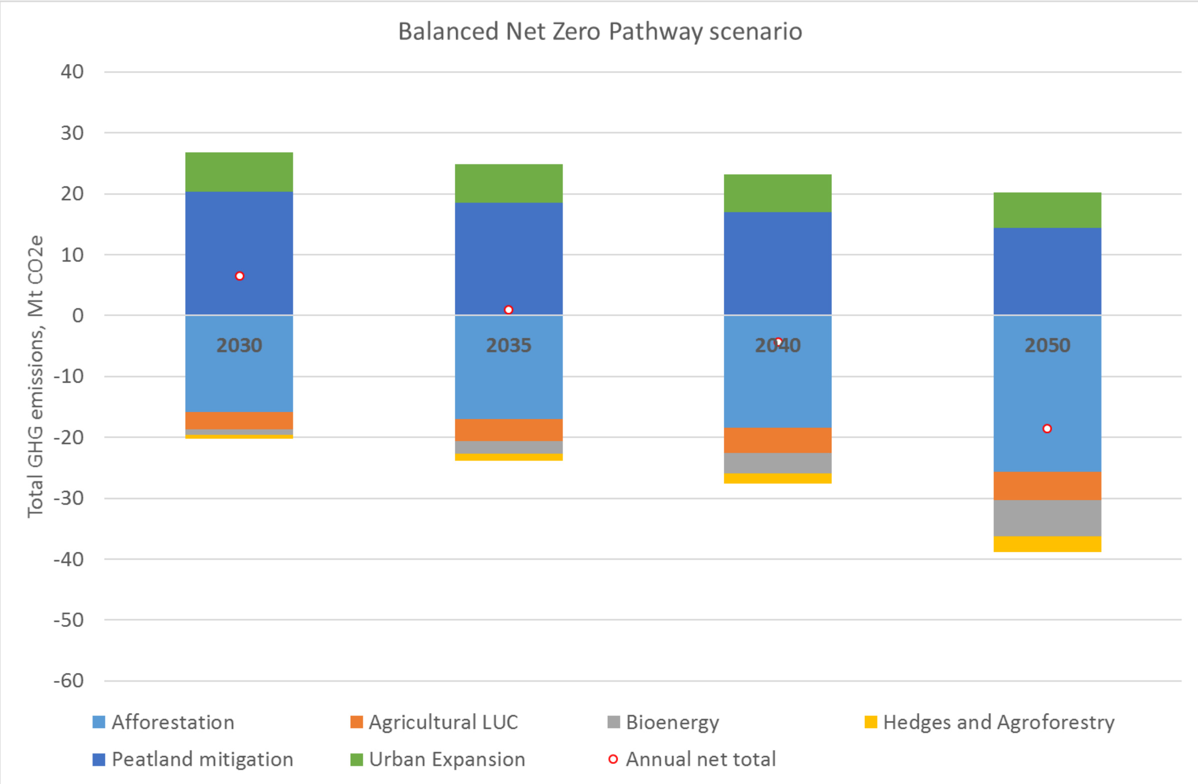
c) Widespread Engagement



d) Widespread Innovation



e) Balanced Net Zero Pathway



f) Tailwinds

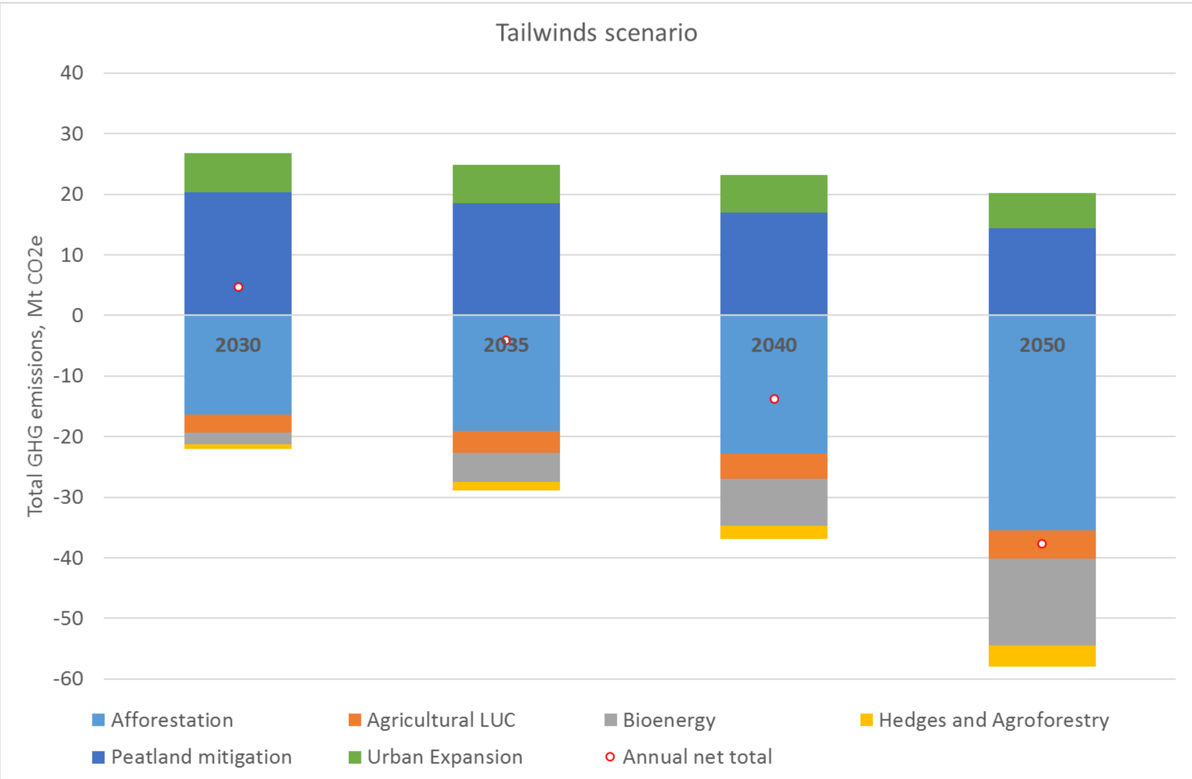
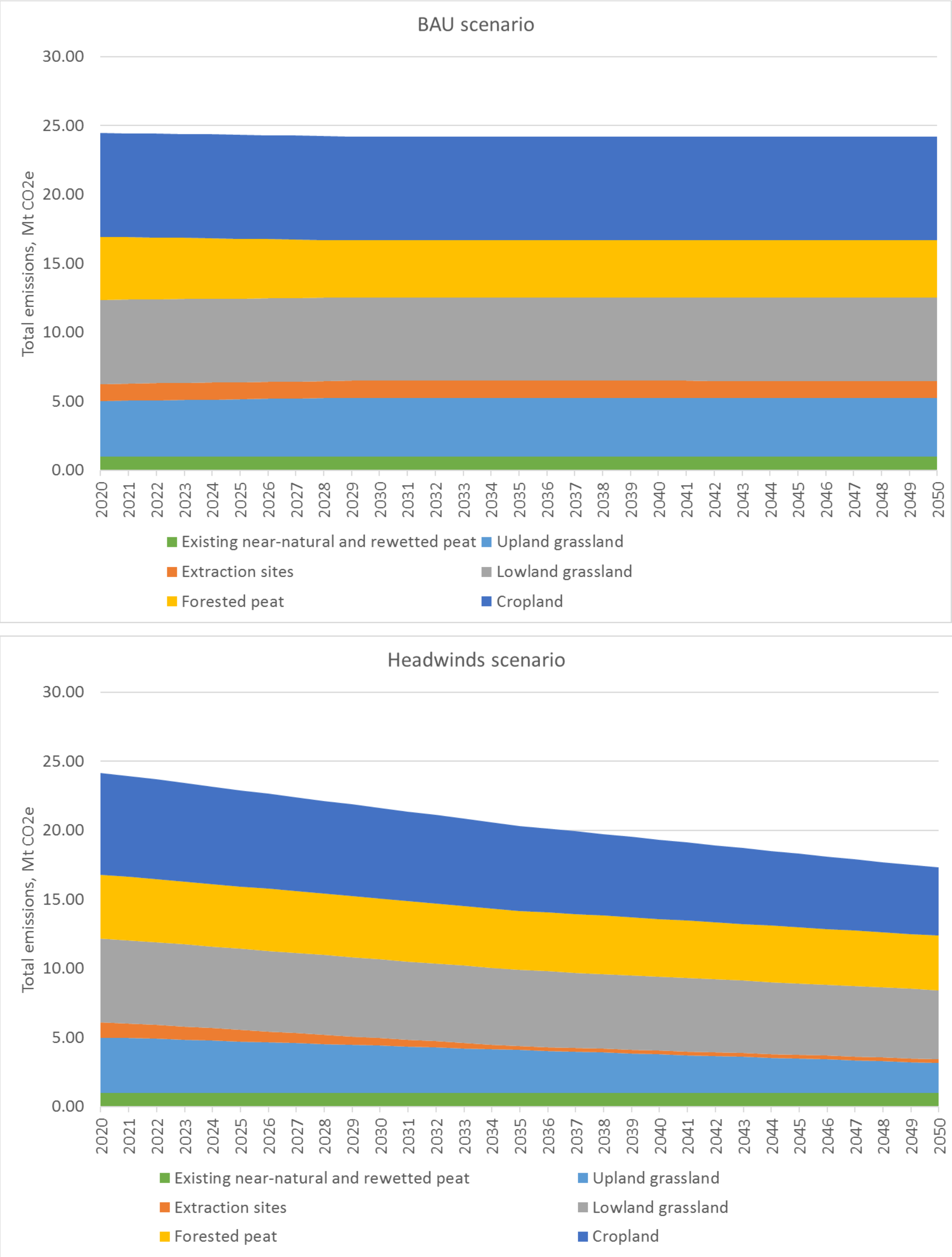
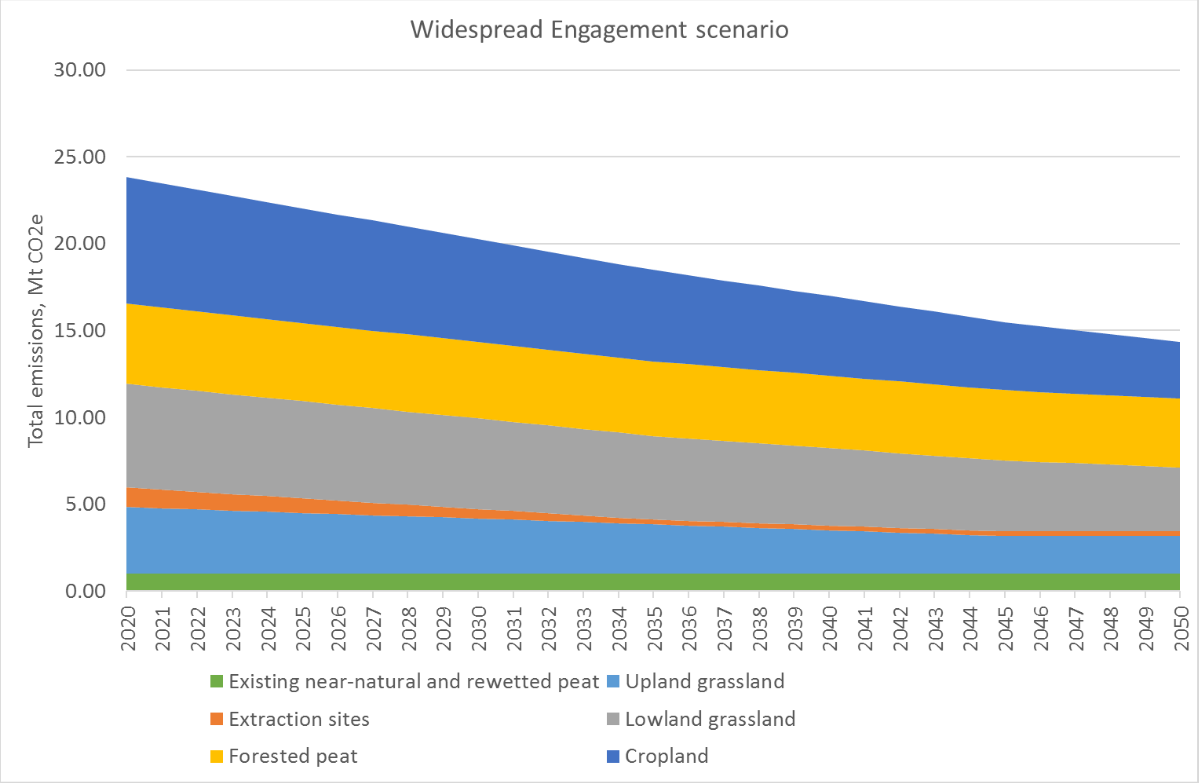
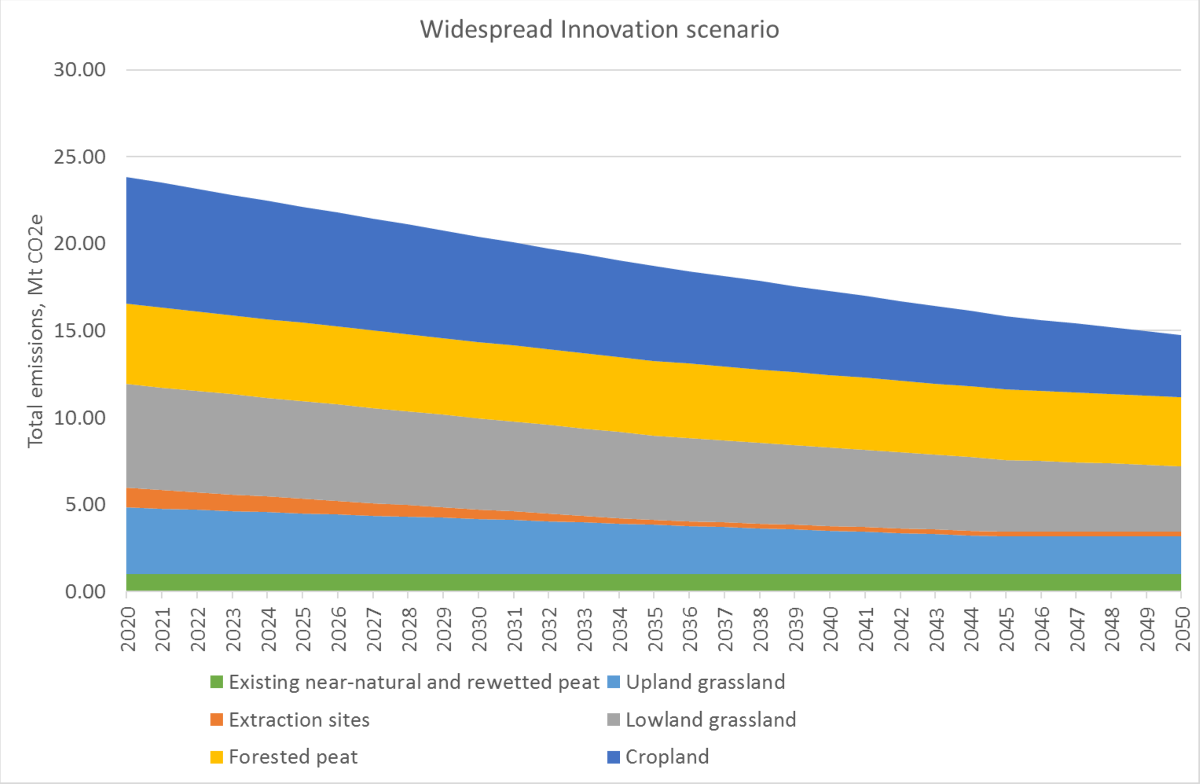


Figure 5: Total GHG emissions reductions from peatland restoration




Widespread Engagement scenario
Total emissions, Mt CO2e
30.00
25.00
20.00
15.00
10.00
5.00
0.00
2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041 2042 2043 2044 2045 2046 2047 2048 2049 2050
Existing near-natural and rewetted peat
Upland grassland
Extraction sites
Lowland grassland
Forested peat
Cropland


Widespread Innovation scenario
Total emissions, Mt CO2e
30.00
25.00
20.00
15.00
10.00
5.00
0.00
2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041 2042 2043 2044 2045 2046 2047 2048 2049 2050
Existing near-natural and rewetted peat
Upland grassland
Extraction sites
Lowland grassland
Forested peat
Cropland

5.3 Fuel and HWP production

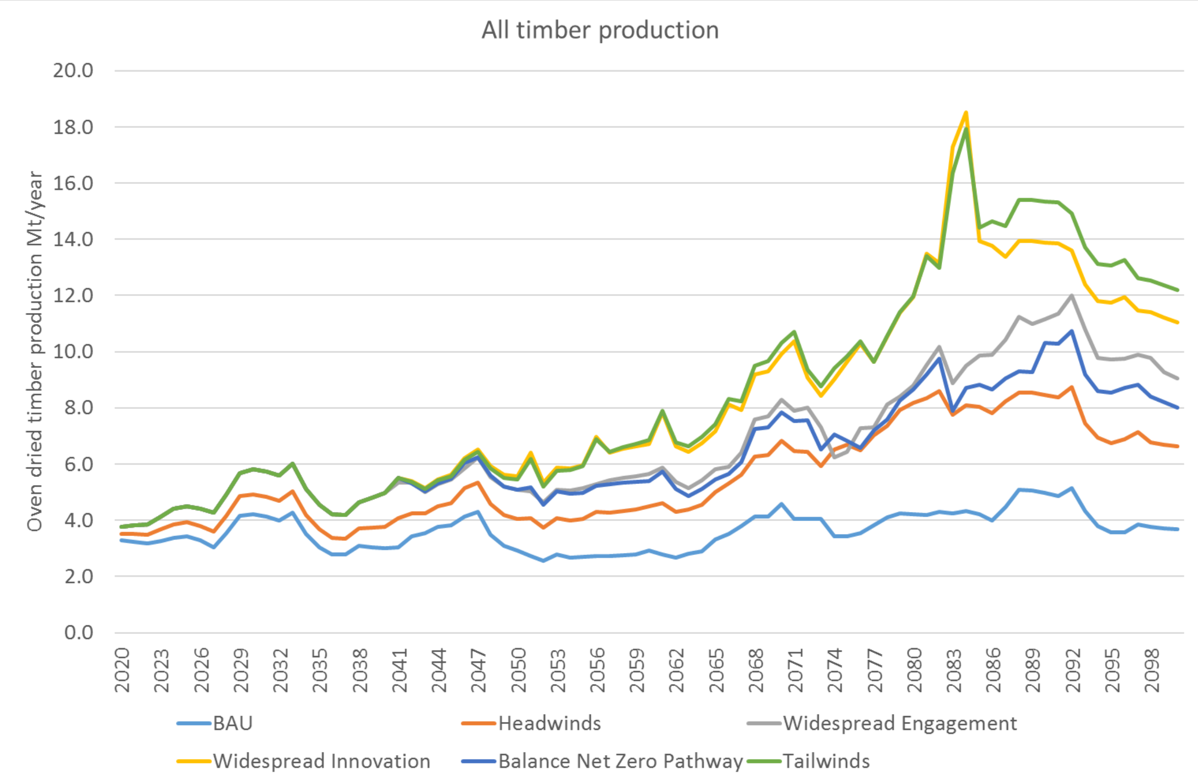
Existing forests and new planting of conifers will produce timber from harvesting and forest management (Table 5). The time-series are shown in Figure 6, illustrating that afforestation and forest management will result in boosted timber production. The peak in timber production in the 2080s and 90s is due to historic planting patterns (visible in the BAU series) and the increase in afforestation from the 2030s onwards results in increased harvesting from the 2080s as the harvesting cycle of Sitka spruce is 53-57 years.

The small difference between time series in 2020 is because different scenarios for the existing forest management start in 2016 (using the results from the 2018 project).

Table 5: Production of timber in Mt oven dried timber

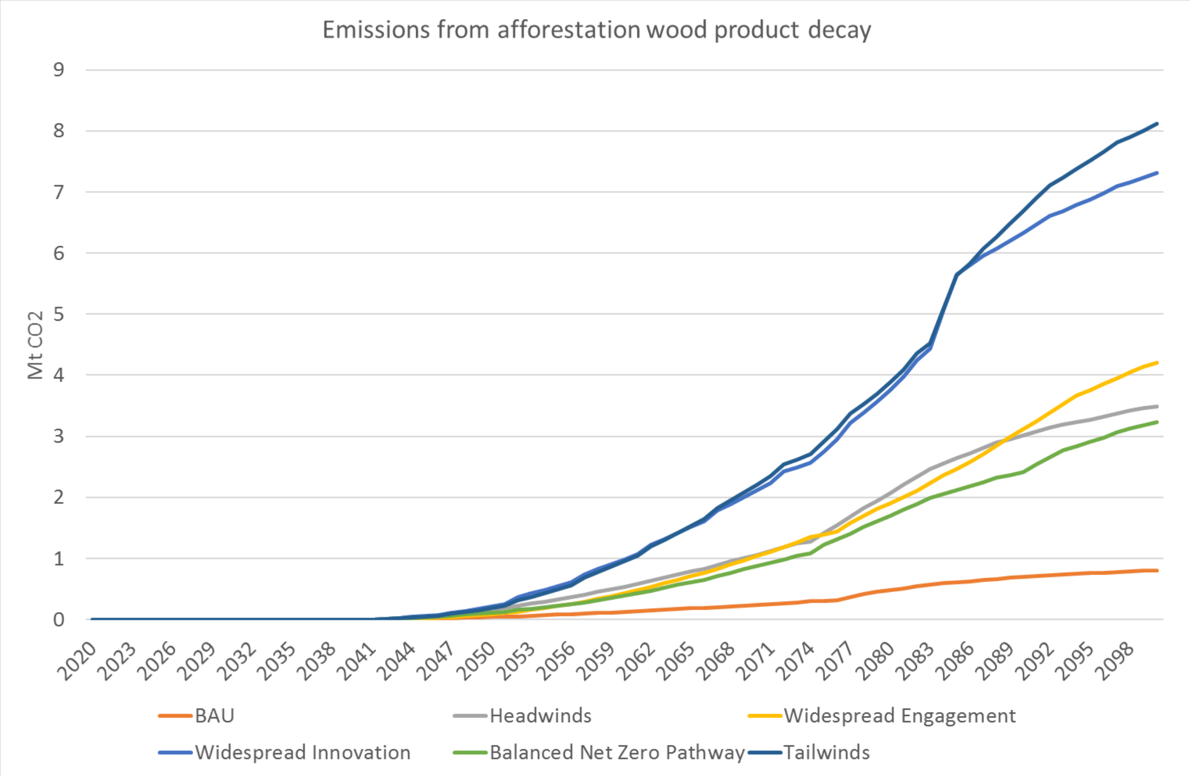
		2020	2035	2050	2080	2100
BAU	**Total**	**3.3**	**3.0**	**2.9**	**4.2**	**3.7**
	Existing forest	3.3	3.0	2.8	3.3	3.0
	New planting	0.0	0.0	0.1	0.9	0.7
Headwinds	**Total**	**3.5**	**3.7**	**4.1**	**8.2**	**6.6**
	Existing forest	3.5	3.7	3.5	4.3	3.7
	New planting	0.0	0.0	0.5	3.9	2.9
Widespread Engagement	**Total**	**3.8**	**4.6**	**5.1**	**8.8**	**9.0**
	Existing forest	3.8	4.6	4.7	5.7	4.9
	New planting	0.0	0.0	0.4	3.1	4.1
Widespread Innovation	**Total**	**3.8**	**4.6**	**5.6**	**11.9**	**11.1**
	Existing forest	3.8	4.6	4.7	5.7	4.9
	New planting	0.0	0.0	0.8	6.2	6.1
Balanced Net Zero Pathway	**Total**	**3.8**	**4.6**	**5.1**	**8.6**	**8.0**
	Existing forest	3.8	4.6	4.7	5.7	4.9
	New planting	0.0	0.0	0.4	3.0	3.1
Tailwinds	**Total**	**3.8**	**4.6**	**5.4**	**12.0**	**12.2**
	Existing forest	3.8	4.6	4.7	5.7	4.9
	New planting	0.0	0.0	0.7	6.3	7.3

Figure 6: Time series of timber production 2020-2100.



Harvested wood products produce CO_2 emissions as they decay, with the rate of decomposition dependent on the product type. We did not project how the proportions of different products might change in the future, but did assess the estimated CO_2 emissions from the decay of products from afforestation if the current proportions of paper, wood panels and sawnwood (solid timber) remained stable in the future(Figure 7). (This does not include emissions from products from existing forests). This was based on the current proportions of these products from domestic harvest in the latest GHG inventory (1990-2018): paper 7.5%, wood panels 42.5% and sawnwood 50%. The IPCC default decay rates (time taken for half the volume to decay) are 2 years for paper, 25 years for panel board and 35 years for sawnwood. Note that these emissions from product decay are offset by the accumulation of carbon in wood products described above.

Figure 7: Emissions from decay of wood products from afforestation, Mt CO_2.



Fuel is produced from the bioenergy crops, agroforestry and broadleaf afforestation and existing management (Table 6 a-f, Figure 8,

Figure 9, Figure 10), although the contribution from agroforestry is only a very small component.

Table 6: Production of fuel, Mt oven-dried fuel.

a) BAU

Categories	2020	2035	2050	2080	2100
Afforestation	**5.4**	**5.2**	**6.0**	**6.8**	**6.1**
Forest Management	*5.4*	*5.2*	*5.9*	*6.4*	*5.9*
New Planting	*0.0*	*0.0*	*0.1*	*0.4*	*0.2*
Bioenergy	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
Miscanthus	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
SRC	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
SRF	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
Hedges and Agroforestry	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
Agroforestry-Silvoarable	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
Agroforestry-Silvopastoral	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
TOTAL	**5.4**	**5.2**	**6.0**	**6.8**	**6.1**

b) Headwinds

Categories	2020	2035	2050	2080	2100
Afforestation	**5.9**	**6.9**	**8.1**	**9.0**	**8.4**
Forest Management	*5.9*	*6.9*	*7.7*	*8.4*	*7.5*
New Planting	*0.0*	*0.0*	*0.4*	*0.7*	*0.9*
Bioenergy	**0.0**	**1.8**	**6.4**	**0.7**	**1.1**
Miscanthus	*0.0*	*1.0*	*3.4*		
SRC	*0.0*	*0.8*	*3.0*		
SRF	*0.0*	*0.0*	*0.0*	*0.7*	*1.1*
Hedges and Agroforestry	**0.0**	**0.0**	**0.0**	**0.3**	**0.1**
Agroforestry-Silvoarable	*0.0*	*0.0*	*0.0*	*0.1*	*0.1*
Agroforestry-Silvopastoral	*0.0*	*0.0*	*0.0*	*0.2*	*0.0*
TOTAL	**5.9**	**8.7**	**14.4**	**10.0**	**9.5**

c) Widespread Engagement

Categories	2020	2035	2050	2080	2100
Afforestation	**6.0**	**7.5**	**8.5**	**10.3**	**8.6**
Forest Management	*6.0*	*7.5*	*7.9*	*8.3*	*7.5*
New Planting	*0.0*	*0.0*	*0.6*	*2.0*	*1.1*
Bioenergy	**0.0**	**1.0**	**3.4**	**0.0**	**0.0**
Miscanthus	*0.0*	*1.0*	*3.4*		
SRC	*0.0*	*0.0*	*0.0*		
SRF	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
Hedges and Agroforestry	**0.0**	**0.0**	**0.0**	**0.7**	**0.2**
Agroforestry-Silvoarable	*0.0*	*0.0*	*0.0*	*0.2*	*0.2*
Agroforestry-Silvopastoral	*0.0*	*0.0*	*0.0*	*0.5*	*0.0*
TOTAL	**6.0**	**8.5**	**11.9**	**11.0**	**8.8**

d) Widespread Innovation

Categories	2020	2035	2050	2080	2100
Afforestation	**6.0**	**7.5**	**8.4**	**10.3**	**8.2**
Forest Management	*6.0*	*7.5*	*7.9*	*8.3*	*7.5*
New Planting	*0.0*	*0.0*	*0.5*	*2.0*	*0.8*
Bioenergy	**0.0**	**2.9**	**11.7**	**1.4**	**2.1**
Miscanthus	*0.0*	*2.4*	*9.0*		
SRC	*0.0*	*1.8*	*8.0*		
SRF	*0.0*	*0.0*	*0.0*	*1.4*	*2.1*
Hedges and Agroforestry	**0.0**	**0.0**	**0.0**	**0.5**	**0.2**
Agroforestry-Silvoarable	*0.0*	*0.0*	*0.0*	*0.2*	*0.2*
Agroforestry-Silvopastoral	*0.0*	*0.0*	*0.0*	*0.3*	*0.0*
TOTAL	**6.0**	**11.7**	**25.4**	**12.2**	**10.5**

e) Balanced Net Zero Pathway

Categories	2020	2035	2050	2080	2100
Afforestation	**6.0**	**7.5**	**8.4**	**9.7**	**8.5**
Forest Management	*6.0*	*7.5*	*7.9*	*8.3*	*7.5*
New Planting	*0.0*	*0.0*	*0.5*	*1.4*	*1.0*
Bioenergy	**0.0**	**1.8**	**6.4**	**0.7**	**1.1**
Miscanthus	*0.0*	*1.0*	*3.4*		
SRC	*0.0*	*0.8*	*3.0*		
SRF	*0.0*	*0.0*	*0.0*	*0.7*	*1.1*
Hedges and Agroforestry	**0.0**	**0.0**	**0.0**	**0.5**	**0.2**
Agroforestry-Silvoarable	*0.0*	*0.0*	*0.0*	*0.2*	*0.2*
Agroforestry-Silvopastoral	*0.0*	*0.0*	*0.0*	*0.3*	*0.0*
TOTAL	**6.0**	**9.4**	**14.8**	**10.9**	**9.8**

f) Tailwinds

Categories	2020	2035	2050	2080	2100
Afforestation	**6.0**	**7.5**	**8.5**	**11.7**	**8.5**
Forest Management	*6.0*	*7.5*	*7.9*	*8.3*	*7.5*
New Planting	*0.0*	*0.0*	*0.6*	*3.4*	*1.0*
Bioenergy	**0.0**	**4.1**	**17.0**	**1.4**	**2.1**
Miscanthus	*0.0*	*2.4*	*9.0*		
SRC	*0.0*	*1.8*	*8.0*		
SRF	*0.0*	*0.0*	*0.0*	*1.4*	*2.1*
Hedges and Agroforestry	**0.0**	**0.0**	**0.0**	**0.7**	**0.2**
Agroforestry-Silvoarable	*0.0*	*0.0*	*0.0*	*0.2*	*0.2*
Agroforestry-Silvopastoral	*0.0*	*0.0*	*0.0*	*0.5*	*0.0*
TOTAL	**6.0**	**11.7**	**25.4**	**13.8**	**10.8**

Figure 8: Fuel production from afforestation and forest management

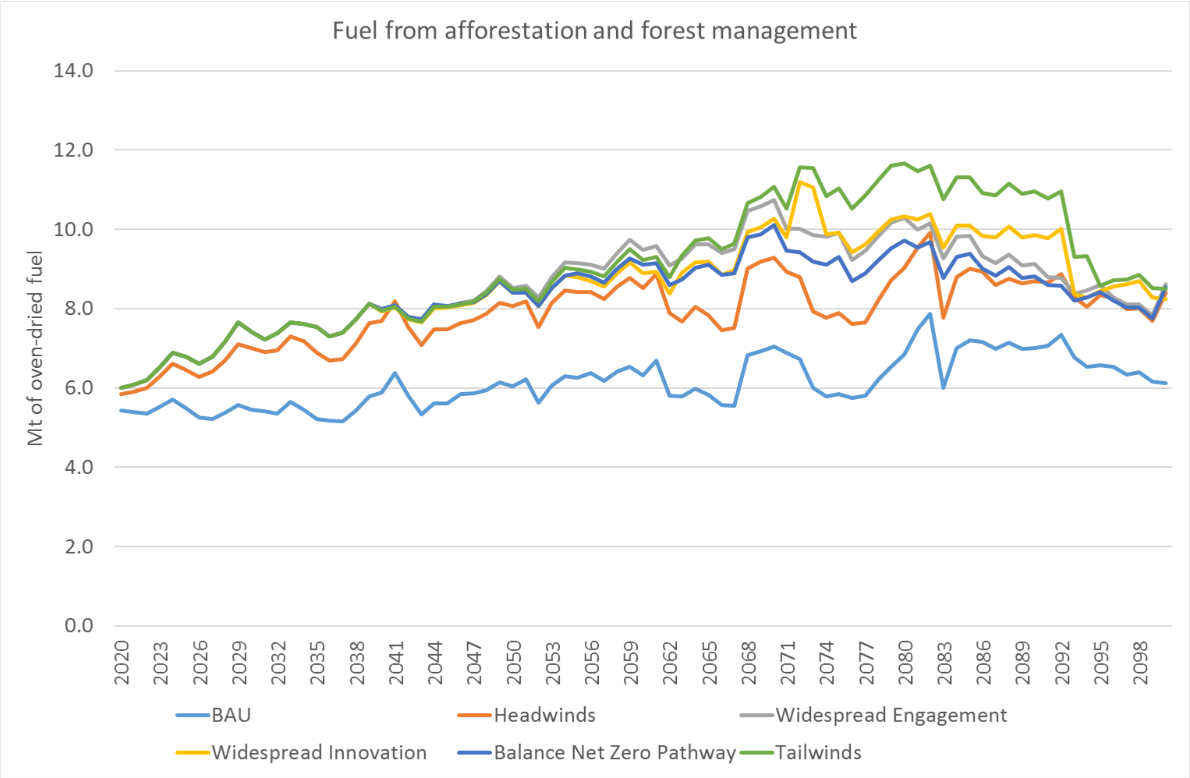


Figure 9: Fuel production from bioenergy crops (Miscanthus and SRC to 2050 only)

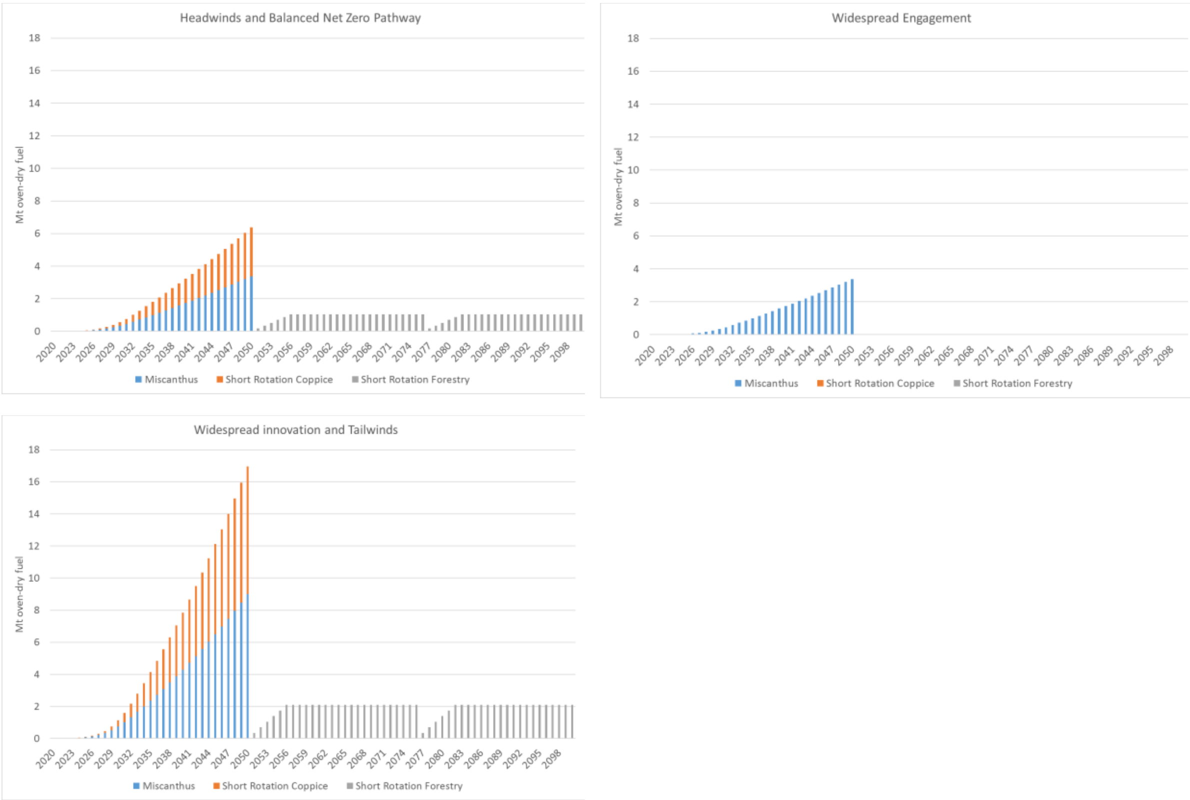
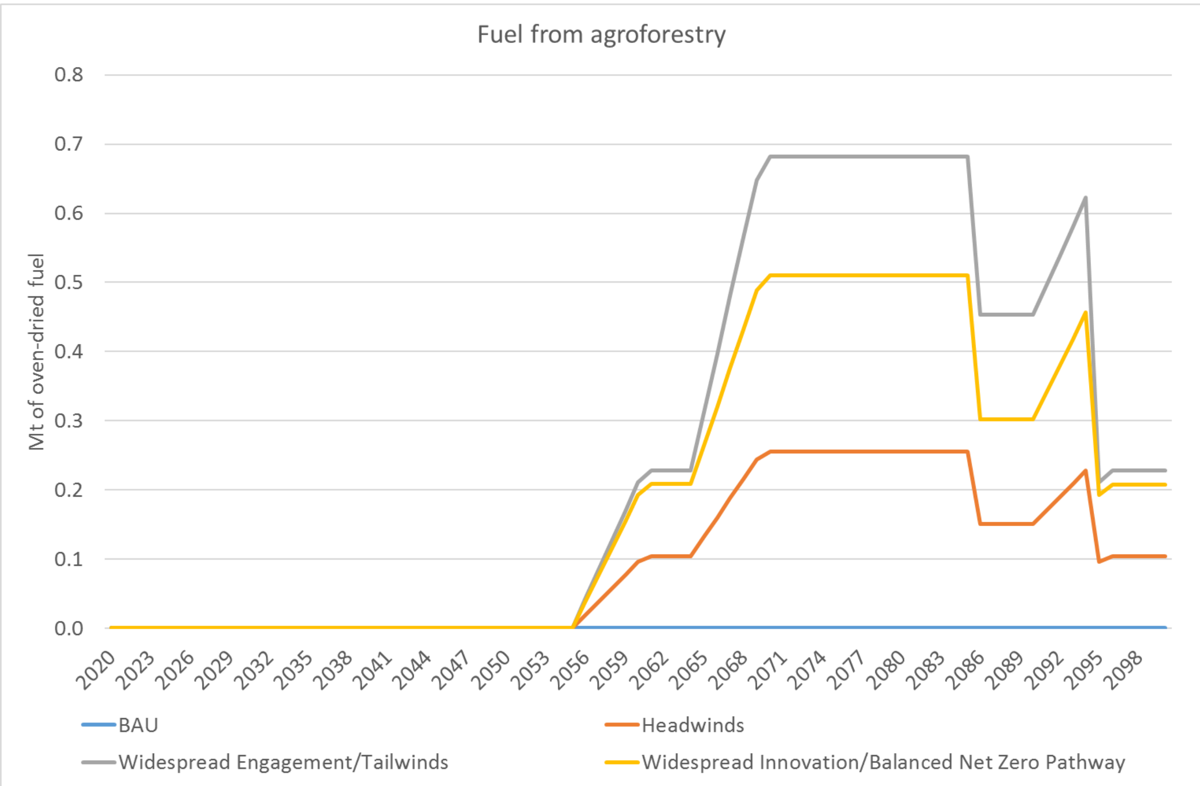


Figure 10: Fuel production from agro-forestry



6 Summary

This project has modelled land use mitigation options to assess their impact on GHG emissions, land availability and 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 mitigation options have been combined into six 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 scenarios are modelled at a high level and should be considered indicative of potential GHG mitigation emissions rather than precise values.

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. Bioenergy crops can contribute substantial emissions reductions but need to be appropriately sited so that soil carbon impacts are minimised. The GHG benefits of agroforestry and bioenergy crops also includes 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.

The Tailwinds and Widespread Innovation scenarios have the greatest combined agricultural and land-use emissions reduction potential and spared the greatest area of land for other uses. The Widespread Innovation scenario had the greatest surplus of spared land by 2050 (i.e. once land requirements for mitigation were taken into account). Under the BAU there was insufficient land to maintain per capita food production at 2019 levels with the forecast growth in population and requirement for additional settlement and infrastructure development on agricultural land. Permanent grassland and rough grazing land were the most in demand for land-based mitigation measures

7 Acknowledgements

Indra Thillainathan and Ewa Kmietowicz of the Committee on Climate Change for development of the scenarios and assumptions.

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9 Appendices

9.1 Appendix 1: Baseline agricultural land use in 2019, kha

These are the baseline areas used for determining the change in land availability and land requirements. They do not include inland water bodies or other non-agricultural land. Forest areas are from data published by Forest Research and take account of small woods (0.1-0.5 ha) and losses due to deforestation. Areas of grassland and cropland come from the annual June agricultural survey for each country. Permanent grassland is grassland over five years old, temporary grassland is under five years old. Rough grazing is the sum of sole right and common rough grazing areas. Cropland is the sum of cropland and fallow/set-aside land. The Settlement area is that estimated in the UK national greenhouse gas inventory (Brown et al. 2018) and includes buildings, infrastructure, mines and quarries. The area of peatland comes from Evans et al. (2017), but all other land use types can occur on organic soils.

Table 7: Baseline land area areas in 2019

Land Use	England	Northern Ireland	Scotland	Wales	UK
Forest (conifer)	342	67	1055	151	1615
Forest (Broadleaved)	1242	48	441	195	1927
Cropland	4219	45	580	95	4938
Permanent grassland	3294	660	1127	1126	6207
Temporary Grassland	696	149	187	161	1193
Rough grazing *	841	144	3728	434	5147
Settlement	1443	65	179	108	1796
Peatland **	153	129	568	34	885

* Includes common land

** Near natural, rewetted peatland and peat extraction sites

9.2 Appendix 2: For England, Scotland, Wales, Northern Ireland

9.2.1 England

Table 8: Annual area (kha) of land use and activity by scenario for England (required areas are the areas of agricultural land to maintain current food production per capita)

a) BAU

Categories	2020	2030	2035	2040	2050
Required land areas					
Cropland	4108	4254	4313	4369	4471
Forest Land	1585	1600	1607	1615	1629
Permanent Grassland	3335	3491	3554	3614	3724
Rough Grassland	851	889	905	919	946
Settlement	1452	1583	1648	1708	1825
Temporary Grassland	704	733	746	757	778
Afforestation	1	16	23	31	45
Hedges and Agroforestry	0	0	0	0	0
Bioenergy	0	0	0	0	0
Peatland restoration	0	0	0	0	1

b) Headwinds

Categories	2020	2030	2035	2040	2050
Required land areas					
Cropland	4108	3746	3606	3473	3201
Forest Land	1589	1681	1732	1783	1884
Permanent Grassland	3335	3027	2900	2766	2429
Rough Grassland	851	665	547	430	189
Settlement	1452	1583	1648	1708	1825
Temporary Grassland	704	642	618	592	528
Afforestation	6	99	151	203	306
Hedges and Agroforestry	0	21	33	46	71
Bioenergy	0	68	165	262	456
Peatland restoration	2	108	164	218	325

c) Widespread Engagement

Categories	2020	2030	2035	2040	2050
Required land areas					
Cropland	4108	3675	3500	3332	2992
Forest Land	1589	1695	1794	1907	2131
Permanent Grassland	3335	2290	1929	1560	632
Rough Grassland	851	539	406	271	-42
Settlement	1452	1583	1648	1708	1825
Temporary Grassland	704	501	432	361	183
Afforestation	5	113	213	327	553
Hedges and Agroforestry	0	45	73	100	156
Bioenergy	0	30	72	115	201
Peatland restoration	3	142	216	287	386

d) Widespread Innovation

Categories	2020	2030	2035	2040	2050
Required land areas					
Cropland	4108	3440	3169	2921	2445
Forest Land	1590	1714	1808	1902	2090
Permanent Grassland	3335	2213	1793	1366	346
Rough Grassland	851	485	310	137	-244
Settlement	1452	1583	1648	1708	1825
Temporary Grassland	704	485	403	320	123
Afforestation	6	132	227	322	512
Hedges and Agroforestry	0	34	54	75	116
Bioenergy	0	140	352	563	985
Peatland restoration	4	143	216	287	386

e) Balanced Net Zero Pathway

Categories	2020	2030	2035	2040	2050
Required land areas					
Cropland	4108	3697	3563	3442	3214
Forest Land	1589	1681	1739	1824	1995
Permanent Grassland	3335	2289	2150	2007	1607
Rough Grassland	851	485	364	245	-12
Settlement	1452	1583	1648	1708	1825
Temporary Grassland	704	501	474	447	370
Afforestation	6	99	158	244	417
Hedges and Agroforestry	0	37	59	80	124
Bioenergy	0	68	165	262	456
Peatland restoration	3	142	216	287	386

f) Tailwinds

Categories	2020	2030	2035	2040	2050
Required land areas					
Cropland	4108	3440	3164	2911	2428
Forest Land	1590	1716	1834	1967	2234
Permanent Grassland	3335	2213	1789	1361	320
Rough Grassland	851	485	310	135	-251
Settlement	1452	1583	1648	1708	1825
Temporary Grassland	704	485	402	319	117
Afforestation	6	134	253	387	656
Hedges and Agroforestry	0	45	73	100	156
Bioenergy	0	140	352	563	985
Peatland restoration	3	142	216	287	386

Table 9: Emissions by scenario and mitigation measure for 2020, 2030, 2035, 2040, 2050 for England in Mt CO_2e

a) BAU

Categories	2020	2030	2035	2040	2050
Forestry	-6	-6	-6	-6	-6
Agricultural LUC	-1	-1	-1	-1	-1
Bioenergy	0	0	0	0	0
Hedges and Agroforestry	0	0	0	0	0
Peatland mitigation	11	11	11	11	11
Urban Expansion	3	3	4	4	4
Grand Total	36	36	36	37	37

b) Headwinds

Categories	2020	2030	2035	2040	2050
Forestry	-6	-6	-7	-8	-9
Agricultural LUC	-1	-1	-1	-1	-1
Bioenergy	0	-1	-1	-2	-4
Hedges and Agroforestry	0	0	0	-1	-1
Peatland mitigation	11	10	9	9	8
Urban Expansion	3	3	4	4	4
Grand Total	36	34	31	29	24

c) Widespread Engagement

Categories	2020	2030	2035	2040	2050
Forestry	-7	-7	-8	-9	-12
Agricultural LUC	-1	-1	-1	-1	-1
Bioenergy	0	0	0	0	-1
Hedges and Agroforestry	0	-1	-1	-1	-2
Peatland mitigation	11	9	8	7	6
Urban Expansion	3	3	4	4	4
Grand Total	35	28	24	20	11

c) Widespread Innovation

Categories	2020	2030	2035	2040	2050
Forestry	-7	-7	-9	-10	-13
Agricultural LUC	-1	-1	-1	-1	-1
Bioenergy	0	-2	-4	-6	-10
Hedges and Agroforestry	0	0	-1	-1	-1
Peatland mitigation	11	9	8	7	6
Urban Expansion	3	3	4	4	4
Grand Total	35	24	18	13	-1

d) Balanced Net Zero Pathway

Categories	2020	2030	2035	2040	2050
Forestry	-7	-7	-8	-9	-11
Agricultural LUC	-1	-1	-1	-1	-1
Bioenergy	0	-1	-1	-2	-4
Hedges and Agroforestry	0	0	-1	-1	-1
Peatland mitigation	11	9	8	7	6
Urban Expansion	3	3	4	4	4
Grand Total	35	28	24	22	15

e) Tailwinds

Categories	2020	2030	2035	2040	2050
Forestry	-7	-7	-9	-10	-15
Agricultural LUC	-1	-1	-1	-1	-1
Bioenergy	0	-2	-4	-6	-10
Hedges and Agroforestry	0	-1	-1	-1	-2
Peatland mitigation	11	9	8	7	6
Urban Expansion	3	3	4	4	4
Grand Total	35	24	18	12	-3

9.2.2 Scotland

Table 10: Annual area (kha) of land use and activity by scenario for Scotland (required areas are the areas of agricultural land to maintain current food production per capita)

a) BAU

Categories	2020	2030	2035	2040	2050
Required land areas					
Cropland	551	570	577	584	597
Forest Land	1498	1519	1555	1590	1661
Permanent Grassland	1129	1139	1143	1147	1154
Rough Grassland	3735	3768	3781	3794	3817
Settlement	180	191	195	199	206
Temporary Grassland	188	190	191	191	193
Afforestation	7	78	113	148	219
Hedges and Agroforestry	0	0	0	0	0
Bioenergy	0	0	0	0	0
Peatland restoration	20	215	215	215	215

b) Headwinds

Categories	2020	2030	2035	2040	2050
Required land areas					
Cropland	551	496	475	455	415
Forest Land	1503	1638	1713	1788	1939
Permanent Grassland	1129	1073	1065	1057	1036
Rough Grassland	3735	3438	3322	3208	2976
Settlement	180	191	195	199	206
Temporary Grassland	188	178	177	175	171
Afforestation	9	166	252	338	511
Hedges and Agroforestry	0	11	18	25	39
Bioenergy	0	24	58	92	160
Peatland restoration	5	349	535	707	1052

c) Widespread Engagement

Categories	2020	2030	2035	2040	2050
Required land areas					
Cropland	551	489	464	440	393
Forest Land	1504	1694	1880	2091	2515
Permanent Grassland	1129	1027	1001	975	909
Rough Grassland	3735	3348	3217	3085	2786
Settlement	180	191	195	199	206
Temporary Grassland	188	170	165	160	148
Afforestation	10	221	418	641	1086
Hedges and Agroforestry	0	31	51	71	110
Bioenergy	0	4	10	16	28
Peatland restoration	5	417	640	849	1079

d) Widespread Innovation

Categories	2020	2030	2035	2040	2050
Required land areas					
Cropland	551	454	415	378	308
Forest Land	1503	1660	1784	1909	2157
Permanent Grassland	1129	987	932	876	758
Rough Grassland	3735	3291	3123	2956	2598
Settlement	180	191	195	199	206
Temporary Grassland	188	163	153	144	123
Afforestation	9	188	323	458	729
Hedges and Agroforestry	0	21	35	48	75
Bioenergy	0	30	74	119	207
Peatland restoration	5	418	642	852	1082

e) Balanced Net Zero Pathway

Categories	2020	2030	2035	2040	2050
Required land areas					
Cropland	551	494	476	460	432
Forest Land	1503	1638	1725	1857	2123
Permanent Grassland	1124	1060	1020	969	868
Rough Grassland	3735	3291	3166	3044	2785
Settlement	180	191	195	199	206
Temporary Grassland	188	170	168	166	160
Afforestation	9	166	263	407	695
Hedges and Agroforestry	0	21	35	49	76
Bioenergy	0	24	58	92	160
Peatland restoration	5	417	640	849	1079

f) Tailwinds

Categories	2020	2030	2035	2040	2050
Required land areas					
Cropland	551	454	414	376	306
Forest Land	1503	1663	1821	2002	2363
Permanent Grassland	1129	987	929	872	749
Rough Grassland	3735	3291	3116	2943	2567
Settlement	180	191	195	199	206
Temporary Grassland	188	163	153	143	121
Afforestation	9	190	360	552	935
Hedges and Agroforestry	0	31	51	71	110
Bioenergy	0	30	74	119	207
Peatland restoration	5	417	640	849	1079

Table 11: Emissions by scenario and mitigation measure for 2020, 2030, 2035, 2040, 2050 for Scotland in Mt CO_2e

a) BAU

Categories	2020	2030	2035	2040	2050
Forestry	-9	-6	-5	-4	-4
Agricultural LUC	1	-1	-2	-3	-3
Bioenergy	0	0	0	0	0
Hedges and Agroforestry	0	0	0	0	0
Peatland mitigation	11	10	10	10	10
Urban Expansion	2	2	2	2	1
Grand Total	12	12	12	13	12

b) Headwinds

Categories	2020	2030	2035	2040	2050
Forestry	-9	-7	-7	-8	-10
Agricultural LUC	1	-1	-2	-3	-3
Bioenergy	0	0	0	-1	-2
Hedges and Agroforestry	0	0	0	0	0
Peatland mitigation	11	10	9	9	8
Urban Expansion	2	2	2	2	1
Grand Total	12	10	8	6	1

c) Widespread Engagement

Categories	2020	2030	2035	2040	2050
Forestry	-9	-7	-7	-8	-13
Agricultural LUC	1	-1	-2	-3	-3
Bioenergy	0	0	0	0	0
Hedges and Agroforestry	0	0	0	-1	-1
Peatland mitigation	10	9	9	8	7
Urban Expansion	2	2	2	2	1
Grand Total	12	9	7	3	-5

d) Widespread Innovation

Categories	2020	2030	2035	2040	2050
Forestry	-9	-7	-8	-9	-13
Agricultural LUC	1	-1	-2	-3	-3
Bioenergy	0	0	-1	-1	-2
Hedges and Agroforestry	0	0	0	0	-1
Peatland mitigation	10	9	9	8	7
Urban Expansion	2	2	2	2	1
Grand Total	12	8	6	2	-6

e) Balanced Net Zero Pathway

Categories	2020	2030	2035	2040	2050
Forestry	-9	-7	-7	-7	-11
Agricultural LUC	1	-1	-2	-3	-3
Bioenergy	0	0	0	-1	-2
Hedges and Agroforestry	0	0	0	0	-1
Peatland mitigation	10	9	9	8	7
Urban Expansion	2	2	2	2	1
Grand Total	12	9	7	5	-2

f) Tailwinds

Categories	2020	2030	2035	2040	2050
Forestry	-9	-7	-7	-9	-14
Agricultural LUC	1	-1	-2	-3	-3
Bioenergy	0	0	-1	-1	-2
Hedges and Agroforestry	0	0	0	-1	-1
Peatland mitigation	10	9	9	8	7
Urban Expansion	2	2	2	2	1
Grand Total	12	8	6	2	-8

9.2.3 Wales

Table 12 Annual area (kha) of land use and activity by scenario for Wales (required areas are the areas of agricultural land to maintain current food production per capita)

a) BAU

Categories	2020	2030	2035	2040	2050
Required land areas					
Cropland	93	97	98	99	102
Forest Land	347	350	351	352	355
Permanent Grassland	1136	1163	1175	1186	1206
Rough Grassland	439	450	455	459	467
Settlement	109	114	116	117	120
Temporary Grassland	163	167	169	170	173
Afforestation	0	3	4	6	9
Hedges and Agroforestry	0	0	0	0	0
Bioenergy	0	0	0	0	0
Peatland restoration	0	0	0	0	0

b) Headwinds

Categories	2020	2030	2035	2040	2050
Required land areas					
Cropland	93	89	87	85	80
Forest Land	349	396	422	447	499
Permanent Grassland	1136	1054	1028	1002	935
Rough Grassland	439	367	326	285	201
Settlement	109	114	116	117	120
Temporary Grassland	163	151	147	143	133
Afforestation	3	50	76	101	153
Hedges and Agroforestry	0	5	8	11	16
Bioenergy	0	8	20	32	56
Peatland restoration	0	12	19	25	38

c) Widespread Engagement

Categories	2020	2030	2035	2040	2050
Required land areas					
Cropland	93	90	88	86	81
Forest Land	349	409	465	527	653
Permanent Grassland	1136	910	838	763	579
Rough Grassland	439	327	282	236	129
Settlement	109	114	116	117	120
Temporary Grassland	163	130	119	108	81
Afforestation	3	63	118	181	307
Hedges and Agroforestry	0	12	19	27	41
Bioenergy	0	1	2	3	4
Peatland restoration	0	15	24	32	41

d) Widespread Innovation

Categories	2020	2030	2035	2040	2050
Required land areas					
Cropland	93	85	80	74	62
Forest Land	349	406	449	492	578
Permanent Grassland	1136	883	790	697	479
Rough Grassland	439	308	248	188	58
Settlement	109	114	116	117	120
Temporary Grassland	163	126	112	98	66
Afforestation	3	60	103	146	233
Hedges and Agroforestry	0	8	13	18	28
Bioenergy	0	19	48	77	135
Peatland restoration	0	15	24	32	42

e) Balanced Net Zero Pathway

Categories	2020	2030	2035	2040	2050
Required land areas					
Cropland	93	94	95	96	101
Forest Land	349	396	425	468	554
Permanent Grassland	1136	910	882	852	772
Rough Grassland	439	308	265	223	134
Settlement	109	114	116	117	120
Temporary Grassland	163	129	125	121	109
Afforestation	3	50	79	122	208
Hedges and Agroforestry	0	9	14	19	30
Bioenergy	0	8	20	32	56
Peatland restoration	0	15	24	32	41

f) Tailwinds

Categories	2020	2030	2035	2040	2050
Required land areas					
Cropland	93	85	79	74	62
Forest Land	349	407	461	522	644
Permanent Grassland	1136	883	789	694	469
Rough Grassland	439	308	247	187	55
Settlement	109	114	116	117	120
Temporary Grassland	163	126	112	98	65
Afforestation	3	61	115	176	298
Hedges and Agroforestry	0	12	19	27	41
Bioenergy	0	19	48	77	135
Peatland restoration	0	15	24	32	41

Table 13: Emissions by scenario and mitigation measure for 2020, 2030, 2035, 2040, 2050 for Wales in Mt CO_2e

a) BAU

Categories	2020	2030	2035	2040	2050
Forestry	-1	-1	-1	-1	-1
Agricultural LUC	0	0	0	0	0
Bioenergy	0	0	0	0	0
Hedges and Agroforestry	0	0	0	0	0
Peatland mitigation	1	1	1	1	1
Urban Expansion	1	0	0	0	0
Grand Total	6	6	6	6	6

b) Headwinds

Categories	2020	2030	2035	2040	2050
Forestry	-1	-2	-2	-2	-3
Agricultural LUC	0	0	0	0	0
Bioenergy	0	0	0	0	-1
Hedges and Agroforestry	0	0	0	0	0
Peatland mitigation	1	1	0	0	0
Urban Expansion	1	0	0	0	0
Grand Total	6	5	5	4	2

c) Widespread Engagement

Categories	2020	2030	2035	2040	2050
Forestry	-1	-1	-2	-2	-4
Agricultural LUC	0	0	0	0	0
Bioenergy	0	0	0	0	0
Hedges and Agroforestry	0	0	0	0	0
Peatland mitigation	1	0	0	0	0
Urban Expansion	1	0	0	0	0
Grand Total	6	5	4	2	-1

d) Widespread Innovation

Categories	2020	2030	2035	2040	2050
Forestry	-1	-2	-2	-3	-4
Agricultural LUC	0	0	0	0	0
Bioenergy	0	0	-1	-1	-2
Hedges and Agroforestry	0	0	0	0	0
Peatland mitigation	1	0	0	0	0
Urban Expansion	1	0	0	0	0
Grand Total	6	4	2	1	-3

e) Balanced Net Zero Pathway

Categories	2020	2030	2035	2040	2050
Forestry	-1	-1	-2	-2	-3
Agricultural LUC	0	0	0	0	0
Bioenergy	0	0	0	0	-1
Hedges and Agroforestry	0	0	0	0	0
Peatland mitigation	1	0	0	0	0
Urban Expansion	1	0	0	0	0
Grand Total	6	5	4	3	1

f) Tailwinds

Categories	2020	2030	2035	2040	2050
Forestry	-1	-2	-2	-3	-5
Agricultural LUC	0	0	0	0	0
Bioenergy	0	0	-1	-1	-2
Hedges and Agroforestry	0	0	0	0	0
Peatland mitigation	1	0	0	0	0
Urban Expansion	1	0	0	0	0
Grand Total	6	4	2	1	-4

9.2.4 Northern Ireland

Table 14: Annual area (kha) of land use and activity by scenario for Northern Ireland (required areas are the areas of agricultural land to maintain current food production per capita)

a) BAU

Categories	2020	2030	2035	2040	2050
Required land areas					
Cropland	45	46	47	48	49
Forest Land	115	117	118	119	121
Permanent Grassland	664	689	699	708	725
Rough Grassland	180	187	189	192	196
Settlement	66	71	72	73	76
Temporary Grassland	150	155	158	160	164
Afforestation	0	2	3	4	6
Hedges and Agroforestry	0	0	0	0	0
Bioenergy	0	0	0	0	0
Peatland restoration	0	0	0	0	0

b) Headwinds

Categories	2020	2030	2035	2040	2050
Required land areas					
Cropland	45	35	29	23	11
Forest Land	116	129	137	144	159
Permanent Grassland	664	616	599	581	534
Rough Grassland	180	145	123	101	56
Settlement	66	71	72	73	76
Temporary Grassland	150	139	135	131	120
Afforestation	1	17	25	34	51
Hedges and Agroforestry	0	5	8	11	16
Bioenergy	0	5	13	21	36
Peatland restoration	5	76	112	122	142

c) Widespread Engagement

Categories	2020	2030	2035	2040	2050
Required land areas					
Cropland	45	22	11	0	-22
Forest Land	116	134	151	171	211
Permanent Grassland	664	513	462	409	278
Rough Grassland	180	128	106	83	30
Settlement	66	71	72	73	76
Temporary Grassland	150	115	104	92	62
Afforestation	1	21	39	60	102
Hedges and Agroforestry	0	10	15	21	32
Bioenergy	0	0	1	1	2
Peatland restoration	5	82	121	134	152

d) Widespread Innovation

Categories	2020	2030	2035	2040	2050
Required land areas					
Cropland	45	17	3	-12	-43
Forest Land	116	133	146	159	186
Permanent Grassland	664	497	434	371	220
Rough Grassland	180	117	86	55	-11
Settlement	66	71	72	73	76
Temporary Grassland	150	112	98	83	49
Afforestation	1	20	34	49	78
Hedges and Agroforestry	0	7	11	15	22
Bioenergy	0	12	31	50	88
Peatland restoration	5	82	121	135	152

e) Balanced Net Zero Pathway

Categories	2020	2030	2035	2040	2050
Required land areas					
Cropland	45	27	24	23	23
Forest Land	116	129	138	151	178
Permanent Grassland	664	512	495	477	426
Rough Grassland	180	117	95	73	27
Settlement	66	71	72	73	76
Temporary Grassland	150	115	111	107	96
Afforestation	1	17	26	41	69
Hedges and Agroforestry	0	8	12	17	26
Bioenergy	0	5	13	21	36
Peatland restoration	5	82	121	134	152

f) Tailwinds

Categories	2020	2030	2035	2040	2050
Required land areas					
Cropland	45	17	3	-12	-43
Forest Land	116	133	150	169	208
Permanent Grassland	658	622	593	562	501
Rough Grassland	180	117	86	55	-12
Settlement	66	71	72	73	76
Temporary Grassland	150	112	98	83	48
Afforestation	1	20	38	59	99
Hedges and Agroforestry	0	10	15	21	32
Bioenergy	0	12	31	50	88
Peatland restoration	5	82	121	134	152

Table 15: Emissions by scenario and mitigation measure for 2020, 2030, 2035, 2040, 2050 for Northern Ireland in Mt CO_2e

a) BAU

Categories	2020	2030	2035	2040	2050
Forestry	0	0	0	0	0
Agricultural LUC	0	0	0	0	0
Bioenergy	0	0	0	0	0
Hedges and Agroforestry	0	0	0	0	0
Peatland mitigation	2	2	2	2	2
Urban Expansion	1	1	1	1	0
Grand Total	9	9	9	9	8

b) Headwinds

Categories	2020	2030	2035	2040	2050
Forestry	0	0	0	0	-1
Agricultural LUC	0	0	0	0	0
Bioenergy	0	0	0	0	0
Hedges and Agroforestry	0	0	0	0	0
Peatland mitigation	2	2	2	2	1
Urban Expansion	1	1	1	1	0
Grand Total	9	8	7	7	6

c) Widespread Engagement

Categories	2020	2030	2035	2040	2050
Forestry	0	0	0	-1	-1
Agricultural LUC	0	0	0	0	0
Bioenergy	0	0	0	0	0
Hedges and Agroforestry	0	0	0	0	0
Peatland mitigation	2	2	1	1	1
Urban Expansion	1	1	1	1	0
Grand Total	9	7	6	5	3

d) Widespread Innovation

Categories	2020	2030	2035	2040	2050
Forestry	0	0	0	-1	-1
Agricultural LUC	0	0	0	0	0
Bioenergy	0	0	0	-1	-1
Hedges and Agroforestry	0	0	0	0	0
Peatland mitigation	2	2	1	1	1
Urban Expansion	1	1	1	1	0
Grand Total	9	6	5	4	2

e) Balanced Net Zero Pathway

Categories	2020	2030	2035	2040	2050
Forestry	0	0	0	0	-1
Agricultural LUC	0	0	0	0	0
Bioenergy	0	0	0	0	0
Hedges and Agroforestry	0	0	0	0	0
Peatland mitigation	2	2	1	1	1
Urban Expansion	1	1	1	1	0
Grand Total	9	7	6	6	5

f) Tailwinds

Categories	2020	2030	2035	2040	2050
Forestry	0	0	0	-1	-1
Agricultural LUC	0	0	0	0	0
Bioenergy	0	0	0	-1	-1
Hedges and Agroforestry	0	0	0	0	0
Peatland mitigation	2	2	1	1	1
Urban Expansion	1	1	1	1	0
Grand Total	9	6	5	4	2

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